Composing Music from Neuronal Activity: The Spikiss Project

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Abstract We describe here an attempt to compose music, constrained by recordings of brain activity where excitatory and inhibitory neurons were discriminated and used to trigger simple tones or more complex sounds. We used experimental recordings of brain activity under the form of "spikes", recorded with microelectrodes in human subjects. The recordings come from different sources, which have been all published in the neuroscience literature. We emphasize here the natural rhythmical activity of neurons, in particular, that of inhibitory neurons. Inhibitory neurons are thus naturally suited for driving bass sounds and rhythmic sections. The sparser activity of excitatory neurons is exploited here to reveal melodic capabilities, which are sometimes exacerbated by subjective choice of scales and tones. We explain step by step how this can be done and provide examples of musical sequences and tracks composed from neuronal activity during different brain states, such as wakefulness, deep sleep, or paradoxical sleep (dreaming). We suggest to extend this approach to more global signals, such as the electroencephalogram or neuroimaging signals.

Introduction

Making music from brain activity has a long tradition, with the first attempt dating back from Adrian and Matthews (1934), who listened to the electroencephalogram (EEG) translated directly to an (analog) audio signal. Another pioneering approach was the experience of Alvin Lucier using EEG for composing his "Music for Solo Performer" (1965), often referred to as the "brain wave piece." In this setup, the

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brain waves of a solo performer were made to excite percussion instruments. Since then, there were many attempts to translate EEG activity into some form of music. For the majority of these approaches, the musical transduction was generated by filtering the EEG in the different frequency bands, such as delta (0.5–4 Hz), alpha (8–12 Hz), beta (15–25 Hz), and gamma (40 Hz and higher). The signal in the frequency band is quantified in amplitude, power, duration, and these signals are used to drive or modulate musical compositions. For example, notes can be triggered by the instantaneous power in each frequency band. A recent study by Lu et al. (2012) followed this classic procedure to generate music using different frequency bands in the EEG and found that it had a strong random character and was not very enjoyable. They found that using another type of signal (from functional Magnetic Resonance Imaging, fMRI), the music obtained corresponded better to the type of music we are used to listen and was more enjoyable. Today, there are many commercial and free systems to propose this approach with affordable portable EEG devices.[1]

Brain music can also be made from discrete signals, such as the activity of single neurons. Conventionally, for researcher in electrophysiology, the derivation of the activity of a single neuron recorded by an electrode into an audio amplifier is well known to greatly help the identification and discrimination of neuronal sources by ear, much more than from visual inspection onto an oscilloscope. Moreover, several theoretical and experimental works reveal the synergetic interactions between neural cells as a way to be gathered into neural assemblies for particular perceptive and cognitive coding and then insist on their synchronous ("or co-rythmhic") properties (Gray et al. 1989; von der Marlsburg 1994). One of the first "sonification" of direct activity from neurons was due to Rodolpho Llinas (shown in a conference in Knokke, Belgium, 1986) and consisted of different "beeps" triggered by the activity of different simultaneously recorded neurons in cerebellum. A similar idea was simultaneously implemented by the group of Ad Aertsen based on monkey unit recordings in cerebral cortex (Aertsen and Erb 1987), an approach called the "neurophone." There are also various other old and more recent examples of sonification of brain activity that can be found.[2]

Music from neurons can also be used as a way to "visualize" the activity in different states of the brain. An attempt called "Neuronal Tones" was published on the *Internet Archive* by Alain Destexhe in 2006 (http://www.archive.org/details/NeuronalTones). This computer-generated music was based on recordings of multiple neurons with microelectrodes in cats during wakefulness and sleep (Destexhe et al. 1999). A given neuron was associated with a fixed tone, and every time this neuron fires, a note is emitted. The music produced gives an idea about the

[1]For example, see the "MindMidi" approach (http://www.mindmidi.com), which is free and produces quite enjoyable music from the EEG. A short recent article reviewing the most interesting attempts to produce or compose music from EEG derived signals can be found here: https://creators.vice.com/en_us/article/10-pieces-of-music-created-by-brainwaves.

[2]for example, see the proceedings of the "International Conference on Auditory Display," ICAD, http://www.icad.org, which is running regularly since 1992.

distributed firing activity of those neurons. The "Neuronal Tones" compares brain activity not only in different wake–sleep states but also with randomly generated notes with the same statistics. Interestingly, the firing of one isolated neuron during wakefulness is undistinguishable from that of random (Poisson) activity, but the distributed activity (i.e., the "melody") in synergy with the group of many recorded neuron is clearly different. This suggests that what makes our brains non-random is not in the firing pattern but lies in the respective timing of the firing activity between different neurons.

In the more recent "Neuronal Melodies," the same approach was applied to human neuron recordings and was published on the *Internet Archive* by Alain Destexhe in 2012 (http://www.archive.org/details/NeuronalMelodies). Here, a dataset of 92 neurons was used—these neurons were simultaneously recorded in the temporal cortex of human subjects, and the main originality of these data is that excitatory and inhibitory neurons could be discriminated (Peyrache et al. 2012; Dehghani et al. 2016). This allowed us to create a musical sequence with two instruments, a woodblock for excitatory neurons and a xylophone for inhibitory cells. From these melodies, one can hear that the distributed firing activity is almost identical during dreaming compared to wakefulness, which emphasizes the high similarity between these two different brain states. These human neuronal melodies were constructed during wakefulness, slow-wave sleep and REM sleep, as well as during an epileptic seizure. In the "seizure melody," the activity starts with normal "Wake" activity, following by an epileptic (focal) seizure, which can be heard very well while listening to that melody.

In the present chapter, we illustrate a different approach, based on the same data (Peyrache et al. 2012; Dehghani et al. 2016; see Fig. 1). Instead of uniformly converting neurons to notes, as in the approaches reviewed here, we have made a more complex conversion by associating selected groups of neurons to different scales and tones, based on the similarity of their rhythmical activity. The goal is here not to study neuronal activity, but to use neuronal activity to drive music composition. This is called the "Spikiss Project" (Destexhe and Foubert 2016a, b).[3]

A Brief Overview of Different Brain Songs

We start by an overview of different tracks created from human brain activity, and next we explain in detail how these sequences were constructed.

[3]Note that the present musical work was published early 2016 on the *Internet Archive* (https://archive.org/details/Spikiss, https://archive.org/details/Spikiss-Sleep, https://archive.org/details/Spikiss-Rem) as well as on *SoundCloud* (https://soundcloud.com/search?q=spikiss). A similar approach called "Neuron Song" was also proposed later in 2016 by Kristin Klark based on patch-clamp recordings (https://www.youtube.com/playlist?list=PLIgiB4tiZmmSF8_m69Z_PbLfxiCEqGO8E) and also aimed at creating music based on brain recordings.

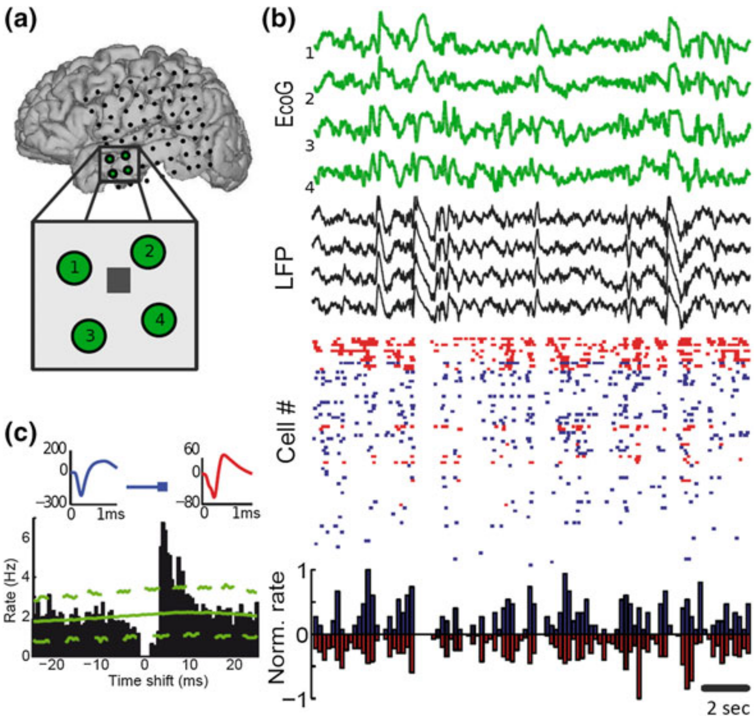

Fig. 1 Human recordings of excitatory and inhibitory neurons. **a** Implantation of an array of microelectrodes in the human temporal cortex. **b** Example of signals obtained with the array, during a period of slow-wave sleep. The surface recordings are shown in green (EcoG) and in black the recording in depth (local field potential, LFP). The red and blue dots show the firing of individual neurons (Cells: red = inhibitory, blue = excitatory; population activity shown in the bottom graph). **c** Example of functional identification of excitatory and inhibitory cells from cross-correlograms. Modified from Peyrache et al. 2012, where all details can be found

"Wake Beats"—Music from the Awake Brain[4]

The first song we illustrate is based on recordings of single neurons in the awake human brain. In particular, we have used recordings where it was possible to formally identify excitatory from inhibitory neurons, and the corresponding spikes were used to drive music. Of course, this was made under certain arbitrary rules or subjective choices to make the music enjoyable.

As explained in section "Detailed Description on How to Generate Brain Songs from Excitatory and Inhibitory Neurons", the principle is that the timing of the spike is used to trigger a given sound. This is done in such a way that each neuron has its own, private sound. This sound can be a bass, a percussion, or something more melodic such

[4]The "Wake Beats" song can be listened at http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20Wake%20Beats.mp3 .

as bells, xylophone. The inhibitory ("fast spiking") neurons are generally more rhythmic and can be used to drive the bass and drum sections. The excitatory ("regular spiking") neurons fire more sparsely and are more appropriate for the melodic sections.

In the first part of the track (first minute), the activity of the different neurons is strictly respected, as well as the respective timing of the spikes of the different cells. However, in the second part (starting after the first minute), we have followed a different strategy using loops to be anchored on the signature/tempo grid. This second strategy was explored as a naive intuition from contemporary electronic music that rigid quantized loops would sound better. Thus, we have selected, from the neuronal activity, periods where the activity of the neurons was particularly rhythmic and interesting (based on totally subjective criteria!). We have isolated these periods, defining "loops" that can be played several times and in any order. This was done for the different sections, such as the bass and rhythmic activity, as well as for the melodic activity. In addition, we have used more sophisticated sounds from analog and/or digital synthesizers. So in this second part, the respective timings of one cell against another were not always respected, but all the music events are driven by neuronal activity.

This illustrates the power of neuronal activity to generate music. Neurons follow collective dynamics and have correlations with each other, and fire together within an ensemble activity which is complex, but not random. Neurons also display marked rhythmic properties, especially for inhibitory neurons which naturally form rhythmic and bass sections.

Note that in this example, all neurons considered were simultaneously recorded by a system of 100 microelectrodes, and the activity was slowed down by about 30%. A natural but slightly fluctuating subjective tempo was estimated around 140 BPM at which data were imported in the sequencer but then slowed down by playing the overall sequence at 110 bpm as a global ~30% time stretch.

"Slow Waves"—Music from the Sleeping Brain[5]

This second track was composed from neurons recorded in humans, during slow-wave sleep. For this track, we decided to come to the initial strategy constraining all respective timing of spikes events among each other thus avoiding "loops" in order to keep the hidden synergy and rhythmicity between cells. A major problem occurring here is then the complete disconnection between all spike-triggered events with the rigid signature/tempo grid used as a container substrate in the sequencer. As above, data were imported at a natural tempo estimated around 140 and slowed down at 110 with this impossibility to lock a precise metronome on the sequence because of a slightly drifting tempo but having the

[5]The "Slow Waves" song can be listened at http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20Slow%20Waves.mp3 .

enjoyable surprise of a more natural sounding interplay between events. As above also, the inhibitory neurons form the rhythmic sections, while excitatory neurons drive the melodic parts. Unlike wakefulness, the activity consists of "Up" and "Down" states, where the neurons oscillate slowly between active and silent periods. We have exploited these dynamics and used slow sound envelopes to follow the modulations the slow waves of sleep.

In the first seconds of the song, one can hear very well the "Up/Down" states typical of sleep, because the bass fires in intermittency, so do all neurons. The slow sounds were driven by excitatory neurons. In the second part of the song, we have used two versions of the slow envelopes ("Woo-Woo"), with major and minor scales, then back to major. The third part (second half of the song), used further slow sounds, mixed with neuronal activities. Note that here, there were no "loops," the respective timings of the different neurons were strictly respected.

See details in section "Generating Songs from the Sleeping Brain".

"REMiniscence"—Music from the Dreaming Brain[6]

This third song was composed from neurons recorded in humans, during paradoxical sleep, also called "rapid eye movement sleep" or "REM sleep." The REM activity is very similar to wakefulness, but we wanted to make it sound a bit different. So we have emphasized the rhythmic sections, still made from inhibitory neurons, and use the excitatory neurons to drive melodic instruments like bells or sounds that evoke the strangeness of dreams. For this track, we defined a third tempo strategy by directly stretching all imported events by exactly the same amount in order to keep their coherence and to approximately match a signature/tempo grid played at 110 bpm. This helps to synchronize BPM-driven effect such as delays and includes external rhythmic loops to enrich the final mix as a taste of exploration.

In the first part of the song (first 2:30 min), the rhythmic section made by inhibitory neurons is emphasized, together with the melodic section made by excitatory neurons (bells and voices). In the second part of the song (up to 3:25 min), the rhythmic section is now accompanied with bells and a drum kit to form a particularly rhythmic ensemble. In the third part, excitatory neurons drive a synthesizer, along with slower sounds and voices which illustrate the strangeness of dreams. The timing between the different neurons was in general respected all through the song. See details in section "Songs from the Dreaming Brain".

The same approach can be followed using recordings of neurons during different brain states, such as different stages of sleep or epileptic seizures for example. It is also possible to consider other signals such as the electroencephalogram (EEG) or the local field potential (LFP) as we are currently working onto.

[6]The "REMiniscence" song can be listened at http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20REMiniscence.mp3.

Detailed Description on How to Generate Brain Songs from Excitatory and Inhibitory Neurons

We now explain how we have translated human brain activity into music. In the song "Wake Beats," we have used recordings at the level of single neurons in human subjects, and in particular, we have used the spikes from identified excitatory or inhibitory neurons, to drive music. Of course, this was made under certain arbitrary rules and subjective choice made on tones and scales mappings to make the music enjoyable! We explain how we have done this step by step.

Recordings of Single Neurons

We provide here some general explanation for the non-specialist, about the type of signals that we use in our project. If you are familiar with neural recording techniques, you can skip this section.

Neurons emit electrical impulses called "spikes." These electrophysiological events show very precise timing (less than 1 ms) and are used by neural cells to transfer local activities through wide communication networks. These dense interplays are also likely used to gather different assemblies of cells into synergetically reconfigurable ensembles. These spiking events can be recorded using microelectrodes, as typically shown in Fig. 2. This example shows the signals from four microelectrodes, during a few seconds. In these four simultaneous recordings,

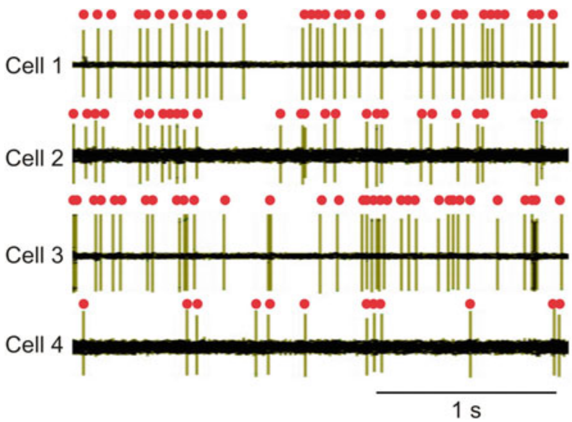

Fig. 2 Example of neuronal activity recorded by four microelectrodes in the brain. The four signals shown come from four different microelectrodes, each of which detects the impulse activity (spike) from a different neuron. The four different simultaneously recorded neurons are labeled "Cell 1" to "Cell 4." For each cell, the spikes are seen as sharp and brief deflections (vertical green bars). The red dots on the top of each signal indicate the time of each spike

one can see very well spikes which appear as vertical deflections (green also indicated by red dots). Each one of these spikes is generated here by a single neuron, and one different neuron is seen by each electrode, so we see here the activity of four neurons altogether.

The electrophysiologists routinely record neurons with such microelectrodes. Instead of representing the full signal, as in Fig. 2, it is more compact to detect the spikes numerically (red dots) and display them as a series of dots, as represented in Fig. 1b (blue and red dots; see also red dots in Fig. 2). Such a compact representation only contains the timing of the different spikes of each cell and is called a "raster." We will see below more examples of such rasters.

How to Convert Neural Recordings into Music?

To convert neural recordings into music, and in particular spikes recordings, we will proceed by examples. We take advantage of the fact that neuron spikes are impulses, well defined in time, so we can use them to trigger particular musical "events". These events are traduced through the MIDI protocol as "notes" having fixed length and fixed velocity and mapped onto the keyboard (initially, white keys of the C-major diatonic scale) in a random order of cells identification (from 1st to 100th cell). This MIDI mapping into a sequencer framework (Ableton, Live9 software) will allow easy affectations and routings of each event to any kind of sound synthesis by conventional MIDI manipulations. This way, when a neuron emits a spike, a sound is played, in a way that each neuron has his private sound, as shown in the examples below.

Example 1 As a first example, let us consider one single neuron (e.g., "Cell 2" above). One can select a "bass" sound and play this sound each time the neuron emits a spike.

To listen to that example, click on "Bass Neuron" (http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20Bass%20Neuron.mp3).

Example 2 Let's try now a more complicated combination, where four different neurons are played simultaneously. To keep its identity, each neuron will play a different percussion sound with a "drum kit" mapped on the keyboard. The raster of these four neurons is shown in Fig. 3.

These neurons were chosen because they are particularly rhythmic. They are all inhibitory ("fast spiking") neurons. To listen to that example, click on "Drum kit Neurons" (http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20Drumkit%20Neurons.mp3).

The rhythmical character of these neurons is quite striking!

Example 3 We now take five different neurons, corresponding to the raster shown in Fig. 4.

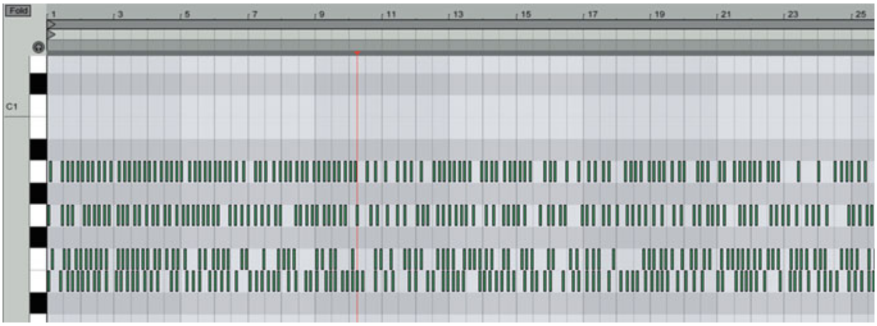

Fig. 3 Raster of four inhibitory neurons in an awake human subject, mapped on the C-major diatonic scale

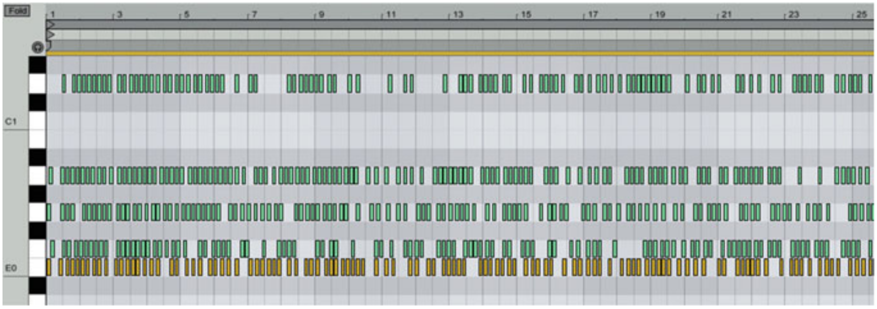

Fig. 4 Raster of five neurons in an awake human subject (C-major diatonic scale). Similar to Fig. 3, these neurons are inhibitory

We now associate these neurons to a “steel drum” sound, and each neuron corresponds to one note on the steel drum mapped on major scale. In other words, each time the neuron spikes the note specific to that neuron is played once. Thus, each neuron has its own note, and the melody is here created here by five neurons playing together on a steel drum.

To listen to that example, click on “Steel drum Neurons” (http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20SteelDrum%20Neurons.mp3).

Example 4 In this example, we show that same scale mapping but other sounds than percussion are possible. For example, one can take a slow sound (with a slow attack and a long decay time) and associate this sound to the same neurons as in Example 3. Similarly, each neuron still has its own note.

To listen to that example, click on “Woo-woo Neurons” (http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20WooWoo%20Neurons.mp3).

Example 5 We can now try to combine some of the examples above. Combining Example 1 (single bass) with Example 4 (woo-woo) gives a more elaborated combination.

To listen to that example, click on “Woo-woo and Bass” (http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20WooWoo%20and%20Bass%20Neurons.mp3).

Example 6 Still going further in complexity, let us now consider the activity of 14 excitatory neurons, which correspond to the raster shown in Fig. 5.

In this example, spikes (or “event”) from the pool of about 80 excitatory cells have been randomly affected and mapped onto the C-major scale. Because of the too many events of high density mapped on the wide tessitura of the 88 notes keyboard produces a very unpleasant “musical overload,” we selectively discard cells (or lines on the raster plot/keyboard) either by random and/or by subjective aesthetic selection/deletion. Let us now associate these neurons to an instrument, a synthetic bell. As above, to keep track of the neuron’s identity, we assign a specific note to each neuron, and that note is played once when this neuron fires a spike. To listen to that example, click on “Neuronal Bells” (http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20Neuronal%20Bells.mp3).

Example 7 Finally, to illustrate a first combination of several instruments, we combined the examples above into a mix. To listen to that example, click on “Neural mix” (http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20Neural%20Mix.mp3).

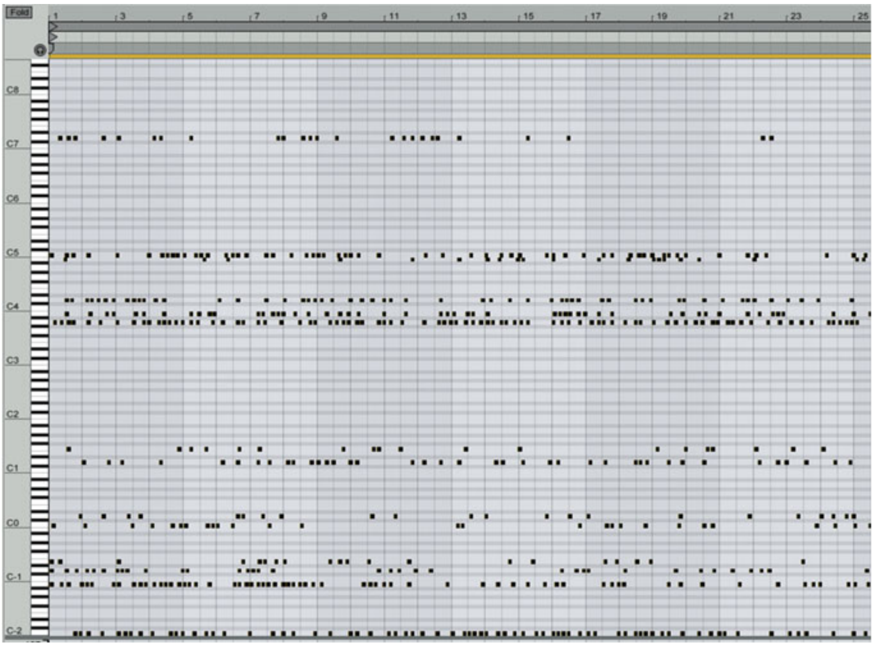

Fig. 5 Raster of 14 neurons in an awake human subject, mapped on the C-major diatonic scale. These neurons are all excitatory (“regular spiking”) neurons, and they were selected among a larger set of neurons

In this example, all neurons considered were simultaneously recorded by a system of 100 microelectrodes. Also note that in all of the above, the activity was slowed down by about 30% compared to real-time. This is the strategy used for the first part of the song http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20Wake%20Beats.mp3 (first minute). As described above, the respective timing between different neurons is strictly respected, as well as the respective timing of the spikes of the different cells. In the second part, we defined "loops" by selecting some moments where the activity was particularly rhythmic. These loops were replayed at different times, and thus in this case, the respective timing of the different neurons was not respected, although each instrument was played from neuronal activity (this strategy was abandoned for the following tracks in order to keep the prevalent coherence between cells events).

Generating Songs from the Sleeping Brain

We now explain how we have translated human brain activity into music, for recordings made while the subject was sleeping, in the deep "slow-wave sleep" phase. This corresponds to the song "Slow Waves" (http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20Slow%20Waves.mp3).

Excitatory Neuronal Activity During Slow-Wave Sleep

The principal difficulty with sleep recordings is that unlike during wakefulness, the neurons' activities are not sustained, but they occur through "waves" of activity, separated by "pauses" where the neurons are silent. This intermittent dynamics, often called "Up" and "Down" states, are paralleled with the production of slow waves in the brain, hence the term "slow-wave sleep." An example of this activity is depicted in the raster of Fig. 6.

One can see very well the different waves, which appear as vertical structures (between 10 and 20 waves are visible). To listen to that example, click on "Sleeping Bells" (http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20Sleeping%20Bells.mp3).

One can hear very well the intermittent character of the neuronal spikes (compare with the similar sound during wakefulness, "Neuronal Bells"; http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20Neuronal%20Bells.mp3).

Even if this intermittency may seem problematic at first sight, it can be exploited to obtain nice musical effects. For instance, one can play the excitatory cells above to a slow sound. To listen to that example, click on "Sleeping Waves" (http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20Sleeping%20Waves.mp3).

This gives a clear impression of slow "waves," and indeed they are entirely generated by the neuronal activity of a sleeping subject.

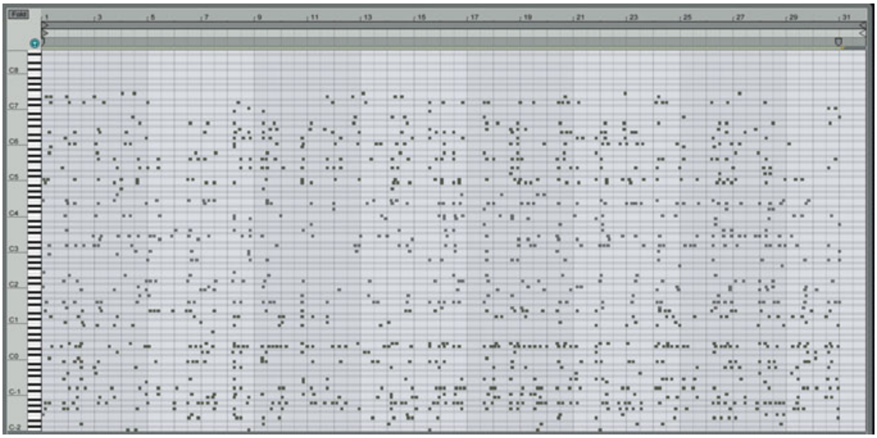

Fig. 6 Raster of excitatory neurons during slow-wave sleep. One can see very well vertical bands, which shows that there are many silences in the activity. The neurons were mapped on the C-major diatonic scale

We can also use sounds intermediate between fast and slow, which allow us to better hear the melody played by neurons. To listen to that example, click on "Sleeping Mid-Waves" (http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20Sleeping%20Mid-Waves.mp3).

These are all generated from the same set of excitatory neurons. Notice that as described in section "A Brief Overview of Different Brain Songs", for this track, absolutely no quantization has been applied on these events so the signature/tempo grid is here completely irrelevant and no metronome-click nor any bpm effect could be synchronized here with this track.

Activity of Inhibitory Neurons During Slow-Wave Sleep

The intermittent character of neuronal discharges during sleep also applies to inhibitory cells. The activity of 11 inhibitory neurons during sleep is displayed in the raster of Fig. 7.

Selecting the four most rhythmic inhibitory neurons from this example, one can play them on a bass (http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20Sleeping%20Bass.mp3) or on a drum kick (http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20Sleeping%20Kick.mp3). Here also, one can clearly hear that the intermittent character is also present in inhibitory cells, but it does not alter their rhythmic capabilities.

Taking five neurons from this group, one can also use the same slow sound as for wakefulness (the "Woo-Woo"), mapping them on either a major scale (http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20Sleeping%20Major-Woo.mp3) or on a

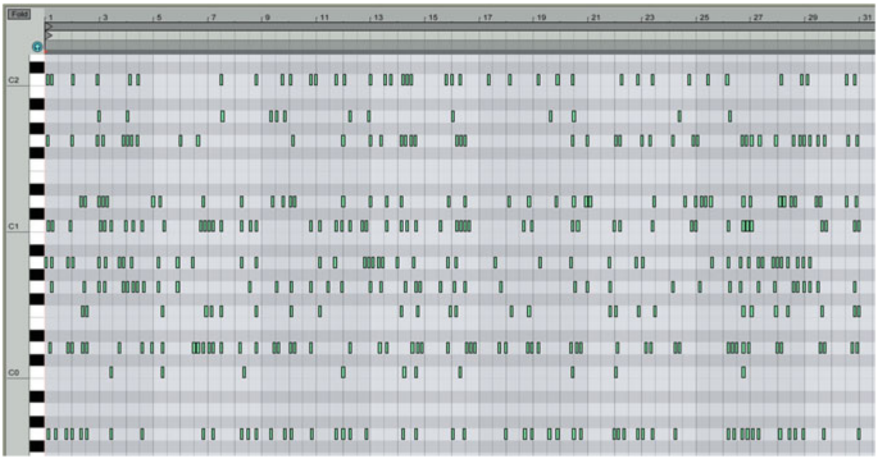

Fig. 7 Raster of 11 inhibitory neurons in a sleeping human subject (C-major diatonic scale)

minor scale (http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20Sleeping%20Minor-Woo.mp3). Here again, one can hear very well the intermittent character of the neuronal discharges during sleep.

These different elements were assembled to compose the track "Slow Waves" (http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20Slow%20Waves.mp3). Here, the first 2 min was made from the sounds described above.

By listening to this song, one can clearly hear that the intermittent character of neuronal discharges is well coordinated between cells. This coordination makes the music coherent because all sounds are modulated by the same envelope; this envelope corresponds to the "slow waves" of sleep, which we hear musically.

Similar to the first part of the Wake Beats track, the activity of the different neurons is strictly respected, as well as the respective timing of the spikes of the different cells, but here for the whole duration of the track. In the last part of the song (after the second minute), different slow sounds were used to further augment the impression of "slow waves." Here again, all the musical events come from neuronal activity.

Songs from the Dreaming Brain

We now describe how we have composed a song based on the activity of the dreaming brain, using recordings made while the subject was sleeping, in the "rapid eye movement" (REM) sleep, also called "paradoxical sleep," where most dreams occur. This corresponds to the song "REMiniscence" (http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20REMiniscence.mp3).

Excitatory Neuronal Activity During REM Sleep

One of the most striking features of REM sleep is that the activity of the brain is very similar—almost undistinguishable—from that during wakefulness. Like in the waking state, the activity of neurons is very irregular and asynchronous. We recorded neurons during REM sleep, and 14 excitatory neurons were played on synthetic bells. To listen to that example, click on "Dreaming Bells" (http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20Dreaming%20Bells.mp3). One can hear very well the irregular aspect of the neuronal spikes (compare with the similar sound during wakefulness, "Neuronal Bells," http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20Neuronal%20Bells.mp3).

One can also play the excitatory cells above to a very high sound, like that of clochettes (small bells). In that case, 18 excitatory neurons were used. To listen to that example, click on "Dreaming Clochettes" (http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20Dreaming%20Clochettes.mp3). We can also use bell sounds at more medium frequencies, using 18 other excitatory cells. This complements very well the clochettes. To listen to that sound, click on "Dreaming midBells" (http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20Dreaming%20midBells.mp3). As done in other songs, one can also use excitatory neurons to drive slow sounds. For example, one can take one of the sets of 18 excitatory neurons played on the same slow "Woo-Woo" sound considered in Wake Beats, click on "Dreaming Woo" (http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20Dreaming%20Woo.mp3).

Finally, to better illustrate the strangeness of dreams, we also have used sounds that remind this strange character, such as voices (also from 18 neurons). To listen to that sound, click on "Dreaming Voices" (http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20Dreaming%20Voices.mp3). We also used other sounds that remind screams (from the same set of 18 neurons). To listen to that sound, click on "Dreaming Screams" (http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20Dreaming%20Screams.mp3). These are all generated from the same ensemble of excitatory neurons, split into groups of 18 cells.

Activity of Inhibitory Neurons During REM Sleep

Like in other brain states, the inhibitory neurons are very rhythmic, and we can exploit this rhythmicity to form the bass and drum sections. In the REM sleep song, we have given a particular emphasis on this rhythmicity. As a first example, we have chosen a set of seven particularly rhythmic inhibitory cells and used these neurons to drive a drum kick. To listen to this sound, click on "Dreaming Kick" (http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20Dreaming%20Kick.mp3). To further enhance the rhythm, we have duplicated this kick and shifted the duplicate by about half a second, which yields a double kick, of particularly striking rhythmicity. To listen to this sound, click on "Dreaming Double Kick" (http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20Dreaming%20KickDouble.mp3).

Finally, we have used two very rhythmic inhibitory neurons to pilot a "Virus" type of synthesizer and tuned by hand the filtering of the sound. This provides a changing rhythm, which was also used in the rhythmic section. To listen to that sound, click on "Dreaming Virus" (http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20Dreaming%20Virus.mp3).

We have assembled all of the above sounds to compose a full song called "REMiniscence" (http://cns.iaf.cnrs-gif.fr/files/Spikiss%20-%20REMiniscence.mp3).

In this song, although the activity was very similar to that of wakefulness, we voluntarily made it sound very different. We explored in this track other scale mapping such as pentatonic or blues scale. We have emphasized the rhythmic character of the inhibitory neurons. Similar to the Wake Beats or Slow Waves songs, the activity of the different neurons is strictly respected, as well as the respective timing of the spikes of the different cells. Moreover, we defined for this track an optimal strategy to keep the coherence between all events and adapt the naturally fluctuating but subjective tempo of the cells ensemble activity to the rigid signature/grid of the sequencer. For this, we simply adapt by ears the stretching of all MIDI events selected all together to the most natural sounding metronome clock. Doing this way for each part of the song, the naturally drifting tempo of the cells assembly can be kept in sync and locked to a regular grid along several measures, and short repetitive sequences, loops, or bpm effect could be synchronized on the global sequence. Thus, we used few additional drum loops samples and an octave-pumping bass to enrich the final mix, but all the rest of the music comes from neuronal activity.

Conclusions and Perspectives

In this chapter, we have provided an overview of an approach to drive music composition from the activity of the brain. We have considered as example recordings of the human brain with microelectrodes. The particularity of these recordings is double: First, they provide unit recordings of single neurons, which is a rare opportunity to access single neuron activity in humans and in different brain states. But the most original aspect of these data is the fact that we could separate excitatory from inhibitory neurons, and that this separation was confirmed by direct neuron-to-neuron interactions (Peyrache et al. 2012). This type of data is very interesting and powerful to generate music, as it appears that inhibitory neurons are remarkably rhythmic and this rhythm is fundamental for this kind of musical composition.

It is important to note that contrary to previous approaches (Aertsen and Erb 1987; Destexhe 2006, 2012), where the music was used as a way to "visualize" neuronal activity, the present approach is aimed at generating musicality with an exploration of subjective aesthetics. The goal is to explore the melodic capabilities of neurons on different scales and exploiting their naturally rhythmic character. It must also be noted that each track described here ("Wake Beats," "Slow Waves," "REMiniscence") was composed with different criteria. It is thus not apparent that the neuronal activity is very similar between Wake and REM sleep, which is a fundamental feature found in animal recordings (Destexhe et al. 1999). This similarity can be found in the "Neuronal Tones" and "Neuronal Melodies" approaches (Destexhe 2006, 2012). Early attempts (Aertsen and Erb 1987) focused only on awake activity in monkey and did not compare with sleep stages. Future musical experiments will explore the remaining set of data recorded during the occurrence of epileptic seizures and the exploration of additional parameters in present in electrophysiological signals (LFPs) to drive other modulations in sound synthesis. Moreover, other scales and melodic modes such as Ionian, Dorian, Mixolydian, or Aeolian among others should also be explored further in conjunction with these recordings of neural activities.

Future approaches should examine other brain signals, such as the local field potential and electrocorticogram, which are also available in human microelectrode recordings. The electroencephalogram (EEG) and magnetoencephalogram (MEG) are also among possible signals to be exploited.

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