2016-06-10

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http://hdl.handle.net/10026.1/9545

Delatour & IRCAM Centre Pompidou

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1   Introduction

Musicians have an extraordinary opportunity today to develop new approaches to composition that would have been unthinkable a few years ago. Imagine if you could play a musical instrument with signals detected directly from your brain. Would it be possible to generate music representing brain activity? What would the music of our brains sound like? These are some of the questions addressed by research into Music Neurotechnology[1], which is an emerging field at the crossroads of music, technology and neuroscience.

There has been a great number of very interesting initiatives within the last decade or so to sonify brainwaves (Baier et al. 2007) some of which might indeed be useful for creative musical purposes (Hinterberger 2007). Also, the burgeoning field of Brain-Computer Music Interfacing (BCMI) is developing powerful methods to generate music in real-time by means of brainwave signals (Miranda 2014) some initiatives of which are even looking into harnessing the potential of biomedically uncertified low-cost equipment for BCMI applications (Grierson and Kieffer 2011). However, in this chapter we discuss an approach that goes beyond sonification of brainwaves and BCMI. We introduce algorithms that we have been developing to compose orchestral music off-line with fMRI[2] brain scans. The chapter is concerned with the impact of Music Neurotechnology to the field of Computer-Aided Composition (CAC).

As we are not concerned with real-time interaction here, we have an opportunity to take advantage of the fMRI brain scanning method. This method is deemed too cumbersome for real-time applications, but considerably more powerful and informative than EEG (electroencephalogram) scanning, which is the method used in sonification and BCMI research (Palaniappan 2014).

The composition methods introduced below were developed in OpenMusic, originally to generate materials for two symphonies by Miranda: *Symphony of Minds Listening* (2013) and *Corpus Callosum* (2015). And they were subsequently used to compose *Shockwaves* (2015) a violin concertino for orchestra. The discussions in this chapter will be mostly in the context of *Symphony of Minds Listening* and *Corpus Callosum*[3].

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[1] The term 'Music Neurotechnology', coined by Miranda and colleagues, appeared in print for the first time in 2009 in the editorial of *Computer Music Journal*, 33(1):1.

[2] fMRI stands for functional magnetic resonance imaging. It is a technique for measuring brain activity, which works by detecting the changes in blood oxygenation and flow that occur in response to neural activity. It works upon the principle that when a brain area is more active it consumes more oxygen and to meet this increased demand blood flow increases to the active area. fMRI can be used to show which parts of the brain are involved in a particular mental process.

[3] IRCAM's ATO-MS software was also used to compose *Corpus Callosum*, and Modalys and AudioSculpt were used in addition to ATO-MS and OpenMusic to compose *Shockwaves*.

We begin the chapter by briefly introducing Miranda's approach to composing with the aid of computers, focusing on using algorithmically generated materials. Then we introduce the compositions *Symphony of Minds Listening* and *Corpus Callosum*. Next, we focus on the technical details of collecting and handling fMRI data, followed by an overview of the OpenMusic patches that we developed for this project and an explanation of how ATO-MS was used to generate orchestrations based on fMRI information. The chapter ends with a brief concluding discussion and acknowledgements to contributors and sponsors.

2 On Computer-Aided Musical Creativity

In the book *Thinking Music*, Miranda (2014) says that every now and then he finds himself with an earworm stuck in his mind. Those earworms often are recognizable excerpts from music that he has heard before. Bur sometimes he is unable to clearly identify them. Would these unrecognizable earworms be new tunes, which his brain creates from scratch? Or would these be distorted versions of music that he might have heard before?

An earworm is popularly defined as a tune that our mind's ear cannot get rid of. However, Miranda says that he often has earworms that are not necessarily a tune. Rhythms, timbres, sound textures, sound effects, orchestral passages, and so on, often get stuck his mind as well. Moreover, every so often those earworms do not seem to match any music that he has heard before. It seems that most of his earworms are distortions of music that he might have heard before, or evoke only particular aspects of them, such as rhythm or harmonic progression.

We hypothesise that the means by which those earworms emerge in Miranda's mind's ear are manifestations of some form of musical creativity, we believe that it is possible to harness such creative process by working with computer-generated materials. We are convinced that the process of designing the generative music algorithms, programming them on a computer, and handling the computer-generated materials, can flush earworms out from a composer's mind's ear that would not have emerged otherwise.

One might wish to make a distinction here between earworms and new musical ideas, but we are not entirely sure where the dividing line is. What is deemed important here, however, is that interaction with computer-generated materials can flush all sorts of earworms out of Miranda's mind and they often evolve and mingle with new musical ideas, transformations, variations, and so forth. We suspect that this might be the case with other composers as well.

Philosopher Friedrich Nietzsche suggested that great artistic creations could only result from the articulation of a mythological dichotomy referred to as the Apollonian and Dionysian. In ancient Greek mythology, Apollo is the god of the sun and is associated with rational and logical thinking, self-control and order. Conversely, Dionysus is the god of wine and is associated with irrationalism, intuition, passion

and anarchy. These two gods represent two conflicting creative drives, constantly stimulating, provoking one another. The notion that the Apollonian and the Dionysian tend to counter each other reminds us of the way in which the brain functions at all levels. Inhibitory processes pervade the functioning of our brain, from the microscopic level of neurones communicating with one another, to the macroscopic level of interaction between larger networks of millions of neurones. Indeed, there are parts of the human brain that are undeniably Apollonian, whereas others are outrageously Dionysian. The Apollonian brain includes largely the frontal lobe of the cortex and the left hemisphere. Generally, these areas are in charge of focusing attention to detail, seeing wholes in terms of their constituents and making abstractions. They are systematic and logical. Conversely, the Dionysian brain includes sub-cortical areas, which are much older in the evolutionary timeline, and the right hemisphere. It is more connected to our emotions. It perceives the world holistically and pushes us towards unfocused general views.

The Apollonian brain is concerned with unilateral meanings, whereas the Dionysian brain tends to forge connections between allegedly unrelated concepts. Miranda believes that this is what his mind does all the time when he is composing: the further his Apollonian brain pushes him to perceive the world according to its agenda, the stronger the pull of his Dionysian brain to perceive the world differently. Hence, computer technology is of foremost importance for his métier, because it allows him to stretch his Apollonian musical side far beyond his ability to do so by hand, prompting his Dionysian side to counteract accordingly. This cognitive push and pull seems to be the driving force behind his musical creativity.

3   Background: *Symphony of Minds Listening*

In Chapter 12 of the book *Guide to Brain-Computer Music Interfacing* (Miranda and Castet 2014), Miranda and colleagues introduced the composition of *Symphony of Minds Listening*, which was a first attempt at putting in practice our Music Neurotechnology approach to CAC, which still is evolving.

Symphony of Minds Listening is an experimental symphonic piece in three movements based on the fMRI brain scans taken from three different persons while they listened to the 2nd movement of Ludwig van Beethoven's 7th Symphony: a ballerina, a philosopher and Miranda. In simple terms, the composer deconstructed the Beethoven movement to its essential elements and stored them with information representing their structural features. Then, he reassembled these elements into a new composition, using the same instrumentation as for Beethoven's 7th symphony, but with a twist: the fMRI information influenced the process of reassembling the music; please refer to (Miranda et al. 2014) for more details.

The fMRI brain scanning method measures brain activity by detecting associated changes in blood flow. The measurements can be presented graphically by colour-coding the strength of activation across the brain. Figure 1 shows a representation of an fMRI scan of Miranda's brain listening to Beethoven's music at a specific window of time. In this case, each time window lasts for 2 seconds. The figure shows 8 planar surfaces, or slices, from the top to the bottom of the brain. Figure 2 shows an example of a 3D rendition of such an fMRI scan, devised by Dan Lloyd, of Trinity

College in Hartford, USA: it displays different areas of the brain, represented by different colours (or, shades of grey), responding in a coordinate manner to the music.
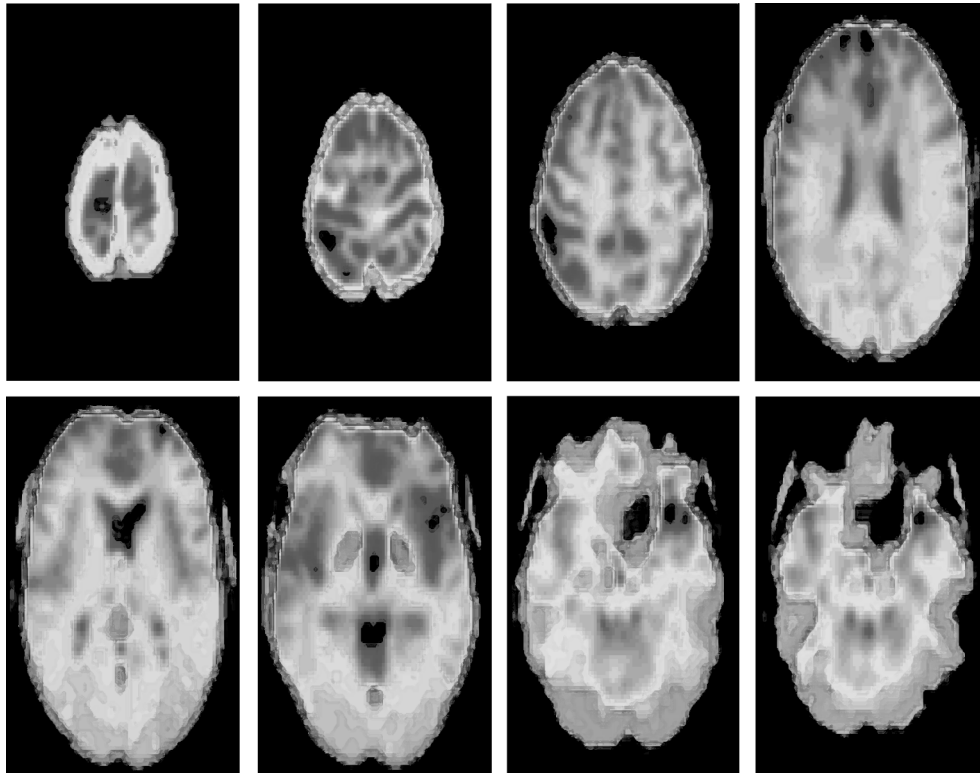

Figure 1: A typical representation of an fMRI snapshot, showing 8 transversal slices of the brain.
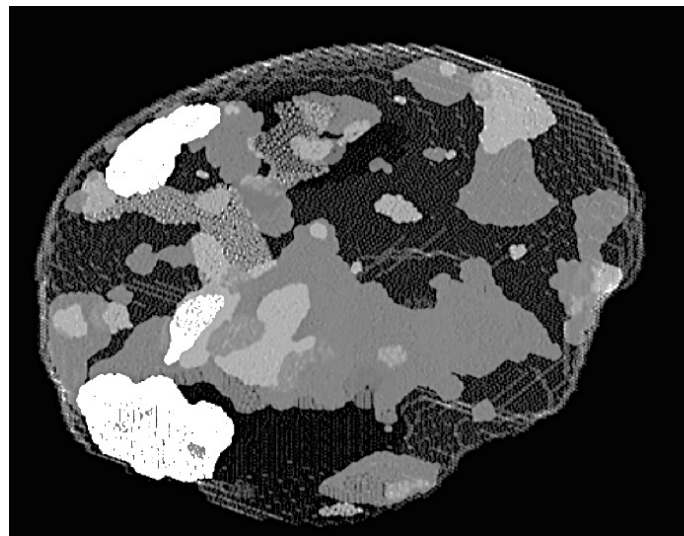

Figure 2: An artistic 3D rendering of an fMRI scan.

Each scanning session generated sets of fMRI data, each of which we associated to a measure of the 2nd movement of Beethoven's 7th symphony. This is shown schematically in Figure 3 and will be explained in more detail later.
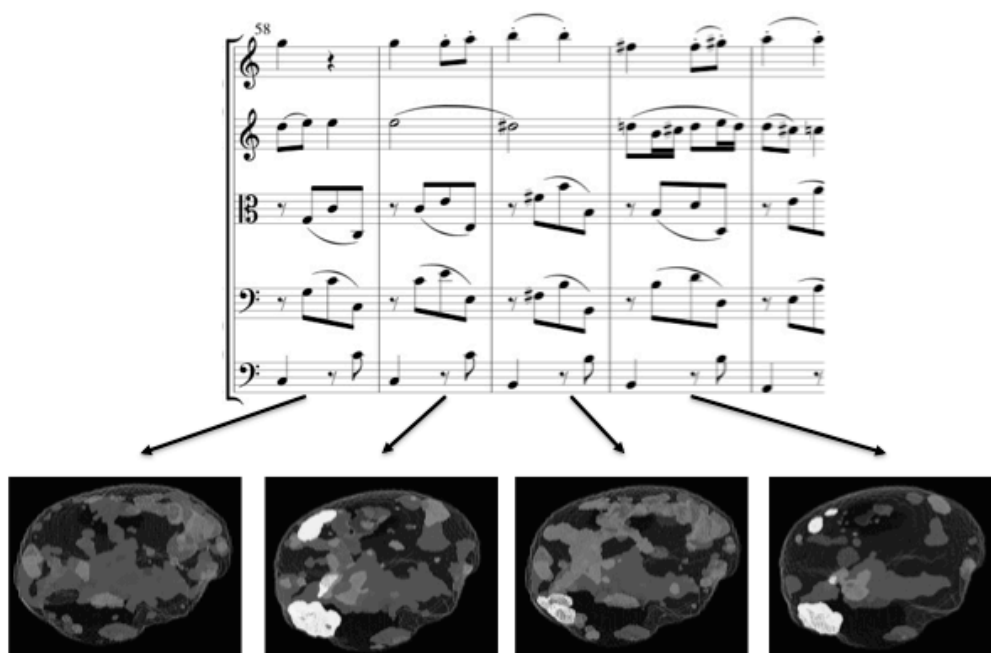
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Figure 3: The result of a scanning section is a set of fMRI data for each measure of Beethoven's piece. (Note: this is only a schematic representation; the brain imaging does not correspond to the actual music shown.)

The score of Beethoven's movement was deconstructed with Artificial Intelligence software developed at ICCMR[4] (Gimenes and Miranda 2011; Miranda et al. 2014), which extracted statistical information about the structure of the music. Then, the composer used this information to reconstruct the Beethoven movement, but the process of reconstruction was influenced by the fMRI data. This will be detailed below, but effectively, during the reconstruction process the fMRI data altered the original music[5]. Not surprisingly, the fMRI scans differed amongst the three listeners. Therefore, brain activity from three different minds yielded three different movements for the resulting composition, each of which displaying varied degrees of resemblance to the original symphony.

In order to test the composition methods (or, the 'reconstruction' method) and OpenMusic patches thoroughly, the composer decided to remain faithful to the original form of Beethoven's movement and avoid as much as possible editing the musical reconstructions generated automatically by the system. The objective was to gain a good understanding of the outcomes in a real-world practical large-scale compositional task. However, this decision heavily constrained his musical imagination during the composition of *Symphony of Minds Listening*. We would say that the compositional process as whole was much more Apollonian here than Dionysian. Even though the piece caught the imagination of the audience[6] and

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[4] Interdisciplinary Centre for Computer Music Research, Plymouth University, UK.
http://cmr.soc.plymouth.ac.uk/
[5] We used a MIDI representation of the score to process the music.
[6] The symphony was premiered on 23 February 2013 by Ten Tors Orchestra, conducted by Simon Ible, at Peninsula Arts Contemporary Music Festival, Plymouth, UK.

received positive press reviews[7], the composer felt that the aesthetic quality of symphony lacked his creative touch and musical experience. Nevertheless, it was a very useful experiment, which the composer followed up with *Corpus Callossum* and subsequently with *Shockwaves*.

4 Corpus Callosum

In *Corpus Callosum* the composer allowed more freedom to the way in which he handled the materials produced by the computer. The compositional process was more Dionysian here than Apollonian. And this time he worked with the fMRI data from his own brain only.

The title of the composition refers to the part of the brain that connects its left and right hemispheres, and facilitates communication between them: the *corpus callosum*. The human brain is divided into two asymmetric hemispheres. As we already mentioned, the left hemisphere is largely engaged in processing the details of things. It is often associated with a more objective, or scientific, knowledge of the world. Conversely, the right hemisphere is largely engaged in taking a more holistic view of things and is often associated with a more subjective, or poetic, interpretation of the world (Toga and Thompson 2003). One should bear in mind that this distinction is controversial because it has been difficult to observe it clearly. In a normal brain the two hemispheres work tightly together: they are highly interconnected and interact through the corpus callosum. Nevertheless this notion is inspiring and good enough as philosophical and artistic metaphors.

During the scanning session listening to Beethoven's symphony, Miranda remembers that sometimes he lost concentration on the music and his mind wondered off. We reckon that this is a typical manifestation of brain asymmetry at work: while one side of his brain was striving to pay attention to musical detail, the other was making mental associations, producing imageries, eliciting feelings, and so on.

The orchestra for *Corpus Callosum* is divided into two groups: one to be placed on the left side of the stage and the other on the right side. The group on the left side represents the left hemisphere of the brain, whereas the group on the right side represents the right hemisphere. The composition develops as an interaction between these two realms. The instruments on the right hand side[8] of the stage play segments that were composed emphasizing orchestration (Figure 4). These passages do not handle rhythm and melody explicitly. Rather, the instruments play clusters of sustained notes. Here the focus is on timbre. Conversely, the instruments on the left hand side[9] play modifications of passages pinched from Beethoven's score (Figure 5). These are noticeably rhythmic and melodic segments; timbre is deemed secondary here.

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[7] For example, see a review in *Gramophone* magazine and news story in *The Times* http://goo.gl/FDM0iX and http://goo.gl/GtacVu
[8] The instruments of the right side are: 2 violins, 1 viola, 1 violoncello, 2 flutes, 2 oboes, 2 clarinets, 1 bass clarinet, 2 bassoons, 2 French horns, 2 trumpets, 1 trombone, 1 bass trombone and percussion (2 players).
[9] The instruments of the left side are: 2 violins, 1 viola, 1 violoncello and 1 marimba (or piano).

Figure 4: Excerpt from the score of *Corpus Callosum*, showing music representing the right side of the hemisphere.

Figure 5: Excerpt from the score of *Corpus Callosum*, showing a string quartet representing the left side of the hemisphere.

In addition to programming OpenMusic patches to make transformations informed by fMRI data, *Corpus Callosum* we also used IRCAM's ATO-MS to generate the orchestrations for the 'right side' of the composition. Before we discuss the orchestrations and transformations, below is brief explanation of how the fMRI data were handled.

5   The fMRI data

The time resolution of the Siemens Allegra 3T scanner that we used to collect the brain data is 2 seconds. That is, it took 2 seconds to take a snapshot comprising 36 image slices of the brain. Each slice comprised 64 x 64 picture elements, known as voxels, or volume pixels. Thus, each snapshot comprised approximated 150,000 continuously varying voxels. The participants were scanned listening to the 2nd movement of Beethoven's 7th Symphony twice. The scanning began with 30 seconds without music, then 460 seconds of Beethoven music, then 18 seconds without music, and finally more 460 seconds of Beethoven again. Thus each run generated 484 snapshots.

The raw fMRI data were first pre-processed following standard procedures for functional neuroimaging using Statistical Parametric Mapping software (Ashburner et al. 2013).

Each of the 484 snapshots produced 150,000 voxels, which are exceedingly complex for direct analysis. Thus, data were further processed with Independent Component Analysis, or ICA (Stone 2004). Basically, ICA analysis identifies groups of voxels that oscillate in unison. These are unified as supervoxels representing temporally coherent networks of brain activity. The different levels of grey on the 3D renditions shown in Figures 2 and 3 correspond to ICA components.

In total, 25 ICA components were calculated from the fMRI data. To rank these components in order of significance, the activity of each component during the first scanning pass through the Beethoven listening was compared to that same component during the second pass. If the two segments of a component time series were correlated (with at least $p < 0.05$), then we hypothesised that the activity might be musically driven, since the stimulus, that is, the music, would be identical at the corresponding time points in the two passes through the music. The strength of the 25 ICA components was ranked as follows: 25, 15, 14, 8, 5, 10, 11, 18, 6, 2, 4, 1, 17, 16, 13, 20, 21, 3, 22, 24, 12, 7, 9, 23 and 19.

The varying components were resampled to match the timing of the Beethoven score measure by measure. Thus, each time point was indexed to a measure of the Beethoven score. The movement comprises 278 measures. Therefore each ICA component comprises a time series of 278 values, ranging from 0 (meaning lowest fMRI intensity) to 9 (highest fMRI intensity). As an example, Table 1 shows the values of the first 5 strongest ICA components (that is, 25, 15, 14, 8 and 5, with $p < 0.002$) for the first 10 measures of the 2nd movement of Beethoven's 7th symphony. Bear in mind that for the sake of clarity and simplicity, the ICA values were normalized to range from 0 to 9 in the examples shown below. Different algorithms and patches required different normalizations throughout the process of coding the software and composing the pieces.

Beethoven Measure	ICA 25	ICA 15	ICA 14	ICA 8	ICA 5
1	7	5	5	5	2
2	5	5	8	5	8
3	7	3	5	5	6
4	5	8	3	5	2
5	5	7	4	4	4
6	6	6	4	5	3
7	7	8	5	6	3
8	4	6	3	4	3
9	6	6	4	5	4
10	5	7	5	5	3

Table 1: The values of the strongest 5 ICA components for the first 10 measures of Beethoven's music yielded by the fMRI from Miranda.

In order to enable easy access to the ICA components practically during the composition workflow, the resulting set of ICA components were stored in a CLASS-ARRAY object in OpenMusic (Figure 6). This facilitated accessing individual components, and specific lookups based on time (Figure 7).
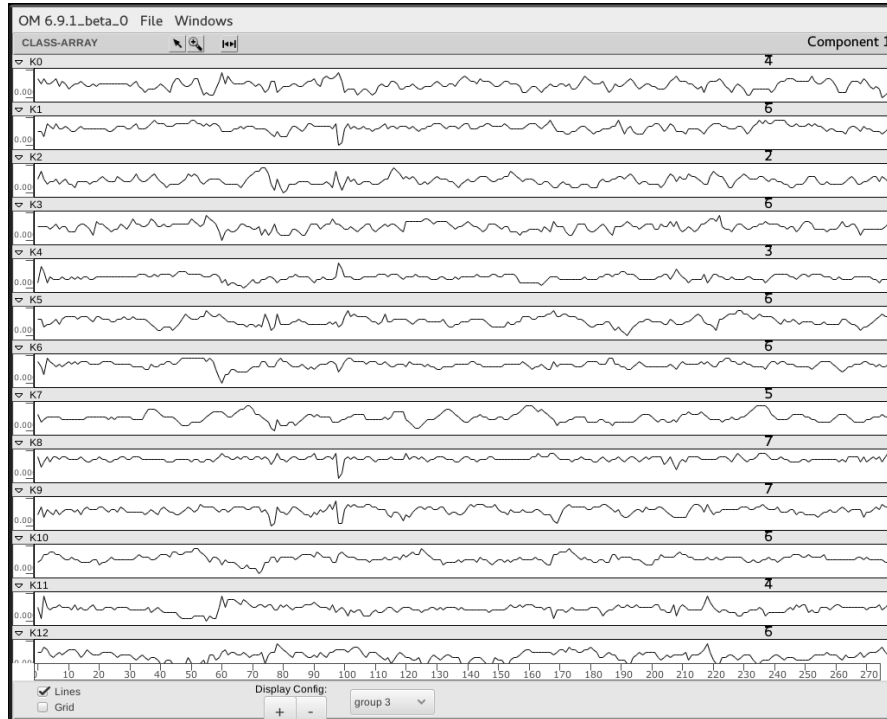

Figure 6: ICA components stored in a CLASS-ARRAY object in OpenMusic.
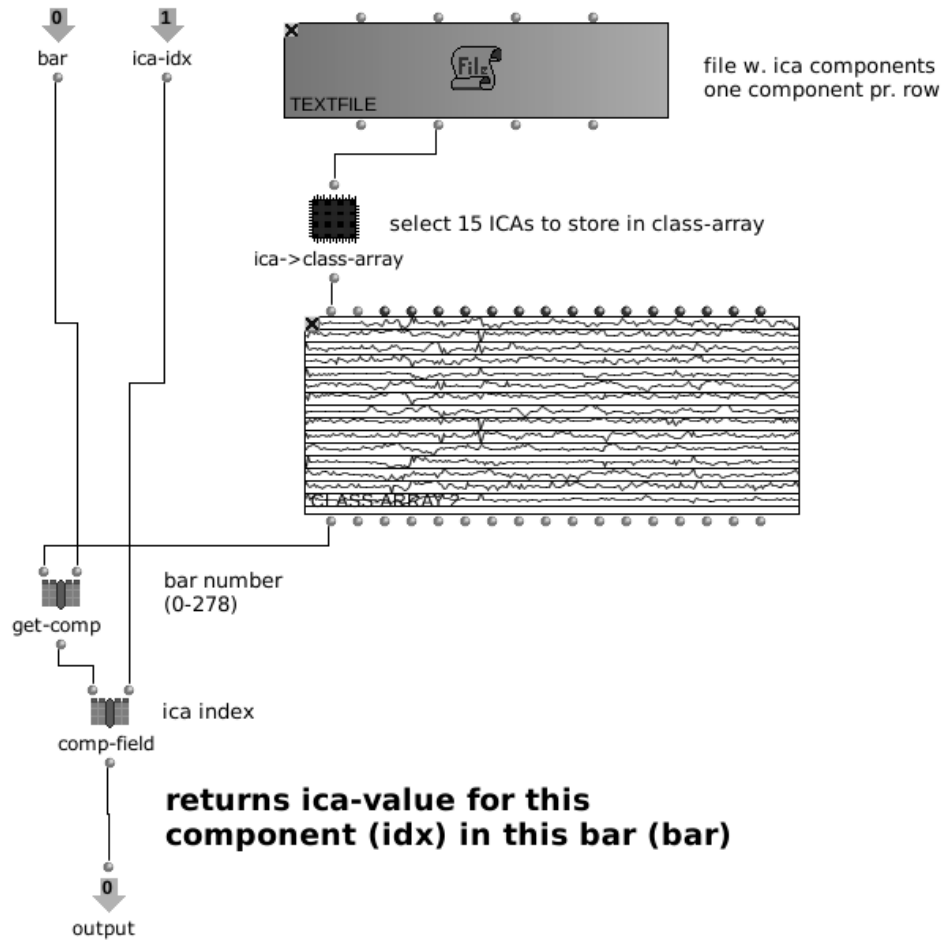
Figure 7: Selecting value from ICA component at a specific measure.

Having the plots of the ICA components visually available in the class-array also provided valuable overviews of the data during the composition process (Figure 8).
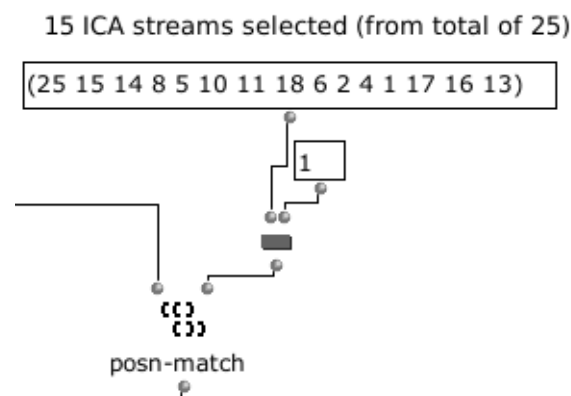

Figure 8: Selecting components from total set of ICA components.

6 Right side: generative orchestrations with ATO-MS

The materials to compose for the group of instruments representing the right side of the brain were created with a piece of software that generates orchestrations. We hacked the Matlab code of ATO-MS (Maresz 2013) in order to enable it to take into account brain data to generate the orchestrations[10]. The process of generating the orchestrations[11] for *Corpus Callosum* is illustrated in Figure 9:
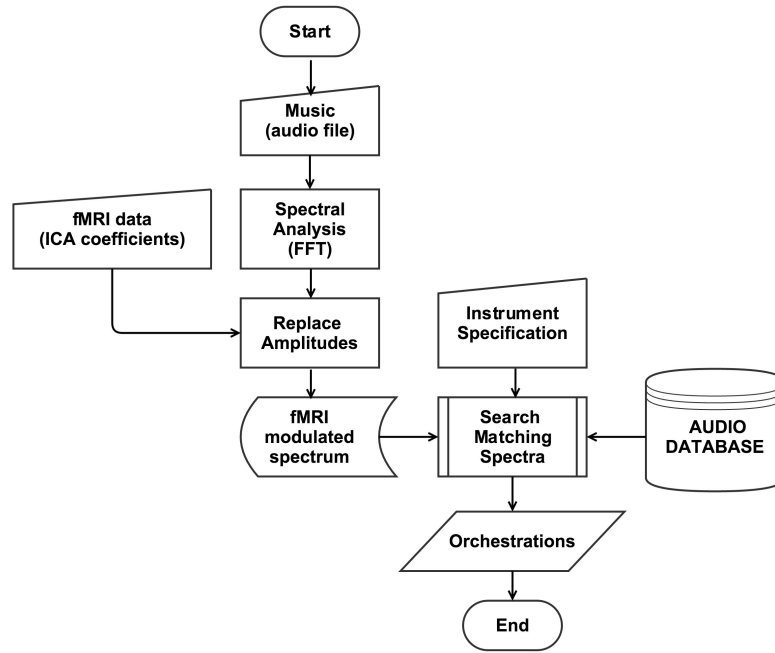
Figure 9: The process of generating orchestrations.

The system takes a given audio file, which is a section from the recording of the Beethoven movement, and analyses its spectrum using Fast Fourier Transform (FFT) with a window lasting for two seconds, which roughly corresponds to 1 measure of the musical score. This analysis enabled us to extract a set of 25 frequency values (in Hz), which are the frequencies of the first 25 most prominent partials of the spectrum for every 2 seconds of audio. Thus, for instance, if the audio lasts for 8 seconds, then the analysis produces 4 sets of 25 frequency values each.

The partials of the spectrum of a sound are normally described by means of frequency and amplitude values. However, we discarded the amplitudes produced by the FFT analysis. Instead, we replaced the amplitudes by the intensity of the 25 ICA components associated to the respective measures of the Beethoven movement. This resulted in what we refer to as the fMRI modulated spectrum (Table 2).

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[10] ATO-MS is an unreleased piece of software developed at IRCAM. This is the predecessor Orchids, which is the software for computer-aide orchestration that IRCAM released in 2014.

[11] Although the focus of this book is on OM, we decided to comment on the generative orchestration aspect of the work here for the sake of completeness. However, we deliberately kept this section short in order to make enough space to introduce the OM patches more thoroughly.

Partial	Frequency in Hz	Amplitude (0 – 9)
1	220.35	6 (ICA 25)
2	381.73	5 (ICA 15)
3	592.57	7 (ICA 14)
4	805.02	6 (ICA 8)
5	1063.28	4 (ICA 5)
6	1210.06	5 (ICA 10)
7	1432.21	5 (ICA 11)
8	1648.53	2 (ICA 18)
9	1812.22	5 (ICA 6)
10	2099.66	5 (ICA 2)
11	2411.76	7 (ICA 4)
12	2466.86	3 (ICA 1)
13	2701.88	4 (ICA 17)
14	2900.26	3 (ICA 16)
15	3206.43	3 (ICA 13)
16	3297.83	6 (ICA 20)
17	3586.17	5 (ICA 21)
18	3947.55	6 (ICA 3)
19	3980.26	6 (ICA 22)
20	4241.45	3 (ICA 24)
21	4535.72	6 (ICA 12)
22	4788.87	4 (ICA 7)
23	4920.14	5 (ICA 9)
24	5018.24	2 (ICA 23)
25	5395.23	4 (ICA 19)

Table 2: The fMRI-modulated spectrum corresponding to measure 139 of the 2nd movement of Beethoven's 7th symphony.

The audio database contains spectral analysis of recordings from all instruments of a symphonic orchestra. It holds information about all musical notes that can be produced by an instrument, including different dynamics, kinds of articulations and playing techniques.

Given the instrument specification, that is the list of instruments that one wants the system to produce orchestrations for, the system searches the database for combinations of sounds whose blended spectrum best approximate the target fMRI-

modulated spectrum. The system produces a number of suggestions for the composer to work with.

As an example, let us examine how the first measure of the excerpt shown in Figure 4 was composed. The audio segment (Figure 10) that was used as a target for the orchestration of the 4 measures of the score shown in Figure 4 corresponds to measures 139 – 147 of the 2nd movement of Beethoven's 7th symphony. The 25 frequencies generated by the FFT analysis of the first 2 seconds of this sound are shown in Table. The ICA components of the fMRI taken at the moment Miranda was in the scanner listening to measure 139 of the symphony are also shown in Table 2. The values of the ICA components replaced the original amplitudes calculated by the FFT analysis of the first 2 seconds of the sound shown in Figure 10, producing the fMRI-modulated spectrum as a result. Then, this result was used at the target for the orchestration software.
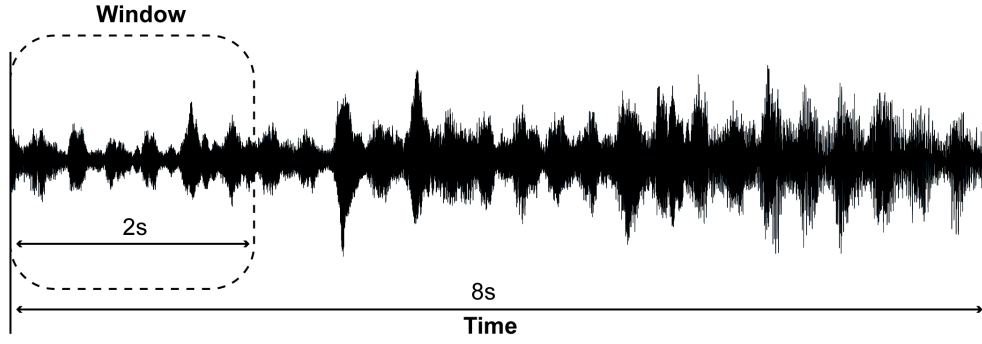

Figure 10: The audio recording of measures 139 – 147 of the 2nd movement of Beethoven's 7th symphony lasts for 8 seconds.

In this case the instrument specification consisted of 2 flutes, 2 oboes, 2 clarinets, 1 bass clarinet and 2 bassoons. Among the various suggestions generated by the system, the notes shown in Figure 4, 1st measure, were selected. Note that 1 oboe was not used and that individual notes have different dynamics, which are necessary to obtain the desired spectral behaviour.

7   Left side: musical transformations with OpenMusic

The materials to compose for the group of instruments representing the left side of the brain were created using a number of transformation algorithms. These are algorithms that modify a given musical sequence. The amount of modification is scaled according to an index, referred to as the *fMRI_index*, which is the value of the ICA analysis extrapolated from the fMRI scans, as explained earlier.

A difference value *d* between the input and the transformed music is also calculated. Then, this is multiplied by *fMRI_index* to give a final scaled modifier value: *SMV*. The *SMV* gives a degree of fMRI-controlled variability in each transformation: a high

fMRI_index value will result in significant transformations to the music, whereas a low *fMRI_index* value will result in less significant transformations (Figure 11).

In this section we introduce 4 transformation patches, which were the ones that were mostly extensively used in *Corpus Callosum*. Due to lack of space, only 2 of them are described in detail. The other 2 are explained at the higher-level of OpenMusic's patch structure depiction. A typical patch for fMRI-controlled interpolation is shown in Figure 12.
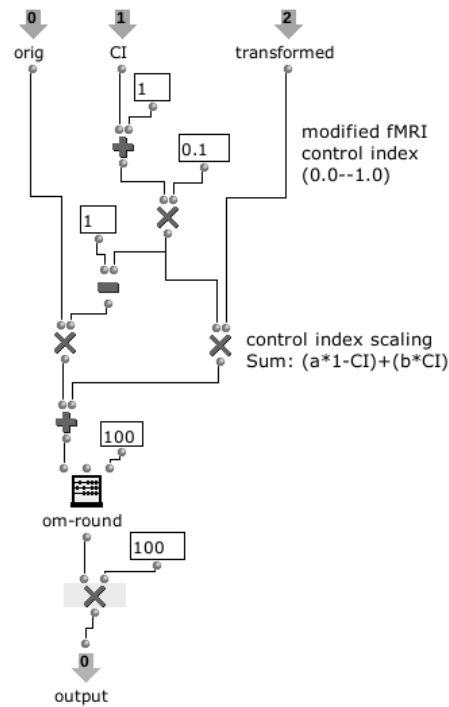

Figure 11: Interpolation using a scaled modifier value.

Figure 12: A typical patch for fMRI-controlled interpolation.

7.1   Pitch inversion algorithm, modulated by brain activity

Given an input musical sequence, the pitch inversion algorithm creates a new sequence, which is effectively the input sequence turned upside-down (Figure 15). For instance, a sequence rising in pitch would descend in pitch after being passed through this transformation. In order to illustrate this, let us consider the example in Figure 13. Firstly, the notes {B4, B4, D5, C5, B4} are represented as MIDI values as follows {71, 71, 74, 72, 71}.

Figure 13: An example of a short musical sequence.

Pitch inversion is achieved simply by subtracting the respective MIDI values from 128. The results are the MIDI values for the new pitches. The transformed pitch values for our example in Figure x are as follows: $(128 - 71 = 57)$, $(128 - 71 = 57)$, $(128 - 74 = 54)$, $(128 - 72 = 56)$ and $(128 - 71 = 57)$. Thus, the resulting MIDI values are 57, 57, 54, 56 and 57, yielding the following pitch sequence {A3, A3, F#3, G#3, A3} (Figure 14):

15

Figure 14: The inverted sequence.

The basic example above assumed a maximal *fMRI_index* value equal to 1.0. However, varied degrees of transformations are possible by scaling the significance of the transformation according to the value of *fMRI_index*. The difference between the input and the transformed interim output (i.e., the would-be maximal inversion) is multiplied by *fMRI_index*, before being summed with the input to create the final transformed output value, as follows:

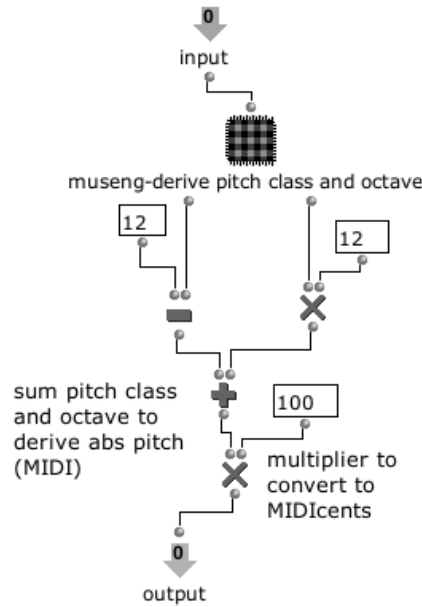*NewPitch* = {*InputPitch* + ((*InputPitch* - *InterimOutput*) * *fMRI_index*)}

Figure 15: Patch for fMRI-modulated pitch inversion.

Let us examine what happens if we set the *fMRI_index* = 0.6. In this case, we would expect an output approximately half way between the original pitch and the inversion; in other words, an almost neutral set of intervals. First, the difference *d* between the maximal inversion and the input signal for each of the MIDI values needs to be calculated as follows:

$d = \{(57 - 71), (57 - 71), (54 - 74), (56 - 72), (57 - 71)\}$
$d = \{-14, -14, -20, -16, -14\}$

Then, the scaled modifier values are calculated by multiplying the difference values by the value of *fMRI_index*:

SMV = {(−14 * 0.6), (−14* 0.6), (−20 * 0.6), (−16 * 0.6), (−14 * 0.6)}
SMV = {−8.4, −8.4, −12, −9.6, −8.4}

Finally, the *SMV* values are summed with the original input to give a transformed set of output values:

NewPitches = {(71 − 8.4), (71 − 8.4), (74 − 12), (72 − 9.6), (71 − 8.4)}
NewPitches = {62.6, 62.6, 62, 62, 62.6}

Pitch values are rounded up to the nearest whole number in order to match the MIDI standard, giving a transformed set of pitch values equal to {63, 63, 62, 62, 63}, which is rendered as {D#4, D#4, D4, D4, D#4}, as shown in Figure 16.

Figure 16: Sequence after inversion with *fMRI_index* = 0.6, giving a nearly neutral set of pitch intervals.

7.2   *Pitch-scrambling algorithm*

In simple terms, the pitch-scrambling algorithm randomly re-orders the pitch values of the input signal, providing an interesting simple stochastic component to the transformation algorithm. Using the musical measure in Figure 13 as a starting point, let us examine the result of applying this transformation four times. The process is as follows (using MIDI representation):

Input pitches: {71, 71, 74, 72, 71}
Order pitches in ascending order: {71, 71, 71, 72, 74}
Scramble the order of pitches randomly: {74, 72, 71, 71, 71}
Output pitches: {74, 72, 71, 71, 71}

In this case, the output would be rendered as {D5, C5, B4, B4, B4}. Re-running the transformation, a further three times would give further variants, for example: {72, 74, 71, 71, 71}, {71, 74, 72, 71, 71} and {71, 74, 71, 72, 71}, rendered as {C5, D5, B4, B4, B4}, {B4, D5, C5, B4, B4} and {B4, D5, B4, C5, B4}, respectively, as illustrated in Figure 17.

Figure 17: The result of applying the pitch-scrambling algorithms four times on the same input.

As with the pitch inversion algorithm, the *fMRI_index* can be used to create a control signal with which the amount of transformation can be varied. In order to illustrate this, let us assume an *fMRI_index* = 0.4.

Considering the same input measure as before (Figure 13) and the transformed values from the first pitch scramble shown in Figure 17, the value of *d*, between the first scramble and the input sequence is calculated as follows:

d = {(74 − 71), (72 − 71), (71 − 74), (71 − 72), (71 − 71)}
d = {3, 1, −3, −1, 0}

The scaled modifier values are then calculated by multiplying the difference values by *fMRI_index* = 0.4:

SMV = {(3 * 0.4), (1 * 0.4), (−3 * 0.4), (−1 * 0.4), (0 * 0.4)}
SMV = {1.2, 0.4, -1.2, -0.4, 0}

Finally, the *SMV* values are summed with the values of the original input to give a transformed set of output values:

NewPitches = {(71 + 1.2), (71 + 0.4), (74 − 1.2), (72 − 0.4), (71 − 0)}
NewPitches = {72.2, 71.4, 72.8, 71.6, 71}

As with, the previous example the resulting values are rounded up to the nearest whole number, giving a transformed set of MIDI values equal to {72, 71, 73, 72, 71}, which is rendered as {C5, B4, C#5, C5, B4}, as shown in Figure 18. Note that the output is significantly closer in overall structure to the unscrambled input (Figure 13) than the first scrambled transformation.

Figure 18: Transformed output created by pitch scrambling algorithm assuming *fMRI_index* = 0.4.

7.3   *Variations based on style analysis*

Methods for analysing musical style, mostly based on statistical methods, were tested and developed in our quest for interesting compositional materials derived from Beethoven's original movement. To this end we applied statistical analysis and compression algorithms using the built-in LZ-library, distributed as part of the OpenMusic package.

Statistical analysis and compression algorithms imply modes of generating new material based on probabilistic processes, effectively rendering variations of the same material on each evaluation of the patch. Both modes provide parameters to control

the degree of proximity to the original input, letting the composer generate and choose material along a scale from close (fairly similar) to remote (very dissimilar), controlled by the parameter *fMRI_index*.
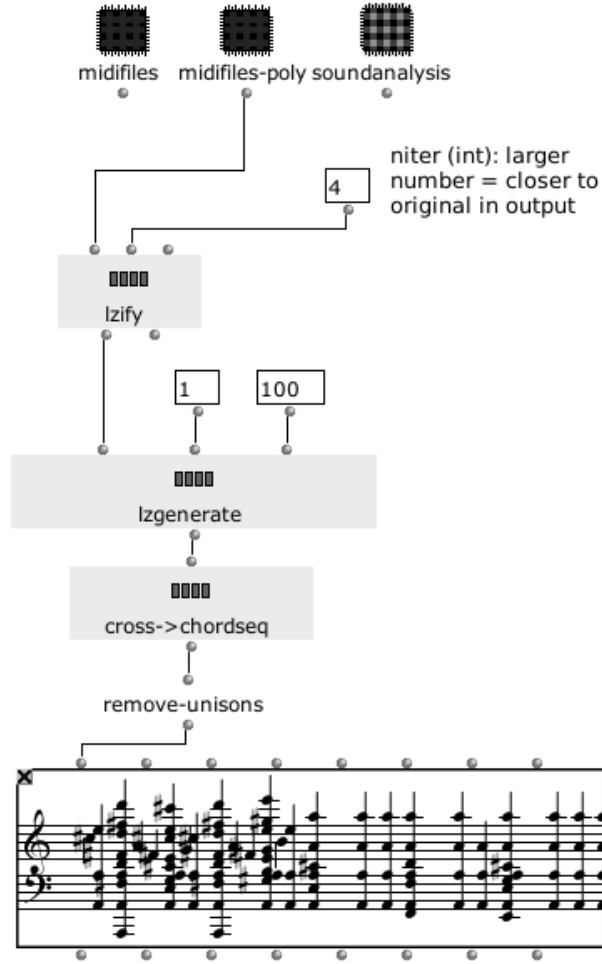

Figure 19: Generating variations based on fMRI-modulated style analysis.

7.4   *Variations generated via sound analysis*

Generating variations based on analysis of recordings of the original Beethoven symphony was another useful way to process Beethoven's music. Such procedure was used substantially in *Corpus Callosum* and also in *Shockwaves*.

Sound analysis algorithms, such as FFT-based analysis, partial tracking and fundamental pitch estimation, provide useful parameters to vary the type of variation one can obtain. For example, one can obtain different results by varying time and frequency resolutions ('sensitivity' in Figure 20) and analysis' threshold that is, adjusting what the analysis algorithm considers to be salient or important information in the sound. Although not explicitly shown in the patch in Figure 20, *fMRI_index* was used to perform sound analysis variations.

Including sound analysis as an intermediate step to generate variations, the composer can select parts or whole of these to work with subsequently (Figure 20). This process provided interesting possibilities for controlling composition, moving along a linear entropy scale, from totally predictable to totally unpredictable in function of *fMRI_index*.
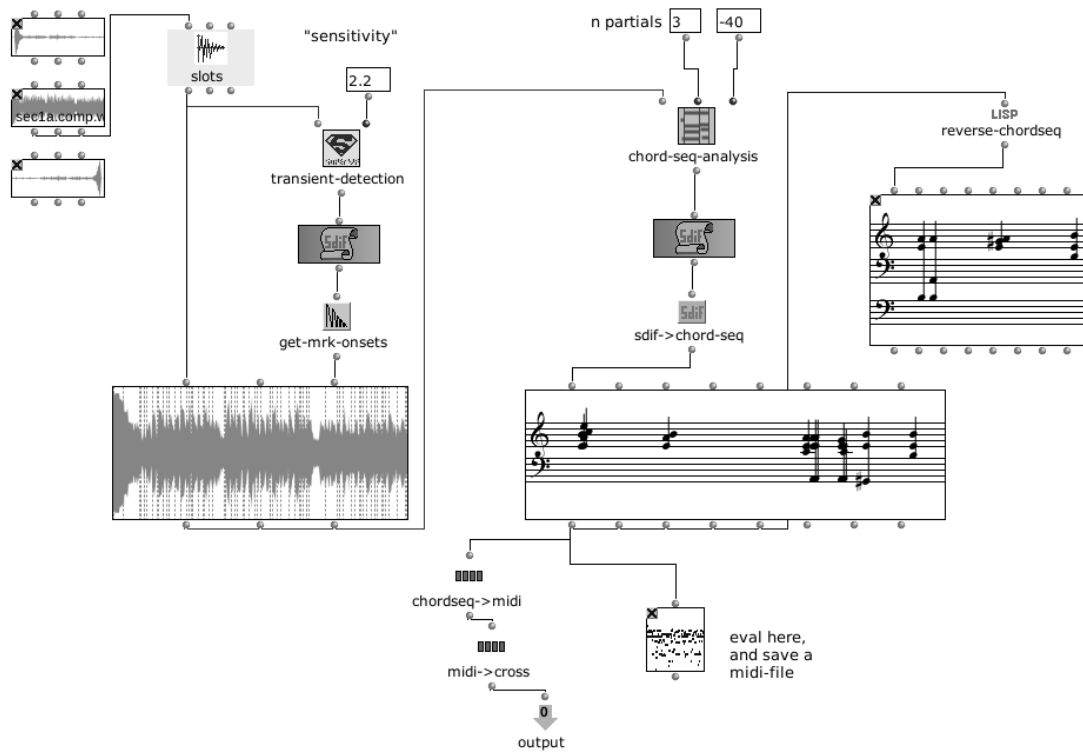

Figure 20: Patch for style analysis passing through analysis of audio.

8 Composing with the computer generated materials

As we mentioned earlier, for the composition of each of the three movements of *Symphony of Minds Listening*, the composer strived to follow the form of the original Beethoven's movement. The scheme we introduce below was devised originally for *Symphony of Minds Listening*, but it was also adopted for *Corpus Callosum* and *Shockwaves*, albeit much more freely.

The composer divided the score of Beethoven's piece into 13 sections, as follows:

- Section 1: from measure 1 to measure 26
- Section 2: from measure 26 to measure 50
- Section 3: from measure 51 to measure 74
- Section 4: from measure 75 to measure 100
- Section 5: from measure 101 to measure 116
- Section 6: from measure 117 to measure 138
- Section 7: from measure 139 to measure 148

- Section 8: from measure 149 to measure 183
- Section 9: from measure 184 to measure 212
- Section 10: from measure 213 to measure 224
- Section 11: from measure 225 to measure 247
- Section 12: from measure 248 to measure 253
- Section 13: from measure 254 to measure 278

Then each section was processed separately and the compositions (or re-compositions) were reconstructed following the same number of measures as in the original Beethoven's score. In other words, the 13 sections provided a template for the new compositions. They informed the overarching forms of the 3 movements of *Symphony of Minds Listening*, and to some extent the forms of the other two orchestral pieces. More information on how this process was carried out is available in (Miranda et al. 2014).

At the lower level of deconstructing the piece, processing the materials on a section-by-section basis and re-assembling the sections, the process tended to be Apollonian, particularly so in *Symphony of Minds Listening*. During the process of re-assembling – or recomposing – the sections, Miranda deliberately avoided interfering with the computer-generated (fMRI-informed transformations) materials as much as possible. But of course he produced a shedload of materials to choose from, by experimenting with different transformation algorithms and running them a number of times. Miranda's choices of the materials that were used in the compositions have no explanations; these were Dionysian processes.

As already mentioned at the beginning of this chapter, Miranda felt that the aesthetic quality of the resulting symphony was compromised by the lack of extensive Dionysian interventions on the computer-transformations and also on the form of the music. A different approach was adopted for *Corpus Callosum* and *Shockwaves*. Again the processing of the materials for these two pieces was carried out on the same 13 sections as shown above. However, the recomposition process saw no barriers with respect to these sections, as some of them were manually shortened, others enlarged and others still overlapped. Also, another dimension to the compositional process was added by the inclusion of computer-generated orchestrations, which were also generated on a section-by-section basis. Needless to say, Miranda meddled with the computer-generated materials extensively before they made their way to the main score. These processes were fundamentally Dionysian and were not documented.

We tend to think of software such as OpenMusic as an aid to Apollonian compositional processes. However, Miranda's Dionysian processes were very much supported by one of the great features of OpenMusic: the immediate access to stashing variations away letting the composer store only those that provide potentially interesting material to work with further along the road. An example is the lower right chord sequence shown in Figure 21.
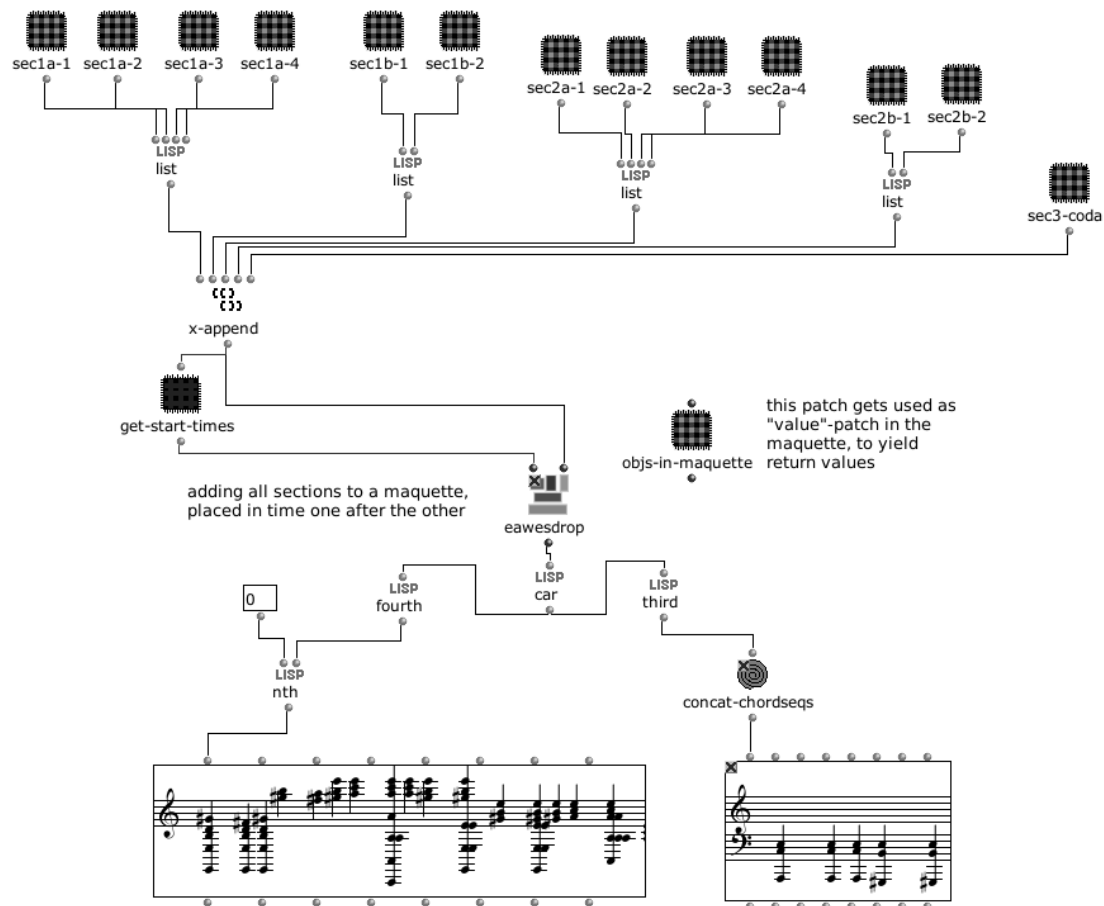
Figure 21: Recomposing Beethoven using transformed material.

9 Concluding Remarks

As well as introducing the algorithms and compositional methods that we designed informed and inspired by neuroscience, this chapter gave a glimpse of the potential of Music Neurotechnology for creativity and more generally to musical research.

The approach to composition introduced in this chapter is inspired by the way in which the brain listens to music: sounds are deconstructed as soon as they enter the ear. Different streams of neuronally coded data travel through distinct auditory pathways towards cortical structures, such as the auditory cortex and beyond, where the data are mingled with data from other senses and memories, and reconstructed into what is perceived as music.

Computing technology is a great tool for modelling creative processes such as the ones we introduced above. However, the authors suggest that composers should not always approach computer-aided composition as a way to substitute their own creative hand and musical intuition. In theory *Symphony of Minds Listening* could be considered as more elegant than the other 2 pieces because the composer followed the methods by the book, so to speak. However from the 3 pieces mentioned in this chapter, the one that the composer considers as most aesthetically successful is the

one that he allowed most flexibility with respect to amending the outcomes from the transformations and prescribed musical form: *Shockwaves*.

The beauty of tools such as OpenMusic is that is allows composers to model creative processes and explore them in flexible ways. In addition to being a powerful programming tool for developing sophisticated models 'of' musical creativity, OpenMusic provides great support for exploring the potential of Music Neurotechnology to develop models 'for' musical creativity.

10 Acknowledgements

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