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MECHASOUNDS: THE SOUND OF MECHANICS

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ABSTRACT

Mechasounds is an interactive sound installation which makes audible properties of microscopic elements, measured by Atomic Force Microscopy, a scientific tool to explore the nanometric world. This project was initiated by two research teams at DyNaMo and GMEM as a proposal for interaction between fundamental research and sound creation, following a research-action methodology. This work intends to show our trans-disciplinary approach for exploring new scientific dissemination tools and the work achieved as a successful collaboration between researchers and artists in an open science context.

1. INTRODUCTION

How do you communicate scientific research on microscopic elements that cannot be seen by the human eye? How do you explain mechanical properties, like softness or rigidity? Like many physical concepts, these describe elements of the world around us, but the associated mathematical tools can make them seem abstract. Is a sensitive approach possible? Can it encourage interaction with a wider audience, over and above disciplinary barriers? These questions have arisen from our diverse research dissemination experiences. To explore them, a partnership has been initiated between DyNaMo, a fundamental research laboratory, and GMEM, a centre for musical creation. The first milestone of this project is described in this paper, an auditive exploration of the microscopic elements which rises up some auditory perceptions research questions to be addressed in the future.

To do so, we will introduce the scientific context and our communication objectives. We will first discuss sonification and the benefits of a multisensory approach. Next, we will discuss the granular synthesis chosen for our sonification tool. We will then describe the interface developed to explore cells mechanics and conclude with a review of our achievements and perspectives.

1.1. What is our research about?

DyNaMo is a fundamental research laboratory. Its researchers focus on the mechanical properties of biological cells. The cell is the fundamental structural and functional biological unit of living organisms. It is the smallest

living unit capable of autonomous reproduction, most humans cells measuring around ten micrometres (i.e. 100 times smaller than a millimetre, a size indiscernible to the human naked eye). Their mechanical properties, i.e. their ability to deform, are crucial for biological function. These properties are affected in a wide range of human diseases, from immune disorders to cardiovascular diseases and cancers [1]. This last example has attracted a great deal of attention, both because of its importance in public health and because of the apparent paradox it presents: cancer cells are softer than healthy cells, whereas the extracellular matrix surrounding the tumour tends to be stiffer and more rigid [2, 3]. These properties can be studied by Atomic Force Microscopy (AFM). This technique is reminiscent of a vinyl player. It uses a nanometric probe (i.e. 1 000 000 smaller than a millimeter) at the end of the soft cantilever to scan a sample by literally touching it (Figure 1, top). A laser reflected at the back of the cantilever towards a detector allows to track the movements of the probe and to reconstruct the topography of the sample [4]. It can also be used to perform “palpation”, i.e. to apply a controlled force on the surface and measure the resulting deformation. This enables us to draw multi-parametric maps on a nanoscopic scale, which describe both the topography of the sample and its mechanical properties. These are characterised by an elastic and a viscous component. Elastic materials, such as rubber, deform when subjected to a force, and quickly return to their original state once the force is released. Viscous materials, like honey, flow over time when stress is applied. Viscoelastic materials may return to its original state but with a certain delay in time.

1.2. Who do we want to share this knowledge with?

1.2.1. Education

As academics, DyNaMo researchers are involved in training activities, both as part of initial university training (especially for bachelor’s and master’s degrees in physics) and as part of continuing education (e.g. during summer schools). They are also involved in training for research through research, by supervising master’s and doctoral projects. As their research topics are highly interdisciplinary, they sometimes welcome students from backgrounds far from physics, like biology. In all these teaching contexts, they aim to impart their knowledge with the

highest standards of precision and accuracy, despite the sometimes tight time constraints.

1.2.2. Science popularisation/Outreach

They are also committed to making the scientific knowledge they produce accessible to everyone and to encouraging young people to take an interest in science. They participate in a number of science culture initiatives aimed at the general public and/or schoolchildren, such as European Researchers' Night, "Fête de la Science" and "Researchers in the Classroom" events. These actions require the implementation of attractive systems. The emphasis is often on experimentation, interaction with the audience and play.

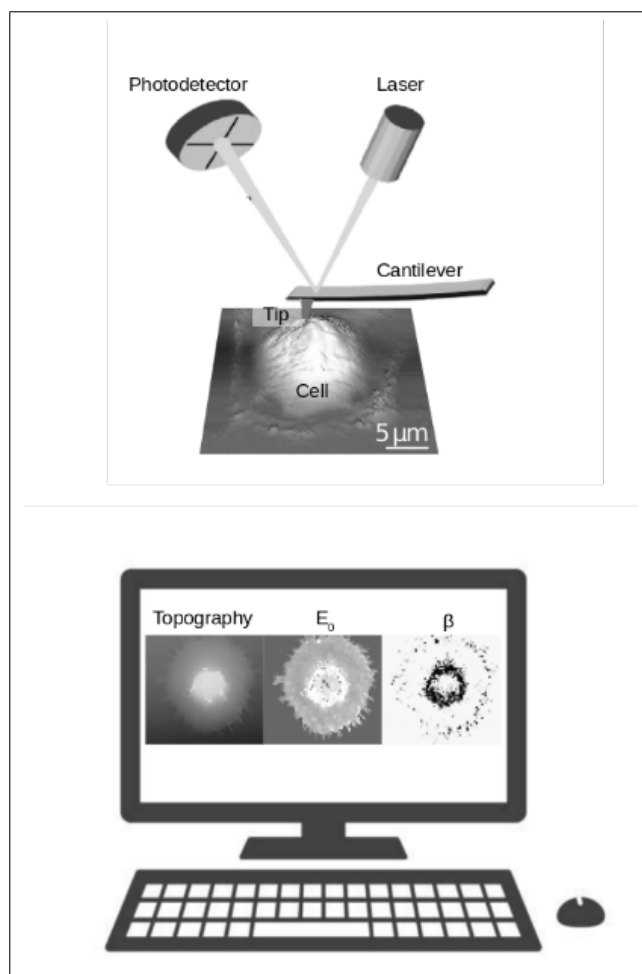


Figure 1. An AFM generates images by scanning the surface of a sample with a tiny tip. This tip is at the end of a flexible cantilever that bends as the tip interacts with the surface. These movements are detected by a laser focused on the back of the cantilever and reflected into a photodetector (top). AFM not only provides the topography of the sample, but can also measure its deformation when a force is applied to the cantilever. This allows the mechanical properties of the sample to be calculated, in particular the E_0 and β moduli, which characterise the sample stiffness and viscous component (bottom).

2. SENSORIMOTOR CELL EXPLORATION

2.1. Why sonification?

2.1.1. From visual exploration to sound exploration

Scientific research generates a vast amount of data that can be used to address a wide range of questions, depending on the field of research. This data is processed using a variety of mathematical and computational tools that allow operations such as dimensional reduction to be performed, making it easier for humans to read through graphs, visual computation, maps, etc. For example, data acquired by AFM is usually represented by several heat maps, each showing the spatial variation of a single parameter. Thus, one colour map may show the surface topography, another the elasticity at each point of the sample, another the viscosity parameter (Figure 1, bottom). The perception of these data by humans can be complex in many cases, especially when processing multi-dimensional data visually, and when popularising and disseminating this data to the general public who is not necessarily familiar with the visual computation of data. The use of sonification is increasingly being developed in an attempt to address these issues [5].

2.1.2. What is sonification?

Sonification is the use of the sound medium outside of dialogue to convey information [6]. This practice, as well as sound design, "is concerned with displaying data and information in sonic form so that listeners (experts and non-experts) can perceive and engage with data structures, complex information and their meaning" [7]. The use of sound and the integration of a sensitive dimension through artistic creation can also create a bridge between art and science, which can facilitate appropriation by the audience [5].

2.1.3. The sensorimotor loop

The multi-dimensional nature of data also mobilises the notion of exploring and navigating within data. In our digital world, touch interfaces are widely used for this purpose [8]. Coupled to sound, they also play with the sensory-motor loop: touching the screen triggers a sensory response - and this in turn influences our manipulation of the interface. This creates a powerful interaction with the user, who is both actor and spectator. What's more, we found the analogy to the 'palpation' performed by the AFM to obtain mechanical properties interesting and meaningful.

2.2. Which sonification tool to use?

The first stage of the project was to define a synthesis engine for the sonification process. We chose granular synthesis for a number of reasons, as described below.

2.2.1. Granular synthesis introduction

A sound grain is a time-windowed portion of a signal with a specific envelop. The time window could be anything from a few samples to a few seconds. By layering many sound grains, you can create a continuous sound stream which sounds nothing like the original signal. During this layering process, you can fine tune a number of parameters on a grain scale, such as grain duration, envelop shape or base material itself, as well as on a stream scale, such as grain density or the perceived pitch of the stream [9, 10].

Considering the possibility of a large number of grains with many parameters for each grain, fine tuning each parameter by hand in real time seems very difficult, if not impossible. A few techniques have been proposed to improve the level of control based, for example, on probabilistic distributions [11] or high level compositional controls [12].

2.2.2. Historical within GMEM

Granular synthesis has been explored at GMEM for a long time with the initial work of Laurent Pottier [13] and the subsequent development led by Charles Bascou [14] among others. This set of open-source¹ tools was originally usable inside Csound² and Max,³ but there are also some versions running on Pure Data.⁴

At the moment, the library, called GMU for GMEM Microsound Universe, is mainly defined by three Max objects: [bufGranul~], [liveGranul~] and [synGranul~], the last two are a variation of the first one which allows to load a sound as a buffer for the envelop and another one to be granulated based on several parameters, such as grain length, amplitude, speed, pan or distance. In 2022, Matéo Fayet and Arthus Touzet reworked the Max package and rewrote the help files to make them easier to use, while implementing the new multichannel functionality of Max 8.

2.2.3. Choice of granular synthesis

Granular synthesis has been used in many works on sonification [15, 16, 17]. It has a number of advantages due to its ability to represent datasets with several dimensions, but also due to its ability to easily synthesize complex audio textures. The nature of this technique allows for a multitude of low-level parameter manipulations, at the cost of reduced intuitiveness, as exposed earlier. There is a first level of similarity between the nanometric scale and the small temporal length of a grain: the combination of each point explored by the AFM would lead to a global representation of a cell, while a layered multitude of temporal grains would give a complex sonic texture. In this way, grain density and length can be correlated with the scale

¹ <https://github.com/gmem-cnmc/GMU>

² <https://csound.com/>

³ <https://cycling74.com/products/max>

⁴ <https://puredata.info/>

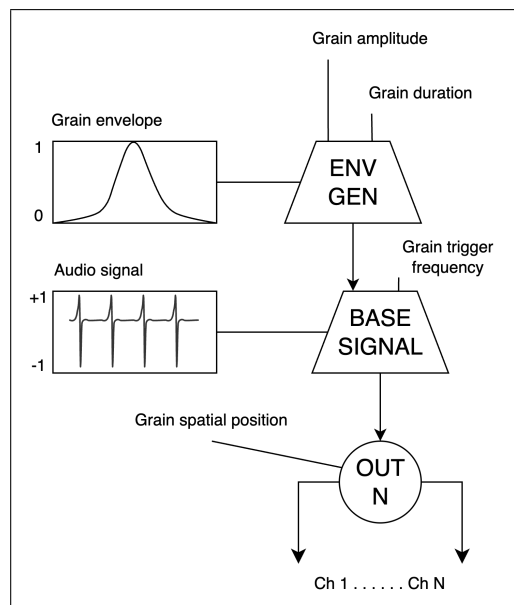


Figure 2. A grain generator with its envelope and its base signal. Inspired from Road’s book. [18]

of the object studied, or can represent multiple parameters for a given point. Finally, the GMEM history with granular synthesis and the multidisciplinary approach of this project definitely convinced us to use this method to create our sonification tool.

2.3. A cell mechanics exploration machine

2.3.1. Methodology

To manage this research project, regular discussions took place between the DyNaMo researchers and the GMEM team in order to define and refine a methodology that combined the scientific rigour of the research field with the creative possibilities offered by sonification. It was important to listen what researchers wanted, to understand what was at stake and to establish a link between sound creation, scientific popularisation and research activity in order to define paths to be explored. Initially, the working process was empirical because we didn’t have yet a global vision of the sonification process. Some of us were more specialized in AFM, others on the audio process and creation. A first meeting allowed us to discuss the research methodology, the research dissemination and the possibilities offered by granular synthesis. This step has established a common framework for all to implement relevant sonification strategies.

Throughout the development of the project, regular meetings were held with GMEM members. These meetings provided feedback from a professional computer music producer, but also from lay people, to test what worked in terms of perception and interaction with the device. This was really valuable to refine the scientific outreach work. At the same time, meetings with the DyNaMo researchers allowed us to stay as close as possible to the accuracy requirements, and in particular to work on the links between

the mechanical properties and the underlying data, as well as the application of the laws of physics to sound generation. In this way, thanks to the various feedback, the project became more and more precise and was finally approved by the different teams.

2.3.2. Scientific content and sonification strategy

The first point we wanted to address was how to make the nanometric scale explored by DyNaMo researchers accessible to everyone. In fact, it is quite difficult for laypersons to realise the physical implications of the nanometric world (and in particular the dominance of random motion). This high level of "noise" can be observed in AFM data and a first idea was to explore this notion through sound, by transcribing signals recorded by the AFM into audible frequencies. However, this proved complicated from a communication point of view and limited from a creative one. The sonification work therefore focused on less abstract aspects, and we decided to work on the mechanical properties of the cells measured by AFM. The idea was to allow the viscoelastic properties of the cells to be heard. This idea was particularly interesting for several reasons:

- These data are multi-parametric in nature: several parameters are measured for each point of the sample (topography, stiffness, elasticity, viscosity). This makes them particularly difficult to display visually (since there are several maps that are difficult to read in parallel or to overlay, making interpretation challenging). This makes sonification particularly advantageous, as the different sound characteristics (pitch, volume, timbre) or granular synthesis parameters (grains frequency, length, pitch, etc.) can be used to transcribe multiple data at once.
- It allows a sound composition based on tangible ('palpable') elements that could be reproduced through sound, using psychoacoustic effects, and thus offers a space for creation.
- Data maps sonification can be based on the development of an on-screen interface, with the sounds playing when the users touches the screen. We found the analogy with the way the AFM works (it is a microscope that 'touches' the samples to access their properties) interesting, as it allows the mediation tool to discuss not only the scientific data, but also their method of acquisition (the development of which is also a subject of research within DyNaMo). Moreover, it creates interaction with the listener, who becomes the driving force behind exploration, increasing engagement. Presenting scientific data using a touch interface is also appealing to young audience that is used to this kind of interface.

We started developing a Max patch and working with the GMU (see Section 2.2.2). Although the aim of this proposal is not to convey the nanometric scale, we still

have some sonification options that do. The use of short grains and high frequency sound elements within the granular synthesis allows us to perceive the working scale. Moreover, a spatial composition was thought to make sound grains move around the head of the listener, in a speed giving us a sense of the size and the scale. However, the main objective was to be able to reproduce the cell mechanical properties through sound, thanks to psychoacoustic effects such as the use of sound invariants. Inspired by Gibson's work on the ecological approach of perception, Gaver theorized [19] the possibility of perceiving the sound emitted by an object on the basis of a specific temporal and spectral pattern within the sound itself. These patterns, also named *invariants* [20], could be decomposed into two different types: a *structural invariant* which conveys information such as the shape, size, state of a sound object, and a *transformational invariant* which describes the action required to produce a sound from the object. One who finds the corresponding invariant could synthesize the desired sound by synthesizing only the invariant itself.

The data to sonify consisted on processed maps of topography, elastic scaling modulus (G_0) and fluidity (α) obtained from AFM mechanical mapping measurements on living white blood cells [21]. The parameters (G_0) and (α), as described below, can be transformed into a viscous component and an elastic component or, similarly, to the dissipated and stored energy, respectively.

To translate these components to sounds, we tried to isolate what characteristics in a sound element could lead to the evocation of the cell viscoelastic properties. These properties are not sound *per se*. Honey, which is quite viscous, does not make any particular sound. The goal was to think of sound characteristics that would evoke viscosity. We chose quite watery audio samples like the sea, cooked beans, the rain, etc., to use it as base signal within granular synthesis. Then, we set a long attack envelope for the grains. The overall composition was composed of a lot of long and soft attack grains per second, with effects added to make it more reverberated and bubbly, and an equalisation to cut the high frequencies. We continued with this idea for the stiffness, which, on the contrary, was based on samples of impacts on steel, stone or iron. These sounds also went through granular synthesis, but with short attack grains, rich in high frequencies, at a speed of a few grains per second. Finally, we thought of the elasticity as a bouncing feedback, mostly based on samples of bubbles and springs.

The sound composition also includes a spatial component that follows the user's tactile movements on the interface, as well as viscoelastic changes. If the user touches a more viscous region, the sound elements will move around the listener's head as the energy is dissipated. On the other hand, on stiffer parts, the sound is more localised in one place and stays there.

In addition, to manipulate the sound levels as the user touches and releases the screen, we got inspired by the following equations describing the mechanical characteristics of the cell. In particular, we used the complex shear

modulus $G^*(f) = G'(f) + iG''(f)$, comprising the elastic term or fraction of stored energy:

$$G'(f) = A \cos\left(\frac{\pi\alpha}{2f}\right) \quad (1)$$

and the viscous term or fraction of dissipated energy:

$$G''(f) = A \sin\left(\frac{\pi\alpha}{2f}\right) \quad (2)$$

Finally, another equation controls the levels of the three sound compositions. In analogy to the expected force response when a cell is pressed, the sound rises with time (t) according to the equation:

$$f(t) = t^\alpha \quad (3)$$

And, when the sound falls, while, formally we should use:

$$f(t) \sim t^{-\alpha} \quad (4)$$

The resulting effect was not satisfactory because it was too short, thus difficult to perceive, and also because the difference between stiff and soft parts were not strong enough. We decided to transform the equation into an exponential decay:

$$f(t) = e^{-t*(1-\alpha)} \quad (5)$$

These functions reflect the viscoelastic response of cells observed experimentally using AFM by the researchers [22].

2.3.3. Form of the developed tool

This work has led to the creation of a multichannel sound installation, that can be deployed on four, eight channels or binaural systems. All the interaction with the Max patch is enabled through a web interface that can be opened on a smartphone or a tablet. This interface is connected to the computer hosting the Max patch and the web server via a local network. Several clients can be connected at the same time, each interacting with the server, which then transmits the data to the patch. This patch maps the movements onto the pre-processed data, which are then associated to synthesis parameters. It outputs the generated audio to headphones (the installation presented was in binaural). A schematic view of the program is shown in Figure 3. More technically, the interface is a website, hosted by a computer on a local network, using Node.js.⁵ The client sends the data (user's positions, cell selection, etc.) to the server using the socket.io library.⁶ The server then conveys those data to Max thanks to the [node.script] object and the Max-API JavaScript library.

⁵ <https://nodejs.org/>

⁶ <https://socket.io/>

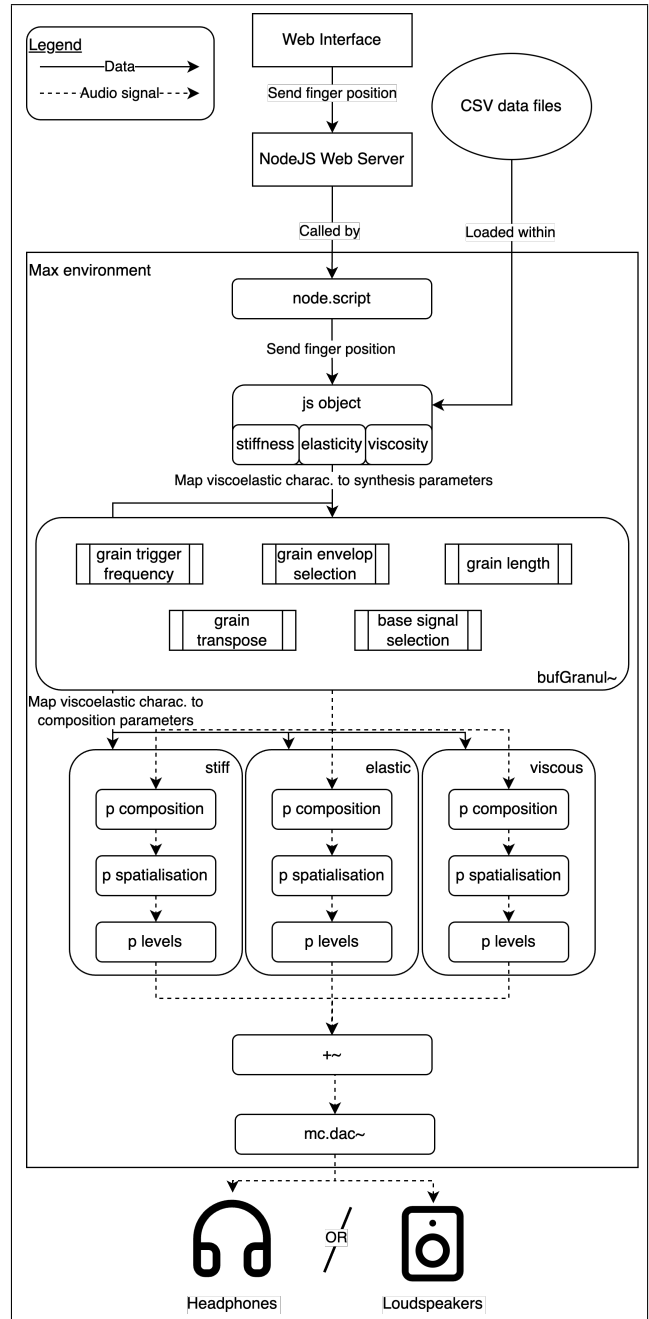


Figure 3. Schematic view of the global system with each processing stage. The data from the CSV file come from the pre-processed AFM measurement. Every box within the "Max environment" is either a patcher or a max object.

When a user connects to the interface, a drop-down menu allows it to choose between several cells, and a button allows to display the image of the cell or not (Figure 4). Empirical testing with GMEM team members brought some feedbacks about the advantages of adding a visual representation to facilitate the representation of a cell after an auditive only exploration. These were created by computing heat maps of the data and added to make the cell tangible, so that the audience could see what it looks like. This strengthens the mental representation of the cell by combining several sensory modalities. Finally, it is nice to

have this visualisation with the sound to give a more precise information about the cell structure (nucleus, membrane). We designed the interface so that when someone starts it, the heatmap is not yet visible, to encourage participants to focus on listening, taking the time to guess where the cell is located, which areas are more viscous, and so on. The data is then explored "blindly", which is the way the AFM works, since this microscopy doesn't use any light allowing to "see" the sample. The user can then switch the button at the top right of the interface to display the corresponding heatmap (Figure 4).

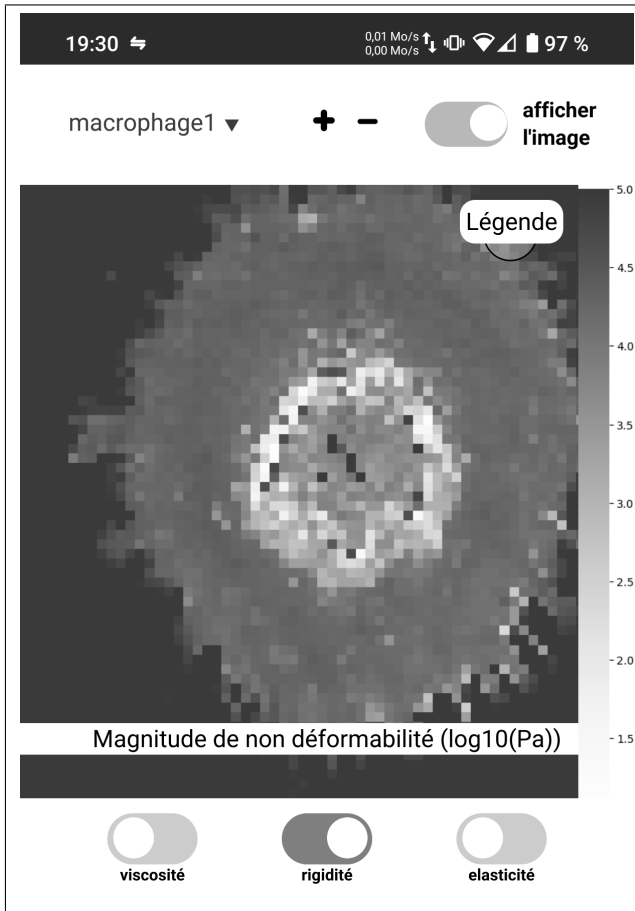


Figure 4. Web interface with the stiffness map of a macrophage displayed. The "legend button" on the interface offered the possibility for the user to display more information about the data, as well as the scale of the heatmap. The user can listen to each property individually, or a combination of different parameters at the same time

The heatmaps were generated from the AFM data. These data are in the form of a matrix containing, among others parameters, the height value (z) and the parameters (A) and (α) defined above for each point X and Y . These data were first translated by a Python script into a multidimensional matrix of reduced dimensions, gathering only the data we were interested in. The height (z) was used to draw the topography map, (A) was used to draw the stiffness map by computing $(\log_{10}(A))$, the elastic term

(G') was used to draw the elasticity map, while the viscous term (G'') was used to draw the viscosity map. The heatmaps were generated in Python using the pandas [23, 24], matplotlib [25] and seaborn [26] libraries.

The interface allows the user to explore and move around the cell map by pressing and dragging on the screen, and to also select which behaviour to listen to (stiffness, viscosity and/or elasticity, Figure 4). For example, one can listen only to the viscosity to be able to apprehend this parameter more easily. By adding the other characteristics, it becomes possible to perceive the interaction between them. In this way, when one listens to viscosity and elasticity, which could be described as opposite from a data perspective (the viscosity describes the amount of energy dissipated, while elasticity describes the amount of energy stored), one can really hear that the viscosity is quite low when the elasticity is quite high.

When the user places a finger on the map, the Max patch retrieves its X and Y Cartesian coordinates, allowing the software to associate it with the data from the AFM measurement at this precise position. This happens thanks to a script contained in a [js] object. This script retrieves the viscosity, elasticity and stiffness from a csv file (csv containing the AFM data resulting of the Python pre-processing stage) of a given point on the cell. This is done within the [p get_data_from_user] patcher in Figure 5. The data retrieved in this way is then mapped to several parameters, including ones from the [bufGranul].

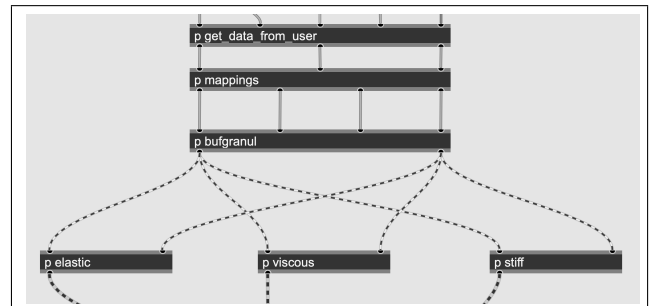


Figure 5. Patch view of the global system with each processing stage.

For instance, stiffness is mapped to grain frequency and transpose, while viscosity is mapped to grain length (see Figure 6). The patch is then split into 3 eight-channels patches: elastic, viscous and stiff. Each one gets a stereo audio stream from the [p bufGranul], and mixes it with some effects or with other sound elements. Each one then goes through a spatial composition with the [spat.pan] object. Finally, each part goes through a [level and FX] subpatch, which follows the equations described in 2.3.2, to control how the sound rises or falls when the user presses and releases the pressure on the screen, as well as adding more general effects, such as reverb or equalisation. The three subpatches are then mixed together and the result goes into a final spat object to change the type of the output (n channels or binaural output).

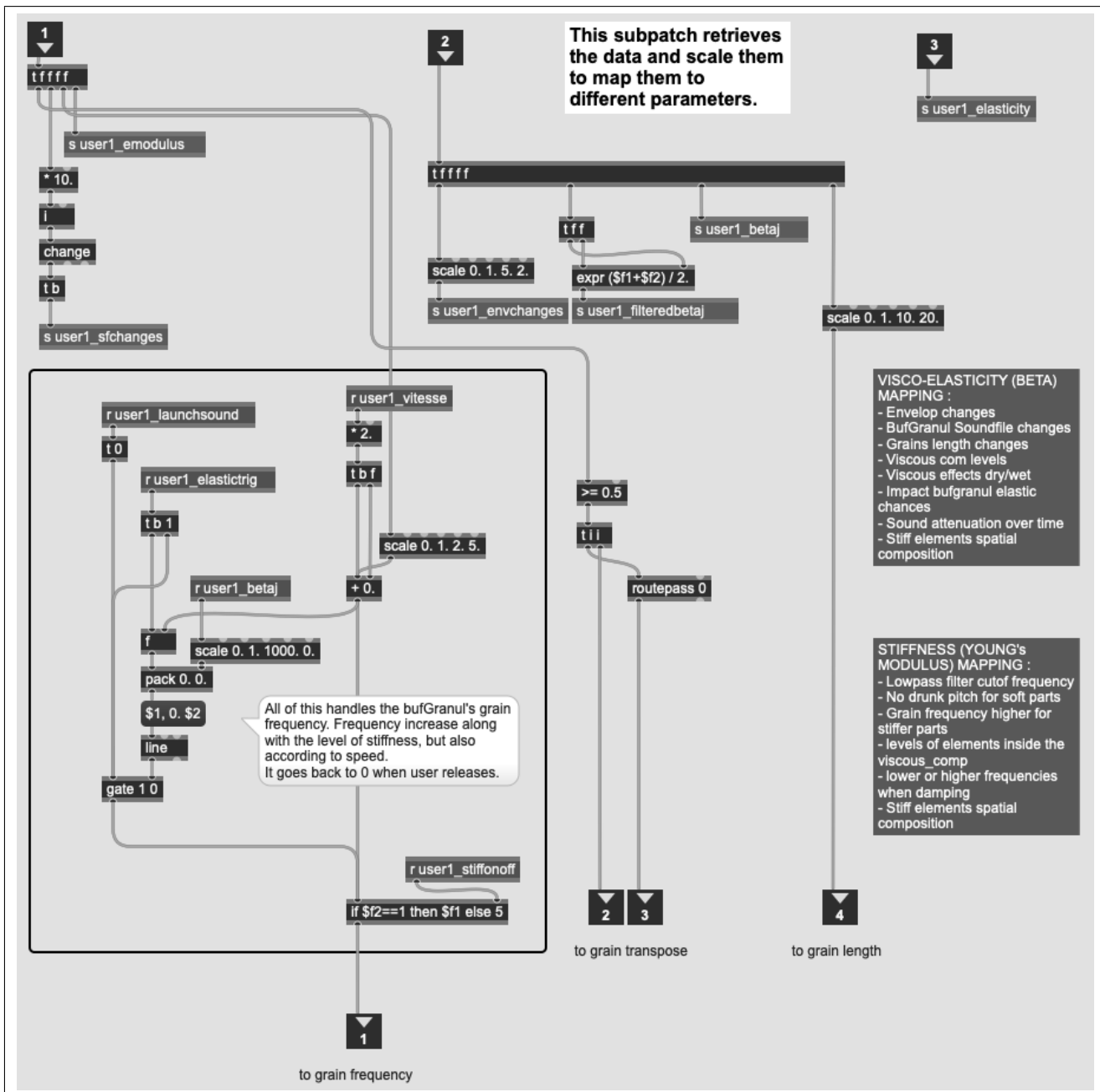


Figure 6. Mapping stage of the patcher.

To summarise, as the finger moves around on the interface, the evolution of its position in real time is tracked and transmitted to the patch through local network. Then, the mechanical data is retrieved and mapped to several parameters of the sound creation. Therefore, the sound and spatial compositions are modulated according on how the measured data are changing.

3. CONCLUSION

3.1. Overview

In this work, we have presented the conception of a sound installation dedicated to the sonification process of cell

viscoelastic properties of cells retrieved thanks to the AFM technology. To do so, we were inspired by Gaver's ecological approach of perception and the research of sound invariants for viscosity, elasticity and stiffness while trying to make audible rigorous equation for teaching and popularisation purposes. Everything made during this project is accessible online⁷ in an attempt to follow open-science principles. A video showing the exploratory processus is also available on Vimeo.⁸

⁷ <https://github.com/leohuet/MechaCellSounds>

⁸ <https://vimeo.com/869072591>

3.2. Work public presentation

The installation was presented at the *Nuit européenne des chercheur·e·s* on September 29 and at the *Fête de la science* from October 13 to October 15. For these two events, our sonification tool was presented as a binaural setup (Figure 7). Indeed, due to the ambient noise at those events and the lack of space, we decided to use a binaural headphone configuration. This also had the advantage of allowing multiple users to discover the sonification work and interact with the device without conflict. We set up five listening stations, each one with two headphones available. Participants could connect to a listening station via the web interface, which they accessed with their smartphone by scanning two QR codes (one to connect to the local network, the other to open the web page). Tablets were also available for visitors without smartphones.



Figure 7. Young audience interacting with the installation at the *Nuit européenne des chercheur·e·s*

We were able to interact with visitors of all ages and profiles, from children and families to teenagers on school outings. In addition, the sounds can also overcome language barriers (while we carry out outreach activities locally in French, we are sometimes approached by international friends and family and some courses at the university are given in English). Feedback from visitors was fairly positive. The interface was fairly intuitive and easy to use. The psychoacoustic choices were well received by the audience. It managed to identify to the sound creation and have a first understanding of what was at stake without being really involved in the scientific research. Overall, the interface enabled a wide range of discussions to take place, both on the data represented and the AFM acquisition technique, as well as on the sonification process, its interests and the issues involved. These rich interactions have encouraged us to continue our reflection and have enabled us to identify several avenues.

3.3. Openings

3.3.1. Choices validation with psychophysical methodology

While the public feedback was positive about the intended goals, it would be interesting to formerly test our hypothesis using psychophysical methodology. It would be interesting to investigate whether some granular synthesis parameters could be correlated with the evocation of viscosity, for example, as it was done for the material in [27], or whether the main evocation comes from the base signal material.

3.3.2. Miniaturisation

One of the problems we faced presenting our work was that the technical equipment required was large and complex. It was suitable for events such as the *Nuit européenne des chercheur·e·s* or the *Fête de la science*, but not for use in school workshops, for example. Also, with one computer doing all the calculations, we were not able to have more than 5 listening stations at the same time. These problems could be avoided with other solutions.

The original idea was to deploy the patch on Raspberry Pi⁹ with Pure Data. This could still be done, with the Raspberry becoming the listening station to which the user connects the headphones. Each device would receive the data from the users in OSC (Open Sound Control, a data transmission protocol over network¹⁰) thanks to a web server hosted on a computer. The web interface would be the same as now, except that instead of sending the data to Max on the computer, it would be sent in OSC to the Raspberry Pi.

Alternatively, to make the interface more accessible, we could rebuild the project as a web application, so that the audience could open it with their smartphones, plug in their headphones and be completely autonomous through the process. This would free us from the constraints of technical equipment, and we could open up the project to people online, just through a website. One possibility to do so would be to convert the Max patch to JavaScript and use the Web Audio API.¹¹

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⁹ <https://www.raspberrypi.com>

¹⁰ <https://opensoundcontrol.stanford.edu>

¹¹ <https://www.w3.org/TR/webaudio/>

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