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SoundSculpt

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SoundSculpt: A Design Framework for 3D Modelling and Digitally Fabricating Sound Patterns.

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This paper presents a design framework for the design and production of a sculptural installation which combines sound experimentation with 3D modelling and digital fabrication. This paper's aim is to make a two-fold contribution. On one hand, it describes the design framework as a support tool for practitioners in their exploration of sound-informed geometries through 3D modelling and digital fabrication. On the other hand, it informs educators on key aspects for combining sound, 3D modelling, and digital fabrication within educational curricula and in their students' design processes. The framework was tested during a workshop where participants produced and fabricated 3D objects informed by sound patterns they created. After describing the design process, the final installation and its shape grammars, as well as participant experiences during the design process, the paper concludes with a discussion on how the design framework can be useful for practitioners and educators.

CCS Concepts: • **Human-centered computing** → **Visualization**; • **Applied computing** → **Sound and music computing**; • **Computing methodologies** → *Shape modeling*.

Additional Key Words and Phrases: design framework, computational design, digital fabrication, sound-informed geometry

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1 INTRODUCTION

The last few years have seen a growing interest in projects which merge seemingly separated fields such as art, science, design and engineering, an antidisciplinary [24] trend which has been referred to as "the age of entanglement" [37], [15]. The visualization (in two dimensions) and materialization of sound waves is one area which has applications across seemingly different fields. Visualized sounds can be placed on a continuum between technical-pragmatic and purely artistic [27], or in other words, on a continuum between concrete and abstract representations [32]. Concrete (or physically accurate) visualizations and materializations of sounds are interesting both for their aesthetic qualities but also for informing thinking about and thinking with sound.

The historical development of acoustics as a field is linked to visualizing sound waves. Its beginnings can be dated back to the Renaissance with mentions of sound vibrations creating patterns in dust from Leonardo [8] and later Galilei[10]. In 1680, the English scientist Robert Hooke observed nodal patterns in flour which occurred by vibrating a glass plate with a violin bow[19]. Ernst Chladni repeated and further developed Hooke's work and noticed correlations

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between sounds and patterns formed in sand. He perfected this method and created different patterns published in "Entdeckungen über die Theorie des Klanges [Discoveries in the theory of sound]" (1827) for the first time [4] and then later in "Die Akustik [Acoustics]" (1802) [5]. Physicists Michael Faraday and Lord Rayleigh expanded Chladni's results in the 19th and early 20th centuries [46]. In addition, singers such as Margaret Watts-Hughes (1842 – 1907) and vocal therapists such as Holbrook Curtis (1856–1920) began to experiment with them [17]. In 1967, Hans Jenny published a widely received book on his experiments that were inspired by Chladni patterns [25] and introduced the self-coined term "cymatics" to describe the study of visible sound vibrations. Recently, mathematicians introduced a method for creating digital 3D Chladni shapes [44].

Nowadays, Chladni patterns are used relatively rarely, but across a broad range of fields. They are used in artworks, to inform the design and better understanding the tonal properties of acoustic musical instruments [13], in design and architecture, as alternative displays, or in therapeutic settings for the creation of multi-sensory experiences. For example, "Cymatics: Science Vs. Music" is one artistic project notable in showing sound vibration patterns in different mediums [45]. The geometry of the "Soundshape Speaker" designed by Ricky van Broekhoven and exhibited during the Dutch Design Week 2013 was informed by Chladni patterns [30]. In [48] a workflow for transforming one Chladni pattern into a sculptural CNC cut piece is presented. In [29] cymatics have been suggested as alternative, novel displays for visualizing the energy consumption of buildings, inspired by properties of energy itself.

But not only the discovery and development of acoustics is linked to sound materialization. The discovery of fractal geometry as a field is linked to accurate sound visualizations [23]. And similar examples in other fields abound. The reason for this is simple: some people think best in formulas, and others think best in shapes [23], while other people might think best through sounds, or through moving their bodies [39]. Travelling across disciplines and using the tools of one to inform another is what entanglement argues for.

The fact that current design methods in HCI are focused on symbolic, language-oriented, and predominantly visual interactions calls for exploring new design frameworks, as has been shown so compellingly in [20] with somaesthetics. Designerly ways of doing differ from one field to another, but many design disciplines share processes which predominantly involve the visual: from industrial design to architecture or interaction design. Design research and practice also share: (a) the fact they constantly look for ways to stimulate and enhance creative processes, and (b) a general poor understanding of how exactly creative work happens or how it should be taught [6], [11], [26]. And so the reasons for exploring new design frameworks are manifold. First, there is a need for moving away from purely visual interactions when designing. Second, more action-based research is needed to help understand how to teach design, and how creative work happens, and this can be done through novel design frameworks. And finally, by entangling different subjects, new knowledge and new research directions can emerge.

Grounded in these arguments, and in continuation of prior research work, this paper presents a design framework which borrows methods from sound production and places them in a setup meant for designing physical objects. The contribution of the paper is twofold. The first one is a design framework that aims to support practitioners in exploring and producing sound-informed geometries through 3D modelling and digital fabrication, by entangling methods from sound design with the visual processes used for 3D modelling and digital fabrication which are now used in many design fields. The second contribution is about how to apply this design framework within an educational setting with the purpose of teaching novices about 3D modelling and digital fabrication - skills which are often taught by prioritizing reason and logic. This approach was taken, since it is argued that introducing sound exploration in a design setup geared toward fabrication where thinking through logic has been privileged for a long time [21], will make doing more engaging also for those who think best aurally, and not only for those who think best visually and/or

mathematically. And this is something desirable from an educational perspective. Furthermore, from a practitioner perspective, introducing a different explorative medium in one's design process can unlock creative endeavours [22]. Finally, apart from the under-explored aesthetic properties of Chladni patterns, concrete sound visualizations are interesting for showing the physical properties of a material - a constant interest when working toward the fabrication of physical artifacts.

Towards this end, the paper is structured as follows. First, the design framework is presented along with a workshop where the framework was tested as a case study. Then, the physical artifact that emerged from the workshop is presented and analyzed, along with participants' experiences of working within this framework and creating the artifact, and our own learned lessons from conducting the workshop. Finally, the paper concludes with a discussion on using the design framework as a support tool for practitioners and as an educational tool.

2 MATERIALS AND METHODS

The idea of using concrete physical representations of sound to inform the fabrication of physical objects was first probed in an iteration where we built a Chladni setup, worked out how to interact with it, and explored how to create 3D shapes from the created patterns. Chladni patterns and cymatic experiments can be done digitally. However, as opposed to the framework presented in [48] we chose a physical or analogue Chladni pattern setup because this would allow to experience the physicality of sound vibrations more vividly than when mediated by a screen. Different fabrication methods were considered. CNC milling was deemed too difficult for first-time fabricators, 3D printing and laser cutting were also tested. We noticed Chladni patterns can lead to designing complex 3D models when these are informed by more than one image of a pitch: showing sounds over time in three dimensions - which we found more interesting. Therefore, preparing these models for 3D printing was considered too tedious, while the sizes of the resulting end-pieces might be too small. These first explorations informed the creation of a the design framework which integrates sound experimentation through analogously produced Chladni patterns, 3D modelling using NURBs software Rhinoceros3D [35], and digital fabrication through laser cutting. This was applied in a 10-day workshop that was part of a digital fabrication course for second semester bachelor of art and technology students.

2.1 Participants

The 16 participants had different nationalities and were all studying in Denmark (fig.1). They were aged 18 to 45 years old and came from different educational backgrounds, making them a diverse group. Most had no experience with 3D modeling before the workshop apart from four of them. All participants had some experience with sound production from a previous course.

2.2 Design Framework

The design framework includes four design spaces, each of a different size, and each requiring a different mode of thinking (fig.2).

Age	18-25 : 13/16	25-35 : 2/16	35-45 : 1/16
Gender	female : 8	male : 8	other / rather not say : 0
Nationality	Denmark : 9, The Faroe Islands : 1, Serbia : 1, Lithuania : 1, Slovakia : 1, Romania : 1, United Kingdom : 1, United States 1		
Previous experience with 3D modelling	12 have none ; 1 has two-years Fusion 360; 1 has been working with Blender for 2 years; 1 has worked with TinkerCad for 2 months; 1 has 'some experience with CAD and Blender'		
Previous experience with sound design / exploration	minimum of one 1 ECTS course in sound design : 16/16		
Previous background	2 came straight out of high school, 1 has three years of professional experience as a graphic designer, 1 has 20 years of experience in teaching music at elementary school level, 1 shifted education from a bachelor in Robotics; 1 shifted from a bachelor in Medicine.		

Fig. 1. Participant demographics and previous experiences.

The first design space, that of the analogue Chladni pattern generator, was a bi-dimensional environment with aural/sound/audio, physical, and visual elements.

The second design space, where students were asked to use the Rhinoceros 3D [35] modelling environment to transform Chladni patterns into 3D models is a three-dimensional Cartesian space, visual and virtual. Compared to the previous space, this was larger, allowing for much more design freedom.

An intermediate step of preparing the 3D geometries for laser cutting had participants enter a third design space. They had to use a custom-made script in a separate visual-programming language interface called Grasshopper [34] which works on top of Rhinoceros3D. This space was visual, Cartesian and three-dimensional and requires thinking in an algorithmic way, both geometrically and visually.

The fourth and last design space was reached when the material, the physical shapes were fabricated. This last space was physical, material and visual, three-dimensional and tactile. It engaged visual thinking and haptics.

2.3 Process: Workflow

These four spaces were explored over the course of 10 days. At the beginning of the 10-day workshop, a design brief was introduced. It asked participants to produce, as a group, an installation of sound informed geometries. A pre-designed 3D model of a wall divided into bricks was provided. The wall, 1.7m wide and 2.1 tall, was made up of 34 bricks, and

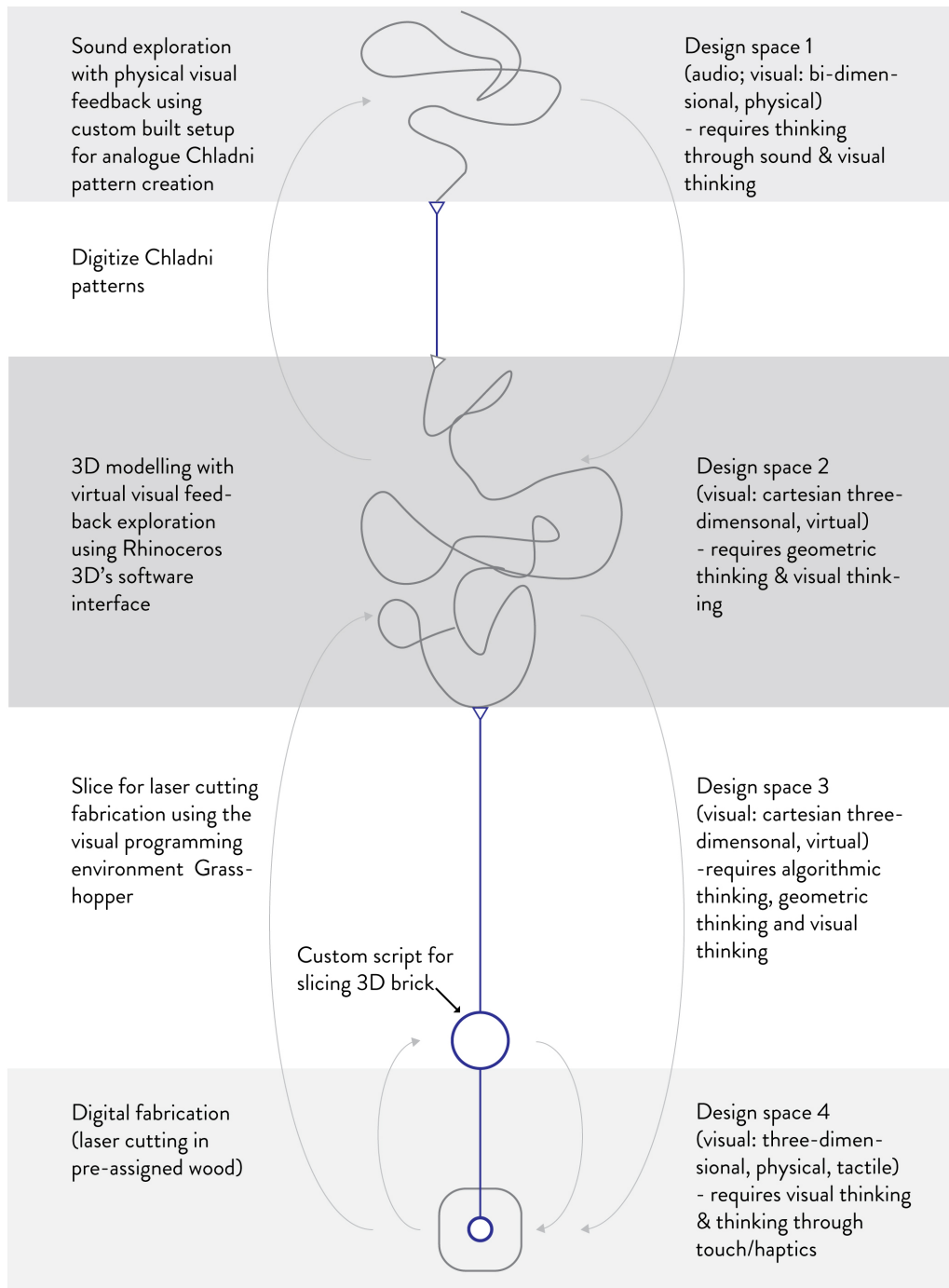


Fig. 2. Design framework and design spaces explored by participants.

each participant was assigned to design at least one brick (fig. 3, step 0). Example bricks were designed by one of the authors in order to facilitate the process. The bricks had variable sizes, ranging between 23x23x20 cm and 23x35x20 cm and everyone was asked to create a unique design for their assigned brick. The requirements were: to use 2D Chladni patterns they themselves produced to inform the 3D design of the brick, to use laser cutting for production, to use a specific building material (0.9 cm thick wood plates of 120x120 cm), and to maintain the outside shell of the bricks so the installation could be assembled and exhibited.

2.3.1 Design Space 1: The Chladni pattern setup. Participants were presented with a setup for creating Chladni patterns in an analogue way (fig. 3, step 1). This setup was made of a microphone connected to an amplifier which was then connected to a vibration generator. They could use any way they wanted for producing sounds within the Chladni pattern generation setup. This first design space was mostly explored through instruments such as phone frequency generators or short pieces of music played on phones, tablets, or laptops. Only three participants engaged with their own voice, while the rest were too shy to do so. This first medium was the smallest in terms of variability - there is a limited number of significantly different vibration patterns that can be observed on one plate.

2.3.2 Design Space 2: The 3D modelling environment. The produced patterns were then digitized (fig. 3, step 2) and participants were free to choose how they wanted to use the data to inform the design of their brick(s). During live-sessions, one of the authors gave live tutorials on how to interact with the 3D modelling interface and designed bricks showcasing the process of transforming 2D images into 3D models by drawing line-work on top of the images and then creating surfaces by extrusions or lofts. Participants were given the freedom to experiment with how they wanted to have the images inform their shapes (fig. 3, step 3).

In the second design space basic navigation such as panning, zooming, and rotating posed an initial challenge to those who had no previous experience with 3D environments. After getting accustomed to basic navigation, many spent a good amount of time here. This space required to start thinking geometrically: determining how to navigate through a 3D space and understanding object views (top, side, perspective) and sections. Two days were spent learning,

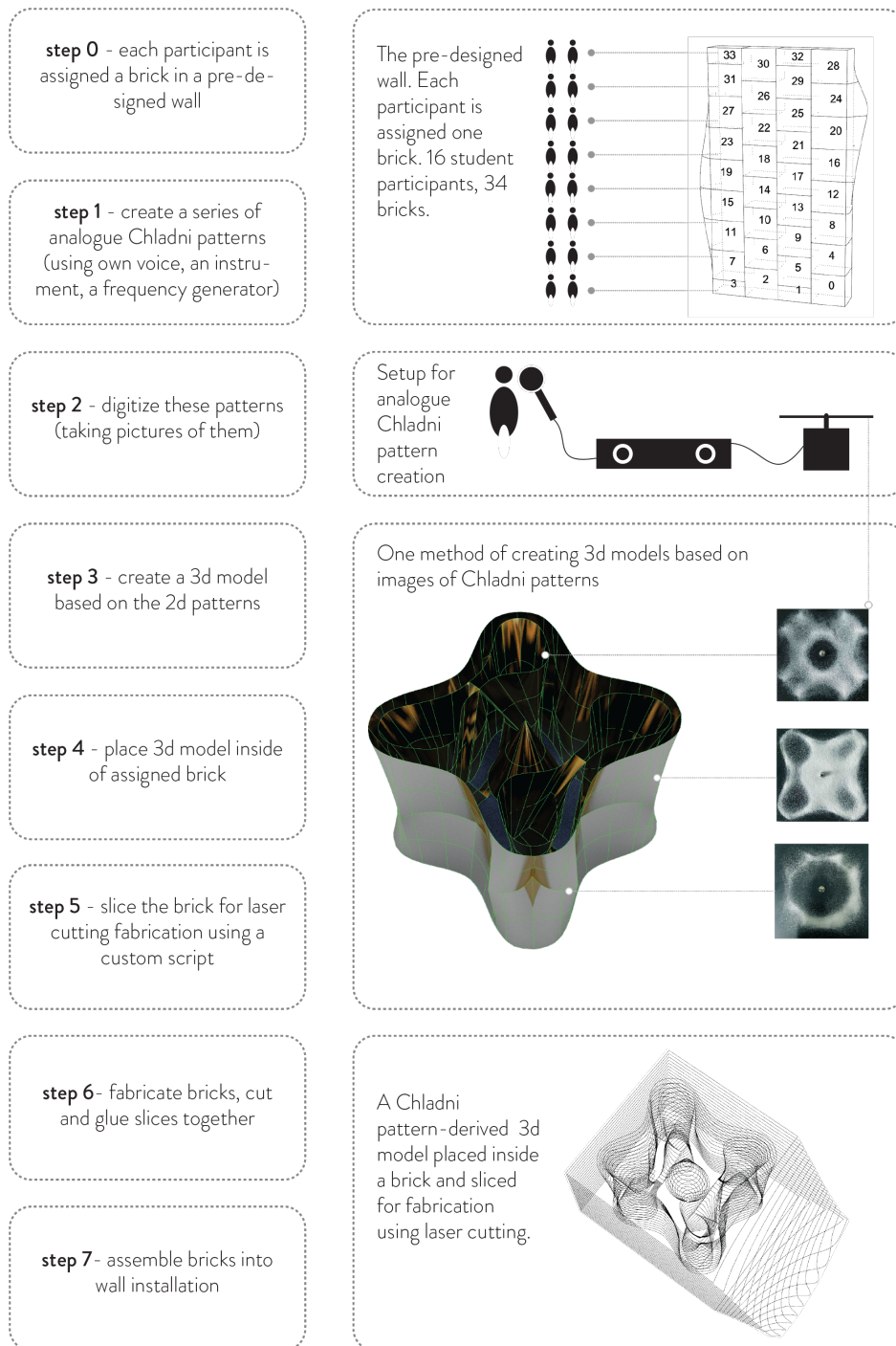


Fig. 3. The workflow for the production of the installation.

modelling and iterating through 3D models and functions such as extrude and loft. Only three participants went back to design space 1 and tried to get different images to inform their 3D geometries.

2.3.3 Design Space 3: The visual programming environment. The produced 3D models were placed inside the frames of the bricks (fig. 3, step 4). As 3D models were taking shape one by one, excitement started building up for the upcoming fabrication process. An intermediate step of preparing the 3D geometries for laser cutting had participants enter the third design space. They had to use a custom-made script in a separate visual-programming language interface called Grasshopper [34] which works on top of Rhinoceros3D. The script was provided by teachers and participants only needed to feed their shapes as input and export line work. One by one the 3D models were sliced, exported, and fabricated using laser cutting (fig. 3, steps 5 and 6)

2.3.4 Design Space 4: Digital Fabrication. In the fourth and last design space the slices were cut and they were glued together to form the bricks (fig. 4). There were a few iterations here - in trying to get the right line work exported for the laser cutter, some participants wanted to build another brick, because they felt the first one could be improved. Three managed to do so, and another five could not because of machine time constraints.



Fig. 4. Brick assembly work in progress. Photograph by authors.

At the final step of the workflow the produced bricks were assembled into the wall installation (fig. 3, step 7). This wall installation was exhibited in the foyer of the University.

2.4 Data Collection and Analysis

The images of Chladni patterns used to create each brick and all 3D files were gathered. Each 3D model was reverse engineered in order to be analyzed geometrically by looking at: the number of Chladni patterns used to create the 3D model, the Rhino operation used to create the surfaces (extrusions, lofts, patches etc), the curvature degrees of the surfaces as well as the number of kinks or control points each surface had, and whether the brick had symmetry on X, Y and/or Z. This (objective) analysis of the artifacts was complemented by remarks about the pieces made by participants during production and assembly, which were noted by one of the authors during the workshop.

Furthermore, at the end of the production process, the participants answered a survey where demographic information was collected together with their previous experiences with sound creation, 3D modelling and digital fabrication. They

also reported, through open questions, on their experiences of exploring, iterating and navigating between the four design spaces of the design framework, and on the level of attachment they felt towards the Chladni patterns, the 3D models and the fabricated bricks.

Participant's responses to these open questions were analyzed qualitatively. First, all data were collected and transcribed by two of the authors. Then, they independently became familiar with the data and coded a subset by using an emergent coding approach [28]. The emergent codes were then negotiated between the two authors, until a final list of codes was produced. This final list of codes was used to then collaboratively code the whole data set. Afterwards, an iterative process started where the codes were affinity diagrammed [18], first separately and then collaboratively by two authors, until the final structure was produced. Based on this analysis, responses on how the design framework was experienced by participants were distilled into three main themes, presented below.

3 RESULTS

The results involve: (1) the physical shapes of the bricks and resulting wall, (2) the way participants experienced the design framework and how they felt about their own works and (3) its educational aspects and its impact on the learning outcomes.

3.1 The wall installation

By the end of the workshop, 17 bricks were finalized by the 16 participants (fig. 5).

The visual grammars of the various bricks (presented in fig. 6, where brick is abbreviated as Br) can be categorized geometrically by (1) number of Chladni pattern images used to inform the geometry, (2) the curvature degree of the surfaces (working in a NURBs 3D modelling environment, all participants worked with surfaces) and (3) whether the geometries have symmetry on X, Y, and Z (fig. 6).

The approach introduced in class by teachers for creating 3D shapes from the Chladni patterns was that of placing several 2D images at certain distances on the Z axis, drawing polylines/curves on top of them, and performing extrusions or lofts. The examples worked with third-degree curves and most of the participant-designed bricks (6 out of 17, Brick 6 - Brick 11) were made using this method. As most were new to 3D modelling, no one explored or seemed to think about other possible ways of generating 3D surfaces from 2D images. Ten shapes were created using two Chladni patterns, and nine shapes are symmetric on all three axes. Only two bricks (Brick 1 and Brick 2) were derived from first degree curves (polylines).

During the ten days, participants commented informally on the works of their peers. Six said that "the most beautiful" brick is Brick 15. This brick does not have symmetry on the X, Y or Z axes, its surfaces are derived from 5-degree curves and is informed by two Chladni pattern images. As opposed to the other bricks which are based on two Chladni pattern images and are informed by curves with degree curvature of 5 (Brick 13, Brick 14, and Brick 16), "the most beautiful brick"'s surfaces all have curvature continuity, in other words, the surfaces are fluid with no visible kinks. This corresponds to previous research in aesthetics: "fluid lines are perceived as more harmonious, relaxing, or pleasant—and more in consonance with nature—than straight or broken lines" [12] or [40]. Brick 17 was described by three participants as "strange". This shape is the only one derived from three Chladni pattern images and used 5-degree curves.

The most beautiful and the strange brick are not far apart from each other: they are both made from 5-degree curves, have a relatively large number of control points, and no symmetry on either X, Y or Z. The strange brick however, has a number of kinks and curve discontinuities. The distinction shows there is a sweet spot in the level of geometric complexity for a shape to be considered beautiful, and a higher complexity causes a different perception. Brick 11 had a

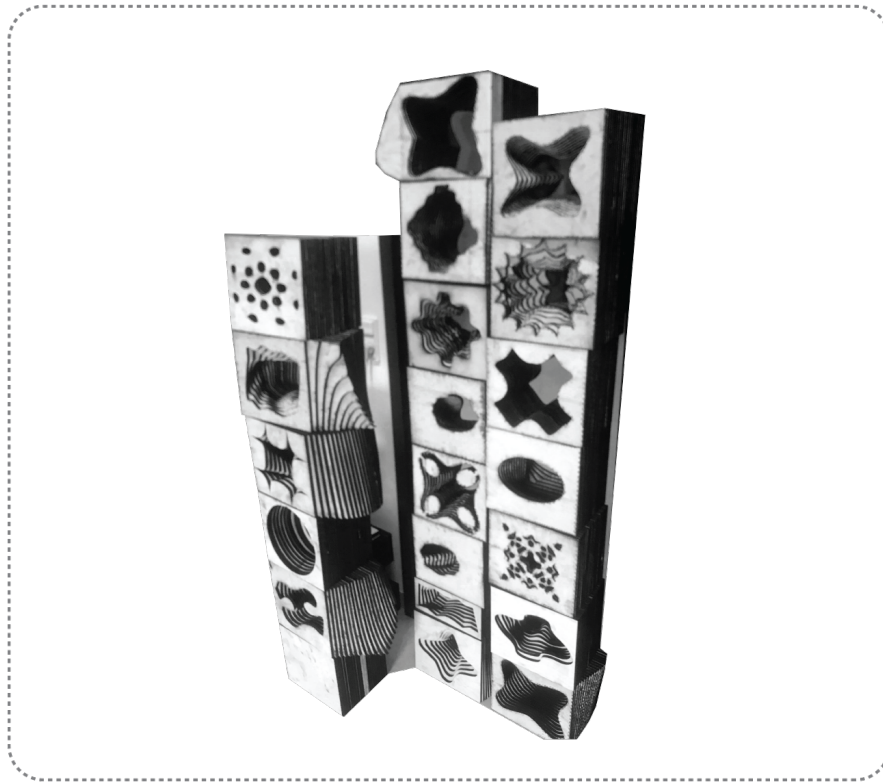


Fig. 5. The assembled sculpture. Photograph by authors.

similar number of kinks and discontinuities to Brick 17, however, Brick 11 was not labelled at all (neither as strange or otherwise) - the difference between these two is that Br11 has symmetry on X, Y, and Z as opposed to Brick 17.

One participant who did not take part in the guided demonstrations developed his own approach resulting in Brick 1. The shape of this brick stands out compared to the others: it was created from first degree curves and surfaces, has the most number of control points, and used one Chladni pattern image to inform the 3D shape. Brick 1 was described by five peers as "special" and by one as "delicate". This shows how much the guidelines given in class influenced the end-products and begs the question how would the installation have looked if participants were left unguided on how the Chladni patterns should inform their 3D creations. Sporadic comments on how heavy bricks felt were also made, however, the relationship between heaviness, the used material, and the 3D shapes were not investigated in detail.

3.2 Experiencing the Design Framework

13 out of 16 participants reported that making something which they found aesthetically pleasing was important for them, one felt neutral and two were not concerned with this. In evaluating their own creation process only 4 of 16 participants reported they were more concerned with making the technology work than worrying about aesthetics or fidelity, while the other 12 reported that they managed to acquire enough knowledge in order to be able to focus more

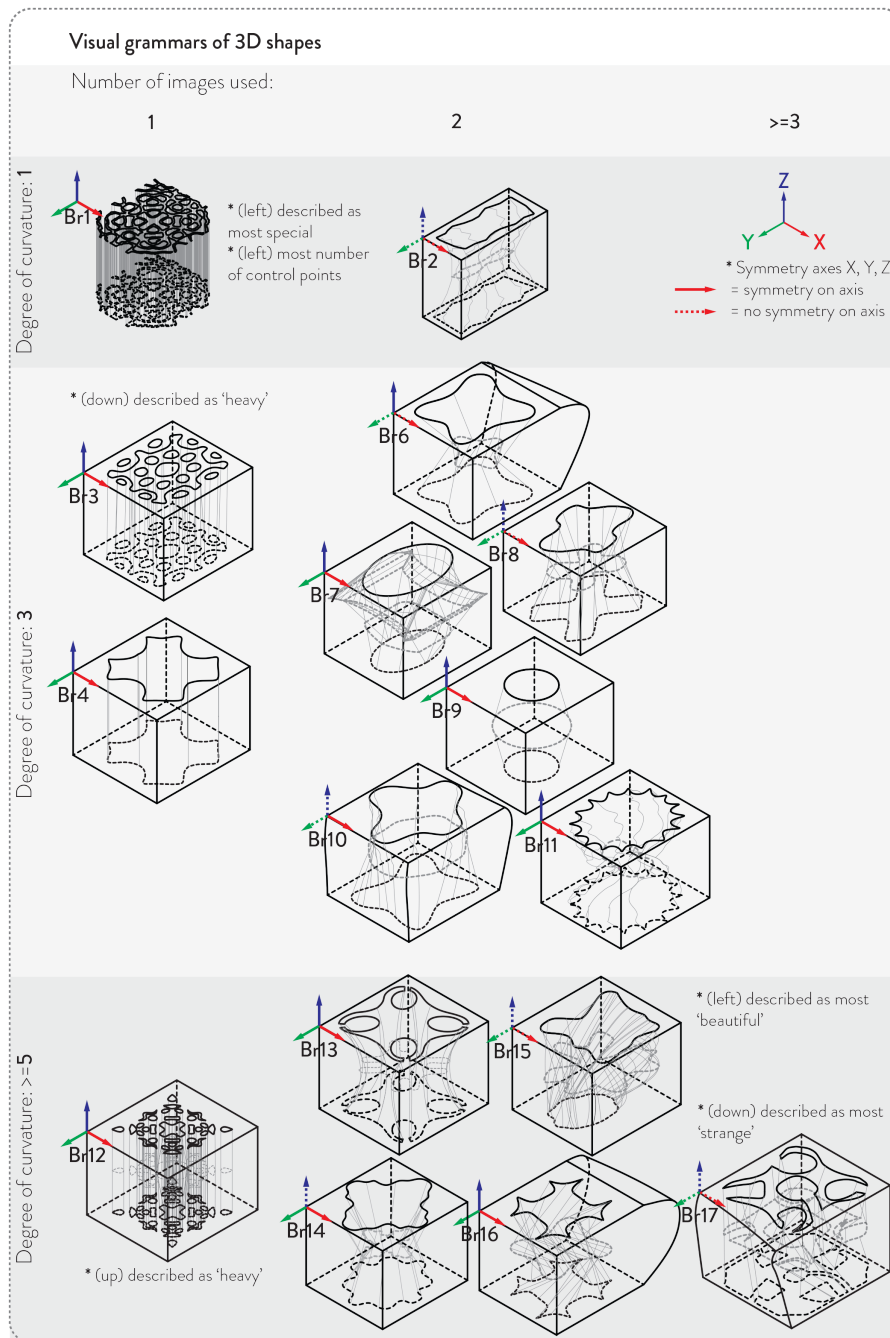


Fig. 6. Visual grammars of 3D shapes in the installation.

on their end products. Additionally, nine explained that it was important for them to produce a 3D shape which closely resembled their produced Chladni patterns.

3.2.1 The Chladni pattern setup. The first design space - where Chladni patterns were created - was generally enjoyed once everyone got over the initial inertia. However, most were too shy to engage in producing sounds with their own voices. One participant described this experience as *"interesting and fun to work with"* while another stated: *"[I] liked playing with the Chladni patterns on the plate, maybe had too much fun with it, forgot to focus on the exercise but it was fun, but I ended up using the pictures from the patterns as an inspiration and not as actual shape."*

3.2.2 The 3D modelling environment. In the second design space, around one quarter were intimidated by the new tools: *"[3D modelling was] difficult to begin with, but I slowly learned more. However, I haven't used the software much after the lectures and couldn't remember too much of how the software works"*. Panning, zooming, and navigating proved difficult getting used to as well as using top, side, or perspective views. This learning curve would have been less steep if participants had been introduced to a more simple CAD environment, such as TinkerCAD [2] earlier in their educational curricula. As expected though, some enjoyed this design space very much: *"It was my first time trying out 3D modelling software, but I got hooked upon it, so after the course I got really into the 3D modelling."*

3.2.3 The visual programming environment. The third space, was the one which allowed most geometric freedom. Here, participants were given a script, and they had to modify its input and output. This space was intimidating for most and only one wanted to investigate further which was expected as the 3D modelling learning path usually goes from simpler to more complex interfaces. Only as users start to outgrow a software and understand it well enough to feel the limits of its interface, they want to move into more elaborate modes of geometric production.

3.2.4 The fabricated objects. For the fourth design space - that of the fabricated pieces - participants could touch, move, smell, and physically engage with their final products. There was a general feeling of excitement at watching the laser cutter execute instructions they had coded, as usual in digital fabrication workshops. However, the process of gluing the layers together and manipulating the material was tedious in general.

3.2.5 Experiencing the design framework. At the end of exploring the Chladni setup, participants had created concrete two-dimensional sound visualizations (Chladni patterns). At the end of exploring the 3D environment they had interpreted these sound visualizations into 3D models, and finally they turned their 3D models in physical objects.

Their experiences of these steps fall within three clusters. Firstly, there are those who felt that their fabricated objects were the best: *"I was more happy about the fabricated brick, as seeing it physically had another impression than 'just' seeing it digitally. I still like both of them though, but I prefer the fabricated one."* Secondly, there are those who preferred working in the 3D environment because there the geometry could be changed: *"the fabricated piece was not as nice [as the 3D model]. The fact that it was physical and never able to change was kinda sad."*, or *"I liked working with the 3D model a little bit more, but it was really fun to touch/observe my work in real life and not only on the screen."* Finally, there were those who were more interested in the process than the final outcome: *"I do not feel any attachment to either the 3D model or for the final brick. I am more interested in the process."*

A few participants talked about the design space of the Chladni pattern being more constraining and abstract than that of 3D modelling: *"I couldn't obtain exactly the right Chladni patterns I wanted. But in the 3D model, I had to modify each pattern and slice that I really felt it was my own brick"*, along the same lines one described his 3D model as *"more complex and aesthetic"* compared to the Chladni pattern. One wrote that *"I used a pre-set Chladni pattern and do not feel*

I own or can own frequencies.". By contrast, the 3D model and the fabricated brick were generally perceived as own work. Nine out of the 16 participants reported having a deep attachment to their fabricated objects because of their engagement in creating it: (i.e. *"The brick I produced in 3D was my brick. I felt ownership."*).

Finally, one participant summed up the entire process as: *"The Chladni pattern was a more abstract concept, while the brick was more tangible and fun to witness it taking shape out of the Chladni patterns. I feel some attachment/pride in it, mainly because it is a memory and a step towards understanding how computer illustrations correlate and can become tangible items."*

3.3 Impact on Learning Outcomes

From the participants' side, all in all the framework was seen as a good learning example for 3D modeling: *"I loved the project and really enjoyed the final wall that was built. I also took many photos of the bricks to document the work of the students."* From the point of view of command of curriculum, 14 out of the 16 students managed to go through all the steps and create sound informed fabricated geometries. Two did not go through all the steps and three managed to create two bricks each. While this is good, it can be improved. The reason two students did not manage to finish their works were technical difficulties of running Rhinoceros 3D on their own laptops. Ideally, everyone taking part in a similar workshop should have access to technology which is powerful enough to support a 3D modelling software. As mentioned before, only 4 students declared that the technology-barrier suffocated their creative process, while the other 12 felt they acquired enough autonomy for design freedom. In terms of iterating, three students declared that only after going through the entire process once, they felt ready to start designing.

A secondary learning goal for the workshop was to expand the typical vocabulary used when doing and teaching design for fabrication and engage another way of thinking. It has been shown that music helps in teaching mathematics [3], by means of extrapolation, sound waves can help when teaching geometry. Often when designing something, the hardest thing is to get started, especially if one has to overcome an unfamiliar software interface before anything. The Chladni pattern setup helped in breaking the ice - participants could design something without any previous knowledge. Additionally, the not too-simple, not-too complex visually appealing symmetrical and geometric Chladni patterns offered students a good starting point for later exploration.

4 DISCUSSION

In this section, the design framework is discussed firstly as a tool for practitioners looking at places where accurate sound visualization and materialisation can be used and secondly as an educational tool.

4.1 Sound Sculpting : the design framework as a tool for practitioners

The proposed design framework aims at the creation of Chladni pattern and cymatic-informed 3D modelled and fabricated objects. This is relevant for practitioners which deal with the production of physical artifacts. A first application area involves the investigation of the acoustic properties of materials when designing with sound in mind. This is relevant in architecture for example, especially in the design of concert halls or rooms which require special acoustics. So far, one conceptual project of a concert hall [43] and one temporary built pavilion of Coop Himmelb(l)au [16] linked cymatics with the built environment. The former allegedly transformed Jimi Hendrix' "Purple Haze" and a passage from Mozart's "Don Giovanni" into architectural elements. Other relevant areas include product design, as done by [30] in informing speakers which "literally embody music" or even wearables as explored by Iris van Herpen [36].

Cymatics have double aesthetic qualities: (1) they create symmetric patterns and (2) the experience of producing sounds and of making the invisible visible or tangible is enjoyable. Symmetry as a positive aesthetic criterion is related to the classical conception of beauty [41] and goes back to Aristotle's writings, for instance, his "Metaphysics" (1078a36)[1]. Many of the resulting 3d objects created in the wall installation were symmetric on at least one axis. Although it is not possible to make statements on the aesthetic qualities of the wall installation, or infer much from the remarks made by participants about their own works (e.g. stating they find it important to make something aesthetically pleasing, or which brick they find "most beautiful" or the "most strange"), the geometries which came out from this exploration are diverse. Thus, it is safe to say that the design framework can help to produce novel shape grammars - which can be relevant for those creating physical pieces.

A second application area involves practitioners who design for multi-sensory experiences. This can be approached from a generative or artistic point of view, or by focusing in specific domains such as participants with autism, synesthesia or hearing impairments as showed in [31] and as done by [7]. It has already been showed in preliminary results that interactive cymatic-based interfaces help with communication for verbal and non-verbal participants [33]. Potentially, cymatics can be used as helpers with language acquisition and voice and musical training. When playing an instrument or learning a new language one is asked to reproduce sounds they are not trained to hear or speak. Other times, hearing impediments make speech acquisition challenging as one struggles with hearing their own voice. Changing the focus from the voice helps to relax and associates "correct" sounds to visual cues. Visual patterns or physical shapes can function as memories of the ephemeral sounds.

Finally, using sound exploration in the design process itself can help to unlock different modes of thinking (not only visual). Theories of creativity are often developed referencing different domains, each domain with its own mediums and tools [47]. Music has sound and musical notations as its medium, and real-time (improvisational) and non-linear (compositional) ways of expression. Designing physical objects usually works in visual, geometric and physical mediums and results in non-linear (or compositional) pieces. Combining modes of thinking through text, sound, images, algorithms - and creating and testing design frameworks which integrate these (and other ways of thinking - through logic, mathematically, visually, through the body) is crucial in relaxing domain boundaries - and so, moving toward interdisciplinary entanglement. In other words, by using our design framework to bridging art and science, new ways of working can be uncovered and this may bring fresh perspectives on research[14], and design. Furthermore, using one's own voice to manipulate sound materialization can introduce the use of one's own body, allowing for a soma-based design [21], in the design process, expanding further tools and methods of creative exploration.

4.2 Sound Sculpting : the design framework as an educational tool

The main learning goal for the design framework was to have participants be able to use a 3D modelling software to produce a unique artifact, prepare, export and fabricate using laser cutting. Overall the design framework was successful as an educational tool. With this discussion, the points considered important in re-using the framework for educational purposes are highlighted.

The selection of used software is very important for the educational outcome, as different software might have produced different shape grammars. Evidently, the selection of Rhinoceros3D as a tool had implications on the final geometries of the bricks and final installation. After all, tools define spaces of possible results, and "steer our thoughts and our imagination towards what is possible or easy and towards what is achievable, practical, or challenging" [9]. If another software had been used (for example a primarily mesh sculpting software like Blender or Maya) the shape grammars would have been slightly different.

Because of their low level of skills in using the tools, the participants can run the risk of creating something non-intentionally and incidentally - things which start as something but end as something else. While this can be acceptable or even desirable in an art setting, it might prove counterproductive for a design curricula. Furthermore, the selection of the used material in the fourth design space (fabrication) is very important, both for aesthetic reasons as well as practical ones. For example, in the case presented here, the 9mm wood plates were too thick for the laser cutter and posed a some technical problems, especially for more complex geometries. A thinner material is recommendable for another iteration.

The four design spaces were significantly different in size: there is a limited number of Chladni patterns to be made on a metal plate of 14x14 cm, but comparatively many more options when playing with 3D models in Rhinoceros3D. Some participants felt constrained by the limited visual space of possibilities offered by the small Chladni plate. A solution for this can be simply using a larger plate, or using cymatic experiments in a fluid. The digital fabrication part allowed participants to iterate a few times, but in general participants did not go back to trying to produce new or different Chladni patterns based on how their finished objects looked like or felt when touched. More iterations are encouraged for future educational applications of the design framework as the participants who produced more bricks felt that they were more sure to take up the design challenge after going through the process once.

Being part of a collaborative project, participants understood that if their peers would not finish their own work - the final assembly and exhibition would not take place. Therefore, there was a great deal of helping each other throughout the ten days. As usual with digital fabrication introduction classes - participants felt strongly about their produced works, and there was often a sense of surprise upon managing to produce pieces from own designs in a relatively short amount of time. By far the most enthusiasm was felt when participants saw their own pieces being fabricated. It is therefore recommended these collaborative aspects of the design framework to be re-used, or even enhanced by, for example, the creation of more groupings and fabrication tasks.

Finally, in most cases, only one or two images were used to create a 3D model. A series of more images would have been interesting as this would have opened more the design space in terms of possible outcomes. On the other hand, having participants create physical representations of more complex sounds, could have also complicated the geometries. Therefore it is recommend that educators allow participants to be more exploratory during the initial spaces of the suggested framework, and to consider asking participants to engage with their own voice in producing the Chladni patterns. As noted previously, this would introduce the use of one's own body in the design process which would further expand tools and methods of creative exploration.

5 CONCLUSION

Historically, sound and design fields which produce physical objects have belonged to different 'thought silos'. However, in the current synthetic age of entanglement [15], it is worth reconsidering why visual literacy and sound literacy are typically considered separately. Both sound and the design of physical objects can benefit from using each other's methods of creative inquiry. Thinking for sound and thinking for visual and fabricated objects is different: traditional representations in design are focused upon visual and geometrical representation of the design object [38]. On the other hand, incorporating new audiovisual technologies and interfaces in music production, where practically any sound material can be used [42] is desirable. Typically - 3D modelling and digital fabrication require working in a non-linear, or compositional way. Sound production allows exploring real-time, improvisational design methods.

Towards this end, a design framework which combines sound exploration, 3D modelling, and digital fabrication is presented together with a case study where it was tested in a higher educational setting with 16 students with little to

no prior experience in either 3D modelling or digital fabrication, and some experience in sound production. The paper reports on how the design framework was experienced by the participants and how it contributed in the creation of a physical installation. It concludes with our reflections on the suitability of the design framework for practitioners that are interested in the materialization of intangible and ephemeral sounds as well as for educators.

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