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Collection of Design Directions for the Realization of a Visual Interface with Haptic Feedback to Convey the Notion of Sonic Grain to DHH Students

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***Abstract*—This paper presents the results of a survey campaign aimed at distilling design directions for the realization of a visual interface with haptic feedback. The scope of the interface is to ease the conveyance of the concept of "sonic grain" to deaf and hard of hearing music students. Results from the questionnaire were leveraged for the realization of a prototype which exploits cross-modal associations among images, colors, sounds and textures to render different types of sonic grains and offer a multisensorial perceptual experience to the users. Such prototype represents a promising starting point for further investigation on how to jointly exploit visual, auditory and haptic feedback to support more inclusive pedagogical approaches to music teaching.**

***Index Terms*—tactile feedback; music education; sonic grain;**

I. INTRODUCTION

Musical education of Deaf and Hard of Hearing (DHH) students is particularly challenging due to the essential involvement of auditory perception [1]. For such categories of subjects, the adoption of extra-auditory cues is pivotal to ease music perception. Indeed, the process of hearing involves a multiplicity of perceptual modes [2], even beyond merely aural functions.

In particular, the notion of *sonic grain* conceptualizes music as a form of *tactilization* of sound that enables a cross-modal mapping of texture between the microstructures of sound and material surfaces [3], thus bridging tactile and sonic experiences. According to [4], high granularity sounds have rapid sonic impacts, which may sound like a sequence of discrete attacks, a cluster of smaller sounds, or something "noisy" with sonic interference. In contrast, low granularity "soft" sounds have little surface fluctuation or have regular pitch fluctuations with smooth transitions. Most soft sounds have a clear tone emanating from a sustained vibration, while coarse-grained sounds tend to have an indeterminate pitch and typically arise from percussive impacts. The similarities in microstructure lead to an understanding of grain as a perceptual phenomenon that works across sensory modalities, suggesting that tactile, auditory, and visual experiences of texture are not only comparable, but also intertwined and concretely interconnected. Indeed, the grain of sound can provide information to the listener about the texture and physical state of the objects used to produce it.

Therefore, exploiting sonic grain for the multi-sensory conveyance of music to DHH subjects appears as a promising direction to support their musical education and its related practices. In particular, our goal is to help DHH students learn how to discriminate among sounds generated by different musical instruments via the cross-modal presentation of their corresponding sonic grain. However, at present there is no widely established consensus on cross-modal associations between auditory, visual and haptic stimuli, with only a paucity of studies examining the nature of such complex and highly-subjective synaesthetic mappings (see e.g. [5]–[7]). Thus, the need of empirically constructing a "dictionnaire" of associations between tactile and sonic experiences arises. To fill this gap, we present the results of a questionnaire offered to 56 respondents, in order to collect statistics about sensory associations among musical instruments, colors, shapes, and textures, inspired by listening to musical excerpts. We then proceed to give some details on how we leveraged those results for the realisation of an interface prototype. The interface associates to recorded musical excerpts generated by different instruments a color, an image of a shape and a texture, according to the grain of the sound emitted by the instruments. The aim of this study is to provide design directions for the realization of a programmable visual interface with customizable haptic feedback to convey the concept of sonic grain to DHH music students.

We envision this interface being used either in a stand-alone scenario, or as building block of a Networked Music Performance (NMP) framework for e-learning purposes, where music excerpts could be retrieved on-demand by a remote instructor from a cloud-located repository and offered to the student, or even generated in real-time and automatically associated to cross-modal features by means of a dedicated mapping algorithm, based on the spectral characterization of the sound. This would pave the way for novel e-learning opportunities specifically tailored for DHH music students, following recent online teaching trials in other educational subjects [8]–[11].

The remainder of the manuscript is organized as follows: Section II briefly reviews the related literature, whereas Section III provides some background notions on DHH impairments and the programmable haptic interface adopted for the envisioned prototype. The results of the survey and the derived interface prototype are presented in Section IV. Some practical considerations about the interface implementation are offered in Section V. Finally, Section VI concludes the paper.

II. RELATED WORK

In the following, we briefly overview related studies in the context of haptic music conveyance and music visualization techniques.

A. Haptic Devices for Music Conveyance to DHH Subjects

A number of studies have investigated the conveyance of musical information through the sense of touch (see [12] for a thorough overview). Tactile rendering setups normally focus on capturing a single music feature, e.g. rhythm, pitch, melody, timbre, and loudness. Up to now, conveyance of sonic grain by means of haptic feedback mechanisms has never been attempted.

The usage of haptic feedback to enrich the emotive experience while listening to music has been experimented by Haynes *et al.* in [13]. In music teaching, vibrotactile feedback has been already demonstrated to convey the concept of rhythm and of the spectrum of sound frequencies to visually-impaired and DHH students by Giordano *et al.* [14] and Darrow [15]. Moreover, systems that transpose gestural cues into haptic feedback have proven to be useful to enrich musical perception and interplay for such categories of performers, as reported by Grosshauser *et al.* [16].

Notably, an emerging sector where haptic feedback has been proven to have a disruptive impact is that of the Internet of Sounds [17], where networked environments are leveraged to offer various types of music-related experiences to their users. In [18], Turchet *et al.* experimented with the use of different kinds of haptic wearable devices to enhance the experience of the audience during such performances, enabling listeners to perceive the performed musical pieces thorough vibro-tactile feedback devices. In the study the devices were responding to the performed music, but the authors envisioned the use of such type of devices also for facilitating the creative participation of the audience in the live performance. Therefore, this study can be considered as a preliminary step towards the investigation on how to integrate haptic technologies in networked systems for Internet of Sounds applications, such as NMP frameworks.

B. Music Visualization Techniques

Visualization can also be exploited to present music content to subjects with auditory impairments: within the rich corpus of scientific literature dedicated to such topic (see [19] for a comprehensive survey), a few studies have specifically targeted the DHH community. Among those, in the work by Kim *et al.* [20] sounds generated by a violin are digitized and associated to movements of objects such as flowers and plants, with the goal of achieving interactive sound visualization to support music education for children with hearing impairments.

Deja *et al.* [21] present ViTune, a music visualization prototype which enhances the musical experiences of the DHH community thanks to the usage of an on-screen visualizer generating effects alongside music.

McHugh *et al.* [22] introduce BufferBeats, a toolkit for creating multimodal experiences for streaming services, aimed at improving accessibility to online music streaming by DHH subjects. The study is motivated by the presence of Digital Rights Management anti-piracy encryption, which often restricts the access to audio data which is required to create multimodal experiences for music streaming.

Focusing on songs, opera and theatrical pieces, displaying criteria of captions and lyrics specifically tailored for DHH audiences have also been investigated by Zarate [23] (such as font and size, number of lines and positioning on the screen).

At present, the joint exploitation of visual, auditory and tactile feedback has never been reported in the scientific literature for the realization of a graphical interface specifically tailored to the needs of music students in the DHH community.

III. BACKGROUND

A. Basic Notions on DHH Impairments

According to [24], hearing loss stands out as one of the most frequently encountered disabilities on a global scale, with over 430 million people experiencing more than 35 dB of hearing loss in their least impaired ear. Moreover, hearing loss can manifest at various stages throughout the lifespan, attributable to diverse factors, including but not limited to genetic predisposition, infections, accumulation of fluids in the ear, chronic medical conditions, and exposure to high-intensity sounds.

Hearing loss can be divided into several categories depending on the anatomical location of the impairment within the auditory system. The principal categories are the following:

- *Conductive Hearing Loss*: this type of impairment arises from pathological conditions affecting the conduction of sound waves from the outer/middle-ear to the inner ear. Typical causes are excessive earwax, disorders affecting the eardrum, etc.
- *Sensorineural Hearing Loss*: it ensues from damage to the inner ear (cochlea) or the auditory nerve, representing the most prevalent form of permanent hearing loss. Usually it is caused by age-related degeneration, prolonged exposure to loud sounds, hereditary conditions, etc.
- *Mixed Hearing Loss*: this is characterized by a combination of both conductive and sensorineural hearing losses.

Hearing loss usually affects the high frequencies, but it is possible to experience hearing loss of some specific frequencies. Due to these issues, music is perceived by DHH subjects in a different way.

B. Attributes for Music Characterization

Though the definition of music varies across cultures, we can describe it in an objective way by considering its properties. In [25], Levitin identifies nine main attributes:

- *Tone*: a discrete musical sound (what you hear). *Note* is also used but it refers to something written on a score (what you see).
- *Pitch*: a psychological construct related to both the frequency of a particular tone and its position on the scale
- *Timbre*: the tonal color which allows to distinguish two different musical instruments when playing the same note.
- *Contour*: describes the shape of a musical melody, considering only the patterns of "up" and "down".
- *Rhythm*: pertains to the time duration of a sequence of musical notes and how these notes are organized into distinct groupings or patterns.
- *Tempo*: the overall speed or pace of a piece.
- *Loudness*: a psychological construct related to how the amplitude of a given tone is perceived.
- *Spatial location*: position of the source of a given tone in a three-dimensional space.
- *Reverberation*: perception of the distance of a given sound source in combination with the size of the room/hall in which the sound source is placed.

These attributes are separable, according to Levitin [25], which means that varying one will not affect the others. Though, the difference between *music* and a *random set of sounds* has to do with how these attributes combine. In [25], Levitin explains that the combination of such fundamental attributes creates higher-order concepts:

- *Metre*: combination of rhythm and loudness cues that refers to the way in which tones are grouped together across time.
- *Key*: a hierarchy of importance between tones.
- *Melody*: the primary theme of a musical composition. A melody is created by arranging a sequence of notes from its designated key, each with distinct rhythm, contour, and other musical characteristics.
- *Harmony*: relationship between the pitches of different notes. It can refer to a chord progression or refer to parallel melodies to the primary one.

While the attributes and higher-order concepts can be understood by non-hearing-impaired subjects, when it comes to DHH subjects those concepts are challenging to describe. Since audio by itself cannot be fully perceived, alternative representations need to be used. Among them, visual feedback or vibration of haptic surfaces can be exploited to represent some of these attributes and concepts. For example, pitch can be associated to colors and loudness to their respective intensity, timbre to the roughness of a surface and rhythm to the vibration of such surface, etc.

C. Programmable Graphical Interfaces with Haptic Feedback

As described in section II, previous studies already experimented visual, auditory and vibrational/haptic feedback to enrich the representation of musical content. However, one of the challenges of designing a solution for multimodal music conveyance is the reproducibility of the setup, which in some cases may not be feasible. For such reason, for the realization of our prototype we opted for an off-the-shelf haptic device which can be used to provide a multimodal experience, through auditory, haptic and visual feedback, with the goal of conveying to DHH students the concept of sonic grain. Another reason that lead us to opt for such kind of device is its versatility. The ability to expand its features beyond the mere haptic feedback opens up possibilities for its integration into NMP frameworks, which would unleash novel opportunities for remote music education, fruible also by DHH students.

In particular, in this study we use the TanvasTouch device[1], which enables a customized design of tactile feedback localized to the user's fingertip without the need for surface vibration, by exploiting electroadhesion-based haptic technology. This way, a new software-defined interaction layer can be overlapped to traditional visual representation [26]. Haptic textures are designed using a simple image-based metaphor: black and white images are leveraged, where white corresponds to rough texture and black to smooth texture. These are integrated via APIs, and then rendered in real time thanks to the TanvasTouch Engine, which is a software driver executed on a general purpose machine that generates friction control commands to be sent via a USB cable to the TanvasTouch Controller, that in turn modifies the friction surface accordingly. In parallel, the images displayed on the TanvasTouch screen can be updated in real- time via an HDMI cable connecting it to the machine.

IV. RESULTS

In this Section we discuss the results of the survey and present the derived cross-modal associations to be displayed via the interface. We then briefly describe the graphical presentation of our interface prototype.

A. Choice of Cross-modal Associations

To collect meaningful cross-modal associations among timbral characteristics of music instruments, colors, shapes and textures, we administered a questionnaire that was offered to a pool of 56 individuals, composed of conservatory/university students and staff (including professors, researchers, and PhD students) of both genders and various ages. The goal of such collection was to identify the sonic grains most typically associated to different types of instruments, in order to render them via the graphical interface.

The questionnaire included 12 questions, one for each of the musical instruments listed in Table I. In each question, the respondent was first asked to listen twice to an audio excerpt of 15-20 sec duration. Once the listening phase was completed, four questions appeared, asking to associate to the audio excerpt a selection of one to three color, light, shape and texture options. The full list of available options

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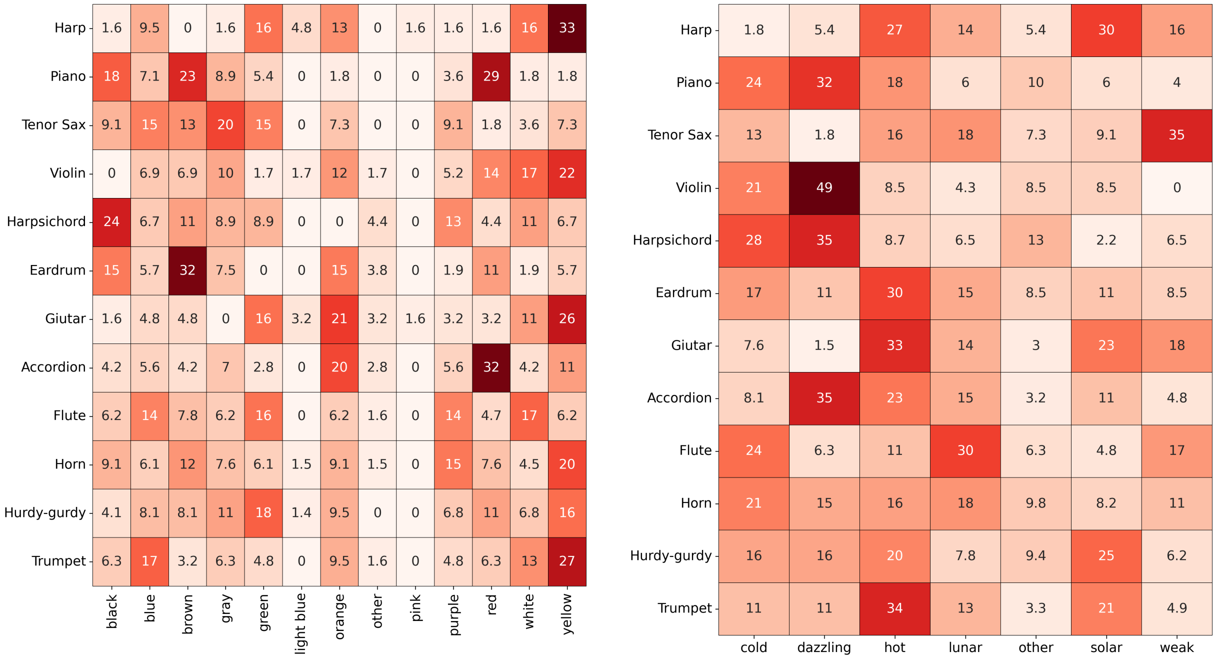
[1] Tanvas. Surface Haptics. https://tanvas.co/technology

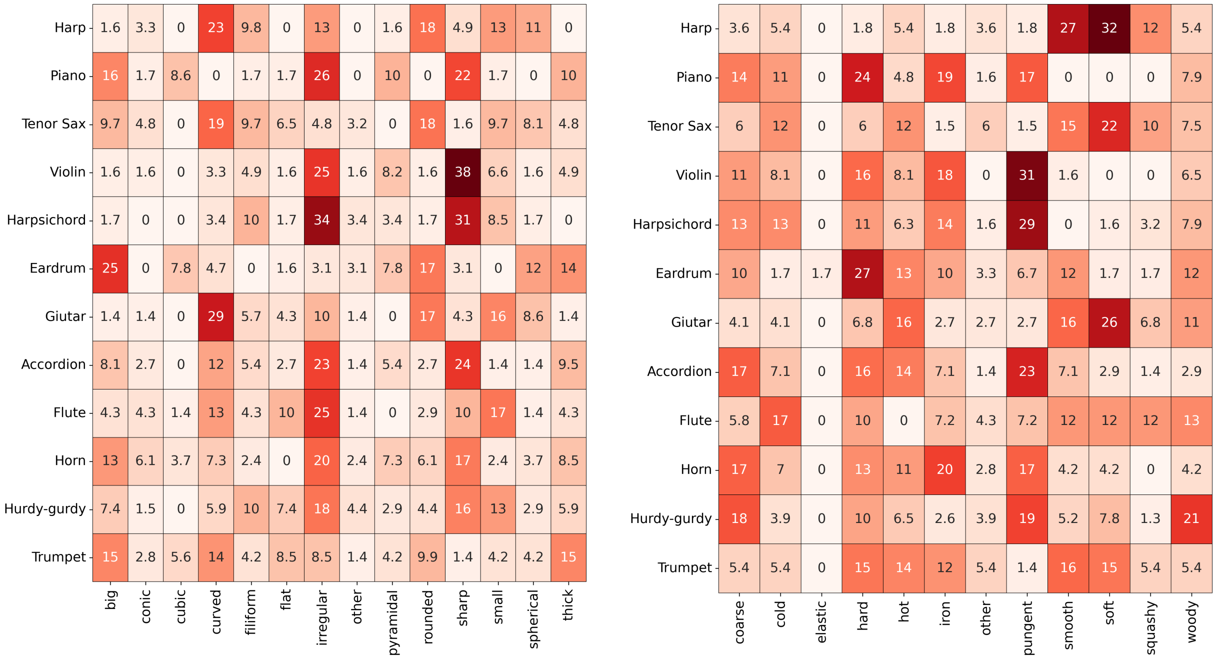


	black	blue	brown	gray	green	light blue	orange	other	pink	purple	red	white	yellow
Harp	1.6	9.5	0	1.6	16	4.8	13	0	1.6	1.6	1.6	16	33
Piano	18	7.1	23	8.9	5.4	0	1.8	0	0	3.6	29	1.8	1.8
Tenor Sax	9.1	15	13	20	15	0	7.3	0	0	9.1	1.8	3.6	7.3
Violin	0	6.9	6.9	10	1.7	1.7	12	1.7	0	5.2	14	17	22
Harpsichord	24	6.7	11	8.9	8.9	0	0	4.4	0	13	4.4	11	6.7
Eardrum	15	5.7	32	7.5	0	0	15	3.8	0	1.9	11	1.9	5.7
Giutar	1.6	4.8	4.8	0	16	3.2	21	3.2	1.6	3.2	3.2	11	26
Accordion	4.2	5.6	4.2	7	2.8	0	20	2.8	0	5.6	32	4.2	11
Flute	6.2	14	7.8	6.2	16	0	6.2	1.6	0	14	4.7	17	6.2
Horn	9.1	6.1	12	7.6	6.1	1.5	9.1	1.5	0	15	7.6	4.5	20
Hurdy-gurdy	4.1	8.1	8.1	11	18	1.4	9.5	0	0	6.8	11	6.8	16
Trumpet	6.3	17	3.2	6.3	4.8	0	9.5	1.6	0	4.8	6.3	13	27

	cold	dazzling	hot	lunar	other	solar	weak
Harp	1.8	5.4	27	14	5.4	30	16
Piano	24	32	18	6	10	6	4
Tenor Sax	13	1.8	16	18	7.3	9.1	35
Violin	21	49	8.5	4.3	8.5	8.5	0
Harpsichord	28	35	8.7	6.5	13	2.2	6.5
Eardrum	17	11	30	15	8.5	11	8.5
Giutar	7.6	1.5	33	14	3	23	18
Accordion	8.1	35	23	15	3.2	11	4.8
Flute	24	6.3	11	30	6.3	4.8	17
Horn	21	15	16	18	9.8	8.2	11
Hurdy-gurdy	16	16	20	7.8	9.4	25	6.2
Trumpet	11	11	34	13	3.3	21	4.9

(a) Matrix of associations of colors to instruments

(b) Matrix of associations of light options to instruments



	big	conic	cubic	curved	filiform	flat	irregular	other	pyramidal	rounded	sharp	small	spherical	thick
Harp	1.6	3.3	0	23	9.8	0	13	0	1.6	18	4.9	13	11	0
Piano	16	1.7	8.6	0	1.7	1.7	26	0	10	0	22	1.7	0	10
Tenor Sax	9.7	4.8	0	19	9.7	6.5	4.8	3.2	0	18	1.6	9.7	8.1	4.8
Violin	1.6	1.6	0	3.3	4.9	1.6	25	1.6	8.2	1.6	38	6.6	1.6	4.9
Harpsichord	1.7	0	0	3.4	10	1.7	34	3.4	3.4	1.7	31	8.5	1.7	0
Eardrum	25	0	7.8	4.7	0	1.6	3.1	3.1	7.8	17	3.1	0	12	14
Giutar	1.4	1.4	0	29	5.7	4.3	10	1.4	0	17	4.3	16	8.6	1.4
Accordion	8.1	2.7	0	12	5.4	2.7	23	1.4	5.4	2.7	24	1.4	1.4	9.5
Flute	4.3	4.3	1.4	13	4.3	10	25	1.4	0	2.9	10	17	1.4	4.3
Horn	13	6.1	3.7	7.3	2.4	0	20	2.4	7.3	6.1	17	2.4	3.7	8.5
Hurdy-gurdy	7.4	1.5	0	5.9	10	7.4	18	4.4	2.9	4.4	16	13	2.9	5.9
Trumpet	15	2.8	5.6	14	4.2	8.5	8.5	1.4	4.2	9.9	1.4	4.2	4.2	15

	coarse	cold	elastic	hard	hot	iron	other	pungent	smooth	soft	squashy	woody
Harp	3.6	5.4	0	1.8	5.4	1.8	3.6	1.8	27	32	12	5.4
Piano	14	11	0	24	4.8	19	1.6	17	0	0	0	7.9
Tenor Sax	6	12	0	6	12	1.5	6	1.5	15	22	10	7.5
Violin	11	8.1	0	16	8.1	18	0	31	1.6	0	0	6.5
Harpsichord	13	13	0	11	6.3	14	1.6	29	0	1.6	3.2	7.9
Eardrum	10	1.7	1.7	27	13	10	3.3	6.7	12	1.7	1.7	12
Giutar	4.1	4.1	0	6.8	16	2.7	2.7	2.7	16	26	6.8	11
Accordion	17	7.1	0	16	14	7.1	1.4	23	7.1	2.9	1.4	2.9
Flute	5.8	17	0	10	0	7.2	4.3	7.2	12	12	12	13
Horn	17	7	0	13	11	20	2.8	17	4.2	4.2	0	4.2
Hurdy-gurdy	18	3.9	0	10	6.5	2.6	3.9	19	5.2	7.8	1.3	21
Trumpet	5.4	5.4	0	15	14	12	5.4	1.4	16	15	5.4	5.4

(c) Matrix of associations of shapes to instruments

(d) Matrix of associations of texture options to instruments

Fig. 1: Listening Test Results

TABLE I: Listening Test Options

Instrument	Harp	Piano	Tenor Sax	Violin	Harpsichord	Eardrum	
	Guitar	Accordion	Flute	Horn	Hurdy-Gurdy	Trumpet	
Color	Black	Blue	Brown	Gray	Green	Light Blue	Orange
	Pink	Purple	Red	White	Yellow	Other	
Light	Cold	Dazzling	Hot	Lunar	Solar	Weak	Other
Shape	Big	Conic	Cubic	Curved	Filiform	Flat	Irregular
	Pyramidal	Rounded	Sharp	Small	Spherical	Thick	Other
Texture	Coarse	Cold	Hard	Hot	Iron	Elastic	Pungent
	Smooth	Soft	Squashy	Woody	Other		

TABLE II: Listening Test Results - Summary - For each instrument and category we listed the two/three most significant associations. The associations are sorted by significance and the notation A/B is used when both were selected by the same amount of respondants.

Instrument	**Color**	**Light**	**Shape**	**Texture**
Harp	Yellow - White - Green	Solar - Hot	Curved - Rounded - Small	Soft - Smooth
Piano	Red - Brown - Black	Dazzling - Cold	Irregular - Sharp - Big	Hard - Iron
Tenor Sax	Gray - Green/Blue	Weak - Lunar	Curved - Rounded	Soft - Smooth
Violin	Yellow - White - Red	Dazzling - Cold	Sharp - Irregular	Pungent - Iron
Harpsichord	Black - Purple - Brown/White	Dazzling - Cold	Irregular - Sharp	Pungent - Iron
Eardrum	Brown - Black - Orange	Hot - Cold	Big - Rounded	Hard - Hot
Guitar	Yellow - Green - Orange	Hot - Solar	Curved - Rounded - Small	Soft - Smooth/Hot
Accordion	Red - Orange - Yellow	Dazzling - Hot	Irregular - Sharp - Small	Pungent - Coarse/Hard
Flute	White - Green - Purple	Lunar - Cold	Irregular - Small	Cold - Woody - Soft/Smooth
Horn	Yellow - Purple - Gray	Cold - Lunar	Irregular - Sharp - Big	Iron - Coarse/Pungent
Hurdy-Gurdy	Green - Yellow - Red/Gray	Solar - Hot	Irregular - Sharp - Small	Woody - Pungent - Coarse
Trumpet	Yellow - Blue - White	Hot - Solar	Big - Thick - Curved	Smooth - Soft/Hard - Hot/Iron

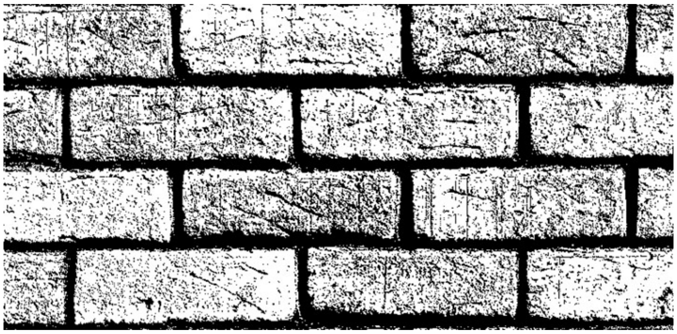


Fig. 2: Black and white image rendering for haptic texture design

by category is reported in Table I. For the sake of limiting the time required for the completion of the questionnaire, a reduced version was also produced, containing a subset of 6 questions obtained by random choice among two predefined splits of the initial set. Students were offered the reduced version of the questionnaire, whereas staff members answered to the full version. On average, around 30 sets of answers per instrument were collected. A summarized version of the results is reported in Table II, where for each instrument and category we listed, in descending order, the two/three most selected attributes. The complete set of associations of attributes to the different instruments and categories is shown in Figure 1. The above-reported results were then used for the selection and adjustment of the various images to display on the interface prototype. The final selection of attributes was performed as follows:

- *Color*: the pair of most voted options were selected and blended (for example, if yellow and green were the two most voted colors, the resulting color adopted for visualization was lime). Minor adjustments of the blends were introduced to avoid associations of the same color to multiple instruments.
- *Light*: the most voted option was selected and the brightness of the displayed color was adjusted accordingly.
- *Shape and Texture*: the most voted option per category was selected and the image of an object with characteristics matching the identified pair was chosen. For example, a combination of rounded shape and smooth texture was associated to the image of marbles.

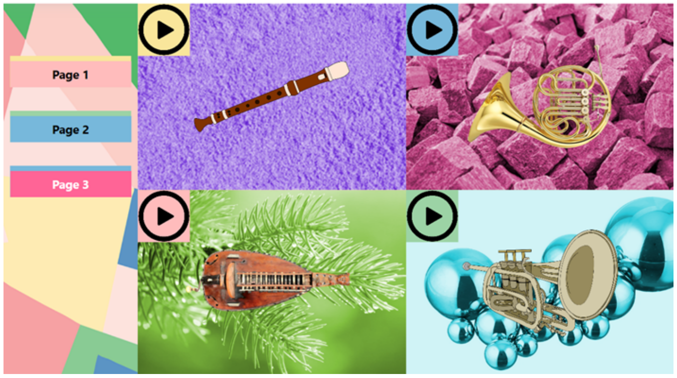
The selected images were then recolored according to the associated color selection and their b/w version was used to generate the superimposed haptic texture (see Figure 2 for an example). In some cases some post-processing was necessary, e.g., to invert black and white to better match the coarse/smooth areas of the image.

B. Visual Presentation

Our envisioned interface is divided in two parts: a sidebar on the left, used for navigation among the different pages, and a main section on the right, which contains, for each page, up to 4 subsections. In turn, each subsection includes 4 main elements: a button on the top left, to play the audio track associated to that specific subsection, a picture of the instrument audible in the audio track, a background image giving a visual representation of the ”texture” associated to the audio track with a chosen background color, and an haptic image which provides the haptic feedback of the ”texture”

(a) First page

(b) Second page



(c) Third page

Fig. 3: Screenshots of the developed interface

associated to the audio track. Once a given page is selected, the associated images and elements will appear, as showed in Figure 3. For each of them, when pressing the play button, the associated audio track will be played and the texture file will be loaded. The haptic feedback is available only while the audio is playing. This is done to help focus the attention of the user on one sound at a time, while avoiding being distracted by other textures when a given sound is reproduced. The final prototype is shown in Figure 3.

V. IMPLEMENTATION DETAILS

In this section we provide some details on the implementation of our TanvasTouch-based prototype and we offer suggestions on how to tackle practical issues that may occur when developing a user interface (UI) for such device. Our preliminary version is developed in C# using the Windows Presentation Foundation (WPF) UI framework of the .NET framework[2]. In order to load the haptic feedback images on the TanvasTouch device, we used the TanvasTouch API[3] provided by the TanvasTouch Software Development Kit (SDK).

The WPF framework uses XAML (Extensible Application Markup Language) to define in a declarative way the UI elements, and uses C# to implement the associated functions. In our case, the XAML code defines the various UI elements on the page, like buttons, images, the layout etc. The C# code instead controls the visibility of the UI elements by showing and hiding the images, for enabling navigation between pages, for playback of audio tracks and for loading and removing the haptic feedback images. Images are implemented in the XAML file using the `Image` element, while the haptic feedback is implemented using the `TSprite` element of the TanvasTouch API.

A common issue that arises when designing textures with the TanvasTouch device is making the visualized image overlap with the haptic textures, due to the coordinate system that the device uses to place images on the screen. By default, visual coordinates are used. However, the dimension and position of the `TSprite`, which is the on-screen haptic object, must be defined in the screen coordinates system. To achieve the above, the size and position of `TSprite` must match the size and position of the graphic image multiplied by the dpiScale. The dpiScale represents the screen scaling factor of the Tanvas device. For example, if the scaling factor is 125% the dpiScale value will be 1.25.

Another aspect to note is that the coordinates in the screen coordinate system are relative to the main screen. That is, the point (0,0) will be the top left corner of the main screen. If a second screen is added, as it happens when the TanvasTouch device is connected, the coordinates of what is presented on the second screen will be relative to the main screen. For example, if the second screen is placed to the left of the main screen, the coordinates on the horizontal axis will be negative for every object displayed on the second screen.

VI. CONCLUSION

This paper reports the results of a survey campaign involving more than 50 participants, aimed at distilling design directions for the realization of a visual interface with haptic feedback to convey the concept of "soinc grain" to deaf and hard of hearing music students. These results were then used for the realization of an interface prototype which exploits cross-modal associations among images, colors, sounds and textures to render different sonic grains and offers a multisensorial perceptual experience to the users.

Such results represent a promising starting point for further investigation on how to jointly exploit visual, auditory

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[2] The code, audio excerpts and images that compose the interface are publicly available at: https://github.com/mariasanguesa/TanvasTouch_interface.

[3] TanvasTouch .NET API documentation is available at: https://api-docs.tanvas.co/tanvastouch/dotnet/5.0.1/api/index.html

and haptic feedback to support more inclusive pedagogical approaches to music teaching. Reaching consensus on cross-modal associations between sounds and visual/tactile experiences to create a common "dictionnaire" is an open research direction, which should be promptly addressed to guide hardware/software designers in the realization of innovative interfaces for accessible fruition of musical contents and multisensory music learning.

In our future work, we plan to expand the capabilities of the Tanvas device by finalizing the interface and integrating functionalities to support cross-modal display of an audio track either acquired in real-time, or retrieved on-demand from a remote repository. Moreover, we plan to investigate the adoption of dynamic visual and haptic representations, where the time dimension comes into play when matching and tailoring visual and haptic content to the audio stream being reproduced. Finally, we intend to experiment with remote interaction capabilities, integrating our prototype in an NMP framework to enable the conveyance of sonic grain also in the context of remote music teaching: this would unleash novel e-learning opportunities for DHH subjects and help overcoming a number of barriers currently being experienced in online education of DHH students.

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