A Case Study on Netychords: Crafting Accessible Digital Musical Instrument Interaction for a Special Needs Scenario

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Abstract. Musical expression significantly impacts individual development, enriching cognitive, emotional, and social capacities. This influence is particularly profound in young individuals with cognitive or physical impairments. To address this, we devised an ecosystem of software tools, paired with specially designed hardware devices, such as an eye tracker. Our approach empowers even severely impaired users, with no prior music education, to achieve musical performance. In this paper, we detail a case study involving a child with cerebral palsy, providing an examination of the strengths and shortcomings of our approach. By utilizing a specialized instrument, called *Netychords*, the child achieved a significant milestone, namely the enrollment in Portugal's Arts Education Program, which fostered musical interaction with his peers and educators. This paper focuses on the technical aspects of the user's experience with the instrument, which catalyzed numerous redesign phases, adapting it to the child's unique needs and motor abilities. Our analysis of this adaptive design process strives to offer valuable insights to extend our approach to cater to various special needs scenarios.

Keywords: Accessibility · Digital musical instruments · Cerebral palsy · Music education · Special needs · Eye tracking

1 Introduction

Music education can have a significant impact on the cognitive, emotional, and social development of individuals. Research has shown that active engagement with music can lead to the development of emotional skills, particularly in the

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field of music education [5]. A systematic review focused on the effects of music on children's emotional development revealed that short-term music training can improve cognitive abilities, such as verbal intelligence and executive function [35]. Music training has also been found to enhance emotion comprehension in children [43]. Longitudinal studies have highlighted the benefits of music programs for at-risk children, such as improved neural encoding of speech sounds [25]. Musical experiences in childhood have been shown to accelerate brain development, particularly in language acquisition and reading skills [18]. Moreover, advantages are not limited to the early stage of life: music-making opportunities can also contribute to the well-being of older individuals [19].

The term "Special Needs" (SN), is commonly used to describe individuals who require support for a range of disabilities that may be medical, mental, or psychological. This broad category includes those with learning disabilities, speech or language disorders, physical disabilities, emotional and behavioral conditions, as well as various developmental or intellectual disabilities [31,47]. Despite the well-documented benefits of music education, its accessibility remains a challenge for individuals with the context of SN. Lubet's book and the "Reshape Music" report by Youth Music highlight how opportunities to participate in musical activities are frequently obstructed for such individuals [27,53]. The complexity of disability, a "multidimensional experience" with significant measurement and classification challenges [51,52], further compounds this issue. Individuals with SN often encounter barriers to accessing music education and reaping its developmental benefits. Such barriers to music education for individuals with SN vary, encompassing physical, social, and financial dimensions. Furthermore, traditional musical instruments, barring a few exceptions, often rely on the use of hands, fingers, breath, mouth/lips, and feet, leading to considerable barriers for individuals with motor disabilities.

Digital technologies, in particular *Digital Musical Instruments* (DMIs), have the potential to support people with SN in their musical learning and development, providing sensory stimulation, facilitating communication and interactions, and enhancing learning experiences through gamification and interactive multimedia. Recent research has highlighted the potential of ad-hoc software products and interactive devices as support tools in music education for children with SN. For example, digital technologies can provide sensory stimulation [7], facilitate communication and interactions [8,26,46], and enhance learning experiences through gamification and interactive multimedia [2,3,50].

From 2018 to 2022, the *Department of Education and Psychology at the University of Aveiro* (DEP-UA) led a project exploring the use of *Accessible Digital Musical Instruments* (ADMIs) for facilitating music education for children with special needs (SN). This project, with a focus on revising classroom practices in Portuguese primary schools' Arts Education Programmes of Music (AEPM), aimed to promote inclusion in musical activities [33,34], enhancing our understanding of inclusive arts education, and the role of digital technologies and ADMIs in facilitating access for students with impairments. As part of a pilot study approved by the University's Ethics and Deontology Committee, DEP-UA researchers conducted targeted experimental activities with a 7-year-old child affected by cerebral palsy, seeking to generalize the learnings from this specific scenario to benefit primary school music education broadly.

Since 2018, the Laboratory of Music Informatics at the University of Milan (LIM-UM), Italy, has centered its research on their ecosystem of ADMIs design and development, particularly for motor disabilities such as quadriplegia. Seeing potential applicability to the child, DEP-UA researchers sought collaboration. This venture involved preliminary studies for identifying suitable technologies and interaction modes for the child and led to adaptations for his specific motor skills. Involving the child, his family, and educators, this collaboration facilitated the child's participation in Portugal's Arts Education Program, necessitating further technological adjustments over his educational journey.

This paper focuses on the technical aspects of the experimentation. It details the customization of *Netychords*, an Accessible Digital Musical Instrument designed for musicians with motor disabilities, supported by software tools, libraries, and hardware. The paper documents the evolution of the instrument since its initial publication in 2021 [14], based on insights gained from the case study. It reviews the challenges faced and progress made in tailoring the instrument's interaction strategies to meet the child's unique needs. Additionally, it highlights the child's subsequent participation in the Arts Education Programme, showing the potential impact of our ADMI development ecosystem in a real-world educational setting.

The remainder of this paper is structured as follows: Sect. 2 provides essential literature background information and a comprehensive analysis of the tools within our development ecosystem; Sect. 3 reviews the main characteristics of *Netychords*; In Sect. 4, we delve into the case study involving the child participant. We proceed by detailing their user profile, the bespoke instrument modifications implemented to suit their needs, and the adaptations needed for their participation in formal music education; Sect. 5 contains reflections on our experiences and attempts to extrapolate our findings to the broader context of customizing ADMIs for individuals with Special Needs. This work aims to promote further discussion and exploration in our research field by detailing the practical challenges and successes encountered in our journey to include a child with SN in music making.

2 Background

2.1 Context

At the beginning of their project DEP-UA researchers looked for possible music learning solutions developed in other institutions and/or countries, to provide for the needs of the child. To this end, they conducted, analyzed, and published a series of documented searches, by means of various literature reviews [33,34]. In these reviews, research works were found that explored both the capacity that students with disabilities possess to acquire musical knowledge using digital technologies and the development of music technologies dedicated to this population.

Examples of the latter can be found in a multimedia tool called PLAIME (PLAtform for the Integration of handicapped children in Music Education) [6], and some technological solutions which can be used to enhance music learning in primary education using Mobile Virtual Reality [24]. Other examples are provided by the development of ADMIs such as Arcana Instruments [1] and SoundBeam.[2] Some studies analyze the use of eye-tracking technologies in Immersive Virtual Reality (IVR) learning environments created by using head-mounted displays [45]. For the development of their research work, the DEP-UA researchers focused on searching for information on the design and/or adaptation of Digital Musical Instruments for the accessibility context, so that the child could have access to music education programs in Portugal [33,34].

DMIs are generally defined as instruments in which sound generation is based on digital means and is achieved by the performer through physical actions detected by sensing devices [30,32]. Thus, these musical instruments have the potential to add to the accessibility of music, relative to traditional instruments, because they allow for different, unconventional, modes of interaction [16]. The term Digital Musical Instrument is not sharply defined in the literature and often overlaps with other forms of musical interfaces. The project undertaken by the LIM-UM researchers primarily focuses on the development of *performance instruments*, following a more stringent definition supplied by Malloch et al.'s conceptual framework [29]. According to this framework, musical interfaces involve interaction behaviors that can be categorized as skill-, rule-, or model-based. Skill-based musical instruments mirror their traditional counterparts in performance and context, demanding internalized movements, muscle memory, and a deep engagement with the instrument's feedback. These instruments also present stringent time constraints for interaction.

Accessible Digital Musical Instruments are specially designed to be used by individuals with disabilities and SN. The literature on accessible interfaces has highlighted the importance of ADMIs and related works in this field. Frid [16] offers a comprehensive review of ADMIs and their use contexts, categorizing them based on interaction channels and modalities. As Frid notes, there have been several recent initiatives and charity organizations focused on developing ADMIs, as well as companies producing ADMIs with inclusive music practices at the core of their mission. Harrison and McPherson [20] identify two types of ADMIs: "therapeutic devices" that provide low-barrier expressive instruments for music-making in group workshops or therapy sessions, and "performance-focused instruments" that enable performers to achieve virtuosity comparable to traditional instruments. LIM-UM's research focuses on the latter category, which requires more practice and is suitable for contexts such as accessible orchestras. ADMIs are engineered to accommodate various disability types, as categorized into *physical*, *sensory*, and *cognitive* groups according to the framework proposed by Davanzo & Avanzini [9], taking inspiration from the classification systems provided by Sears et al. [44] and The Washington Group on Disability

[1] Arcana Instruments website: https://arcanainstruments.com/.
[2] SoundBeam website: https://www.soundbeam.co.uk/.

Statistics [52, p.26]. Physical disabilities impact motor skills and proprioception, sensory ones affect senses like sight, touch, and hearing, while cognitive disabilities impede learning and brain-related skills. ADMIs targeted at musicians with physical impairments are designed to leverage the users' residual motor abilities. Davanzo & Avanzini's framework categorizes the extent of catered motor disability from 'quadriplegic Paralysis', with only neck-upward control, to 'Lock-In', with only eye control. It implies that, in some cases, ADMIs for quadriplegic users could be extended to those with less restrictive motor impairments, provided the interaction channels above the neck remain functional.

Since the main focus of researchers at LIM-UM are instruments for quadriplegic users, they coined the term *HeaDMIs* [11] to redefine the concept of ADMI as one shaped entirely around the residual motor abilities of the musician, adapting its interaction modalities to the remaining viable physical interaction channels. In the aforementioned work, interaction channels suitable for HeaDMIs are summarized into four principal groups [11]: *eyes* (e.g. gaze pointing), *mouth* (e.g. voice and breathing), *head* (e.g. rotation and neck tension), and *brain* (e.g. mental state and motor imagery). An essential aspect of the development of HeaDMIs and Digital Musical Instruments, in general, is the challenge of mapping the physical interaction channels of a performer to musical events or outcomes. The term *mapping* usually refers to the strategy employed to establish this link between the performer's action and the musical result [11,30].

A 2020 study by Davanzo & Avanzini [11] examines 15 HeaDMIs, most of which use gaze pointing as their primary interaction channel for note selection. Gaze pointing refers to the selection of visual elements on a screen through one's gaze, detected through eye trackers. Gaze-based instruments include examples such as *Lumiselo* [1], which uses gaze and breath aided by head-mounted goggles with an eye tracker and a breath sensor for pitch control and note manipulation; *EyeHarp* [49], a gaze-controlled instrument with a dual-layer interface for performing melodies and looping accompaniments; *Eye Conductor*[3], which incorporates gaze pointing, eyebrow movements, and mouth-lip movements for varied control levels; and *EyeJam* [36], which enables melody playing through a unique "context-switching" interaction paradigm using two identical on-screen keyboards. Notably, only EyeHarp allows a certain degree of chord playing control, while other chord-playing Accessbile Digital Musical Instruments rely on other interaction channels, such as tongue-activated PET boards, mouth-moved cursors, or electroencephalogram-based interfaces, as in *Tongue-Controlled Electro-Musical Instrument* [39], *Jamboxx*[4], and *P300 Harmonies* [48].

2.2 The LIM-UMDevelopment Ecosystem

Building on this theoretical framework, in the past years, the LIM-UM staff crafted an ecosystem of software and hardware tools that explicitly caters to

[3] Eye Conductor, from A. Refsgaard's website: https://andreasrefsgaard.dk/projects/eyeconductor/.

[4] Jamboxx official website, on Web Archive: https://andreasrefsgaard.dk/projects/eyeconductor/.

quadriplegic musicians or aspirants. Specifically, this ecosystem addresses quadriplegic disabilities, not incorporating intersectional scenarios involving other types of disabilities such as sensory or cognitive impairments.

The ecosystem encompasses a suite of software Digital Musical instruments, each acting as a comprehensive interaction-solution package including action-to-sound mapping strategies, keyboard layouts, and more. These instruments provide *reference items*, serving as self-contained, fully operational starting points for customization operations tailored to individual needs. Notably, these instruments are "mute", meaning they are MIDI controllers with no sound generation unit, delegating this role to external synthesizers, which ensures extensive customization options and a broad array of sound choices. The chronology of developed instruments includes *Netytar* [5] [15], which utilizes gaze pointing and breath pressure detection for note selection and intensity control, and features an automated scrolling virtual keyboard. *Netychords* [6] [14] is a polyphonic Accessible Digital Musical Instrument that combines gaze pointing and head movement for chord selection and strumming. *Resin* [7] [12] is a monophonic ADMI that manipulates MIDI note selection and sound intensity through mouth shape and head rotation. *DJeye* [8] [4] is an eye-controlled DJ tool for fundamental mixing operations and incorporates unique eye interactions like winking. *Kiroll*,[9] similar to *Netytar*, uses eye gaze and breath for sound control with a scrolling keyboard layout.

Those instruments are all released under GNU GPL-v3 Free Open Source license. Except for DJEye (which relies on the *JUCE* [10] library), all of them were developed using the C# language within *NithDMIs*, an open-source software library part of the LIM-UM ADMIs ecosystem. This library facilitates the swift development and customization of HeaDMIs by offering a modular architecture and straightforward programming metaphors. It addresses various facets of an ADMI structure, including sensor interfacing, MIDI protocol communication, and audio analysis assistance. The library supports cost-effective or easily assembled sensors and peripherals via DIY methods.

The NithDMIs library supports the *NithSensors* [11] collection of open-source hardware peripherals, including a breath pressure sensor, a head tracker, and a speaker plus microphone system used in Resin. Additional peripherals such as a tooth pressure sensor are being developed to broaden the range of tools suitable for individuals with quadriplegia. These peripherals prioritize ease of construction, open-source microprocessors, easily procurable materials, and hardware reproducibility through the publication of construction projects and schemes

[5] *Netytar GitHub* repository: https://github.com/LIMUNIMI/Netytar; Web version link: https://annafusari.github.io/netytarweb/.
[6] *Netychords GitHub* repository: https://github.com/LIMUNIMI/Netychords.
[7] *Resin GitHub* repository: https://github.com/LIMUNIMI/Resin.
[8] *DJeye GitHub* repository: https://github.com/LIMUNIMI/DJeye.
[9] *Kiroll GitHub* repository: https://github.com/LIMUNIMI/Kiroll.
[10] *JUCE* official website: https://juce.com/.
[11] *NithSensors GitHub* repository: https://github.com/Neeqstock/NITHSensors.

under Creative Commons licenses. A standard and simple communication protocol ensures interchangeability, abstraction and easy mappings implementation.

3 Characterization of Netychords

Among the instruments available in the ecosystem, the child protagonist of our experimental activities showed a preference for *Netychords*, primarily driven by the possibility to make ensemble music and the subsequent prompt gratification. Here we review its main characteristics.

First published in 2021 [14], *Netychords* is a polyphonic HeaDMI that addresses the lack of Accessible Digital Musical Instruments able to play chords. It allows chord performance through a dual-control mechanism involving gaze pointing for note selection, and head movements for chord strumming. Head and eye tracking are known as effective interaction methods for accessible applications, demonstrating varying performance in selection tasks as per Fitts' Law tests [10]. Gaze pointing exhibits rapidity and stability, especially after data filtration, whereas head movement is slower yet highly stable. Nevertheless, the potential speed limitation of saccadic eye movements [21] may impact the efficiency of rapid sequences, especially in melodic lines, while could be adequate for chord changes. *Netychords* can be operated through low-cost sensors. It employs a *Tobii* [12] eye tracker for note selection and an ad-hoc head tracker (*NithHT*), part of the aforementioned *NithSensors* collection, built using an *MPU-6050/GY521* accelerometer/gyroscope and an *Arduino Uno* microcontroller for head rotation detection. A demonstration video of the instrument being played is available on YouTube.[13]

The interface, as it appears on screen, along with a complete depiction of the software and the related devices necessary for its operation, is depicted in Fig. 1. As in the image, the instrument's virtual keyboard presents color-coded keys denoting different chords: each root note corresponds to a unique color, while rows of color codes denote their chord family. Each key possesses a round-shaped gaze-sensitive area, or *occluder*, whose size may differ from the key's size, being balanced against the eye tracker's inherent signal noise to optimize selection accuracy versus movement length. *Netychords* uses an auto-scrolling feature to present unlimited keys on a limited screen, centering the key under the user's gaze, exploiting the eyes' natural smooth pursuit capabilities [42]. The scrolling speed is proportional to the square of the distance from the observed point to the screen center, creating an infinite playing region.

Eye gaze typically moves through short saccades [41]: the instrument features a key layout designed to minimize large and unwieldy saccadic eye movements. Its key arrangement is based on the *Stradella* bass system[14], commonly

[12] *Netychords* is compatible with both Tobii gaming series eye trackers and those designed for accessibility.

[13] *Netychords* demo video on YouTube: https://youtu.be/D18603o46ho.

[14] Balestrieri, D. (1979): Registers of the Standard Stradella Keyboard. http://www.accordions.com/articles/stradella.aspx.

Fig. 1. A laptop running *Netychords*, with a *Tobii* eye tracker and *NeeqHT* head tracker. *Netychords*' full interface is shown, in its default configuration.

found in Italian accordions, which organizes chords according to the circle of fifths. In this layout, each column represents a root note, while each row symbolizes a different voicing or chord family, as illustrated in [14, Fig. 3]. Unlike the *Stradella* system, which usually comprises four chord families, Netychords includes eleven of them: major, minor, dominant 7th, diminished 7th, major 7th, minor 7th, dominant 9th, dominant 11th, suspended 2nd, suspended 4th, and half-diminished 7th. To adapt to the specifics of gaze interaction, the original *Stradella* layout has been modified in a new layout, dubbed *Simplified Stradella*. All chords families have been grouped into five groups (major, minor, dominant, diminished, and half-diminished). Differently from *Stradella*, the starting chord for each row varies according to the chord family, with the harmonized diatonic scale chords clustered together to minimize eye movement for musical pieces in a single key. Figure 2 depicts a section of the layout which clusters in a small square all the chords necessary to play the harmonization of the C-major diatonic scale. The specific chord names are inscribed within the keys, while scale degrees are indicated beneath. Rows are characterized by chords of identical types. The direction of the circle-of-fifths, in horizontal movements, is demonstrated by an arrow. Additionally, genre-specific presets have been created by selectively omitting rows, facilitating music styles such as pop, rock, and jazz.

The current version of *Netychords* incorporates a straightforward system for customizing presets through the editing, addition, or removal of chord rows. This feature enables musicians and educators to craft user-tailored presets suitable for a specific music genre or piece.

In its initial design, *Netychords* employed head rotation, specifically yaw, to trigger chord strumming, converted into MIDI note on/off events and velocities. The sound intensity, or MIDI velocity, was originally proportional to the deviation from a calibrated central position. A subsequent revision tied sound

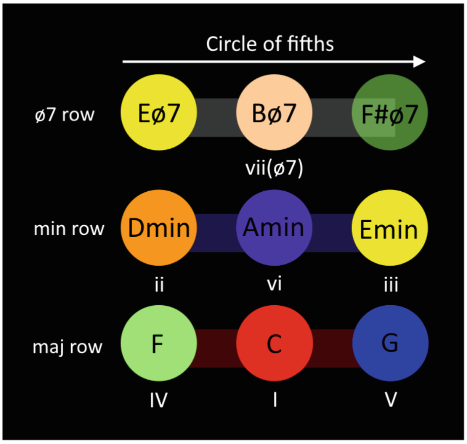

Fig. 2. Detail of the *Simplified Stradella* layout. The 9 keys are associated with the harmonization of the C-Major scale.

intensity to the average rotational speed before rotation reversal, eliminating the need for a central zone and precise absolute head position tracking. This allowed the use of simpler accelerometer sensors, forgoing a magnetometer. The strumming interface provided visual feedback on the fixated key, with a white handle indicating the relative head rotation [14, Fig. 6].

4 Case Study

In this section, we will present the case study involving a Portuguese child with cerebral palsy, as mentioned in Sect. 1. The experimentation aimed at the inclusion of the young user in classroom music activities thanks to the adoption and customization of *Netychords*. The process involved the child, his family, his caregivers, and the two research groups defined in Sect. 1, namely DEP-UA and LIM-UM researchers.

4.1 User's Profile

A preliminary study involving interviews with the child and his family was conducted by the DEP-UA researchers with the aim of characterizing the user. Utilizing structured interview scripts the Portuguese researchers gathered insights from the family and the child's professional care team [33,34]. At the start of the period under study, the child was 7 years old and was attending primary school. The child is diagnosed with cerebral palsy, manifesting a severe dyskinetic form in his upper limbs, resulting in involuntary movements and bilateral restrictions. Further, the child displays signs of hypotonia, particularly noticeable in his lower limbs. Alongside these conditions, the child is also diagnosed with epilepsy. He can move with a wheelchair and walker, needing support from people to perform his daily activities. He cannot speak or write in a conventional manner, but he is able to interact with his peers. The family, together with professional caregivers, have been working hard to develop his communication and learning capabilities. Communication occurs through gestures, facial expressions, and the use of assistive devices, namely a laptop, *Grid 3*,[15] and the *Tobii PC Eye Mini* [16] [33,34].

The child never had the opportunity to engage in musical performance experiences before. Our project introduced him to the realm of musical performance and expression for the first time. Therefore, the child also needed a basic introduction to both music theory and performance through the Accessible Digital Musical Instrument under exam.

The child and his family spent a period in Italy in July 2021. During this time, a number of interactions occurred with LIM-UM staff in order to choose the best-fitting tool, tailor the experience, and adapt the control interface.

4.2 Instrument Tailoring

During the first interaction with LIM-UM researchers, a key challenge we encountered was the child's difficulty in utilizing *Netychords* or the other instruments as intended. A significant issue arose due to the child's spastic movements and mild difficulty in controlling residual body movements. Despite these challenges, gaze pointing did not present any notable problems. In fact, eye trackers employing Near Infrared technology can tolerate minor head movements without losing signal and with minimal inaccuracy. These devices comprise illuminators and cameras that track the pupil's position and the Purkinje corneal reflections within the eye, allowing for the triangulation of the gaze point [37].

Conversely, following head movement with the *NithHT* head tracker proved to be difficult due to the child's small spastic movements. In fact, such an instrument demands precise control of head movement, as the detection resolution for the strumming action is exceptionally high. Additionally, the full range of head rotation cannot be exploited, as excessive rotation would cause issues in gaze-pointing detection and hinder the ability to simultaneously view the screen. This added to the concern that the proposed interaction method may not be initially intuitive or natural for him, requiring time to master, and potentially leading to the child's discouragement.

During the first encounter, we attempted a solution that considered the child's residual movement capabilities in his left or right arm. In the field of accessibility, large keys are frequently employed to compensate for limited mobility.

[15] *Grid 3* is a software tool for users with cognitive or speech neuromotor limitations. Its use needs to be complemented with adapted accessories, in this case, an eye tracker.

[16] *PC Eye Mini* by *Tobii Dynavox* is an eye tracker peripheral that allows users with neuromotor limitations to access the computer through eye movement and gaze tracking. It allows the user to work with potentially any application that can be controlled with the mouse, through its emulation.

As a preliminary step, we created a mock-up of a large key by attaching a sizable plastic plate (e.g., a CD case) to the computer keyboard's spacebar, thus simulating an accessible key. This way, the keypad would have replaced the strumming mechanism by substituting head rotation, renouncing temporarily the ability to control sound intensity dynamics. Gaze pointing would have maintained its role in chord selection. This approach was then assessed for viability, with plans to refine it in future iterations. This solution however proved not functional, as the child's arm movement induced even stronger spastic head movements, resulting in difficulties in gaze pointing detection and a sudden lack of eye tracking signal. The outcome of the initial meeting was primarily marked by a sense of frustration, discouragement, and resignation for both the child and his relatives, who were present during the tests.

Subsequently, we implemented on-the-fly solutions to provide instrument customizations tailored to the child's needs that emerged during the meeting. The first solution, called *auto-strumming*, introduced a straightforward mechanism enabling the automatic strumming of chords. The user gazes at the key corresponding to the desired chord, which is then played at full velocity. The user is only required to select the preferred tempo (in BPM) and the strumming follows a basic 4/4 time pattern, with a chord played every beat. The second solution, called *blink strumming*, allows a strum to be executed at full velocity when both eyes blink simultaneously. Such a strategy is generally robust and easy to implement. For instance, in *Tobii* eye trackers, it is sufficient to detect if the eye signal is lost for a specific number of samples to trigger an event of type "eyes not present". The ability to voluntarily blink is typically retained by most individuals, barring severe diseases or conditions (e.g., facial paralysis conditions such as Bell's Palsy [17]). Nonetheless, implementing this paradigm presents several challenges. Firstly, the frequent occurrence of involuntary eye blinks requires distinguishing them from voluntary ones to prevent inadvertent note performance. Voluntary blinks are typically rapid, making their duration a possible discriminator. However, prompting users for prolonged eye closure might cause unwanted delayed audio feedback, potentially hindering high-tempo interactions [40]. Secondly, sustained eyelid muscle activity could result in fatigue due to an unaccustomed frequency of movement. Additionally, eye closure during *blink strumming* results in temporary gaze point absence, which could prove problematic at high tempos with abrupt eye closures. This absence not only obscures the selected chord during the blink but also causes brief eye-tracking inaccuracies, as the signal does not necessarily persist on the last observed point with open eyes. Finally, to our knowledge, no existing research explores human blinking capacity in terms of rhythm, such as maximum frequency and speed constraints.

During the second meeting, the implemented changes were explained to the child, who was given the opportunity to try them out. The blink-based solution did not prove immediately effective: The young user found it somewhat challenging and frustrating to navigate through blinking, despite the solution technically working. Conversely, the automatic strumming solution proved immediately sat-

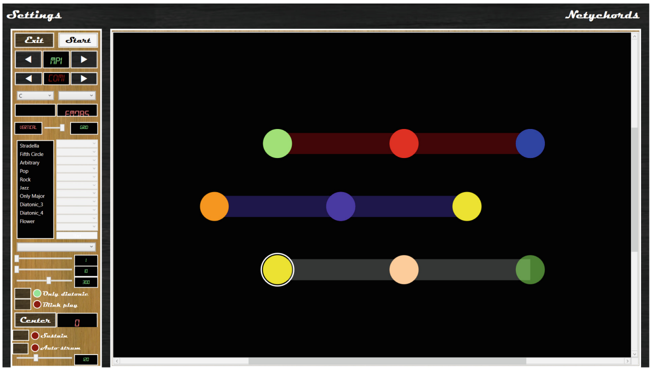

Fig. 3. The old version of *Netychords*' interface, with settings located on a left sidebar.

isfying, allowing him to play independently and enjoy the process of music creation. This method required less cognitive and physical effort and this likely played a key role in his appreciation. He explored the keyboard layout and various chords available for several dozen minutes before being asked to limit the chords played to a few specific ones, in order to let one of his tutors improvise a melody with a violin. The latter collaborative activity provided a sense of "playing together", which was a totally new experience for the child. The two continued to play for several minutes, and both the child and his family were visibly satisfied at the end of the experience. At the end of the session, the family requested guidance on how to use the software at home in Portugal.

After the period in Italy, the child enrolled in the *Arts Education Programme* in Portugal, overseen by an expert in Special Educational Needs. As a consequence, several changes and enhancements were implemented in *Netychords*, as documented in Sect. 4.3. Additionally, the instrument interface was completely reworked to achieve the following objectives: **(a)** Obtain more screen space – The settings column, previously located on the left side of the screen, was converted into a pop-up accessible through a button/switch; **(b)** Create a system for saving customizations – A system was introduced to develop new presets for layouts, save them, and select them upon subsequent launches. This allows both the user and the teacher to create specific layouts for each song or exercise; **(c)** Provide autonomous control over the software with no external support – A straightforward system was implemented to provide users with SN with full control over the interface. Firstly, buttons were enlarged to compensate for eye tracker signal noise (eg. approximately 1° on the visual angle for the *Tobii Eye Tracker 5* [22]). Additionally, to address potential size insufficiency, the last gazed button will be highlighted in a special color (yellow) and remain selected even if the gaze moves out of its area. A hybrid interaction selection strategy (as defined in [13]) is employed, wherein the gaze is used to select targets, and either double blinking or head strumming confirms the selection and activates the visual element (Figs. 3 and 4).

Fig. 4. An updated *Netychords*' interface featuring a retractable settings panel and accessibility solutions such as and gaze-based settings navigation solutions.

Future enhancements for Netychords based on our observations will include enriching the auto-strumming feature: while the current version was found effective, its simplicity leaves room for refinement. For instance, instead of the constant quarter beat strumming pattern, we could introduce a variety of advanced patterns and a basic beat sequencer for customization. An automatic arpeggiator to sequence notes within a chord could enrich the customizability. Moreover, the present version does not offer control of sound intensity dynamics with auto-strumming or blink strumming. A feasible solution might be integrating breath-based control. This system would utilize gaze pointing for chord selection, blinking for chord selection/change, and breath for controlling dynamics.

4.3 Adaptations in Arts Education Program

The effectiveness of the customized version of the instrument, in terms of music education and practice, was evaluated thanks to the enrollment of the young user in Portugal's Arts Education Program. An early phase was dedicated to establishing the prerequisites necessary for the child to participate. In fact, after adapting the instrument interface and features to take into account the user's characteristics, also curricular activities and goals had to be readjusted.

A constant dialogue was established between the researchers who designed the instrument (from LIM-UM) and the teachers along with the child's tutors (including DEP-UA researchers). The aim was to foster an environment of continuous improvement for the instrument and its setup, accommodating various requests as they arose. The majority of the instrument's modifications were primarily centered around the need for pedagogical supports, such as simplification tools, visualization systems, and customization of layouts. Gradually, various features were introduced. For example, in accordance with the educators' requests, the instrument was provided with some simplified views, to highlight smaller sections of the keyboard: *diatonic 3* shows only the diatonic harmonization of a major (akin to Fig. 2), while simplified single-row presets like *only major* or *only* *minor* show respectively only the major chords of such harmonization (which are the I, IV and V degrees of the scale) or the minor chords (ii, iii and vi degrees).

In particular, significant adaptations were implemented by the Piano teacher and the Music Training teacher. For the former course, these included: **(i)** Composing and arranging accompaniments for performance in *Netychords*; **(ii)** Suggesting modifications for the layout, interaction, and mapping strategies to meet the instrument programme requirements **(iii)** Adapting scores for simultaneous reading and playing.

The teacher dedicated significant effort to exploring the technical possibilities provided by the *Netychords* instrument and structured a music education program around its unique capabilities. One of the initial modifications required was the re-adjustment of the repertoire of songs taught to the child. Some compositions were also adapted to accommodate the constraint imposed by the constant auto-strumming pattern. Given the specific characteristics of *Netychords* as a harmonic instrument, the teaching was centered on the harmonic elements usually delegated to the left hand in traditional piano instruction. Out of the classical repertoire typically provided in piano teaching, few selected pieces were maintained. The remaining repertoire was composed explicitly for *Netychords* by the piano teacher, reflecting the instrument's unique characteristics. A significant aspect of standard music instruction involves mastering the control of sound dynamics or intensity. However, the tailored strumming solutions (auto-strumming/blink-strumming) implemented for the child did not provide a way to control dynamics. Consequently, this aspect of instruction was temporarily deferred until an accessible method for the child to manage dynamics is identified.

Concerning the Music Theory course, adaptations comprised: **(i)** Establishing codes for various rhythmic cells which the student could quickly write using *Grid3* and an eye tracker; **(ii)** Facilitating auditory chord identification through distinct facial expressions for major and minor chords. Specific emphasis was placed on teaching structured theory based on the unique key layout of *Netychords* (described in Sect. 3). For instance, the child was taught the sequence corresponding to the various degrees of diatonic harmonization of a scale, enabling him to identify the different degrees. Similarly, considerable attention was also dedicated to mastering the circle of fifths.

Within his music education period, the child was able to engage in multiple public music presentations and small concerts, including two piano performances. The first performance included a solo piece and a duet with the teacher, with the child playing harmony and the teacher handling the melody. In the second performance, the child performed his own harmonically composed piece, accompanied by a teacher's melody, demonstrating collaborative performance.

As a result of these efforts, the child's involvement in musical activities proved engaging. It was enabled through agreed curricular adaptations, consistent with the School Leaving Certificate Profile Policies. Those cater to varied learning styles, adjust objectives without compromising the curriculum, and introduce alternative learning respectively.

With regard to this, and to provide an example, throughout the musical activities it was found that the child presented a degree of voluntary control over his foot movement, albeit limited. This observation was made by their piano teacher who noticed the child tapping his foot rhythmically on a flat part of his wheelchair. Upon informal testing, it was confirmed that this movement was indeed voluntary and controllable. Given this discovery, further studies are planned to explore potential instrument adaptations that could capitalize on this newfound motor ability. For instance, a dynamic-sensitive stomp pedal could be implemented to perform temporally controlled strumming. The pedal would detect the intensity of the beat and map it onto the strumming intensity. This device could be built using dynamic resistors or piezoelectric sensors, aligning with the Open Source Hardware standards set for the *NithSensors* collection.

5 Generalization and Reflections

A key understanding, arising from the necessity for personalization in interaction design for musicians with motor disabilities, is the distinctiveness of each individual's condition, thus the need for interaction customization. Disabilities are often classified into specific patterns such as quadriplegia or hemiplegic paralysis, with the assumption that affected individuals will display a specific set of movement capabilities and be able to rely on certain interaction channels. Although generalizations may be made during the initial instrument design phases to cater to the needs of a particular population (e.g. quadriplegics), those generalizations are not always effective. Common factors, such as the interplay between interaction channels, as exemplified in the child's case, further complicate the situation. We argue that, in interaction design, it is crucial to account for those complex interplays between channels. As a result, we highlight the importance of enabling swift customization of instruments in the last design phases to create an interaction style specifically tailored to the individual concerned.

As a *first solution* to achieve this, a set of easily accessible mappings directly within the software interface could be provided, eliminating the need for specialized computer-science expertise from the users. Potential systems could also be investigated and developed to automatically generate mappings based on different connected sensor peripherals. As a *second solution*, a software developer with expertise in accessible interaction could intervene to rapidly develop specific mappings. This requires instruments to be designed using modular and efficient code, employing frameworks that facilitate effortless customization, alteration, and implementation of new interaction techniques and support for novel sensors. While the former solution could address the most common scenarios, the latter solution's drawback is the requirement for intervention from skilled personnel. In both scenarios, we suggest the open-source philosophy which characterizes our framework, so that specific solutions devised by an IT expert for a given user could be shared with the community. Those can successively be included in the software interface and converted into automatic mappings, thus falling under the first option. This underlines the significance of a modular framework, remarking on the value of flexibility and adaptability in designing accessible instruments.

While customization is essential, it is important to note the significance of a shared repertoire developed collectively on a musical instrument, as emphasized by Magnusson and Hurtado [28]. This notion somewhat pushes toward the idea of a community-shared experience, which may seem contradictory to the need for adaptation and individual customization. Nevertheless, as an instrument's expressive potential and playing style are influenced by its mapping strategies [23], those could be designed in a way that the instrument's characteristics are similar for everyone, providing at least a partial common structure (e.g., keys layout). In our opinion eye tracking related interaction channels, encompassing gaze pointing and blinking, could serve well this purpose. Except for extreme conditions such as *completely locked-in syndrome* [38], the ability to move one's eyes is often preserved even in the presence of complex disabilities. While not free from limitations (as analyzed in [11] and [13]) gaze pointing and blinking could serve as a robust common ground shared across various instruments, while other channels could be dedicated to different aspects of musical interaction.

As a final remark, since musical instruments (and HeaDMIs in particular) are usually skill-intensive and challenging to master, it can be difficult to discern whether a user is merely disheartened, the musical experience is not engaging, or the required movements are genuinely uncomfortable, awkward, or even impossible to perform given a specific disability. In our case study, language barriers with the child, who struggled with clear articulation, undoubtedly exacerbated the situation, as he was unable to thoroughly and effortlessly convey his impressions.

6 Conclusions

This paper's case study revealed several limitations and constraints encountered during the design, implementation, and adaptation process. These included technical issues regarding the usability of some interface controls and problems in communicating with users. Despite years of experience in developing a software tool ecosystem and careful intervention planning, field experimentation was necessary to identify problematic aspects. The experimentation also raised unanswered questions, such as which functionalities developed or revised for the child could be beneficial to other users with similar disabilities.

A forthcoming publication will present a qualitative analysis from an educator's point of view, based on the researcher/observer's notes from the experience, which is the emphasis of the DEP-UA researchers work. The evaluation will concentrate on the connections formed among diverse stakeholders, including the child, educators, researchers, fellow music students, and family members. Furthermore, it will investigate interactions within varying environments, the reciprocal influences between these environments and their respective contexts, and their intersection with larger encompassing contexts.

It is important to note that the specific scenario may have influenced the scope and generalizability of the findings, potentially introducing biases that could have affected the results. Nevertheless, the authors hope that the results can contribute to a broader understanding of the subject matter and promote wider adoption of digital technologies in music education and expressiveness. The authors believe that some aspects of their approach are transferable, particularly the methodologies, experimental designs, and techniques that have demonstrated effectiveness. Thus, the insights gained from the single case study can serve as a foundation for broader investigations involving larger sample sizes, diverse populations, or different contexts.

This research could signify a societal impact, particularly in the educational realm for children with cerebral palsy, by illuminating their learning challenges and proposing music as a potential developmental strategy, thus laying the groundwork for further research and novel implementations.

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References

1. Bailey, S., Scott, A., Wright, H., Symonds, I.M., Ng, K.: Eye. breathe. music: creating music through minimal movement. In: Proceedings Conference Electronic Visualisation and the Arts (EVA 2010), pp. 254–258. London, UK (Jul 2010)
2. Baratè, A., Ludovico, L.A., Oriolo, E.: Investigating embodied music expression through the leap motion: experimentations in educational and clinical contexts. In: McLaren, B.M., Reilly, R., Zvacek, S., Uhomoibhi, J. (eds.) CSEDU 2018. CCIS, vol. 1022, pp. 532–548. Springer, Cham (2019). https://doi.org/10.1007/978-3-030-21151-6_25
3. Beveridge, S., Cano, E., Agres, K.: Rhythmic entrainment for hand rehabilitation using the leap motion controller. In: 19th International Society for Music Information Retrieval Conference, Paris, France (2018)
4. Bottarelli, F., Davanzo, N., Presti, G., Avanzini, F.: DJeye: towards an accessible gaze-based musical interface for quadriplegic DJs. In: Proceedings of the 2023 Sound and Music Computing Conference. Stockholm, Sweden (Jun 2023)
5. Campayo-Muñoz, E., Cabedo-Mas, A.: The role of emotional skills in music education. Br. J. Music Educ. **34**(3), 243–258 (2017). https://doi.org/10.1017/S0265051717000067
6. Cano, M.D., Sanchez-Iborra, R.: On the use of a multimedia platform for music education with handicapped children: a case study. Comput. Educ. **87**, 254–276 (2015). https://doi.org/10.1016/j.compedu.2015.07.010
7. Cibrian, F.L., Tentori, M., Weibel, N.: A musical interactive surface to support the multi-sensory stimulation of children. In: Proceedings of the 10th EAI International Conference on Pervasive Computing Technologies for Healthcare, pp. 241–244 (2016)
8. Clements-Cortès, A.: High-tech therapy: music technology in music therapy. Can. Music. Educ. **54**(4), 37–39 (2013)

9. Davanzo, N., Avanzini, F.: A dimension space for the evaluation of accessible digital musical instruments. In: Proceedings of the 20th International Conference on New Interfaces for Musical Expression (NIME '20). NIME '20 (Jul 2020)
10. Davanzo, N., Avanzini, F.: Experimental evaluation of three interaction channels for accessible digital musical instruments. In: Miesenberger, K., Manduchi, R., Covarrubias Rodriguez, M., Peňáz, P. (eds.) ICCHP 2020. LNCS, vol. 12377, pp. 437–445. Springer, Cham (2020). https://doi.org/10.1007/978-3-030-58805-2_52
11. Davanzo, N., Avanzini, F.: Hands-free accessible digital musical instruments: conceptual framework, challenges, and perspectives. IEEE Access **8**, 163975–163995 (2020). https://doi.org/10.1109/ACCESS.2020.3019978
12. Davanzo, N., Avanzini, F.: Resin: a vocal tract resonances and head based accessible digital musical instrument. In: Proceedings of the 2021 AudioMostly Conference Trento, Italy (online conf.) (Sep 2021)
13. Davanzo, N., Avanzini, F.: Design concepts for gaze-based digital musical instruments. In: Proceedings of the 2022 Sound and Music Computing Conference, pp. 477–483. Saint-Etiénne, France (Jun 2022)
14. Davanzo, N., De Filippis, M., Avanzini, F.: Netychords: an accessible digital musical instrument for playing chords using gaze and head movements. In: Proceedings of the '21 International Conference on Computer- Human Interaction Research and Applications (CHIRA '21). Online conf. (2021)
15. Davanzo, N., Dondi, P., Mosconi, M., Porta, M.: Playing music with the eyes through an isomorphic interface. In: Proc. of the Workshop on Communication by Gaze Interaction, pp. 1–5. ACM Press, Warsaw, Poland (2018). https://doi.org/10.1145/3206343.3206350
16. Frid, E.: Accessible digital musical instruments—a review of musical interfaces in inclusive music practice. Multimodal Technol. Interact. **3**(3), 57 (2019). https://doi.org/10.3390/mti3030057
17. Gilden, D.H.: Bell's Palsy. N. Engl. J. Med. **351**(13), 1323–1331 (2004). https://doi.org/10.1056/NEJMcp041120
18. Habibi, A., Cahn, B.R., Damasio, A., Damasio, H.: Neural correlates of accelerated auditory processing in children engaged in music training. Dev. Cogn. Neurosci. **21**, 1–14 (2016). https://doi.org/10.1016/j.dcn.2016.04.003
19. Hallam, S., Creech, A., McQueen, H., Varvarigou, M., Gaunt, H.: The facilitator of community music-making with older learners: characteristics, motivations and challenges. Int. J. Music. Educ. **34**(1), 19–31 (2016)
20. Harrison, J., McPherson, A.P.: Adapting the bass guitar for one-handed playing. J. New Music Res. **46**(3), 270–285 (2017)
21. Hornof, A.J.: The prospects for eye-controlled musical performance. In: Proceedings of 14th International Conference on New Interfaces for Musical Expression (NIME'14). NIME 2014, Goldsmiths, University of London, UK (Jul 2014)
22. Housholder, A., Reaban, J., Peregrino, A., Votta, G., Mohd, T.K.: Evaluating accuracy of the Tobii eye tracker 5. In: Kim, J.-H., Singh, M., Khan, J., Tiwary, U.S., Sur, M., Singh, D. (eds.) IHCI 2021. LNCS, vol. 13184, pp. 379–390. Springer, Cham (2022). https://doi.org/10.1007/978-3-030-98404-5_36
23. Hunt, A., Wanderley, M.M., Paradis, M.: The importance of parameter mapping in electronic instrument design. J. New Music Res. **32**(4), 429–440 (2003). https://doi.org/10.1076/jnmr.32.4.429.18853
24. Innocenti, E.D., et al.: Mobile virtual reality for musical genre learning in primary education. Comput. Educ. **139**, 102–117 (2019). https://doi.org/10.1016/j.compedu.2019.04.010

25. Kraus, N., et al.: Music enrichment programs improve the neural encoding of speech in at-risk children. J. Neurosci. **34**(36), 11913–11918 (2014)
26. Lee, L., Chang, H.Y.: Music technology as a means for fostering young children's social interactions in an inclusive class. Appl. Syst. Innov. **4**(4), 93 (2021)
27. Lubet, A.: Music, Disability, and Society. Temple University Press (2011)
28. Magnusson, T., Hurtado, E.: 2007: the acoustic, the digital and the body: a survey on musical instruments. In: Jensenius, A.R., Lyons, M.J. (eds.) A NIME Reader. CRSM, vol. 3, pp. 317–333. Springer, Cham (2017). https://doi.org/10.1007/978-3-319-47214-0_21
29. Malloch, J., Birnbaum, D., Sinyor, E., Wanderley, M.M.: Towards a new conceptual framework for digital musical instruments. In: Proceedings 9th International Conference on Digital Audio Effects. pp. 49–52. Montreal, Canada, September 18–20, 2006 (2006)
30. McGlynn, P.: Interaction Design for Digital Musical Instruments. Ph.D. thesis, National University of Ireland, Maynooth (2014)
31. McLeskey, J., Rosenberg, M.S., Westling, D.L.: Inclusion: Effective Practices for All Students. Loose-Leaf Version, Pearson Education (Mar (2017)
32. Miranda, E.R., Wanderley, M.: New Digital Musical Instruments: Control And Interaction Beyond the Keyboard. A-R Editions Inc, Middleton, Wis, 1st edition edn. (Jul 2006)
33. Moreno, D., Moreira, A., Tymoshchuk, O., Marques, C.: A child with cerebral palsy in arts education programmes: building scaffoldings for inclusion. In: Costa, A.P., Reis, L.P., Moreira, A., Longo, L., Bryda, G. (eds.) WCQR 2021. AISC, vol. 1345, pp. 172–190. Springer, Cham (2021). https://doi.org/10.1007/978-3-030-70187-1_13
34. Moreno, D., Moreira, A., Tymoshchuk, O., Marques, C.: Análise de conteúdo utilizando o webqda: Opção metodológica para caracterizar uma criança com paralisia cerebral. New Trends in Qualitative Research 2, 687–702 (Jul 2020). https://doi.org/10.36367/ntqr.2.2020.687-702, https://publi.ludomedia.org/index.php/ntqr/article/view/127
35. Moreno, S., Bialystok, E., Barac, R., Schellenberg, E.G., Cepeda, N.J., Chau, T.: Short-term music training enhances verbal intelligence and executive function. Psychol. Sci. **22**(11), 1425–1433 (2011)
36. Morimoto, C.H., Diaz-Tula, A., Leyva, J.A.T., Elmadjian, C.E.L.: Eyejam: a gaze-controlled musical interface. In: Proceedings of the 14th Brazilian Symposium on Human Factors in Computing Systems, pp. 37:1–37:9. IHC '15, ACM, Salvador, Brazil (2015). https://doi.org/10.1145/3148456.3148493
37. Morimoto, C.H., Mimica, M.R.M.: Eye gaze tracking techniques for interactive applications. Comput. Vis. Image Underst. **98**(1), 4–24 (2005). https://doi.org/10.1016/j.cviu.2004.07.010
38. Murguilday, A.R., et al.: Transition from the locked in to the completely locked-in state: a physiological analysis. Clin. Neurophysiol. **122**(5), 925–933 (2011). https://doi.org/10.1016/j.clinph.2010.08.019
39. Niikawa, T.: Tongue-controlled electro-musical instrument. In: Proceedings of the 18th International Congrerss on Acoustics. vol. 3, pp. 1905–1908. Acoustical Society, International Conference Hall, Kyoto, Japan (Apr 2004)
40. Pfordresher, P., Palmer, C.: Effects of delayed auditory feedback on timing of music performance. Psychol. Res. **66**(1), 71–79 (2002). https://doi.org/10.1007/s004260100075
41. Purves, D., et al.: Types of eye movements and their functions. Neuroscience. 2nd edition, pp. 361–390 (2001)

42. Robinson, D.A., Gordon, J.L., Gordon, S.E.: A model of the smooth pursuit eye movement system. Biol. Cybern. **55**(1), 43–57 (1986). https://doi.org/10.1007/BF00363977
43. Schellenberg, E.G., Mankarious, M.: Music training and emotion comprehension in childhood. Emotion **12**(5), 887–891 (2012)
44. Sears, A., Young, M., Feng, J.: Physical disabilities and computing technologies: an analysis of impairments. In: Sears, A., Jacko, J.A. (eds.) The Human-Computer Interaction Handbook, chap. 42, pp. 829–852. Lawrence Erlbaum Associates, second edn. (2008)
45. Shadiev, R., Li, D.: A review study on eye-tracking technology usage in immersive virtual reality learning environments. Comput. Educ. **196** 104681 (2022). https://doi.org/10.1016/j.compedu.2022.104681
46. Swingler, T., Brockhouse, J.: Getting better all the time: using music technology for learners with special needs. Aust. J. Music. Educ. **2**, 49–57 (2009)
47. Turnbull, A., Turnbull, R., Wehmeyer, M.L., Shogren, K.A.: Exceptional Lives: Special Education in Today's Schools. Pearson, Upper Saddle River, N.J., 7th edition edn. (Jan 2012)
48. Vamvakousis, Z., Ramirez, R.: P300 harmonies: a brain-computer musical interface. In: Proceedings of the 2014 International Computer Music Conference/Sound and Music Computing Conference, pp. 725–729. Michigan Publishing, Athens, Greece (Sep 2014)
49. Vamvakousis, Z., Ramirez, R.: The EyeHarp: a gaze-controlled digital musical instrument. Front. Psychol. **7**, 906 (2016). https://doi.org/10.3389/fpsyg.2016.00906
50. Wong, M.W.y.: Fostering musical creativity of students with intellectual disabilities: strategies, gamification and re-framing creativity. Music Educ. Res. **23**(1), 1–13 (2021)
51. World Health Organization: International classification of functioning, disability and health (2001)
52. World Health Organization: World report on disability (2011)
53. Music, Y.: Reshape Music. Tech. rep, Youth Music (Oct (2020)