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Analysis of Accessible Digital Musical Instruments through the lens of disability models: a case study with instruments targeting d/Deaf people

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Music educators and researchers have grown increasingly aware of the need for traditional musical practices to promote inclusive music for disabled people. Inclusive music participation has been addressed by Accessible Digital Musical Instruments (ADMIs), which welcome different ways of playing and perceiving music, with considerable impact on music-making for disabled people. ADMIs offer exciting possibilities for instrument design to consider and incorporate individual constraints (e.g., missing arm, low vision, hearing loss, etc.) more than traditional acoustic instruments, whose generally fixed design allows little room for disabled musicians inclusivity. Relatively few works discuss ADMIs in the context of disability studies, and no work has investigated the impact of different disability models in the process of designing inclusive music technology. This paper proposes criteria to classify ADMIs according to the medical, social, and cultural models of disability, then applies these criteria to evaluate eleven ADMIs targeting d/Deaf people. This analysis allows us to reflect on the design of ADMIs from different perspectives of disability, giving insights for future projects and deepening our understanding of medical, social, and cultural aspects of accessible music technology.

KEYWORDS

Accessible Digital Musical Instruments, disability studies, music and disability, participatory design, Deaf culture, deafness

1. Introduction

In the last few decades, the disability rights movement has sought to affirm basic human rights, promoting equal access and inclusion for people experiencing different disabilities (Howe et al., 2015). Such activism has motivated landmark legislation that has raised challenges related to the inclusion of disabled people in music-making and music classroom activities (Hammel and Hourigan, 2011). Participation in music activities allows for emotional growth and sociability and the development of fine motor skills and cognitive capabilities (Hammel and Hourigan, 2011). These benefits highlight the importance of promoting broad access to music, which is particularly important for disabled people, whose physical and social barriers frequently exclude them from full participation in society (Adams et al., 2015).

The Accessible Digital Musical Instrument (ADMI)[1] field opens up new opportunities for inclusion by accommodating bodily differences and valuing multiple ways of perceiving music, such as through tactile and visual means (Davanzo and Avanzini, 2020). Scholars have observed that the development and design of ADMIs are often based on physiological "needs" at the expense of social and cultural ones (Frid, 2019a; Lucas et al., 2020). Authors have argued that studies on ADMIs have not dealt with the possibility of thinking about disability more deeply (Adams et al., 2015; Frid, 2019a; Lucas et al., 2020), highlighting that most studies in the field have focused mainly on approaches that can be identified with the medical model of disability (Frid, 2019a).

This paper provides original research by proposing criteria to classify ADMIs according to the medical, social, and cultural models of disability and apply these criteria to evaluate eleven ADMIs targeting d/Deaf[2] people. This analysis allows us to reflect on the design of ADMIs from different perspectives on disability, giving insights for future projects and deepening our understanding of medical, social, and cultural aspects of accessible music technology. This has not yet been explored in the existing literature. The paper addresses the following main needs: (1) the research in accessible music technology should connect with the different disability approaches found in the literature (Haag, 2017; Lucas, 2023), (2) researchers in the field should develop a literacy of disability models and present discussions about the impact of the model in their study (Haag, 2017; Lucas, 2023), and (3) studies in the ADMI field should consider approaches other than the medical model (Frid, 2019a; Lucas, 2023).

We address the three needs mentioned in the previous paragraph by proposing an analysis of ADMIs according to the three main disability models examined in the literature and by discussing the impact the different disability models may play on the ADMI design process. To enable this analysis and discussion, we proposed criteria to analyze ADMI development. These criteria are inspired by aspects of the medical, social, and cultural models of disability and can be used at any point in the development process, including before and during design. They can also guide future ADMI projects. First, our study addresses need 1 by providing an introduction and discussion of different disability models in the context of music and technology. Second, our criteria can be used to analyse, classify, and develop ADMIs according to the medical, social, and cultural models of disability, leading researchers to reflect on the importance of developing a literacy of disability models (need 2). Third, we propose a discussion about the implications of our criteria to the design of new ADMIs, highlighting the importance of considering design aspects beyond the medical model (need 3) and opening different perspectives on disabled musicians participation, inclusion, and evaluation. To our knowledge, no previous work proposes reflecting on ADMIs according to the medical, social, and cultural models nor considers how these models might affect the design of new ADMIs.

Another original point of this research is that we discuss ADMIs in the context of the cultural model of disability, presenting disability as a source of cultural diversity that can impact the development of new ADMIs. This avenue has not yet been explored in the existing literature. This discussion opens doors for reflections on music and technology from different cultural perspectives and provides researchers with a way of analyzing ADMIs that takes into account individual and collective practices and the experiences of disabled musicians.

The criteria proposed in this study were used to analyse eleven papers focused on ADMIs, all of which describe instruments that are used or potentially used by d/Deaf individuals. A search of the literature revealed that few studies are specifically designed for d/Deaf people (Frid, 2019a), suggesting that this research direction needs to be further explored. After introducing the medical, social, and cultural models of disability (Section 2.1) and discussing their implications for music and technology (Section 2.2), the paper proposes criteria to analyse ADMIs through the lens of these three models (Section 2.3). We then analyse eleven selected ADMIs according to those criteria (Section 3) and then discuss potential new insights for ADMI design in the context of the medical, social, and cultural models of disability (Section 4). The insights from using these criteria include: analyses of inclusive technology under different perspectives on disability, reflections on participatory methods, and reflections on the value of disability as a source of sociocultural diversity that can inspire and guide the development of new ADMIs.

2. Materials and methods

2.1. The medical, social, and cultural models of disability

The Western conception of disability has changed over the past 300 years. Straus (2011) explains that some conditions once legitimated by medical diagnoses no longer exist (e.g., hysteria, neurasthenia, fugue, and nostalgia) while others that never existed before (e.g., attention deficit disorder, autism, anorexia, and obesity) are now part of the discourse on disabilities. By the 18th century, disability was commonly conceived as a sign of divine disfavor, a punishment from God, and thus the external mark of an internal moral failing (Straus, 2011). In the 19th century, disability was generally characterized as a sign of divine inspiration and conceived as something to be left behind after

1 In the current paper ADMI is defined as "accessible musical control interface used in electronic music, inclusive music practice and music therapy settings" as proposed by Frid (2019a, p. 3). There are many terms describing research focusing on making digital music instruments accessible, for example, "adaptive digital musical instruments" and "assistive music technology" (Frid, 2019a). However the author explains that the word "assistance" implies an external source that provides aid to a person in need, whereas "adaptive" implies a constant state of refinement and adjustment to the musician (Frid, 2019a).

2 The term "Deaf" (capitalized) refers to people who value their Deafness and identify culturally as Deaf, usually communicating in Sign Language, and utilizing visual and tactile cultural behaviors (Jones, 2015; Holmes, 2017). Whereas deafness with a lowercase d denotes an audiological condition and is used here to identify people who have a hearing impairment (Jones, 2015; Holmes, 2017). We use the term d/Deaf when referring to both groups. Although conceptions of d/Deafness are more complex than these definitions imply, it is beyond the scope of this article to articulate them further.

spiritual transcendence (Straus, 2011). Since around 1800, disability has been largely considered as an individual pathology or defect that could be corrected by medical procedures (Straus, 2011). From the 1960s and 1970s, in the context of civil rights, disability began to be thought of as a sociocultural construct, not a fixed medical condition (Garland-Thomson, 1997).

In the next subsections, the three main models of disability (medical, social, and cultural) are presented and discussed in the context of music and technology as a basis for proposing criteria for ADMI analysis. Llewellyn and Hogan (2000) explain that models of disability are not synonymous with theory as their usage does not involve data collection and are not based upon data collection or methodology; however, they may serve as a tool to help us solve problems in research. They may have some usage as generators of hypotheses and enable us to represent information in a way that may aid understanding and generate explanations, providing us with different ways of examining the world of the disabled person (Llewellyn and Hogan, 2000).

Llewellyn and Hogan (2000) discuss the danger of overgeneralization when using disability models, arguing that researchers have to ask themselves if the advantages of a given model justify usage. In the present paper, we use the medical and social models as they have dominated the discussions in disabilities over the last 50 years (Toro et al., 2020), and they have been discussed in the ADMI literature (Frid, 2019a; Davanzo and Avanzini, 2020; Lucas et al., 2021). In addition, we choose to also include the cultural model, intended to provide us with a way of analyzing ADMIs by taking into account individual and collective practices and experiences of disabled musicians. However, other models or ways to conceptualize what "disability" means can be found in the literature: the Transactional Model (Llewellyn and Hogan, 2000) that is based on the basic premise that, beyond non-sport environments, disability is caused and sustained by problematic social relationships; the Ecological-Enactive Model (Toro et al., 2020), intended to disentangle the concepts of disability and pathology, locating the difference between pathological and normal forms of embodiment in a person's capacity to adapt to changes in the environment; and the Social-Ecological Models (Shogren et al., 2018) that challenge the assumption that disability resides only within the person and provides a conceptual framework to operationalize the understanding of disability.

2.1.1. Medical model

The medical model is based on the disease model used in medicine, considering all disability as the result of some clinically observable physiological impairment in bodily structure or function that needs appropriate "treatment" (Llewellyn and Hogan, 2000; Toro et al., 2020). Overall, the goal is to return the individual to a state of normalcy, allowing full participation in society (Lucas, 2023). The human being is considered as adaptable to the environment while society is fixed and unalterable (Llewellyn and Hogan, 2000). The medical model assumes a normative standard from which disability is an individual deviation that could be remedied and adjusted. Within this model view, disability is conceptualized as an individual body problem, and the solution is provided by medically oriented institutions, experts, and professionals (Beaudry, 2016). These experts and professionals have the task to treat the individual for the disabling condition, an idea that is often internalized once a person receives training, acquires expertise, and works in an environment dominated by the medical model (Oliver, 1983).

While the medical model recognizes a myriad of environmental factors linked to individual functional limitations, disability is understood in terms of the body of the disabled person as described objectively and scientifically, failing to recognize the lived embodiment of disabled persons (Toro et al., 2020). Waldschmidt (2018, p. 69) explains that from the medical approach "everything begins from the impairment, by presupposing that there are bodily, mental or psychological conditions that cause restrictions of participation and result in disability". For example, the appropriate medical response to learning problems is to treat impairments (such as hyperactivity disorder or dyslexia) through therapeutic intervention and to support the individuals to come to terms with their deficits (Waldschmidt, 2018).

Llewellyn and Hogan (2000) explain that this model has been seen as a force only to change disabled people into some more normal beings, disregarding social factors and not allowing disabled people to claim their major role in defining their own disability. Lucas (2023) points out that, in its extreme, the medical model sees diseases as attributable to biological and somatic factors that are possible to identify in a laboratory or clinical setting, omitting psychological, social, and cultural factors. The medical model is inclined to accept what is considered physiologically, socially, and culturally "normal" and does not allow much room for discussions about changes in the social status of disabled people (Straus, 2011).

The medical model could be associated with the status quo of Western music traditions and institutions that often seem to dictate what is "normal" in music, creating ideas about the right way musicians should play, compose, use instruments, etc. (Howe, 2015). A biased perception that music has to follow "normal" standards has the potential of leading researchers in music technology to design instruments intended to promote the "right" way musicians should play, compose, use instruments, etc. (Howe, 2015). From the medical perspective, music technology researchers are the experts responsible for understanding how individual impairments prevent participation in music and proposing technological solutions to overcome the disability, allowing the person to make music "normally" (Haag, 2017).

2.1.2. Social model

The social model switches the focus from individual limitations to the way the physical and social environment imposes limitations upon certain groups of people (Oliver, 1983). This model presents disability as a form of inequality caused by societal practices of disablement or incapacity to remove obstacles faced by disabled people rather than by impairments within the individual (Beaudry, 2016; Waldschmidt, 2018). From this perspective, disability is not a fixed, medical condition; rather, it emerges from a society that chooses to accommodate some bodies and exclude others (Garland-Thomson, 1997). Under the social model, adjustment becomes an issue for society, and the reflections about the able or disabled

are displaced from the individual to the design of buildings, housing environments, expectations of others, working conditions, organizations of production, etc. (Oliver, 1983).

Within a social model of disability, it is argued that disability exists insofar as it is socially constructed and imposed on people with impairments; there is a de-emphasis on the individual, putting the discussions on disabilities back into the collective responsibility of society, emphasizing that limitations experienced by disabled people are caused by factors that come from outside of the person not from their impairment (Llewellyn and Hogan, 2000; Toro et al., 2020). The social model intends to contribute to the emancipation of disabled people, posing important questions about the barriers society imposes on them and reflections on policies intended to promote inclusive arrangements (Waldschmidt, 2018).

There are two main critiques of the social model. First, it does not address individual truth, perceptions, and beliefs about disability (Llewellyn and Hogan, 2000); the focus on society leads this model to neglect the embodied lived experience of the disabled person in the world (Toro et al., 2020). Second, the social model leaves little space for differences, such as race, age, and gender, between disabled people once this model focuses on collectivity to drive political change, sustaining that disabled people will benefit by banding together (Lucas, 2023).

An important characteristic of the social model is the distinction between impairment and disability. Impairment is related to loss or diminution of sight, hearing, mental ability, etc. susceptible to individual treatment/therapy, while disability is considered to be generated by the incapacity to remove obstacles faced by disabled people and generally associated with societal practices of disablement or exclusive social environments (Llewellyn and Hogan, 2000; Waldschmidt, 2018). For example, a d/Deaf person is disabled by oral language, but not by sign language; a wheelchair user is disabled by curbs, but not by sloped curbs. Oliver (1983) explains that if the problem of housing, for example, is taken from the medical perspective, the discussion would be around terms related to getting in and out, bathing, accessing the kitchen, and so on. That way, the discussions around the social model make it possible to see the creation of disability by the way housing is unsuited to certain individuals. Thus, there is a shift in emphasis from providing personal aids and therapy to adapting environments (Oliver, 1983). Beaudry (2016) argues that exclusion is the real problem; it is caused by a social failure to make adequate inclusive arrangements, accommodating some bodies and excluding others. For example, the access barrier of built environments may be observed through the attitudes held by building designers who may have overlooked or even devalued the requirements of wheelchair users (Lucas, 2023).

Lucas (2023) explains that the broader contextual factors raised by the social model can be applied to the design of technological products or musical instruments. The history of Western music has perpetuated an idea of normalcy tied to physical constraints, constructing an idea of a normal performance body (Lucas, 2023). For example, the acoustic piano requires the players to fit the piano's dimensions, being able to sit while moving and coordinating arms and legs. The social model perceives non-inclusive musical environments (concert halls, theaters, opera houses, etc.) and tools (music instruments, interfaces, stages, etc.) as disabling factors (Howe, 2015). In this way, the design, implementation, and use of assistive techniques and technologies may be an alternative to overcome barriers in music-making (Howe, 2015). Also, a study in consonance with the social model intends to contribute to the musical emancipation of disabled people. The research under the social approach promotes the participation of disabled musicians, allowing them to contribute to the design of new technologies that have the potential of overcoming social barriers and therefore facilitate inclusion and access to music (Haag, 2017; Lucas, 2023).

2.1.3. Cultural model

The cultural model of disability challenges "normality" and investigates how normalizing practices result in disability (Waldschmidt et al., 2017). Waldschmidt et al. (2017) explains that this model considers disability neither as only an individual fate, as in the medical model, nor as merely an effect of discrimination and exclusion, as in the social model. The cultural model investigates disabilities as a category constructed within a certain cultural and historical background that defines normalities and deviations, exclusionary and inclusive practices in everyday life and different institutions (Waldschmidt, 2018). Thus, attitudes toward impairments and the relation between impairment and disability are defined according to the cultural context. For example, deafness is typically regarded as a lack of hearing by non-disabled people; however, the cultural model supports the Deaf community view of deafness as a cultural difference and a source of linguistic competence in the form of sign language (Waldschmidt, 2018).

The cultural model maintains that disability exists only, and insofar as, certain differences (bodily and embodied) can be distinguished and thought of as "relevant for health" within a given cultural and historical order of knowledge and institutional support (Waldschmidt, 2018). Following this line of thinking, research does not simply investigate, for instance, the life course experience of disabled persons, but also those of persons considered non-disabled. Such a research approach challenges stigmatized cultural identities and outworn stereotypes by asking, for example, why personal autonomy is important for modern society and what normative expectations and constraints are attached to it (Waldschmidt, 2018). Similarly to the social model, the cultural model perceives non-inclusive musical environments and tools as disabling factors. However, the cultural approach allows us to go further and also include attitudes toward music, such as musical paradigms, musical pedagogical approaches, musical technique, etc. These environments, tools and attitudes are often not directed at disabled musicians.

The cultural model allows us to have different perspectives on common ideas and practices related to music and music technology. For example, Bowman (2009) explains that the practices related to music education define inclusion based on dominant-culture notions of what is adequate or inadequate, good or bad, and successful or unsuccessful. Deaf people, for example, are disabled by hearing-centric views of music, normalized listening paradigms (Straus, 2011), and music technology resources inspired by these views and paradigms. Such conceptions of music disregard the fact that Deaf listeners, music teachers, and musicians are proposing a much more multisensory hearing experience

(Jones, 2015). Deaf musicians are creating new ways to "feel" and "see" music and use music technology within the social and cultural context of the Deaf community (Best, 2016a,b). They are creating a musical movement that covers Deaf schools (Fawkes and Ratnanather, 2009), Deaf ensembles (Swinbourne, 2016), YouTube channels (Best, 2016a), and music technology projects (Hawley, 2016). Through these musical movements, Deaf musicians introduce new ideas about hearing, composition, education, and technology. The cultural model can promote this argument by celebrating disability as a cultural difference.

2.2. Accessible music technology and disability models

Music involves the integration of a wide range of cognitive, perceptual, motor, and emotional human capabilities. As Holland et al. (2019) explain, "music is a highly embodied activity in which performers and listeners routinely engage in complex synchronized movements in time with sound" (p. 2). Disabled performers (those with fewer fingers, weaker muscles, smaller lungs, or less vision than their instruments and sociocultural context require) lead us to ask what a performer can do (with one part of the body) and what a performer cannot do (with another part of the body); accessible musical instruments can accommodate the diversity related to these performers (Howe, 2015). The complexity of music poses challenges for developments in Human Computer Interaction (HCI), which should allow the accommodation of performers' impairments in comfortable and expressive ways.

The literature concerning disability in HCI has favored approaches tied to the medical model of disability (Haag, 2017). Lucas (2023) explains that this tendency partly originates from the lack of awareness of disability models within the HCI community. In this context, research projects present disability models implicitly and "researchers rarely state the model that frames their perspective" (Lucas, 2023, p. 14). Haag (2017) points out three possible parallels between the medical model and HCI studies addressing disability: (1) a shared exploration of technology as a corrective apparatus for defective bodies, (2) the comparable role of doctors and researchers to determine the nature of disability and design, and (3) a similar underestimation of disabled people's perspectives. Most of the papers reviewed by Haag (2017) are either explicitly based on the medical model or do not present an explicit reference to a particular model of disability. Haag (2017) urges the HCI community to update its discourse with respect to the vast literature on modern conceptions of disability. The problems that emerge from this field and their potential solutions are both constrained by the underlying model of disability (Haag, 2017), thus linking these solutions to the model implicitly or explicitly used. Research can help clarify the conceptual intricacies of disability to create more effective frameworks for developing solutions that fit the needs of the end beneficiaries (Haag, 2017). As Haag (2017) argues, researchers should ideally develop a literacy of disability models and state the model to which their research adheres.

One class of HCI development is linked to Digital Musical Instruments (DMIs) (Miranda and Wanderley, 2006). In the context of inclusive music practice, these instruments are known as Accessible DMIs or ADMIs. ADMIs are typically composed of a control surface where disabled musician interactions are measured by sensors whose values are mapped to sound synthesis algorithms. These interactions are mediated by gestural controls that are decoupled from sound production (sound control dissociation) but connected according to a mapping strategy. The sound control dissociation precludes any mechanical or physical constraints on sound production or gesture controls. Therefore, ADMI designers have more freedom than builders of acoustic instruments to provide tools intended for inclusive contexts (Frid, 2019b). The dissociation also allows the use of mappings between sounds and images or haptic elements. These instruments allow us to overcome the idea of a normally performing body (Howe, 2015) which usually possesses all limbs, appendages, physical capacities, and so on. Furthermore, ADMIs dismantle the dichotomy of a "right" or "wrong" way of playing an instrument, incentivizing curiosity and exploration, and promoting a sense of empowerment (Frid and Ilsar, 2021).

2.3. Criteria for ADMI classification through the lens of the medical, social, and cultural disability models

In this section, we connect ADMI design to the medical, social, and cultural models discussed in Sections 2.1 and 2.2 proposing criteria for ADMI classification based on four design elements. Despite Haag (2017)'s evidence for the value of broader disability literacy and greater transparency about disability models, researchers still tend to adhere exclusively to the medical model and frequently neglect to disclose their chosen approach (Haag, 2017). To encourage the exploration and transparent disclosure of different disability models, we propose that researchers analyse different ADMIs through the criteria of *user participation*, *disability view*, *inclusion view*, and *impact view*. These criteria are based on the three aforementioned disability models.

As observed by Frid (2019a), ADMI projects generally do not follow a straight line from conception to project design and do not clearly explain the project development steps. However, ADMI reviews (Frid, 2018; Frid, 2019a) and evaluations (Davanzo and Avanzini, 2020; Lucas et al., 2020) shed light on four commonalities among most ADMI projects: 1) specification of the potential user, 2) frequent reflections on disability, 3) occasional consideration of access and/or inclusion, and 4) discussion of the instrument's potential impact. These four common points inspired the four criteria we propose to analyse ADMI literature: 1) participation of users in the research process (*user participation*), 2) disability references or descriptions (*disability view*), 3) mentions of inclusion or/and access (*inclusion view*), and 4) potential impact of the ADMI on music-making for musicians with or without disabilities (*impact view*). The four elements are described below in relation to each model, and then summarized in Table 1.

User participation is defined here as the degree of participation attributed to users in the ADMI research process and can be classified according to each of the three disability models. Under the medical model, ADMI research concentrates on

fixing impairments. Research is typically designed and conducted exclusively by the researchers, restricting the participants' role to only evaluating the instrument according to the researcher's view, sometimes, participants with disabilities are not even involved in the research process. Participants are mostly involved in order to address impairments and discuss how ADMIs may overcome them. Under the social model, the active participation of users focuses on addressing how to overcome social barriers (music environments, music tools, etc.) that limit access to music. According to the cultural model, reflections on culture guide our understanding of disability. As in the social model, users active participation contribute to overcoming cultural barriers (musical paradigms, musical pedagogical approaches, musical technique, etc.) to accessing music.

Our investigation on participation is not intended to describe in detail the participation approaches (Harder et al., 2013) used by the researchers in the papers to be analyzed. Associating the participation approach with the disability models, we classify each approach according to the inclusion or exclusion of the disabled person in the ADMI design process. If the disabled person is part of this process, the nature of the participation is identified by pointing out medical, social, or cultural aspects or characteristics as explained in Subsection 2.1 and illustrated by the analysis of each instrument in Section 3.

The *disability view* describes how ADMI research presents disability according to the three models. Researchers following the medical model investigate which individual conditions prevent the inclusion of disabled people in music, while those following the social model explore social conditions, practices, and attitudes that prevent their inclusion. Research influenced by the cultural model strives to understand the meaning of music-making in a given culture or society, and what cultural conditions, practices, and attitudes inhibit disabled people from participating in music activities.

The *inclusion view* refers to how ADMI research conceptualizes inclusion through the three models of disability. Research aligned with the medical model inquires whether and how technology and music practices support the overcoming of "music deficits". Socially oriented research examines how technology and music practices may "empower" disabled persons and promote accessible music environments by removing societal practices of disablement in music and deviating from "normalcy" (Howe, 2015) in the design and use of musical instruments. Culturally influenced research explores how technology and music resources may incorporate conceptions or music ideas from disabled performers. The way disabled people make music may inspire the development of technology. For example, the design and development of gesture controllers can accommodate the needs of diverse bodies, and culturally diverse perceptual modes may inform systems intended to visualize or feel music by using visual and haptic devices.

The *impact view* refers to the way that ADMI research evaluates the impact of instruments according to the medical, social, and cultural models. By way of the medical model, research on the benefits of ADMIs focuses on evaluating whether the instruments are "fixing" the disabilities of people living with them. No impact of these instruments is measured for people living without disability. Socially focused research advocates the benefits of ADMIs for disabled people and encourages the design of instruments that accommodate disabilities and enable independent music-making. This branch of research thus emphasizes ADMI benefits in the context of breaking down social barriers to music access. Research following the cultural model similarly emphasizes the benefits of ADMIs for both the disabled and non-disabled by integrating cultural diversity into instrument design. Culturally diverse approaches focus on breaking cultural barriers to make musical activities more accessible, while framing the artistic output of disabled people as valuable for everyone.

2.4. Methodology

2.4.1. Data collection

In order to find works describing ADMIs targeting d/Deaf individuals, we applied the method proposed by Frid (2019a) adapted to the d/Deaf context. Accordingly, we consulted the same databases (ScoPus, Google Scholar, and Web of Science Core Collection), using the same search phrases: ("Digital Music* Instrument*" OR "New Interface* for Musical Expression" OR "music* interface*" OR "music controller") AND (accessib* OR adapt* OR assistive OR inclus* OR empower*) AND (disabilit* OR health OR need OR impairment OR therap* OR disorder*). However, in order to adapt the last group of terms to the d/Deaf

TABLE 1 Criteria for ADMI classification according to the medical, social, and cultural models of disability.

	User participation	Disability view	Inclusion view	Impact view
Medical model (M)	No participation or limited participation, intended to validate the instruments designed by the experts.	Individual conditions prevent music participation.	Technology supports disabled persons in overcoming their "musical deficits".	The research does not consider the impact on non-disabled people, focusing only on disabled individuals.
Social Model (S)	Active participation in the design and evaluation process, with a focus on music needs to overcome social barriers to music access.	Societal conditions, practices, and attitudes prevent music participation.	Technology promotes accessible music environments by removing social barriers in music.	The research considers how the instruments benefit disabled people in overcoming social barriers.
Cultural model (C)	Active participation in the design and evaluation process, with a focus on cultural elements from disabled musicians/communities.	Cultural practices and discourses prevent music participation.	Technology incorporates culturally diverse ways of hearing and music-making.	The research considers how the benefits of developing technology inspired by different cultural backgrounds can impact everyone.

TABLE 2 Workflow.

Element	Question 1	Answer	Question 2	Disability model
User Participation	Are there disabled people participating in the research?	No.		M
		Yes.	Medical-based participation.	M
			Social-based participation.	S
			Cultural-based participation.	C
Disability view	What prevents participation in musical activities?	Individual/medical conditions.		M
		Societal conditions, practices, and attitudes.		S
		Cultural practices and discourses.		C
Inclusion view	How does the ADMI promote inclusion?	Technology supports disabled persons in overcoming their "musical deficits".		M
		Technology aims to remove social barriers that prevent access to music.		S
		Technology incorporates culturally diverse ways of hearing and making music.		C
Impact view	What is the context for discussions about the impact of the ADMI?	Medical reflections focusing only on disabled individuals.		M
		The instruments social benefits impact everyone.		S
		Technology inspired by different cultural backgrounds impacts everyone.		C

context, we replaced the phrases (disabilit* OR health OR need OR impairment OR therap* OR disorder*) with the phrases (deaf* OR hearing impairment OR cochlear implant OR deaf hearing OR hearing loss). Studies that were included in our analysis had to: a) present at least one ADMI directed to d/Deaf individuals, mentioning the potential target group(s) in either the title or the abstract; b) describe the implementation of an ADMI that enabled real-time manipulation of input or control data.

Following Frid's method (Frid, 2019a), we considered conference proceedings, journal papers, PhD theses, and book chapters written in English. The review considered both academic and gray literature (meaning valuable commercial and other non peer-reviewed literature that emerges through database searching). We selected the articles most appropriate to the purpose, with the following questions in mind: Does the study present the development of an ADMI or DMI targeting d/Deaf people or potentially addressing them? Does the study mention disability? Does the study provide any description of ADMI design and evaluation?

2.4.2. Data analysis

Our analysis focuses on four distinct elements of ADMI design as shown in Table 1. We intend to analyse ADMI design; however, we have to go through the overall research process to analyse and understand how the elements related to design are linked to the different disability models presented in Section 2.1. Our workflow is presented in the next paragraphs and summarized in Table 2.

First, we identified whether the researchers plan to include disabled people in the design process, the noninclusion indicates a medical approach; when the disabled individuals are included we have to analyse the nature of the interaction between researchers and individuals regarding the medical, social, and cultural models. The nature of the interaction is classified as: medical, when the focus is on overcoming disabilities; social, when disabled individuals and researchers work together to overcome social barriers; cultural, when the disabled individuals' cultural practices are put in the foreground. That way, we have the elements to establish the project's *user participation* (Section 2.3) in the design stage. We additionally analyzed the ADMI evaluation process, classifying *user participation* in accordance with the descriptions of instrument use and identifying which model guides the collaboration process with the disabled participant (medical, social, and cultural).

Second, we scrutinized how different researchers defined the design requirements by identifying the various intended target participants and the contexts of instrument use. This preliminary definition phase also uncovered researchers assumptions about the relationship between impairment and disabilities, allowing us to classify the project in terms of the *disability view* as described in Section 2.3.

Third, we examined the design choices of different instruments to identify associations between the *inclusion view* (Section 2.3)

since the design choices reflect the ways in which technology promotes access. These associations can be classified into: 1) medical model, when design choices are aimed at overcoming individual deficits; 2) social model, when design choices target musical environments and aim to empower disabled musicians; or 3) cultural model, when design choices take into account or are inspired by the cultural practices of disabled musicians.

Fourth, we reviewed the conclusion and discussion sections of each article to classify their alignment with the *impact view* (Section 2.3) and the three disability models in terms of the different instruments benefits and the targets of these benefits. The *impact view* is classified as medical when benefits are discussed in the context of disability correction. Otherwise, the *impact view* can be classified as social or cultural, depending on whether the discussion of benefits focuses on social or cultural aspects related to the analyzed ADMI.

We tried to keep the analysis of each criterion to the elements of ADMI design mentioned in the previous paragraph. However, sometimes we had to adapt our analysis when some papers presented different structures or the criteria were identified across different elements or phases. For example, the elements that made it possible to identify the *disability view* or the *inclusion view* were frequently distributed through ADMI descriptions.

We point out that the models are not mutually exclusive, which is why some categories may be associated with more than one model. We use the letters M, S, and C to identify the medical, social, and cultural models respectively. When a category is associated with more than one model, the letters are ordered according to the model dominance, which is related to the number of answers to the questions in Table 2. For example, C, S, and M indicate that the cultural model is dominant (most of the questions in Table 2 are answered/classified with the cultural model), followed by the social and medical models.

3. Results

By applying our selection criteria, as presented in Section 2.3, we found eleven instruments targeting this population. The chosen papers are briefly presented in the next paragraphs.[3]

Mórimo (Zubrycka and Cyrta, 2012) aims to provide a platform for musical expression, with an emphasis on the tactile properties of sound. The work investigates the human body-music interaction, within the performative context in particular, targeting non-deaf and deaf people. There is no mention of deaf participants in the research process. Future works are intended to include deaf and non-deaf individuals, possibly within the context of music education.

Mogat (Zhou et al., 2012) is an ADMI-like tool in the form of three musical mobile games aimed at improving musical auditory skills for deaf children post Cochlear Implantation (CI participants). The mobile design was based on feedback from deaf children to understand their "deficiency" in terms of pitch, rhythm perception, and pitch production in contrast to non-deaf peers. The authors also proposed a user study with CI participants to demonstrate the effectiveness and efficiency of Mogat.

A new DMI proposed by Burn (2016) would enhance the musical experience for deaf musicians by using visual and haptic feedback systems to represent the components of sounds produced by DMIs, delivering a multi-sensory experience similar to that provided by acoustic instruments. Burn (2016) intends to design and evaluate the system together with deaf musicians.

Music aid (Søderberg et al., 2016) explores how music creation can occur collaboratively between deaf and hearing people. The overall goal of the research was to explore first, how to design an interface that would allow a deaf person to create music, and second, how this interface would support collaboration between hearing and deaf people. The authors propose the music interpretation and interaction through the visualization of sound along with haptic feedback. The design process relied on deaf and non-deaf people. Three alternative prototypes were developed to address the needs elicited from the design phase. These prototypes were then qualitatively evaluated in a controlled environment where non-deaf and partially deaf participants explored the prototypes by creating music together, followed by in-depth interviews with the two groups.

Duarte and Tavares (2017) present an ADMI implemented as a smartphone application with two options simulating piano or drums. The instruments are intended to allow the musician to have haptic and visual feedback from music in the context of music education. The instruments were evaluated with Deaf and hearing participants.

Wearable Musical Haptic Sleeves (Trivedi et al., 2019) are wearable haptic devices that deaf people can use to experience music. The devices are combined with a visualization system and can be controlled by an interface control. Deaf people are not included in the design and evaluation process.

Toc-Tum (Chaves et al., 2021) is an ADMI-like tool in the form of a virtual reality-based educational game accessible for deaf people. According to the authors, the system was "validated" in two different ways: (a) with the target audience to evaluate the interest in the game and (b) with people who have musical knowledge or who have had contact with the deaf, to assess the game's impact on musical instruction for deaf learners.

Smartphone Drum (Iijima et al., 2021) is a smartphone app that presents a vibrotactile sensation similar to that of a drum when the musician makes a drumming motion in the air with their smartphone as a drumstick. d/Deaf people are not included in the design process, but they are included in the evaluation process.

Cavdir and Wang (2022) present three wearable musical instruments (Bodyharp; Felt sound; and Touch, Listen, and (Re)Act) intended to deliver an embodied musical experience for diverse bodies. The instruments are developed according to an inclusive participatory design and performance practices to create more inclusive music performances. The Bodyharp does not rely on d/Deaf participants, while the Felt sound instrument includes them in the evaluation process, and the Touch, Listen, and (Re)Act includes them in both the design and evaluation.

In order to classify the ADMIs according to the medical, social, and cultural models, we analyzed the eleven ADMI papers, applying four criteria (Table 1). Table 3 classifies the ADMIs

3 In this section the terms "Deaf" and "deaf" are presented in the same way they appear in each paper analyzed.

TABLE 3 Classification of eleven ADMIs directed to deaf people according to the medical (M), social (S), and cultural (C) models of disability.

Date	Project name	User participation	Disability view	Inclusion view	Impact view
2012	Mórimo	No information	C	C	M and C
2012	Mogat	M	M	M	M
2016	No title (Burn, 2016)	C and M	C and S	C	C
2016	Music Aid	S	S	S	S and C
2016	No title (Duarte and Tavares, 2017)	M and C	S and M	M and S	S and C
2019	Wearable Musical Sleeves	M	M	M	M
2019	Toc-Tum	S and M	S, M, and C	S and M	S and M
2021	Smartphone Drum	M and S	M	M	M
2022	Bodyharp	M	C and M	C	C
2022	Felt Sound	C and M	C and M	C and M	C
2022	Touch, Listen, and (Re)Act	C, S, and M	C and M	C and M	C

TABLE 4 Occurrence and dominance (medical, social, and cultural models) for the 11 ADMIs analyzed.

	User participation (Occur./Dom.)	Disability view (Occur./Dom.)	Inclusion view (Occur./Dom.)	Impact view (Occur./Dom.)	Total (Occur./Dom.)
M	9/5	8/3	7/4	5/4	29/16
S	4/2	4/3	3/2	3/3	14/10
C	4/3	6/5	5/5	7/4	22/17

TABLE 5 Occurrence of combined models.

	User participation	Disability view	Inclusion view	Impact view	Total
C and M	2	3	2	0	7
S and M	1	1	1	1	4
M and S	1	0	1	0	2
M and C	1	0	0	1	2
S and C	0	0	0	2	2
C and S	0	1	0	0	1
S, M and C	0	1	0	0	1
C, S and M	1	0	0	0	1

according to our criteria, with a more frequent appearance of the medical model (M) than the other two models (S and C).

From Table 4, we can observe a greater occurrence of the medical model; however, when referring to dominance, we notice that these models present close numbers. This indicates that although the projects are considering different models, the medical model is the one with the highest occurrence in general, being present in practically all projects, except for Music Aid (Søderberg et al., 2016).

Interestingly, the data in Table 5 show that most combinations include M (83,3% of the total); however, M is not the dominant model for the majority of the combinations, indicating that the research projects are analyzing social and cultural aspects of disability, although they tend to recur to medical ideas at some point.

4. Discussion

The recurrence of the cultural model in Table 2 highlights the fact that the ADMIs analyzed rely on a few d/Deaf individuals as reference for their reflections about music and deafness. For example, the Felt Sound and Touch, Listen and (Re)Act projects consider and incorporate aspects of Deaf culture by investigating the use of sign language and consulting with d/Deaf people in the design process. Otherwise, most of the papers analyzed do not take into account the music movements within Deaf culture (Maler, 2015; Holmes, 2017) or elements of sign language (Maler, 2015; Best, 2016a).

The frequent occurrence of the medical model in our analysis is in line with Partesotti's argument of that most ADMI proposals limit their technology development to user needs that could be incorporated in the design (Partesotti et al., 2018). Such an

approach can be compared to medical treatment models that disregard cultural and social elements associated with different types of disabilities (Lucas et al., 2020). However, our classification criteria allow us to observe that in our sample, ADMIs also consider sociocultural aspects of disabilities, even if these aspects are not prevalent. Thus, our criteria facilitate our understanding of how different disability approaches are distributed in the ADMI design process, sometimes combined, as shown in Table 5, and other times characterized by the frequency of their occurrence, as shown in Table 4. In this way, our framework allows us to consider and measure the occurrence of the three models and to reflect on their impact on each ADMI.

The combination of different models can be a way to keep ADMI design open to different perspectives and promote participation according to different musicians needs. The social and cultural models may give disabled musicians an active voice in the ADMI design process by advocating the active participation of disabled people in issues that concern them. We observed that the cultural model is predominant in the three most recent ADMIs analyzed, but it still lags behind the medical model overall, as we can see with the other eight ADMIs (Table 3). We also observed that the ADMIs that use the social and cultural model give special attention to the participation of disabled individuals in the design process.

Frid (2019a) points out some key concepts for the success of ADMIs, including adaptability and customization, iterative prototyping, user participation, and interdisciplinary development teams. The author also argues for the huge potential of the field to diversify and for ADMIs to benefit larger groups of disabled musicians. These outcomes could be achieved by implementing more advanced sensing technologies and gesture acquisition, incorporating vibrotactile feedback, exploring more diverse sound synthesis methods, and using more diverse mapping strategies (Frid, 2019a). However, this process does not guarantee the promotion of inclusion and diversity. Discussions of diversity and inclusion in computer music should consider the users and developers of these technologies, as well as who has access to technology (Frid, 2019b).

Frid and Ilsar (2021) highlight the importance of disabled musicians to build their own custom instruments – instruments designed by disabled musicians for disabled musicians. However, we note that the works reviewed here, with the exception of Cavdir and Wang (2022), either neglect to provide space for opinions of disabled people or do not clearly mention the use of participatory methods intended to include them in the ADMI design process. In the next two paragraphs, we discuss participatory research methods and technology in the hope of providing new ways to think about participatory approaches in ADMI design.

The literature further highlights some initiatives intended to promote participatory technology design. For instance, Parke-Wolfe et al. (2019) encourage the development of instrument-building toolkits, showing that disabled people, music teachers, and music therapists are capable of ingenious instrument designs when they can access the right tools. The re-use of high-quality modular technical resources will likely facilitate the development of bespoke Accessible Music Technology (AMT). Following a modular structure in hardware, software, and coding procedures can make it easier to fix, update, and expand DMIs (Lucas et al., 2020). These sensing devices can be used to control completely different types of parameters or detect different movements, enabling the control of different musical functions through a mapping strategy (Marshall et al., 2009).

As evidenced in the literature, the design of ADMIs should remain open to a diverse range of perspectives and preferences (Wright, 2020). Some studies, such as Förster et al. (2020) and Lucas et al. (2021), propose participatory ADMI design and emphasize the importance of approaches that take sociocultural aspects of music into account. Incorporating the the views of disabled people is a vital part of the ADMI design process (Frid, 2019b). The use of participatory design methods significantly helps to enable inclusive sonic interaction through the design of custom instruments (Frid, 2019b). For instance, action-research methodologies promote the autonomy of disabled people and balance the relations of power between investigators and participants in the research process. Ward (2023) presents a modular toolkit that illustrates use of participatory and iterative methods to address the issue of accessibility to music-making with music technology. McMillan and Morreale (2023) argue that the incorporation of lived and cultural aspects related to the experiences of disabled musicians can lead to more effective and personalized instrument design. Also, Lindetorp et al. (2023) highlight the importance of ADMIs in music performances facilitated by assistants.

The term "action research" covers a diverse range of approaches to research, aiming to change social practices and make research more productive, sustainable, just, and inclusive (Kemmis et al., 2014). These approaches have the potential to promote the autonomy of disabled people in the ADMI development and design processes once action research recognizes that (1) people in particular settings are capable of participating actively in all aspects of the research process and (2) participants have special access to how social and educational life are conducted in their surroundings. Therefore, these approaches can lead to research directed at making improvements in practices and participant settings (Kemmis et al., 2014). Action-research methodologies (Kemmis et al., 2014) can also play an important role in ADMI design, development, and evaluation. These methodologies could potentially be used to ensure the active participation of disabled people in the process of ADMI design. A primary concern of action research is to recognize research participants as capable of engaging actively in all aspects of the research process and value participants as "insiders" who have privileged access to the functioning and social rules of their settings (Kemmis et al., 2014).

In action research, the investigator can play the role of an outside consultant who can provide valuable support to participant researchers when it is useful. The outside consultants do not need to be members of a community undertaking an action research initiative, but can become engaged participants alongside "insiders" as long as they remain critically alert to differentiate their own self-interests from those of other participants (Kemmis et al., 2014). As Frid (2019b) states, such an approach can be useful in ADMI research, as the quality of ADMIs can be improved by incorporating the views of disabled people (insiders) and working in multidisciplinary teams, including engineers, interaction designers, music teachers and so on (outside consultants).

Finally, the recent increase of available computational resources, miniaturization, and sensors further enables the

development of ADMIs that use non-conventional interaction paradigms and interfaces, opening up new opportunities for inclusion by accommodating bodily differences, and valuing multiple ways of sensory accessibility (Davanzo and Avanzini, 2020). Sensors associated with computing elements can be used to capture and process gestures, expanding the range of possibilities for computer music instruments (Wessel and Wright, 2002). The introduction of new instruments or the adaptation of existing ones can be an opportunity to transform musical cultures and contribute to shifts in listening modes (Pinch and Bijsterveld, 2004).

5. Conclusion

The criteria proposed in this paper allowed the researchers to identify a lack of participatory approaches and an overall tendency toward the medical model of disability for the eleven surveyed ADMIs. Our analysis indicates that participants do not have room for active participation in the research process and that most research does not consider the social and cultural aspects related to disabilities and music. Indeed, most of the studies based on the medical model did not include disabled people in the research process, unlike studies focused on the social and cultural models, which generally included disabled people.

Our chosen criteria allowed the analysis of 11 ADMIs according to the medical, social, and cultural models of disability. Our criteria also enabled the observation of different models across the data analyzed and the potential impact of the different disability models on the ADMI design process. The approach proposed here brings several benefits to the ADMI field: 1) it provides a way to introduce researchers to different disability models in the context of music and technology; 2) by classifying ADMI papers according to the medical, social, and cultural models of disability, it increases ADMI researchers awareness of different models of disability; 3) by considering technology outside of the medical context, it generates insights for the design of new ADMIs through different approaches to disabilities and different perspectives on disabled people participation, inclusion, and evaluation. Our study also emphasizes the importance of participatory methodologies and the value of disability as a source of cultural diversity that can impact the development of new ADMIs.

Our use of the proposed criteria demonstrates the insights that researchers can gain from applying our framework. Our analysis allowed the classification of the selected ADMIs, confirming the medical model as the most frequent approach, while further showing the continued influence of the social and cultural models, either in combination or individually. Our method thus provided a way to examine previous studies and reflect on them from different perspectives, opening up opportunities for more inclusive, comprehensive, and diverse ADMI developments in the future.

The criteria proposed here can help researchers reflect on previous and future projects and designs through the lens of different disability models. The criteria contribute to the field by providing insights about the development of inclusive technology under different perspectives on disability and by valuing disability as a source of sociocultural diversity to be considered in the ADMI design process.

Although our criteria encourage the understanding of ADMI design from different disability perspectives, our analysis of a limited data set of instruments (eleven) minimizes the potential for generalizations. Most of the ADMIs analyzed here do not allow the participants to engage actively in all aspects of the research process. Usually, the participants are consulted after the design process is finished. Their roles are restricted to answering questionnaires about their experience with the instruments, or performing activities that outsiders have designed to evaluate how the ADMIs can address their needs. These processes do not allow participants to have an active role in the design of the instruments or the activities. We addressed these issue by arguing about the potential impact of action research on the ADMI design process. The use of such approaches would allow the collaboration between disabled participants and engineers or music teachers, while keeping participants needs and preferences in the foreground.

We hope that our study will help to connect music technology researchers with the literature related to modern conceptions of disability, helping to develop frameworks that look to find solutions from multiple disability perspectives and leading researchers to reflect on the importance of developing a literacy of disability models, stating and discussing the model they adhere to in their research. Our contribution is intended to promote ADMI design that goes beyond physiological needs related to the medical model, considers social and cultural aspects related to disabilities, and thinks about disability more deeply.

A natural progression of this work is to consult with the designers of the ADMIs analyzed to discuss how our approach impacts their critical reflections on their work. A further study could evaluate the implications of applying the proposed criteria to analyse ADMIs targeting participants other than d/Deaf individuals as well as to help develop new ADMIs.

Data availability statement

The data supporting this research can be found in the nine articles mentioned in Section 3, further inquiries can be directed to the corresponding author.

Author contributions

ED proposed the concept for the article. All the authors discussed the article content, structure and research results. ED wrote the manuscript with the support from IC and MW. All authors contributed to the final manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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