A Dimension Space for the Evaluation of Accessible Digital Musical Instruments

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ABSTRACT

Research on Accessible Digital Musical Instruments (ADMIs) has received growing attention over the past decades, carving out an increasingly large space in the literature. Despite the recent publication of state-of-the-art review works, there are still few systematic studies on ADMIs design analysis. In this paper we propose a formal tool to explore the main design aspects of ADMIs based on Dimension Space Analysis, a well established methodology in the NIME literature which allows to generate an effective visual representation of the design space. We therefore propose a set of relevant dimensions, which are based both on categories proposed in recent works in the research context, and on original contributions. We then proceed to demonstrate its applicability by selecting a set of relevant case studies, and analyzing a sample set of ADMIs found in the literature.

Author Keywords

Dimension Space, Analysis, Design, ADMI

CCS Concepts

•Applied computing → Sound and music computing; •Social and professional topics → People with disabilities;

1. INTRODUCTION

Digital musical instruments (DMI) have the potential for augmented accessibility with respect to traditional ones. Thanks to the exponential increase of computational power, miniaturization, and available sensors, research on DMIs has expanded during the last two decades [16] into the use of non-conventional interaction paradigms, interfaces and physical channels.

The term "accessible DMIs" (ADMIs) is often used to refer to instruments designed for persons with disabilities. The terms "assistive music technologies" [8] and "adaptive music technologies" [9] have also been used. All these definitions bring about slightly different meanings. The word "assistive" implies an external source (technology) that provides aid to a person with disabilities to complete a task (e.g., TTS can help a visually-impaired user to read a text). In contrast, the word "adaptive" emphasizes the ability of the instrument to adjust to the context and to the situation of the musician. In the remainder of this paper we use the term ADMI, in order to emphasize aspects related to inclusion and universal design. Nonetheless, the concept of adaptability remains a central property of accessible instruments, as discussed next.

ADMIs and related works in the context of accessible interfaces have carved out an important niche within the literature, including NIME (some recent examples are provided by [35, 19, 24, 21]). As indicated by Frid [8] in her review work, several initiatives and charity organizations focusing on these topics were born in recent years, as well as several companies producing ADMIs and having inclusive music practices at the core of their mission.

Accessible instruments are designed and created for different contexts, health conditions, and impairments. The benefits of providing access to music to persons with disabilities have been discussed in many of the works mentioned above, and include rehabilitation, social inclusion, personal expression, physical and psychological wellbeing. Cappelen and Anderson [4] refer to the ensemble of activities enabled by music access through the word "musicking", originally coined by Small [33, 4]) to subsume all the activities related to music.

Despite the publication of studies dedicated reviewing the state-of-the-art of ADMIs [8, 19, 9, 25], there is still a lack of contributions towards a systematic analysis of the most important dimensions of their design. As an example, Frid [8] categorizes instrument reviewed in her work in terms of control interface type (tangibles, wearables, gaze-based, etc.), for the purpose of making statistics on the literature.

The goal of this paper is to contribute to the advancement of this research direction by proposing a more comprehensive framework for evaluating and classifying a broad range of ADMIs. In doing so, we discuss a set of relevant requirements and design choices for this class of instruments. Section 2 presents the chosen analysis framework (dimension space analysis) and proposes a dimension space specifically devoted to ADMIs. Section 3 and 4 discuss the dimensions associated to the proposed space. Finally, Sec. 5 presents a small set of case studies, that help exemplifying the applicability of the proposed framework to existing ADMIs.

2. PROPOSED DIMENSION SPACE

Several approaches have been proposed to classify and evaluate the main design aspects of a broad range of "musical devices" (musical instruments, interactive installations, games, and so on) [34, 28, 30]). Among them, the dimension space analysis proposed by Birnbaum *et al.* [1] is particularly appealing both for its applicability to a variety of

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NIME'20, July 21-25, 2020, Royal Birmingham Conservatoire, Birmingham City University, Birmingham, United Kingdom.

contexts and for the effectiveness of dimension plots, which allow to visualize and rapidly compare musical devices along a set of design dimensions.

Birnbaum empirically observed that the functionality of a space is not affected in plots with as many as eight axes, and proposed seven dimensions for analyzing musical devices in their broadest meaning: Required Expertise, representing the level of practice of the performer; Musical Control, specifying the level of musical control exerted by the performer; Degrees of Freedom, indicating the number of input controls available to a user; Feedback Modalities, specifying the degree to which a system provides real-time feedback; Inter-actors, representing the number of people involved in the musical interaction; Distribution in Space, indicating the total physical area in which the interaction takes place; Role of Sound, representing the category of sound role (with three main values: artistic/expressive, environmental, and informational).

The flexibility of the dimension space approach lies in the ability to redefine the axes. In fact, alternative representations have been proposed: Magnusson [22] presented an "epistemic" dimension space, as opposed to the more "phenomenological" Birnbaum space. Some other authors proposed more specialized spaces, aimed at evaluating specific categories of musical devices: Hattwick and Wanderley [12] presented a dimension space for evaluating collaborative music performance systems. In a similar fashion, Hödl and Fitzpatrick [13] targeted hand-controlled guitar effects for live music and described a related design space.

Following these examples, here we resort to the dimension space analysis approach to propose a new space dedicated to ADMIs. The aim of this effort is to reflect on the dimensions that define their design space and to offer a tool for labeling, discussing, and evaluating such instruments. As such, the proposed space is not intended as an alternative representation to the one designed by Birnbaum, but rather as a finer layer of description devoted to a specific class of instruments. Therefore, a complete description of a single ADMI could be obtained by classifying it both along the seven-axis Birnbaum space and along the eight-axis space proposed in this work. The two descriptions are complementary, as discussed in the remainder of the paper.

The eight-axis configuration resulting from our analysis is shown in Fig. 1. The eight axes can be conceptually grouped into two subsets: the four axes in the lower part of the plot (labeled in blue) relate to the intended target users and to the use contexts of the instrument, while those in the upper part of the plot (labeled in green) are related to the design choices of the instrument. These groups reflect two distinct phases of the design of an ADMI, where the first one is more related to preliminary definition of requirements, and the second one is concerned with subsequent choices in the design. We discuss these two subset of axes in Secs. 3 and 4, respectively.

3. TARGET USERS AND USE CONTEXTS

In this section we discuss the four axes in the lower half of the proposed dimension space (see Fig. 1).

Disability is a "complex multidimensional experience" [38] which poses challenges for measurement and classification. In the "International Classification of Functioning, Disability and Health" (ICF) [37], the World Health Organization categorizes problems with human functioning in three interconnected areas: *impairments* are problems in body function or alterations in body structure, and are often identified as symptoms or signs of health conditions; *activity limitations* are difficulties in executing specific activities; *participation restrictions* are problems with involvement in any area of life. *Disability* refers to difficulties encountered in any or all these three areas of functioning.

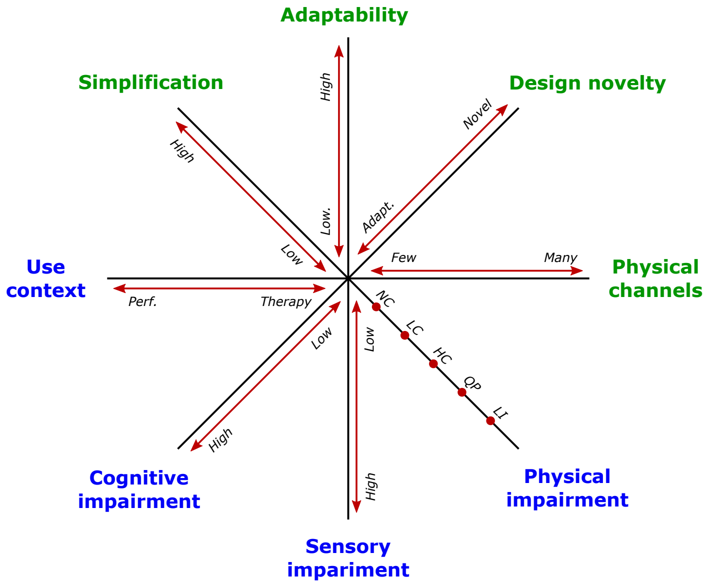


Figure 1: A visual representation of the proposed dimension space. Axes are grouped in two subsets: *Target users and use contexts* (blue), and *Design choices* (green).

The Washington Group on Disability Statistics [38, p.26], an international, consultative group of experts aimed at facilitating the measurement of disability, applies an ICF-based approach which covers six functional domains or basic actions: seeing, hearing, mobility, cognition, self-care, and communication.

In the context of human-computer interfaces, Jacko *et al.* [31, Ch.43] proposed a conceptual scheme aimed at defining categories of impairments and their relation to the use of interactive technologies. Specifically the authors considered five broad categories: (a) hearing impairments, (b) mental impairments, (c) physical impairments, (d) speech impairments, and (e) visual impairments. Each is composed of a collection of related clinical diagnoses which, in turn, influence certain functional capabilities that are critical to accessing specific classes of technologies.

For the purposes of this work, categories of impairments are further clustered into three main axes: physical, cognitive, sensory (or perceptual). These three broad categories are often employed in the literature of accessible HCI [31, Ch.41-44]. Previous reviews on ADMIs [8, 25, 20] suggest that target user groups can be classified into these three categories. Moreover, the multidimensional character of disability also means that physical, sensory, and cognitive impairments are often intertwined.

Usually, ADMIs aimed at musicians with **physical impairment** are designed to address a specific degree of motor ability. With a handful of exceptions (the harmonica, the kazoo, and possibly a few more), traditional musical instruments include upper limbs (hands and fingers in particular) among their physical interaction channels, with the possible addition of the feet (used for example to control pedals and foot switches), and breath. Consequently, this axis indicates the level of motor impairment addressed by the instrument along a discrete scale of five points, each representing the minimum motor skill level required by the instrument. The rationale behind this classification is that instruments devoted to higher levels of impairment can potentially be used also for lower levels of impairment. The proposed levels are as follows (see Sears *et al.* [31, Ch. 42] for an overview of related health conditions and traumas):

1. *Uncompromised motor skills (NC)* - Includes instruments dedicated to fully motor skilled users, therefore aimed at other types of impairments.
2. *Lightly compromised motor skills (LC)* - Includes instruments for users who do not have full control of (or have difficulty controlling) limbs. This could be given by cerebral palsy, heart attack, and other conditions.
3. *Heavily compromised motor skills (HC)* - Includes instruments dedicated to people who have at least one limb completely compromised, unable (or almost completely unable) to move. DMIs dedicated to users with situations such as hemiplegic paralysis or paraplegia belong to this category.
4. *Quadriplegic paralysis (QP)* - Includes instruments dedicated to people who no longer control upper and lower limbs. These instruments can take advantage of interaction channels available from the neck upwards (face muscles tension, gaze, brain frequencies, breath, etc.) [5].
5. *Lock-in syndrome (LI)* - This is a condition in which a person is awake and conscious but can only move his eyes. This category includes instruments that use only eye based interaction (e.g. gaze-based or blink-based), or electroencephalogram (EEG) based interaction.

Frid [8] remarks that a very limited amount of existing ADMIs are specifically designed for users with **sensory impairments**. As an example, only 3.6% of the 83 instruments reviewed in her work focused on persons with visual impairments, while 6.0% focused on persons with hearing impairments. This is therefore a research direction that needs to be further explored. The corresponding axis in the proposed dimension space indicates the level of sensory impairment addressed by the instrument. Unlike the physical impairment axis, this is a continuous axis ranging in value from low to high levels of impairment. The reason for this choice is that different or multiple types of sensory impairments may be addressed, which makes impossible to define a unique discrete scale of levels.

The **cognitive impairment** axis may include several different target groups, such as children with special educational needs (SEN), learning and developmental difficulties, behavioral disorders, autism spectrum disorder (ASD), as well as elderly people with aging-related losses of cognitive abilities, and persons with severe intellectual deficits lacking conceptual and/or communication skills. In the literature, reference is often made to four levels of intellectual impairment (mild, moderate, severe, profound) [2, 14, 26], ranging from situations in which the person is able to learn practical skills and communicate, to scenarios in which the person does not have any degree of autonomy and independence. However these categories are not easily related to musical abilities: for this reason, in the proposed dimension space this is a continuous axis ranging in value from low to high levels of impairment.

The fourth and last axis in the lower half of the proposed dimension space is related to the **use context** for which the instrument is intended. Regardless of the type(s) of impairment of the target users, defining the context of use influences all the subsequent design choices. Harrison and McPherson [11] make a distinction between two broad categories of ADMIs. On one side, "therapeutic devices" are meant to provide a means for persons with disabilities to enjoy the health, social and psychological benefits of music making, demonstrated by music therapy practices. Instruments in this class often have a low-barrier to expressive music making, and work particularly well in group music workshop contexts, or as part of music therapy sessions. On the other hand, the category of "performance-focused instruments" refers to instruments which allow the performer to reach high levels of expression and virtuosity, similarly to traditional instruments for able-bodied performers. Instruments in this category often require larger amounts of practice and are particularly suited for inclusive music performance contexts, such as orchestras accessible to performers with disabilities.

It has to be noted that therapy and performance are not mutually exclusive use contexts and may co-exist in the design of an ADMI. Therefore, in the proposed dimension space **use context** is a continuous axis ranging in value from therapy to performance, depending on the aims of the instrument.

4. DESIGN CHOICES

Having defined the potential target groups and the use contexts of the instrument, the remaining dimensions relate to fundamental choices in the design of the ADMI. These can strengthen some aspects of inclusion rather than others, influencing the accessible qualities of the instrument. By analyzing previous works in the literature, we extracted four dimensions of design which are especially relevant for accessibility. These are represented in the upper half of the proposed dimension space (see Fig. 1) and are discussed next.

Adaptability has long become a key concept in the field of accessible HCI. When designing for persons with disabilities, every user has different and individual requirements and needs, and adaptive interfaces have the potential for accommodating a wide range of users. Jacko *et al.* [31, Ch.43] discuss several adaptive interfaces in the context of sensory impairments. An analysis of the ADMI literature shows that existing instruments generally allow for limited adaptability to the specific needs of an individual user. Thus, this remains one of the ultimate challenges in this context, as acknowledged by various scholars [8, 19, 6]. Some instruments may include the possibility of customizing parts of the interface and instrumental features. However a deeper form of adaptability should be based on user models with respect to their abilities and should consequently include the possibility of modifying the interface, the employed interaction channels, and the musical mappings. An emerging trend amounts to using interactive machine learning techniques in order for an instrument to learn preferred or idiosyncratic gestures of an individual user, and to map the learned gestures to musical parameters. A notable related example is the Wekinator software [7], in which various supervised machine learning approaches are used to build musical mappings through training examples. Interestingly, this sofware has been used in a recent project aimed at building customized musical rehabilitation devices for children with severe motor impairments [17].

Regarding the **design novelty** of the instrument, a distinction can be drawn between instruments that are designed from scratch having persons with disabilities as target users, and adaptations of existing instruments. The definition "adapted instrument" is often used to refer to a modification of a traditional or pre-existing instrument, obtained through either mechanical, electroacoustic, or digital means: in this case the focus is thus shifted towards the "assistive" facet of technology. On the other hand, in the case of completely novel instruments the focus is shifted towards the "accessible" facet of technology, which calls for cyclical, participatory design approaches that only recently started to enter the mainstream of DMI research [23]. Similarly to some of the axes discussed above, there is a continuum of possibilities in between these two dichotomic alternatives. As an example ADMIs employing existing control metaphors (e.g., the piano keyboard) may be assigned an intermediate rank along this axis. Tending towards one of the two extremes of this axis depends on the target users and contexts of use. Although a completely novel interface may possibly better accommodate the necessities of persons with disabilities, offering the possibility to play a traditional instrument may provide an added value for inclusive music practices.

The usability and the expressivity of the instrument are largely affected by the amount of **physical channels** that the user can employ in the interaction. This axis thus relates to the number of motor skills needed by the user. Examples are finger movements, breath, EEG features, head movements, gaze pointing, etc. These in turn are related to the types and levels of impairments, especially physical ones, but also sensory and cognitive ones. This axis has some relation with the "Degrees of Freedom" dimension indicated in the space for generic musical devices. However, that axis indicates the "number of input controls" and is thus focused on the sound production unit of the instrument; on the other hand, this axis shifts the focus to the perspective of the users and their functioning.

The fourth and last axis in the lower half of the proposed dimension space is related to the degree of **simplification** designed into the instrument. The word "simplification" in this context is once more borrowed from the literature of accessible HCI, where it is often used to refer to simplified interfaces aimed at reducing the cognitive load and/or simplifying motor actions required to complete a task [31, Ch.23]. However, here we use this term in a wider sense: the degree of simplification of an ADMI along this axis refers to all the aspects of the instrument design aimed at aiding the user in completing musical tasks. These may include enlarging of elements of the visual interface, but also temporal quantization of musical events to compensate for rhythmic difficulties, simplified gestures to play chords or arpeggios, etc. Related concepts have been investigated in the context of DMIs for novices and non-musicians (beginning with the "low entry fee with no ceiling on virtuosity" claim by Wessel and Wright [36]), and are discussed by McPherson *et al.* [25]. Correspondingly, the Birnbaum space includes the dimension "Required expertise". Here, however, the focus is not on user expertise, but rather on user abilities and on the related design simplifications aimed at providing an engaging and rewarding experience.

As a final remark, it has to be noted that the **adaptability** axis plays a special role in the definition of the space, as it can affect the remaining dimensions related to design choices. As an example, a high level of adaptability may imply that the instrument can address various levels of physical impairments, or be equally suited to music therapy contexts and to performance contexts through ad-hoc setup changes, and so on. Therefore, in the case of an instrument with high *adaptability* it would be recommended to classify it according to the most common use case, or provide a judgment that reflects the maximum level attained for a given axis.

5. CASE STUDIES

In this section we review 8 ADMIs, including academic projects, commercial products, and non-academic projects funded through charity programs. All the chosen instruments appear in at least one recent reviews of ADMIs [8, 25, 20, 5]. The purpose is to demonstrate the applicability of the proposed space to the analysis of existing instruments, and to provide further discussion on its dimensions.

Figure 2 presents the visualization of the ADMIs in the dimension space. The plots show that each of the reviewed instruments scores extreme (high or low) values along at least one axis. In fact, each instrument has been chosen because it is especially relevant to discuss at least one of the 8 dimensions.

Examples of ADMIs focused on *physical impairments* abound in the literature. Miranda and coworkers developed several Brain-Computer Music Interfaces (BCMI). One in particular [27] (Fig. 2a) was specifically designed for users with severe motor impairments, and was tested with a patient with Locked-in Syndrome. The instrument allows for real-time generation of melodic lines through a reactive brain-computer interface based on steady-state visual evoked potentials (SSVEPs).

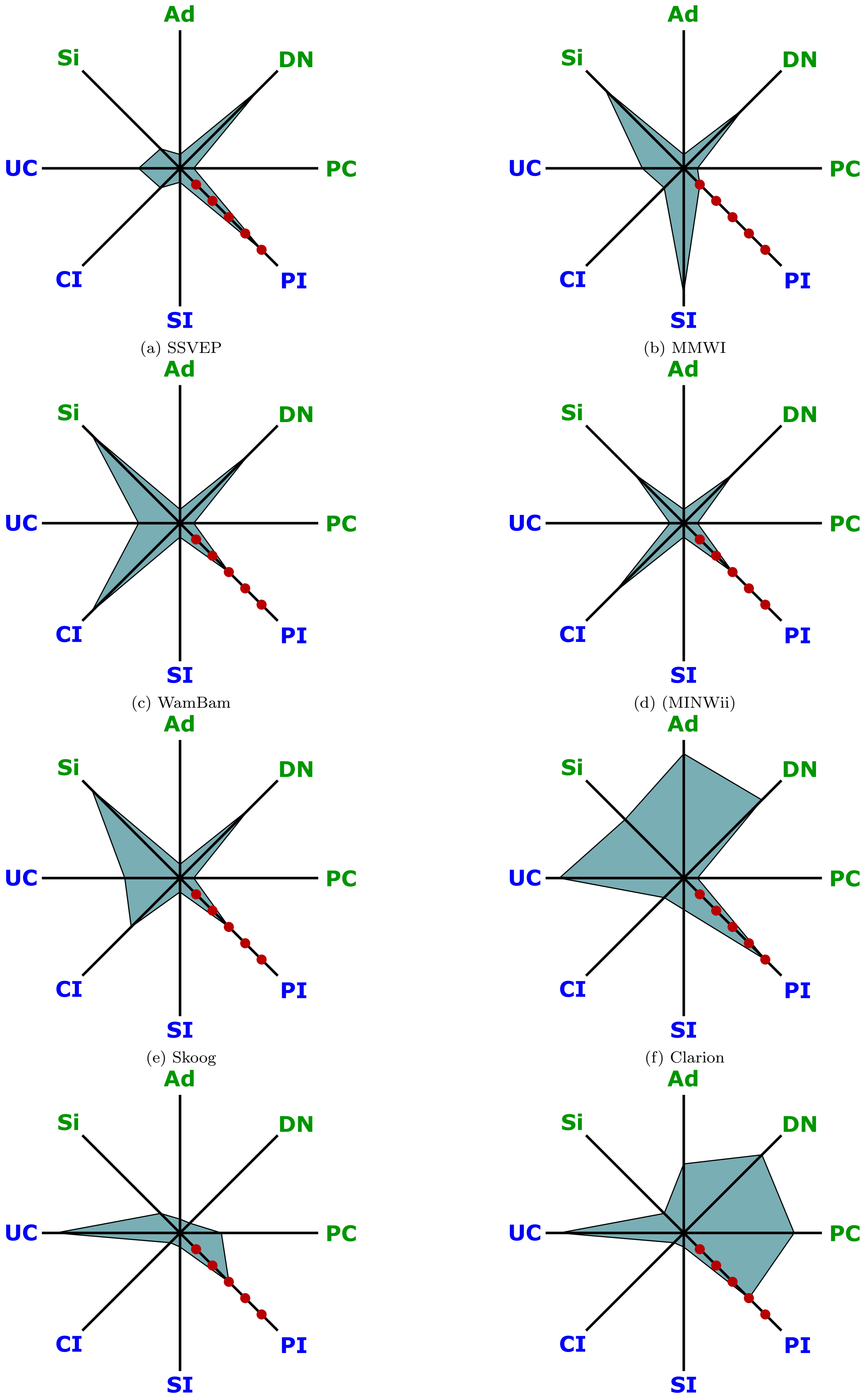
In contrast to the above, as already discussed, relatively little work has been done regarding instruments for persons with *sensory impairments*. One interesting example is provided by Grierson [10], who developed an interactive audiovisual performance system for hearing impaired persons ("Making Music With Images", MMWI hereafter, Fig. 2b). The system visualizes sound in real-time to allow hearing impaired individuals to interact with an experiential representation of sound. The author foresees its use in rehabilitation mainly, but collaborative performance are also considered as a possible use context.

One notable example with a strong focus on *cognitive impairments* is provided by WamBam [15] (Fig. 2c). This is a self-contained electronic hand-drum meant for severely intellectually disabled users. It is shaped as a dome made of various soft pads with different colors and textures, which provide acoustic and vibrotactile feedback when touched. The authors foresee applications in music therapy sessions mainly, but discuss potential uses also in the context of musical performance.

Unlike the previous instruments, the MINWii project [3] (Fig. 2d) is conceived and designed exclusively as a *therapeutic instrument*. It is a music game which lets players improvise or play songs by pointing at a virtual keyboard with color-coded keys, using a Wiimote Pistol. Different implementations of the system were used both with children suffering from behavioral disorders and with elderly patients suffering from mild to moderately severe Alzheimer's disease, also taking into account possible related motor impairments.

The Skoog [32] (Fig. 2e) is a commercial DMI which is presented as a "tactile instrument" and consists of tangible interface that can be paired with a compatible mobile device. The interaction metaphor is loosely based on a drum instrument, and provides an example of extreme *simplification*, as potentially complex musical events are produced by pressing on one of five colour-coded buttons. The instrument is said to be used both for performance and therapy, in particular it is used with children with SEN and ASD, as well as individuals with physical impairments.

One of the few examples of ADMIs with a high degree of *adaptability* is provided by the Clarion [29] (Fig. 2f). This is an instrument developed through a long-term charity pro-



(a) SSVEP

(b) MMWI

(c) WamBam

(d) (MINWii)

(e) Skoog

(f) Clarion

(g) Augmented Bass

(h) Biomuse

Figure 2: Dimension space analysis of the reviewed ADMIs.

gram, with the goal of allowing performers with physical impairments to play in an orchestra. It has a strong emphasis on participatory design, interface adaptability to individual needs, and exploitation of off-the shelf assistive technologies used by persons with disabilities in their everyday lives. It can use various alternative physical channels, including gaze pointing and head movements, depending on the type and level of individual impairment, but can also be played with the fingers or the feet.

Harrison and McPherson [11] present a system for adapting the bass guitar for one-handed musicians (Fig. 2g). Possibly not a DMI in a strict sense, this may be regarded as an assistive technology that enables bass guitar playing by performers users with upper-limb impairments. Specifically, it enables MIDI-controlled actuated fretting via a foot pedal control. As such, this project provides a notable example of an adapted traditional instrument along the *Design Novelty* dimension.

BioMuse [18] (Fig. 2h) is a pioneering project which underwent several implementations, all having at their core a HW/SW developed specifically to collect electroencephalographic, electrooculographic, and electromyographic signals from a large number of *physical channels*. These are then processed to extract a set of relevant features and map those to MIDI events. BioMuse has been used to augment traditional musical instrument performance or as a stand-alone DMI, in the latter case being suitable also for performers with physical impairments.

6. CONCLUSIONS

We have shown a possible dimension space for ADMIs design analysis, demonstrating its descriptive potential through the analysis of some state-of-the-art instruments.

There is often little information about the availability of technologies in disability related contexts. In addition to being a conceptual design tool, the dimension space we propose could prove to be a classification and categorization aid suitable for searching in catalogs. Assuming to search an instrument suitable for a specific musician's condition into a database of classified ADMIs, the system could allow quick access to a list of proper instruments.

However, the system we propose certainly has limitations in the field of classification: it does not reflect all the possible parameters and all the ADMI classification systems presented in past literature, nor does it provide a complete definition of ADMI design choices. There are some highly categorical variables (e.g. related to sensors choice) that can hardly be inserted in a web chart like this.

Future works could be aimed at using this system in new case studies to verify its efficiency, as well as cataloging new instruments to highlight other design trends within the literature. New works about the relationship between impairments and musical abilities could lead to a better definition of the three axes *Cognitive impairment, Perceptual impairment* and *Physical impairment*, or to their discretization.

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