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# Interactive Sonification to Assist Children with Autism During Motor Therapeutic Interventions

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# Interactive sonification to assist children with autism during motor therapeutic interventions

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# Abstract

Interactive sonification is an effective tool used to guide individuals when practicing movements. Little research has shown the use of interactive sonification in supporting motor therapeutic interventions for children with autism who exhibit motor impairments. The goal of this research is to study if children with autism understand the use of interactive sonification during motor therapeutic interventions, its potential impact of interactive sonification in the development of motor skills in children with autism, and the feasibility of using it in specialized schools for children with autism. We conducted two deployment studies in Mexico using Go-with-the-Flow, a framework to sonify movements previously developed for chronic pain rehabilitation. In the first study, six children with autism were asked to perform the forward reach and lateral upper-limb exercises while listening to three different sound structures (i.e., one discrete and two continuous sounds). Results showed that children with autism exhibit awareness about the sonification of their movements and engage with the sonification. We then adapted the sonifications based on the results of the first study, for motor therapy of children with autism. In the next study, nine children with autism were asked to perform upper-limb lateral, cross-lateral, and push movements while listening to five different sound structures (i.e., three discrete and two continues) designed to sonify the movements. Results showed that discrete sound structures engage the children in the performance of upper-limb movements and increase their ability to perform the movements correctly. We finally propose design considerations that could guide the design of projects related to interactive sonification

**Keywords:** Interactive Sonification, Autism, Motor Therapeutic Intervention, Children

# 1 Introduction

Worldwide, autism is estimated to affect 1 in 59 children [1]. In Mexico, the incidence of autism in children in 2016 was 1 in 115 [2]. Autism is a neurodevelopmental disorder associated with impairments in attention, social interaction, and behavior [3]. According to the DSM-V [3], the severity of the impairments determines the autism level of function, ranging from mild to severe. Motor problems are more frequent and challenging for children with autism that is severe in comparison to those with mild and low autism [4].

Impairments in motor development in individuals with autism (severe) include motor stereotypies (e.g., hand and finger mannerisms, body rocking and arms flapping) [3], gait abnormalities, and significant motor coordination problems [5, 6] (e.g., limited motor control, poor upper, and lower limb coordination). Consequently, children with autism often appear to be clumsy and execute aimless movements (i.e., by guiding their movement in the wrong or vague direction with imprecise aim) [7]. Several studies have found motor deficiencies in strength [8, 9] and posture [10–12] in children with autism by using sensing technologies that allow capturing children's motor patterns. Examples of sensing technologies are tablets [8], elastic displays [9], and robots [10–12]. Motor development is essential for children to conduct self-care activities independently.

Motor therapeutic interventions might help children with autism to improve their motor skills. These therapies heavily rely on the practice and continuous repetition of specific motor movements [13]. For example, during a motor therapeutic intervention for upper-limb movements, patients with autism have to conduct several repetitions of the lateral, push, and cross-lateral movements (Table 1). Then, children must redirect their limb movements from an initial position to a specific target[1] while following the predefined movement trajectory — in other words, they must complete these movements with an appropriate aim; this is, aimed movement [14].

Conducting a successful motor therapeutic intervention is not an easy task since children with autism find task-repetition, required during a motor therapy, very tedious, and not rewarding; this leads them to disengage from therapy tasks before the goals of the motor therapy are met [15]. Further, due to their motor coordination impairments and attention problems, children with autism spend a considerable amount of therapy time practicing aimless movements [16]. Thus, it is critical to find ways to ensure adherence to the therapy and make the movement practice more effective.

In Mexico, institutions with early intervention programs for children with autism exist, but they are insufficient or unaffordable. Moreover, limited knowledge on how children with autism interact with ubiquitous technologies imposes new challenges, including the lack of technology-savvy staff and "anytime and anywhere" access to technology. For this reason, it is crucial to design cost-effective and "easy to use" solutions to support motor therapy interventions in developing countries. There is also little research into how the context of use and sociotechnical characteristics of a developing country with low-income users like Mexico might shape the design and evaluation of such technologies.

An emerging approach for improving motor therapeutic interventions is the use of interactive sonification or the use of sound within a human-computer interface where the auditory signal provides information about data or activity [17]. Interactive sonification provides real-time auditory feedback to guide and increase patients' awareness of their movement execution [18–23] and usually does not require sophisticated technology; this can make them suitable for developing countries such as those in Latin America. Sonification has been used in previous research for directing and motivating movement or physical activity, but sound models used in previous research were not designed to encourage children with autism to engage with the practicing of upper-limb movements [18, 20, 21, 24–27].

In this paper, we aim to provide the basis for developing sonification technology to increase adherence to therapy for children with autism by providing a more efficient and engaging space for motor training, taking

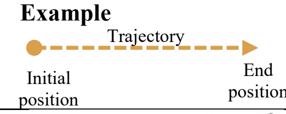
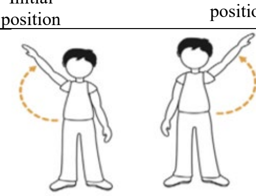
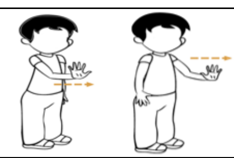
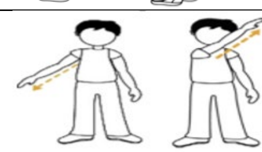
[1] Henceforth, we will use the term anchor point to refer to the target points of the movement. For example, the initial position and the end position of the movement.

into account the context of use in developing countries. For this, we conducted two studies to understand the needs of children with autism in a school-clinic in the Northwest of Mexico. The first study aims to understand if children with autism exhibit awareness of the sonification of their movements, and the second one explores the potential motor impact of different sound structures in the movements of children with autism. When working with children, some authors have emphasized the importance of using high-fidelity prototypes to better understand their needs [28, 29]. High fidelity prototypes get a more realistic picture of how children are going to use the prototype, are more engaging, and reduce the risk of misinterpreting design recommendations [30]. Therefore, we adopted and refined the Go-with-the-Flow[2] application [21] to fit our population needs and the sociotechnical characteristics of Mexico [3].

The main contributions of this paper are:

- a case study in Mexico showing the use of interactive sonification in autism by using an instantiation of the Go-with-the-Flow framework;
- qualitative and quantitative empirical evidence showing how interactive sonification can support motor therapeutic interventions for children with autism (severe level);
- a set of design insights to guide the design of interactive sonification for children with autism.

**Table 1.** Examples of the movement trajectories children with autism must practice during motor therapy sessions

| **Aim Movements** | **Description of aim movements** | **Example**  |
|---|---|---|
| Lateral upper limb movement | **Initial position:** The child is standing with his/her arms down<br>**Trajectory:** The child moves each arm from down to up "swiping" in a lateral movement and drawing a half-circle in a trajectory<br>**End position:** The child is standing with the arm raised on the same side where the movement began |  |
| Push upper limb movement | **Initial position:** The child brings his/her arms to her chest<br>**Trajectory:** The child stretches an arm forward in a horizontal way (i.e., parallel to the floor)<br>**End position:** The child has an arm fully extended forward in a horizontal position (i.e., parallel to the floor) |  |
| Cross-lateral upper limb movement | **Initial position:** The child is standing with his/her arms down<br>**Trajectory:** The child moves each arm from up to down up crossing the right arm from right to left and the left arm from left to right<br>**End position:** The child is standing up raising his/her arm on the opposite side where the movement began |  |

# 2 Related work

In this section, we critique how exergames are used to support motor therapeutic interventions of children with autism to contextualize our work. While there are many exergames using sound (e.g., just dance), many of these do not support therapeutic interventions for children with autism [31, 32], nor use sonification techniques. Thus, those studies were not included. We then highlight research related to two different approaches to interact with sounds either by using musical interfaces to create music or interactive sonification to support rehabilitation of people with disabilities.

[2] Go-with-the-Flow is the named given to a Framework proposed in [21], that includes a set of design principles, sonification paradigms, and alterations. The app developed using the framework guidelines (e.g., smartphone/wearable application) is also named Go-with-the-Flow in [21]. In this paper, we used the Go-with-the-Flow mainly to name the app that was built using the framework

[3] https://youtu.be/UJttpUJcIM4

## 2.1 Serious games for physical activity for children with autism

Recent research has shown that children with autism have substantial motor coordination deficits [6]. However, research on designing interactive technology to support motor skills for people with autism in Mexico remains scarce [33, 34]. Most research in this area has been conducted in the United States and Europe and is focused on promoting physical exercise in a classroom setting, in a motor therapeutic context, or on helping children to recognize and express emotions through movements [35–37].

Exergames have been designed to help children with autism to support motor skills, such as FroggyBobby, an exergame designed for children with autism. In FroggyBobby, children use arm movements to control and redirect the tongue of a frog avatar to collect flies in the air, in the path between two visual targets [34]. In the exergame, children with autism practice motor coordination exercises while avoiding aimless movements by following a visual target that points the trajectory from an initial point to the endpoint. FroggyBobby was found to improve attention and the development of control over aimed movements in children with autism after seven weeks of using the exergame [34].

Overall, these results show that interactive technology can be useful in supporting motor therapeutic interventions for children with autism. However, not much attention has been paid to how the use of sound feedback could be used to guide the movements of children with autism and increase motor awareness of those movements.

## 2.2 Musical interfaces for rehabilitation

Musical interfaces can be used to exchange music between the user and an interactive interface. They can include digital musical instruments, augmented traditional instruments, alternative controllers, or interactive installations [38]. Musical interfaces have been proposed to support individuals with motor disabilities during therapeutic interventions in a variety of conditions [33, 39–42]. For example, MINWii [39] is a game that helps people with dementia to improvise or to play predefined songs on a virtual keyboard. A deployment study of MINWii showed that combining both tangible and gestural interactions could facilitate playing with music for people with motor and cognitive impairments. However, MINWii does not provide appropriate real-time auditory feedback that allows patients with motor impairments to practice motor skills.

Natural user interfaces make it easier for individuals with disabilities to interact with music, as shown in the example above. However, they are not always designed to create awareness of movement. For example, AUMI [41] is an interactive musical interface that enables users to make music based on one’s body movement. Children with motor problems showed improvements in coordination, attention, and self-expression when they used it. However, AUMI was designed for patients with significant problems in controlling voluntary movements (e.g., patients with brain and spinal cord injuries). There is a lack of evidence regarding how such solutions could be used to support the needs of children with autism. Furthermore, none of the above studies have been evaluated with children with autism in a therapeutic context.

## 2.3 Interactive sonification for motor therapeutic interventions

Interactive sonification is an emerging approach to expanding and improving motor therapeutic interventions. Interactive sonification is "the use of sound within a tightly closed human-computer interface where the auditory signal provides information about data under analysis, or about the interaction itself, which is useful for refining the activity" [17]. It offers real-time interaction between an individual and an auditory display [17]. In our study, the data under analysis is body movement. Hence, according to [24], “sonification transforms parameters of human movement patterns into sound to enhance perception accuracy.” Various studies have shown that the sonification of movement is effective in increasing awareness of movement and supporting rehabilitation [43]. Sonification exploits the fact that the sound directly represents some quality or characteristic of the movement that generates it and can thus be useful for motor therapeutic interventions. The sonification of body movements, as a means to inform people about the execution of a movement, has been shown to improve motor control [24], especially during sports [25, 26], when dancing [27], and for rehabilitation [18, 20, 21].

In physical rehabilitation, sonification has shown that sequences of tones can facilitate movement training after a stroke or spinal cord injury [20, 44], and guide a person toward an end position of a movement [19]. This type of sonification was used to support patients with low body awareness and coordination abilities to follow specific trajectories; the movement difficulties of these patients are similar to those faced by children with autism [45].

Singh et al. [21] proposed the Go-with-the-Flow framework to design movement sonification to help increase body awareness and confidence in movement in people with chronic pain. Based on the principles of the framework, they created a Go-with-the-flow smartphone app, which can be strapped on the body for movement sonification. The app (also named Go-with-the-flow) tracks and sonifies people’s movements to provide them with an awareness and understanding of how much they can move. The sound changed at pre-set points called anchor points (i.e., important movement milestones) set by the user to provide them with information about where they are within a movement as they execute it. The Go-with-the-Flow app has available three sounds that provided feedback at the anchor points, the *wave*, *water*, and *wichchimes*. In control studies conducted in London, researchers evaluate the Go-with-the-Flow framework [21], they showed that real-time sound feedback based on people’s body movements could increase awareness and motivation in doing the movements. Further, a simple sonification structure was more effective in enhancing body awareness than complex sounds. The framework suggests that the sonification feedback needs to be designed to enhance the perception of critical points in the trajectory and the sense of accomplishment to people with reduced movement awareness. Smartphone apps such as Go-with-the-flow also provide an affordable option to explore movement sonification in low resource settings in developing countries.

Research on sonification has not only investigated the effect of sonification on motor control and motor skills but also what type of sound appears to be most effective, that is, if the quality of the sound can provide information about the quality of the movement. For example, Tajadura et al. [46, 47] used shoes that sonify one’s footsteps to show that altering the frequency of the sounds led to faster (high-frequency sound) or slower leg movement (low-frequency sound) and affected the perception of one’s weight.

Interactive sonification has also shown to be effective with children [22, 48, 49]. For example, the sonification of writing has been used as a rehabilitation program for children with dysgraphia [48]. The sounds were designed to inform the participants of their writing velocity using a synthesized rubbing sound on a metallic plate. An evaluation study with seven children with dysgraphia found that children were able to improve the control of their handwriting movements after sonification-based rehabilitation. Children wrote faster and more fluently without reducing the readability of their writing. This study shows that children can use interactive sonification to master their motor skills.

Another study conducted by Frid et al. [49] used interactive sonification to guide the spontaneous gross movements of children. In this research, three different sound structures, based on filtered noise, were created and tested. The first sound structure produced a smooth, wind-like sound, the second one produced a more abrupt sound, and the third one produced a choppy, clicking sound. An evaluation study with eleven children (aged 5-6 years) found that sounds have an effect on children's body movements [49].

These studies show the importance of the type of sounds used in sonification as it may have an impact on the quality of movement that sonification facilitates. However, there is no previous research on the use of interactive sonification to support body movement awareness in children with autism. Further, there is no research study that has investigated whether or not children with autism can perceive that their movements are sonified, and if so, how sonification could support their motor development. This is an open question given the fact that the effect of sonification often relies on the concept of agency [50].

The work presented in this section shows that enhancing the awareness of movement through appropriate sonification could help children with autism improve their motor coordination. However, before applying frameworks to achieve improvement in motor coordination in children with autism, it needs to be ascertained that they can engage with interactive sonification; this means that they show awareness of a relation between their movement and sound feedback, given their different body awareness [45]. Further, we need to investigate what sound structures could be useful in assisting motor therapeutic interventions in children with autism, as this kind of intervention is different from other types of rehabilitation. In rehabilitation, people are working on regaining lost capabilities or improving their confidence in movement, whereas children with autism are practicing and developing motor skills. Finally, there is a need for more affordable technology for use in low resource settings in developing countries, such as those in Latin America, as many technologies developed in this context (motor therapeutic interventions for autism) may be unsuitable or unaffordable for such settings [33, 34].

In the next sections, we present two deployment studies: the first study aims to understand if children with autism exhibit awareness of the sonification of their movements, and the second one explores the potential motor impact of different sound structures in the movements of children with autism. Our study does not aim to prove that children with autism fully understand the cause-effect relationship between body movement and sound (this is beyond the scope of this work). We want to understand if sonification is a viable way to engage children with autism and address the repetitive movements that they generally find frustrating or tedious.

# 3 Study 1: An exploratory study to understand the use of interactive sonification

## 3.1 Methods

To explore the role of sonification in supporting motor therapeutic interventions for children with autism, we conducted a study using the Go-with-the-Flow app in a school clinic, called Pasitos[4], for children with autism The following research questions guided the study:

- Does interactive sonification affect the way children with autism engage with their body movement?
- What initial evidence exists on whether children with autism associate their movements with sounds?
- How can interactive sonification assist children with autism during motor therapeutic interventions?

### 3.1.1 Design of study 1

We conducted the study in a room of the Living Laboratory at Pasitos [51]. The room, with dimensions of 3.65 m x 1.83 m, contained two video cameras to record the users, one located in front of the user, recording user reactions when playing with the exergame, and the other one located behind the user, recording participants' interactions with the Go-with-the-Flow app. We removed all of the visual stimuli from the room (e.g., toys).

We used a within-subject design approach where children performed the lateral and reach forward exercises with three pre-defined sounds used in the Go-with-the-flow application (i.e., wave, water, and windchimes). Each child was allowed to explore the different sounds and movements without following a rigid structure, as we were interested in understanding their reactions in a more naturalistic manner. All the sounds followed the same order.

### 3.1.2 Participants

We recruited six children with autism (Avg. age = 7, SD = 2.6) and one psychologist. All children exhibit sensory (e.g., under- or over-sensitive) and cognitive (e.g., attention, and executive function) differences (Table 3). Half of the children were non-verbal. For inclusion criteria in the study, the children had to have an autism diagnosis, were able to follow instructions, were not medicated, did not have a bone fracture or a sprain, were able to tolerate sounds, and had moderate or no coordination problems.

[4] *"Pasitos" is a school-clinic located in Mexico specialized in the care of children with autism where 15 psychologists-teachers attend to close to 60 children with severe and mild autism. Both deployment studies were conducted at this clinic.*

To recruit participants, we followed the ethical considerations suggested by Pasitos. The Institutional Board of Pasitos approved the study, and all parents consented on behalf of their children. We recruited participants through a meeting we had with the staff of Pasitos, where we explained the study and the risks and benefits for children's participation. The staff of Pasitos carefully selected children who were able to participate, met the inclusion/exclusion criteria and had the parents' consent.

**Table 3**. Socio-demographic of children participants for study 1 and study 2

| Study 1 | | | | Study 2 | | | |
|---|---|---|---|---|---|---|---|
| **Children** | **Verbal** | **Age (years)** | **Severity** | **Children** | **Name** | **Age** | **Severity** |
| 1 | Non-verbal | 6 | Severe | 1 | Non-verbal | 5 years, 1 month | Severe |
| 2 | Non-verbal | 7 | Severe | 2 | Non-verbal | 4 years, 11 months | Severe |
| 3 | Verbal | 11 | Mid | 3 | Non-verbal | 5 years, 7 months | Severe |
| 4 | Verbal | 4 | Mid | 4 | Non-verbal | 6 years | Severe |
| 5 | Non-verbal | 5 | Severe | 5 | Non-verbal | 9 years 2 months | Severe |
| 6 | Verbal | 9 | Mid | 6 | Non-verbal | 6 years 9 months | Severe |
| | | | | 7 | Non-verbal | 5 years 6 months | Severe |
| | | | | 8 | Non-verbal | 6 years 5 months | Severe |
| | | | | 9 | Non-verbal | 7 years 1 month | Severe |

### 3.1.3 Materials: The Go-with-the-Flow framework

In this paper, we extend the Go-with-the-Flow sonification framework [21] by providing new rules to build sound structures that meet the needs of motor therapy for children with autism. Besides, we added to the device the set of newly instantiated sonification functions. We selected Go-with-the-Flow because its design focuses on supporting motor awareness and gross movement, is easy to deploy, and can be used in low-cost settings. The Go-with-the-Flow framework provides a set of principles to support the design of sound structures for enhancing awareness of body movements in individuals with chronic pain (ref [21], page 344). The Go-with-the-flow framework has been implemented in an app with a list of instantiated sonification functions (the app is also named Go-with-the-flow). The phone could be worn on the body to track movement using a vest with a pocket in the back to hold the phone in position or using a smartphone armband. The vest provided with the Go-with-the-flow app does not have sensors embedded. It is made of fabric and only serves to hold the smartphone on the back.

The Go-with-the-flow app has a simple visual interface that allows users to select an auditory structure for sonification (Figure 1). It is important to note that the visual interface of the smartphone is in English, and it was not translated to Spanish because it was meant for use by the research team who are fluent in English. The research team only used the interface to configure the sounds and did not evaluate its usability. The application ran on an Android 4.4 smartphone or superior, with a 2.2 GHz dual-core processor, 2 GB RAM, and 8 GB storage.

The sounds available followed two sound structures: "discrete" and "continuous" (Table 2). "Discrete sounds" were those sound structures that equally divide the sounds into intervals; the intervals serve as an intermediate milestone to drive the movement (i.e., *wave* sound). This sound was designed to enhance the sense of progress through a movement despite low proprioception and low self-efficacy. "Continuous sounds" provided continuous sound feedback on users' movements with and without anchor points (i.e., *water* and *windchimes*).

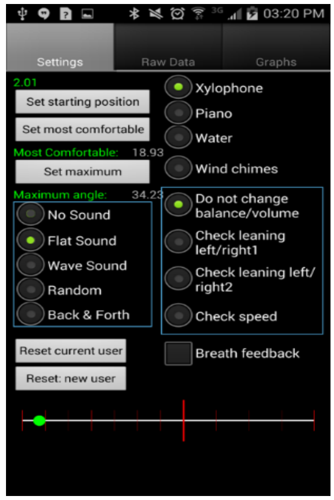



**Figure 1.** The visual interface of the Go-with-the-Flow app

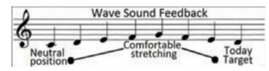
The sounds enhanced engagement while increasing the awareness of movement. For the *water* and *wave* sonification, the Go-with-the-Flow application would transform the user's movement into sound only when the movement execution was between the anchor points. The movement transformation based on the users' movement would stop past the ending anchor point. While both "continuous" and "discrete" sounds aimed to increase awareness of the body in movement, marked changes during the sonification (e.g., *wave* and *water*), providing an awareness of how far the person had moved. Changes in movement speed would result in changes in the speed of the sound feedback to increase awareness of movement speed (e.g., rushing through the movement vs. going too slow).

The sounds were designed for the forward reach exercise and upper-limb movements. For the forward reach exercise, participants were asked to lift their arm forward to shoulder level, then bend their hips forward without moving their feet (Table 1). During this exercise, the phone with the app was in the vest pocket (Figure 2). For the upper-limb movement, participants were asked to stand with their arms down, and then move the arm up swiping laterally. During this exercise, participants wore an armband with the smartphone in it (Figure 2-left).

The Go-with-the-Flow app uses the smartphone's gyroscope to transform the movements into sounds in real-time. For example, when worn on the back, it tracks and sonifies trunk movements (Figure 1). The sound pitch going down was designed to provide information to the user about when they had gone past their comfort zone within the movement. In this study, we only want to understand whether children with autism (severe level) were able to perceive the sonification as a production of their movement.


**Figure 2.** From left to right: a child with autism using the Go-with-the-Flow in his left arm at the initial position of the lateral movement; next, the same child at the final position of the lateral movment; next a child with autism looking at the Go-with-the-Flow device; next, a child with autism using the Go-with-the-Flow attached to a vest to track trunk movements; finally a mockup showing the three anchor points. [THE PARTICIPANT'S AND CARER'S WRITTEN CONSENT FORM TO PUBLISH THE PHOTOS WAS OBTAINED]

**Table 2.** Description of the Go-with-the-Flow sounds structures

| Type of Sonification | Sound Name | Description | Start | Comfortable position | Max stretching | Example |
|---|---|---|---|---|---|---|
| Discrete sound with trajectory | Wave | Two major ascending scales: separated by the anchor point C: 7 equidistant ascending tones before C and 4 equidistant descending tones after | Lower pitch note of the scale | Highest tone | Lowest tone of the descending scale. |   |
| Continuous sound with target points | Water | The continuous sound of water | Water sound | Splash | Water sound | |
| Continuous sound | Windchimes | The continuous sound of windchimes | The continuous sound of windchimes | The continuous sound of windchimes | The continuous sound of windchimes | |

### 3.1.4 Data collection materials

We video-recorded all the participants while they used the Go-with-the-Flow application. Participants used the application at least once to perform the lateral arm movements for at least three minutes. However, given the sensory issues exhibited by children with autism[3], only three participants consented to wear the vest to conduct the forward reach exercise for another three minutes.

We conducted semi-structured interviews with five psychologists to understand the following topics:

- experience of children with autism using the Go-with-the-Flow application (e.g., What is the child's attitude towards the device?);
- potential therapeutic impact (e.g., How do you think the use of sonification can impact on children's therapy? Prof: examples.);
- if they thought the children were aware that their movements produced the sounds (e.g., Do you think the child's movement was voluntary or stereotyped? Why? Prof: example).

The questions were extracted from a corpus of data from our lab. This corpus has been previously used to evaluate the user experience of children with autism using interactive technology and motor development (e.g., [33, 34]).

We relied mainly on psychologists' interpretation of the collected data to address our questions due to the high disability level of the children. Further, although they are not the final users, they are the primary caregivers of the children at the clinic and were used as "proxies" to gather their perceptions. This "proxy" technique is commonly used when working with non-verbal populations [52].

### 3.1.5 Procedure

The study allowed children to explore the sonification of their arm and trunk movements. The same movements are used by Singh et al. when using Go-with-the-Flow for people with chronic pain [21]. The following procedure was used when conducting the study.

- **Calibration of arm movement:** The psychologist brought the child into the room and showed him/her the armband and how it is worn. Next, the psychologist set the armband on the child's dominant arm and asked him/her to perform one lateral movement while a researcher calibrated the Go-with-the-Flow application for the initial, comfortable (i.e., middle), and end positions of the movement/ exercise. For the calibration, the psychologist asked the child to maintain each position for a few seconds before moving to the next position. The calibrated range was then used to map the child’s degree with the lateral movement into sound;

- **Arm movement exercises:** For each sound *wave*, *water*, and *windchimes* (Table 2), the child was asked to perform at least three lateral movements, and he/she stopped when asked by the psychologist. The app tracked the child's movements and played the sounds;
- **Calibration of trunk movement:** The psychologist showed the participant the vest with a pocket on the back. If the child was willing to wear the vest, the psychologist helped him/her to wear the vest and placed the phone inside the vest's pocket. Next, the psychologist and the child started the calibration of the sonification movement range. The calibration consisted of capturing three anchor points of the smartphone during the performance of a forward reach movement; the anchor points were the starting straight-up position (set as initial position), the middle point of a forward reach movement, and finally the full extension point of the movement. For the calibration, the psychologist asked the child to maintain each position for a few seconds before moving to the next position. The calibrated range was then used to map the child's degree of forward reach into sound;
- **Trunk movement exercises:** As in the case of the arm movements, the child was asked to perform three forward reach movements for each sound *wave*, *water*, and *windchimes* (Table 2), and he/she stopped when asked by the psychologist. The app tracked the child's movements and played the sounds.

During the study, the psychologist demonstrated the movement or prompted the children to facilitate the exploration of sonification when necessary. Since the study aimed to explore how the children used Go-With-the-Flow and their overall perception, we presented the sounds in the same order. The psychologist suggested presenting the sounds according to the number of anchor points provided by each sound. We started from the *wave* sound, as it provides anchor points during the whole trajectory of the movement, followed by the *water* sound with only one anchor point, and then the *windchime* sound. Each participant took at least three minutes to conduct the calibration of the arm movement and the lateral arm movement repetitions. Then, they took another three minutes for the calibration of the trunk movement and the repetitions of the trunk movement exercises.

### 3.1.6 Data analysis

Data analysis followed a mixed-methods approach—we used a quantitative approach to analyze the videos of the children, and a qualitative approach to analyze the psychologists' interviews.

To analyze the video recordings, we used techniques inspired by structured observation [53]. The coding scheme contains behaviors used in previous works that observed similar tasks for children with autism [34, 54, 55] (Table 4). We focused on the following factors when observing each video: the amount of time the children spent focused on the task [54], whether they exhibited positive or negative emotions [55], how many movements each child performed and if the movements had an aim or not [34], and the kind of help they needed to execute the movement. For instance, help could be verbal (e.g., the psychologist says "move your arm"), physical (e.g., the psychologist moves the arm of the child) or gestural (e.g., the psychologist moves his/her arm to show the children how to do the movement) [54]. Only the "prompts" given by the psychologist could occur simultaneously (e.g., the psychologist moves the arm of a child and gives him/her a verbal instruction at the same time). For the rest of the categories, researchers were instructed to select the one they considered most remarkable. Researchers coding the data were trained in using techniques for behavior analysis of autism.

Two researchers systematically scored participants' behaviors for all the videos following the coding scheme (Table 4). The inter-observer agreement, among the two researchers, was acceptable (Fleiss kappa Avg. $\kappa = 0.8$). Total and descriptive statistics of the time and frequency children spent executing each behavior were computed for each child and under each condition.

All interviews with psychologists were recorded, transcribed, and analyzed using a deductive approach. In particular, we focused on identifying potential quotes where psychologists described behaviors of participants as demonstrating awareness of how their movements produce the sounds and the potential benefits of such an awareness in the development of motor skills. Additionally, we used inductive approaches to allow new themes to emerge from our data. To support our inductive analysis, we used open and axial coding and affinity diagramming [56].

**Table 4.** Brief definitions of the codification scheme used to code the target behaviors

| Category | Target behavior | | Definition | Type of measurement |
|---|---|---|---|---|
| Users' Behaviors | Attention [54] | On task | The child is engaged and focused on the activity | Time |
| | | Off task | The child is distracted | Time |
| | Emotions [55] | Negative | The child is crying (sad), frowning (angry), and stretching his/her lips (fear). | Time |
| | | Positive | The child is smiling (joy), clapping (happy), laughing (amused), | Time |
| | | Neutral | The child does not express any emotion | Time |
| | Prompts [54] | Verbal | The psychologist gives a verbal instruction to the child | Frequency |
| | | Physical | The psychologist physically moves the child | Frequency |
| | | Gestural | The psychologist gently redirects the attention of the children by pointing to a potential target. | Frequency |
| Users' motion | Arm | | The child moves his/her arm | Frequency |
| | Back | | The child stretches forwards | Frequency |
| | Other | | The child does another type of movement | Frequency |
| Directness | Aim movement [34] | | When a child is capable of following the predefined path of a movement from an initial point to an endpoint. | Frequency |
| | Aimless movement [34] | | When a child makes inaccurate movements and guides them in the wrong direction | Frequency |

## 3.2 Results

In this section, we present the two main themes that were identified from our data: the use and adoption of the Go-with-the-Flow application and potential motor impact on the development of children. Overall, we found that children enjoyed using Go-with-the-Flow and exhibited some awareness about how their movements produced sounds. Also, our scoring from the videos showed that interactive sonification might be useful to increase the repetition of aim movements.

### 3.2.1 Use and adoption

All the psychologists reported that most participants appeared to be motivated when using Go-with-the-Flow, and they enjoyed producing sounds while they were moving. Psychologists said that participants found Go-with-the-Flow "easy to use" and learned how to produce sounds very rapidly and with minimum training,

*"[Children] like a lot [Go-with-the-Flow], I think they enjoyed a lot [to produce the sounds]*[5]*…"* Psychologist A

Although children with autism lack the predisposition to play spontaneously [57] and usually need assistance to conduct an activity [58], one psychologist pointed out that one participant showed initiative to discover more sounds spontaneously by exploring different movements. The psychologist thought that the child wanted to produce a different kind of sound:

*"[The movements] were very natural, when [Child A] was using the vest, he bent down differently. He was trying to discover different sounds …"* Psychologist B

The other participants did not show a similar initiative, but they positively responded to the use of Go-with-the-Flow.

According to our quantitative results, four of the six participants exhibited positive emotions; they were smiling or laughing while using Go-with-the-Flow. Even though the psychologists agreed that none of the participants exhibited negative emotions when using the Go-with-the-Flow app (e.g., none of the children covered their ears when listening to sounds), we observed that one child exhibited negative emotions for fewer than 30 seconds. So, when we asked 'Psychologist P' about this behavior, she stated:

[5] Psychologist's quotes were translated from Spanish to English

*"[Participant M] would prefer another type of sounds, and that is why he said 'no!'…"* Psychologist P

There was no one specific sound that the psychologists thought the majority of the children enjoyed, when they were asked about the childrens' preferred sound:

*"I think the [continuous sound of] water [was the sound Participant D enjoyed the most] …"* Psychologist S

*"I saw [Participant U] was more excited with the [continuous sound of] windchimes…"* Psychologist P.

*"I think [Participant M] likes the [the discrete sound wave]. It was the sound he found more engaging …"* Psychologist B

These results suggest that Go-with-the-Flow offers an enjoyable and non-intimidating experience that enables children with autism to explore how to use their bodies to produce sounds spontaneously. However, it also shows that sound preference differs, and this may have an impact on the adoption of the device.

#### 3.2.1.1 Learning how to produce sounds

All the participants needed different prompts to discover how to use the device in practice. However, after getting used to the device, they needed fewer prompts (Figure 3-left). According to the quantitative data from the videos, participants spent on average 80% of the time receiving prompts from the psychologist while they were listening to the first sound ("discrete sound" of *wave),* 66% of the time when listening to the second sound ("continuous sound" of *water),* and 35% of the time when listening to the last sound ("continuous sound" of windchimes) (Figure 3-left).

Indeed, one psychologist explained:

*"… [During] the first [activity], when [Participant J] was moving his arm with the piano sound [referring to the discrete sound of wave], he didn't understand [that his movement was the one that produced the sound] and with the [continuous sound of] water he still didn't associate [the sound with his movements]; so he wasn't interested in the activity. But, now [with the continuous sound of windchimes], he knows that he is [the one who produces the sound]. As a consequence, he is more interested [because he learned how to 'operate' the application] …" Psychologist P*

These results show that children with autism could learn to use sonification after wearing Go-with-the-Flow a few times and getting some help from teachers. However, fading out prompts from others is paramount to enabling children with autism to apply new skills they learn during therapy to real-life scenarios.

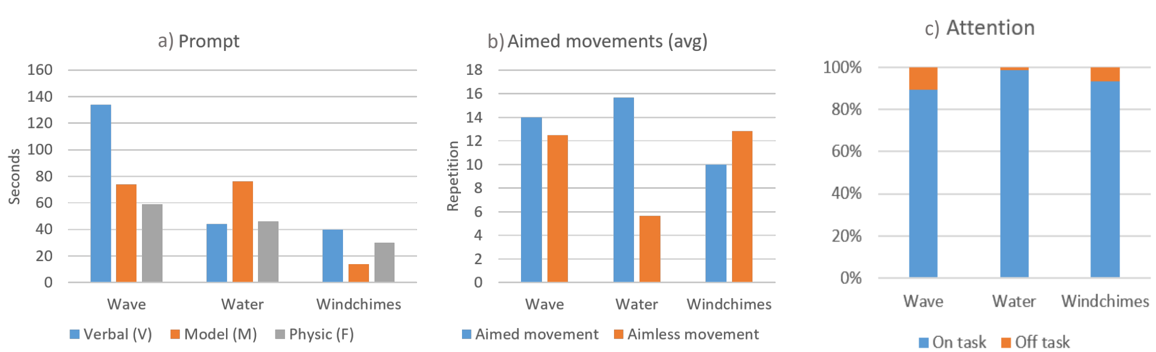



**Figure 3.** a) Time therapists gave to participants' verbal (blue), model (orange), or physical prompts (gray). b) Number of aimed movements (i.e., movements that follow a trajectory from an initial position to a specific target; blue) and aimless movements (i.e., movements done in a wrong or vague direction; orange) repetitions participants completed per sound. c) Average percent of the time that participants stayed on talsk (blue) and off taks (orage)

### 3.2.2 The potential impact on the development

The psychologists perceived that the use of Go-with-the-Flow might help children with autism to maintain their attention, gain body awareness, and improve their motor development.

#### 3.2.2.1 Attention

The psychologists suggested that Go-with-the-Flow might have an impact on attention. They observed that most participants stayed focused when using the device and followed the instructions that they provided:

*"I think [Go-with-the-flow] could be used for [sustained attention], because children have to stay focused on the sounds, so they can discover how far their movement could produce sounds …"* Psychologist P

According to our quantitative results, on average, participants focused on the task (i.e., using the Go-with-the-Flow app while doing movements) for 91% of the time. When participants used the *water* sound, they focused 98% of the time, in contrast to the *wave* and *windchimes* sound, where they were focused 90% of the time (Figure 3-right). This result suggests that Go-with-the-Flow effectively captures participants' attention.

According to our observations, distractions did occur but did not affect the movements of the participants. At times, we observed that half of the participants felt distracted when wearing the armband. Most distractions were due to issues related to the use of wearable technology. First, none of the participants had ever worn an armband before. Second, teachers have taught our participants that smartphones are fragile —for example, they have learned that they cannot throw a smartphone to the floor; so, participants were cautious and highly aware when the smartphone was attached to their arm via the armband. Third, participants wanted to locate the source of the sounds, as one psychologist pointed out:

*"In the end, [Participant M] looked at the device because he understood that it was the device that produced the sound …"* Psychologist P

These results suggest that Go-with-the-Flow effectively captures participants' attention. It should be noted that these results may be due to the unavoidable "novelty effect" of the use of Go-with-the-Flow. Therefore, further research should be conducted to understand if the attention is maintained in the long-term.

#### 3.2.2.2 Subjective awareness of cause and effect

We asked the psychologists if the children made an association between their movements and the production of sound. Our results showed that four out of six participants made the association. For example, one psychologist pointed out,

*"… [Participant U] moved his body because he noted that with his movements, he was making the sound…"* Psychologist L

During the video analysis, we observed that one participant repeatedly raised his hand to hear the sounds; then, he stopped moving and noticed the silence; afterwards, he moved his arm again. This repetition of movement may indicate an understanding of the relationship between cause and effect and could indicate that the participant gained awareness about the function of interactive sonification through practice. Also, we observed that participants sometimes tried out different movements such as "walking backward while dancing," in order to control the sounds,

*"Basically, [Participant D] was trying to understand where the sound comes from and what he needs to do to make the sound …"* Psychologist S

One verbal participant, Participant J, believed he was turning into a musical instrument. He said, '*I am a Piano!'* A psychologist explained:

*"[Participant J] feels the piano sound comes out of him ... He knows it is because he wears the vest, and that is good because this is his way of showing that he likes and understands [his movements produce the sounds] ..."* Psychologist P

The psychologists expressed that this behavior might indicate that participants started to be aware of how their actions could produce a reaction, this means, how their movements could produce sounds, and this may help them to understand concepts related to perceptual-motor skills. The psychologists also noticed that participants' movements were not stereotyped; this could mean that most of the movements conducted by participants were voluntary,

*"[This movement] was voluntary, at the end [Participant D] understood that he was the one that was making the sound ..."* Psychologist A

Given that participants understood that their movements could produce sounds, they were curious and continuously tried to discover more sounds by performing voluntary movements; thus, our results suggest that children with autism might gain awareness about how the sonification of movements works.

#### 3.2.2.3 Motor development

All the psychologists agreed that Go-with-the-Flow could potentially help participants to develop motor skills. and could be used to encourage more repetitions of movements during motor therapeutic interventions.

*"I think [Go-with-the-Flow could have an impact] on the gross motor skills, as it motivates children to practice different movements ..."* Psychologist L

Our quantitative results show that participants performed, on average, 34 movements while they were using Go-with-the-Flow with the armband (SD=14), and 22 movements while using the vest (SD=8). From those movements, participants did 38% with the "discrete sound" of *waves*, 30% with the "continuous sound" of *water*, and 32% with the "continuous sound" of *windchimes*.

Psychologists explained that Go-with-the-Flow could be useful to help children with autism to practice specific movements and provide feedback about the direction of the movement:

*"I also believe [Go-with-the-Flow] could help children to deal with laterality issues ... they could perform lateral movements from up to down and using both their right and left hand ..."* Psychologist A

*"I believe [Go-with-the-Flow] could help children to improve the aim of their movements, as [Go-with-the-Flow could provide the feedback] to help children to execute more movements in a more precise manner because if the children listen to the sound and they like it, they will try it again…"* Psychologist S.

Our quantitative results show that 56% of the movements were aimed movements –participants redirected their limb movements from an initial position to a specific target. From those movements, participants did 22% with the "continuous sound" of *water*, 20% with the "discrete sound" of *wave*, and 14% with the "continuous sound" of *windchimes* (Figure 3-center).

These results suggest that the structure of the sounds of Go-with-the-Flow could provide useful information to children with autism regarding their movements. However, the sounds lack the structure to guide the movements children practice during therapy. Thus, there is a need to re-design the sounds to guide movements better.

### 3.2.3 Re-designing the sounds structures to customize them to the needs of children with autism

Using principles from the Go-with-the-Flow framework, and the needs of motor therapy for children with autism, we proposed five different sounds, all variations of the previous ones (Table 5). The new sounds aim to provide sonification feedback at the starting point of upper-limb movements, during its trajectory, and at the endpoint.

We designed three sounds with two variations of the "discrete sound" of *waves*:

- "discrete sounds without trajectory," include those sounds that only provide feedback at the start and the end of the movement (drums);
- "discrete sounds with trajectory," include those sounds that provide feedback at the start and the end of the movement and at particular points during the movement trajectory (ascending scale and melody);

We also designed two sounds with one variation of the "continuous sound with target points" of water:

- "Continuous sound," including those sounds that provide feedback from the start of the movement and continue without interruption until the end of the movement (water, wind).

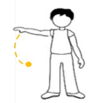
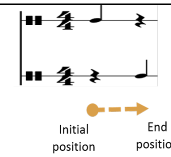
The design of the "discrete sounds" aims to increase children's awareness of the starting and ending points of movements, as well as to encourage and reward reaching those points. The sonification of the trajectory aims to increase awareness of the body being in movement. In contrast, the lack of sound with the trajectory aims to increase their curiosity in finding the ending sonified points.

We instantiated two forms of "discrete sounds with trajectory." The first one was the *wave* sound, derived from the original Go-with-the-flow. We changed the sound from the original by removing the intermediate anchor point, and instead rewarding the achievement of the ending target point to encourage the return. On reaching the second (ending) anchor point, the movement and hence the sound reversed towards the starting position to complete the movement (Table 5). We selected this sound because the simplicity of the sound was shown to increase awareness and control of movement in previous studies [21, 59]. The second sound was a *melody* sound derived from a song known to children. We selected this song as it was suggested by the Pasitos psychologist-teachers, as they sang the song frequently during their classes. The aim was to increase engagement in children, as previous research has shown [60].

We also kept almost the same "continuous sound" of *water* as, unlike the w*indchimes,* it had a clear anchor point. We proposed a new "continuous sound" of *wind*, as it was previously used for the sonification of movements for children [49]. This sonification mimics the sound produced by the friction created between the wind blowing and the movement of the arm (similar to the sounds of the branches of trees when wind blows).

All the sounds were played in reverse when the arm movement of children returned to the initial position. Also, the speed of the sounds changed according to the speed of the children's movement. To change the speed of the sound, we computed the acceleration from the smartphone's accelerometer sensor and used it to speed up or slow down the musical notes. These changes were considered important to help children to learn to control movement qualities such as the speed of movement, as children with autism usually struggle to control their movements [61].

**Table 5.** Description of the proposed sounds for the upper limb movements.

| **Type of Sonification** | **Sound Name** | **Description** | **Start**  | **Trajectory**  | **End**  | **Out of the trajectory** | **Example** |
|---|---|---|---|---|---|---|---|
| Discrete without trajectory | Drums | Percussions of drums | Drumbeat sound | No sound | Drumbeat sound | No sound |  |
| Discrete with trajectory | Ascending scale (first part of the Wave) | Major ascending scale notes without chords using the piano instrument | Lower pitch note of the scale | Notes of the scale | Highest pitch note | Change pitch |  |
| | Melody | Two compasses of the Twinkle, twinkle little star melody notes without lyrics and chords using the piano instrument | The first note of the melody song | Notes of the melody song | Final note of the second compass of the melody song | Change pitch |  |
| Continuous | Wind | Continuous sound of the wind | Continuous wind circulating | Continuous wind circulating | More intense wind sound | Change the sound of wind (e.g., storm with wind) | |
| | Water | Continuous sound of water | Water sound | Water flow | Splash | Change the sound of water (e.g., water over rocks, change density) | |

# 4 Study 2: Uncovering the sound structures to promote repetitions of upper limb movements in children with autism

## 4.1 Methods

We conducted a second deployment study to understand the appropriateness of the newly designed sounds (Table 5) as auditory feedback when children with autism practice lateral, cross-lateral, and push movements during motor therapeutic interventions. For one week, the study was conducted at Pasitos and aimed to answer the following research question: How do the designed sound structures assist the motor therapeutic interventions of children with autism?

### 4.1.1 Design of study 2

The study was conducted in the same room as Study 1 (for more details, see subsection 3.1.1). Given the number of conditions (5 different sounds and 3 different movements), we used a Split-plot design [62]: i.e., we investigated the movements with a between-group approach and the sounds with a within-group approach. Each child then completed three repetitions of only one randomly selected movement of the three movements, either lateral, cross-lateral, or push movements (Table 1), while listening to the five available sounds (Table 5). These movements were carefully selected from the recommendation of motor therapeutic interventions for children with autism and have been previously used in technologic therapeutic interventions [33, 34].

The order of the sounds was randomly selected. In this manner, each participant completed at least 15 repetitions –mimicking the number of repetitions therapists ask children to complete during motor therapeutic interventions at Pasitos.

### 4.1.2 Participants

We recruited nine children with autism (Avg. age= 5.89, SD= 1.5). None of these children had participated in the previous study (presented in Section 3). All of them present sensory (e.g., under- or over-sensitive) and cognitive (e.g., attention, and executive function) differences (Table 3). Inclusion criteria were that the children had a severe autism diagnosis, were able to follow instructions, were not medicated, did not have a bone fracture or a sprain, were able to tolerate sounds, and had severe or moderate coordination problems. We also recruited one psychologist working at Pasitos. All the parents consented to the study on behalf of their children. To recruit participants, we followed the same procedure as study 1.

### 4.1.3 Procedure

The study exposed children to the sonification of three types of arm movements using five types of sounds. The procedure to conduct the study was as follows:

- **Calibration.** The researcher randomly selected one of the three types of movement (i.e., lateral, cross-lateral, or push movement) that the participant performed during the study. The psychologist took the participant into the room and showed the participant the armband and where it should be worn. She then put the armband on the dominant hand of the participant. After that, the participant practiced the movement once to calibrate the Go-with-the-Flow app;
- **Arm movements.** The participant practiced at least three repetitions of the selected movement while listening to the five available sounds (Table 5). A researcher assigned the sounds in random order.

When required, the psychologist gave verbal, model, or physical prompts to help participants to perform the movements. Each participant took at least five minutes to conduct the calibration and the repetitions of the arm movements.

### 4.1.4 Materials, data collection, and analysis

We used the Go-with-the-flow application (see subsection 3.1.3) updated with the re-designed sounds (see subsection 3.2.3).

During the study, we video-recorded all the sessions. Participants used the application once to perform the movements for around five minutes. After each participant finished the activity, the psychologist answered a brief semi-structured interview. The interview aims to explain how the psychologist perceived the child felt when listening to different sounds and his/her overall performance during the therapy (e.g., How do you think the child felt or reacted to performing the movement with the best sound? Proof: positive or negative observations; What is it about the sound that most attracted the child to move?). Those questions were extracted from our lab data corpus that has been previously using to evaluate the user experience and motor development of children with autism (e.g., [33, 34]).

## 4.2 Results

According to the psychologist's opinions, participants enjoyed using Go-with-the-Flow with the new proposed sounds with a slight preference for the "discrete sounds." We also observed and scored from the videos that the "discrete sounds without trajectory" were instrumental in increasing the number of completed upper-limb movement repetitions, whereas the "sounds with trajectory" encouraged the practicing of aimed movements.

### 4.2.1 Use and adoption

All participants successfully used Go-with-the-Flow with the newly designed sounds (we excluded one participant as he did not want to enter the room.) The psychologist reported that all participants wanted to move their arms after hearing the sounds:

*"I think [participant I] was very excited, he was heavily enjoying the sounds, he was laughing …"* Psychologist K

According to the type of sonification, the psychologist believed participants preferred the "discrete sounds with trajectory," specifically, the melody sound. She explained that participants might have liked the melody sound because they were familiar with the song:

*"I think [participant G] was engaged; he even recognized the [Twinkle, twinkle, little star] song. He was moving like he was about to start to dance…"* Psychologist *K*

Our observational data regarding emotions confirmed this result. Six out of eight participants exhibited positive emotions when using Go-with-the-Flow. Some of them were even laughing while listening to the sounds –even though children with autism rarely exhibit emotions. Only one participant exhibited signs of having negative feelings for a short time (~18 s). In general, we observed that participants felt more positive when listening to "discrete sounds," and they exhibited less positive emotions when listening to the "Continuous sound with trajectory" (see more details in Table 6).

We also observed that all the participants needed verbal, modeled, or physical prompts while using Go-with-the-Flow. Participants needed fewer prompts while listening to the "discrete sound without trajectory," and they needed more prompts when listening to the "Continuous sound" (Table 6).

Overall, these results could suggest that participants enjoyed playing with the newly designed sounds as they exhibited more positive emotions and needed fewer prompts.

### 4.2.2 Potential therapeutic impact

Our results suggest that the "discrete sounds without trajectory" increased the number of completed repetitions, whereas the "discrete sounds with trajectory" encouraged the practicing of aimed movements. Also, children with autism were more focused when listening to the "discrete sounds with trajectory"—especially when those sounds included familiar melodies.

**Table 6.** Summary of the results of the preferred sounds according to the behaviors observed.

| Category | Target behavior | Formula | Discrete without trajectory (drums) | Discrete with trajectory (Melody) | Discrete with trajectory (Ascending scale) | Continuous (Wind) | Continuous (Water) |
|---|---|---|---|---|---|---|---|
| Use and adoption | **Positive emotions:** The child is smiling (joy), clapping (happy), laughing (amused) | (100 * Avg. time of children exhibiting positive emotions/ Avg. time of the session) | 72% | **80%** | 78% | 66% | 45% |
| | **Prompts**: The psychologist gave verbal, physical or gestural prompt | (100 * Avg. time of children receiving a prompt/ Avg. time of the session) | **6%** | 8% | 14% | 14% | 17% |
| Potential therapeutic impact | **Repetition:** when a child is capable of completing a movement. Percent (%) represents the distribution of the repetitions completed per sound. | (100 * Number of repetitions done by children per sound/ Total of repetition with all the sounds) | **25%** | 17% | 18% | 17% | 23% |
| | **Aimed movements:** when a child is capable of correctly followed the path moving their limbs from an initial point to an end point. Percent (%) represents the ratio among the average repetitions with those that were aimed | (100 * Number of aimed repetitions doing per sound / Number of repetitions doing per sound) | 82% | **96%** | 92% | 88% | 82% |
| | **Attention:** the child is engaged and focused on the activity. Percent (%) represents the average of time children spend on the task, | (100 * Avg. of time children spend on task/ Avg. of time of the session) | 35% | 51% | **55%** | 32% | 54% |

#### 4.2.2.1 Repetition of movements

We observed that participants completed, on average, 19 repetitions of the lateral movement (SD=4), 18 repetitions of the cross-lateral movement (SD=3), and 20 repetitions of the push movement (SD=10) (Figure 4-left). Although we asked participants to perform only 15 repetitions in total, this is, 3 repetitions per sound, five out of eight participants completed more repetitions. The psychologist explained that the push movement was the most difficult for the participants to perform,

*"[The push movement] is the hardest movement for [participants to practice]. They are not very flexible, so practicing this movement is more challenging for them …"* Psychologist K

These results suggest that, although the movements could be complicated for participants, interactive sonification may encourage them to complete the repetitions they need to practice during motor therapeutic interventions.

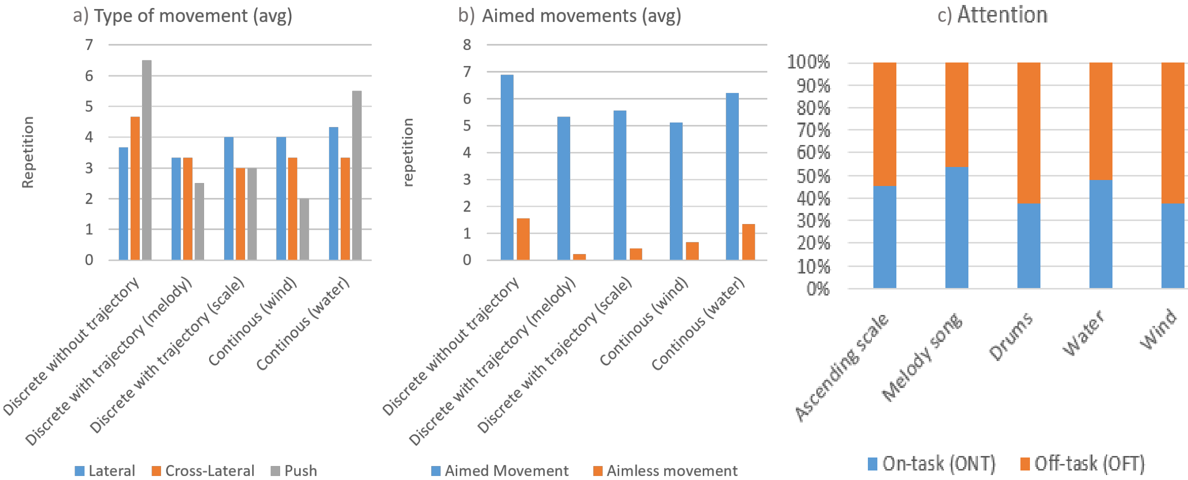



**Figure 4.** a) Frequency of the type of movement, the lateral (blue) pushing (grey), and cross-lateral (orange). b) Frecuency of aimed movements (blue), and aimless movements (orange). c) Percent of time that participants spent on task (blue), and off-task (orange)

According to the type of sound, we observed that participants conducted more repetitions when listening to the "discrete sounds without trajectory" (25% of the completed repetitions), followed by the "Continuous sound of water" (17%) (Table 6). The psychologist attributed this behavior to the fact that the "discrete sounds without trajectory" is very rhythmic, which helps participants to increase the number of completed repetitions.

*"From the beginning, [Participant V] started to move her arms according to the music rhythm [referring when the participant V was using Go-with-the-Flow listening to the "discrete sound without trajectory] …"* Psychologist K

*"Maybe if the water sound [referring to the continuous sound with trajectory] has a stronger difference [in the sound] that allow the participant to understand in which moment they need to raise their arms [again]; like include that [extra anchor point], it will be better for them …"* Psychologist K

For the "continuous sound" of *water*, the end of the movement was a 'splash' (i.e., the sounds simulates the hand entering the water and the trajectory by the sound of the water). This splash sound could be less easy to perceive than a simple drum beat.

#### 4.2.2.2 Aimed movements

According to our observations from all the completed repetitions, 87% were aimed movements (Figure 4-center; Figure 5). Participants performed more aimed movements when listening to the "discrete sounds with

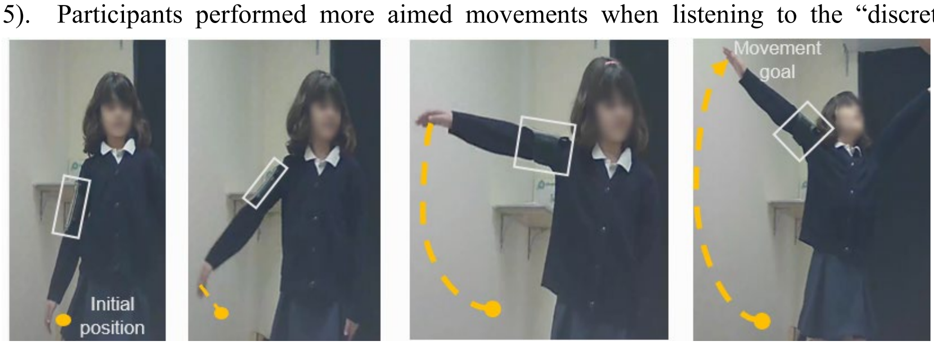



**Figure 5**. Participant wearing the Go-with-the-Flow application doing an aimed lateral movement while listening the "discrete sounds with trajectory". WRITTEN CONSENT FOR SHOWING THESE PHOTOS WAS OBTAINED FROM THE PARENTS

trajectory" (96% of directed movements) than when listening to the "discrete sounds without trajectory" (82% of directed movements) and the "continuous sound" (2% of directed movements; Figures 4, Table 6). The psychologist believed that the "intermediary" sounds during the trajectory of the movement provided participants with better guidance, enabling them to stay more focused when conducting the movements and consequently improve their aim.

*"I think [participant T] was more silent; he was sort of more focused on the piano [referring to the "discrete sound with trajectory"] while he was moving. I think those music changes [referring to the changes in the pitch] better engaged the participant …"* Psychologist K

It would appear that the structure of the "discrete sounds with trajectory" could serve as a step-by-step guide of the movement's direction. This guidance could also serve as a short-term reward that might encourage children to accomplish the goal of the movement. Open questions remain regarding if these effects can be observed or deepened in further investigation.

#### 4.2.2.3 Attention

Our results show that, on average, participants stayed focused 39% of the time when they were using Go-with-the-Flow. The psychologist perceived that the sounds facilitated participants' attention while they were moving their arms.

*"The sounds are better than the silence [referring when the participant conducted a movement without a sound] because they maintained their attention …"* Psychologist K

We observed that participants stayed more focused when listening to the "discrete sounds with trajectory" (55% of the time) than when listening to the "continuous sounds with trajectory" (32% of the time; Figure 4-right; Table 6).

This result could mean that the arrangement of the "discrete sounds with trajectory" is more congruent with the participants' motor movements; i.e., the pitch increases if children raise their hands, and decreases if the arm is brought down. This pitch arrangement could give children a sense of movement direction [63, 64], given that the most robust crossmodal correspondence of ascending pitch is elevation [65].

# 5 Design considerations of interactive sonification for children with autism

Reflecting on our results, we identified a set of design considerations for researchers interested in developing interactive sonification technology to support the motor needs of children with autism.

## 5.1 Improving the appearance of wearable technology for the sonification of movements

Wearables should be comfortable and discreet, so they are unnoticed by children with autism. Wearables should fit and be proportional to the size of the body part where the children will use them. In our particular case, the psychologists regularly gave us suggestions on how to improve the "look and feel" of the smartphone running Go-with-Flow app. The psychologists suggested reducing the size of the device as the smartphone we used covered almost three-quarters of the child's arm (see figures 2 and 5). One psychologist explained during an interview:

*"I think it would be perfect if [the device] was smaller; in this way [the device] will not cover the entire arm…"* Psychologist L

Also, the psychologists recommended changing the color of the armband to camouflage it and avoid distractions as much as possible. At the beginning of each trial, some of the participants were fixated on the smartphone, trying to figure out its purpose (Figure 2). One psychologist explained:

*"I think [the device should be disguised with] colors, to avoid competing for children's attention... if the [device] is the only shiny thing and everything else is black, then [participants] will get distracted by trying to look directly into the device's display …" Psychologist B.*

Perhaps, using discreet colors or armbands with textured patterns could better convey the message that the user is wearing a "technology box" instead of a smartphone that invites interactivity.

On the other hand, children must notice the sound of the wearables. Then, wearable speakers should be of good quality so that users can hear the sounds in the presence of background noise. We conducted our study in a quiet room in a controlled environment. However, if we wanted to use such technology in noises situations, such as people talking in the background, this would interfere with the hearing experience. Wearing headphones could help, some children with autism might refuse to wear them.

Therefore, it is recommended to explore alternatives for discreet devices with noticeable sounds. We envision two alternatives, either using wearables (e.g., Arduino Lilypad, smartwatch) or optical sensing (infer the movements with depth cameras such as Kinect or Orbeec). Wearables can be worn at the wrist like a smartwatch, on different limbs, or embedded in children's clothes using smaller devices such as Arduino. Wearables should be comfortable, unnoticed, and emit high-quality sounds. However, there is a trade-off between using a smartphone that most individuals already own and only need to install the application on, versus getting a new personalized device with the sole purpose of sonifying their movements.

On the other hand, if children are reluctant to wear a device, we can use depth cameras to track their motor movements and give them the auditory feedback accordingly. However, this solution may not be portable enough and require a complete room to have the set-up. Overall, tradeoffs of wearable and depth camera usability issues should be further investigated.

## 5.2 Crossmodal correspondence between movements and sounds

The multisensory integration and the motor responses are more likely to occur when the stimuli in different modalities are synchronised with each other and with the movement [65]. To ease the sensory integration, the sounds and movements must correspond with each other.

One psychologist explained that this crossmodal correspondence should be personalized for each movement and its qualities (i.e., speed, direction, strength). Thus, when participants hear a sound, they could easily match it with the movement executed. For example, when users are using Go-with-the-Flow to practice how to raise their arm, the sound structures should include sounds that could signal going up or moving up. This result could be done by increasing the volume or the pitch of the sounds. By doing so, children's brains will be able to match the sound with the movement every time they wear the application.

Beyond going up and down (moving the body in the Y-axis), crossmodal correspondence will also take into account issues when moving from right to left (moving the body in the X-axis), and from forward to backward (moving the body in the Z-axis). For example, we matched the movements with the pitch (in the discrete sounds) or the volume (in the continuous sounds). Then, when the child is in an initial position of the movement, he/she could hear a low pitch or volume, and while he is raising his hand, the pitch or volume increases until he arrives at the final position of the movement. This crossmodal correspondence between the movements and the sounds is in line with research regarding the sounds' location in space [63, 64].

# 6 Discussion

Overall, our results suggest that participants enjoyed using Go-with-the-Flow. Most of the children successfully wore the device, exhibited positive emotions, and embraced sound discovery. The sounds produced by the sonification evoked different responses in participants, including increasing attention to their movements and to the way they perform them.

We found that while Go-with-the-Flow captured participants' attention, using the armband was distracting for some children. Therefore, open questions remain about investigating the possible use of other wearable devices that could be subtler or less delicate (not a smartphone but a smaller robust bracelet embedded with sensors and speakers), or different ways to wear Go-with-the-Flow to avoid unnecessary distractions. Wearables are a promising way to support children with autism, but it has been shown that customizable solutions and the development of real-world applications are still an open challenge [66].

Even with the armband distraction, Go-with-the-Flow encouraged participants to perform the repetitions of movements needed during a motor therapeutic intervention. In Study 1, for example, most of the repetitions of movements performed by the children were single or spontaneous, making them insufficient to meet therapy goals [14]. A possible explanation is that the sounds included in the original version of Go-with-the-Flow do not address the specific needs of a motor therapeutic intervention for children with autism. It has been proved that the sound structure is highly related to the therapy outcome [22, 48, 49]. Therefore, we proposed the use of "discrete sound without trajectory," "discrete sound with trajectory," and "continuous sounds."

We conducted a second deployment study to understand if the proposed sounds were a better fit for motor therapeutic interventions. We found that participants preferred the "discrete sounds" and found it challenging to understand the "continuous sounds." "Discrete sounds " are more similar to nursery rhymes [60] and have a more understandable structure, with a rhythmical and predictive pattern [60, 63]. Therefore, children with autism were more engaged and conducted more repetitions of upper-limb movements with these sounds. In contrast, the "continuous sounds" may be more abstract and lack understandable cues to signal to participants when the movement is about to end as the sound is always ongoing. Therefore, we recommend using more less abstract sounds.

In our study, we also found out that the type of sound is highly determinant of the therapeutic impact, as previous researchers have shown [22, 48, 49]. Whereas participants performed more repetitions without many prompts when listening to "discrete sounds without trajectory," the number of aim movements and their attention was low. In contrast, when listening to "discrete sounds with trajectory," participants stayed more focused, exhibited more positive emotions, and their movements were aimed, but they needed more prompts, and completed fewer repetitions. It will be interesting to investigate if these results are replicated by children at different levels of the autism spectrum (e.g., children from study 1).

Finally, in terms of the context, this paper presents a case study of children with autism using ubiquitous technology in Mexico, where we take advantage of a low-cost technology used and tested in a developed country (i.e., London). Until now, there are only a few studies in Latin America showing these scenarios. It should be noted that in 2017 more than 70% of people in Mexico had a mobile phone[6]. Therefore, conducting studies using technology that is available to the majority of the population is important. So we chose to use a low-cost device to increase the scalability of our solution given the Mexican context. The studies presented in this paper are among the first studies of its kind conducted in a developing country. The replication of both studies across countries will help to investigate if such finding work also for other developing countries. We believe that these results should be replicated in other developing countries in Latin America, but first, researchers should personalize the sounds and movements according to their context. Although most Latin American countries have limited healthcare resources, and their educational systems are starting to look for solutions to include neurodiverse children, more studies need to be conducted to generalize our results and discover novel, cost-effective and easy to use technologies that close the gap in accessibility between treatments and children in need. O, what we can learn from these studies is that children (1) can perform repetition of movements wearing the application, (2) children engage with the application, (3) and that most of the repetitions were done correctly.

[6] https://www.inegi.org.mx/contenidos/saladeprensa/aproposito/2019/internet2019_Nal.pdf

# 7 Limitation

Although our research reached our goals, we observed the following limitations. We conducted the study in only one school-clinic of children with autism. Therefore, to generalize the results for other populations, the study should be replicated with a much larger population. Additionally, children with autism only used Go-with-the-Flow once, so the “novelty effect” is unavoidable. For this reason, it would be interesting to conduct a long-term study to fully understand the effect of sonification within therapy. However, given that the objective of this study was not to generalize our findings but to get an overall understanding of the potential of interactive sonification of movement for children with autism, our results are valuable for researchers exploring the design space of interactive sonification to support motor therapeutic interventions.

# 8 Conclusion

In this paper, we described two deployment studies, conducted in Mexico, of children with autism using the Go-with-the-Flow sonification framework in a wearable device.

Through Study 1, we discovered that children with autism were aware that their movements produced sounds. However, the sound structures were not appropriate. Thus, we designed a new set of sound structures to support the lateral, cross-lateral, and push movements used during a motor therapeutic intervention for children with autism. The sound structures included variations in pitch and music content and provided auditory feedback in real-time at the start and end of the movement. The auditory feedback can be continuous or discrete, with or without sounds during the trajectory of the movements. Then, we conducted Study 2 with the new sound structures. Results indicate that interactive sonification has multiple benefits for children with autism regarding engagement, attention, and motor development.

Overall, these results provide empirical evidence that interactive sonification can be efficient and engaging to conduct motor training for children with autism and uncover design considerations for developing sonification technology that could increase adherence to therapy. As future work, we are exploring challenges related to the integration of auditory feedback with visual and tactile stimuli. Moreover, it would be interesting to explore different songs and instruments that may be appropriate to develop interactive sonification solutions to support children with autism with the practice of movements.

# Conflict of interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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