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# Music Therapy in Virtual Reality for Autistic Children with Severe Learning Disabilities

Valentin Bauer  
valentin.bauer@universite-paris-saclay.fr  
Paris-Saclay University, CNRS, LISN  
Orsay, France

Ali Adjorlu  
adj@create.aau.dk  
Aalborg University  
Copenhagen, Denmark

Linnea Bjerregaard Pedersen  
linbped@gmail.com  
Aalborg University  
Copenhagen, Denmark

Tifanie Bouchara  
tifanie.bouchara@universite-paris-saclay.fr  
Paris-Saclay University, CNRS, LISN  
Orsay, France

Stefania Serafin  
sts@create.aau.dk  
Aalborg University  
Copenhagen, Denmark

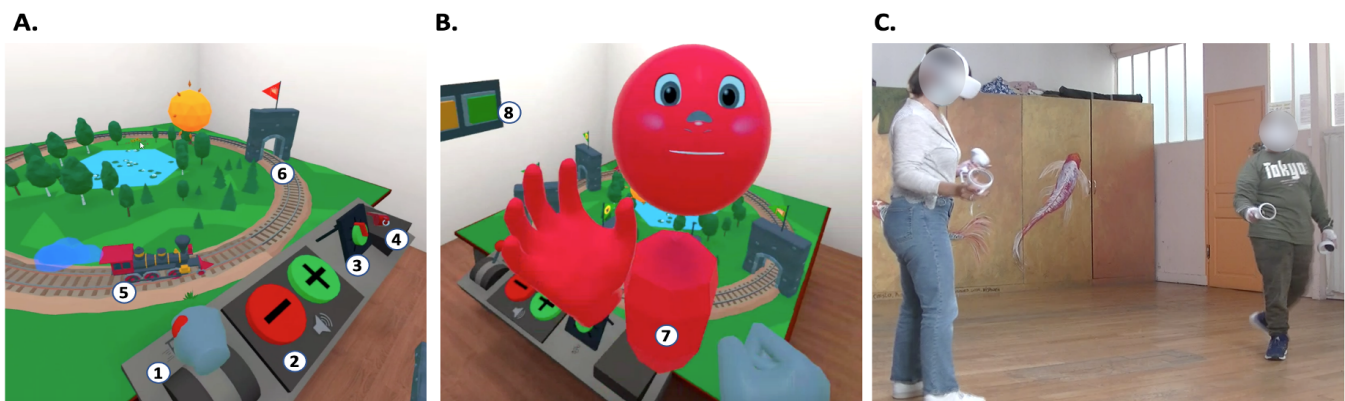


Figure 1: Design of the VR train music loop. (A) Child's VR view. 1: The lever used to control the locomotive's speed. 2: Button to change the sound volume. 3: Knob to change the frequency of the sounds. 4: The whistle. 5: The locomotive. 6: The gate activates different sound effects once the locomotive drives through it. (B) Child's VR view. 7: The virtual avatar. 8: The buttons on the wall that can change the color of the player's avatar. (C) Child and therapist playing together in the room.

## ABSTRACT

Music Therapy (MT) has shown many benefits in helping autistic children, but some challenges remain due to children's social anxiety and sensory issues. Yet, very few studies have investigated how Virtual Reality (VR) could help to increase the accessibility of MT approaches. This paper presents an exploratory study investigating the use of VR to perform MT sessions for autistic children with severe learning disabilities and complex needs. The study is performed in terms of acceptability, usability, and social communication. A collaborative MT approach was designed in close collaboration with music therapists from Denmark and psychologists from France, using head-mounted display-based VR. Testing were conducted with thirteen children with various neurodevelopmental conditions and intellectual disabilities at a children's day hospital in Paris. The results indicate positive acceptability and usability for these children, and suggest a positive effect of MT in VR regarding communication.

## CCS CONCEPTS

• **Human-centered computing** → **Virtual reality**; • **Social and professional topics** → *People with disabilities; Children*; • **Applied computing** → *Performing arts*.

## KEYWORDS

music therapy, virtual reality, autism, intellectual disabilities

## 1 INTRODUCTION

Autism is a neurodevelopmental condition that involves difficulties in terms of social communication and interaction, sensory issues, and repetitive patterns of behavior [4, 38]. Autistic individuals<sup>1</sup> display these features in various proportions along a spectrum. Some have mild learning disabilities and low support needs, with difficulties understanding social cues and engaging in conversations. Others have severe learning disabilities and complex needs, sometimes with associated intellectual disabilities. Severe learning disabilities lead to minimal communication abilities, with some individuals being non-verbal, and significant difficulties participating in everyday tasks [33].

Music Therapy (MT) has shown promising results in developing social and communicative skills in autistic individuals across the entire spectrum (e.g., turn-taking, joint attention) [24, 32]. Music therapists use music as a tool to create interactive approaches

<sup>1</sup>This paper adopts a terminology close to autism stakeholders' preferences [7, 21]. Therefore, identity first-language (e.g., autistic people) is used, and potentially offending terms are excluded (e.g., "disorder", "severe autism").

(e.g. playing an instrument, moving to the rhythm of a song) that are tailored to the specific needs of autistic individuals, to enable non-verbal or verbal self-expression through music [15]. However, several challenges remain when working with autistic individuals. First, social anxiety can make them feel uncomfortable participating in activities involving a therapist or other children [8]. Second, they may feel anxious about making mistakes or feeling judged by their peers, leading to reluctance to participate. Moreover, they can feel overwhelmed by the sensory experiences involved in music therapy sessions [18]. The combination of social and sensory stimuli in MT sessions can therefore make autistic individuals feel uncomfortable and less motivated to participate.

Virtual Reality (VR) seems promising to address the challenges that music therapists face with autistic children. Indeed, it affords to create a controlled space where collaborative musical activities can occur through the use of virtual avatars [20]. Sensory information can be precisely controlled to avoid sensory overloading. Moreover, easy-to-play instruments can be designed to cater for the children's sensory abilities, and be more accessible than in the real-world [34]. Previous studies have illustrated that VR is promising to support autistic individuals with social skills training [12], daily living skills training [2, 3], and exposure therapy [1]. However, while music therapy is used with children over the entire spectrum, most VR studies focus on individuals with mild learning disabilities and low support needs, and without intellectual disabilities [5, 20].

Surveys among music therapists indicate that they often use music technologies to provide their clients with learning disabilities with alternative input compared to traditional instruments [17, 23]. The musical interfaces used with autistic children often consist of traditional screens [31], being used to track progress, improve social interaction, or musical performance [22]. To our knowledge, only few VR MT studies focusing on autism exist [10, 35]. Bryce et al. [10] exposed four autistic children with severe learning disabilities to a 360° video of a children's choir, but findings were inconclusive. Shahab et al. [35] created a Head-Mounted Display (HMD)-based VR xylophone allowing a child to play with a robot avatar. Testing with five autistic children with mild learning disabilities were promising regarding music and cognitive abilities. Moreover, both studies only relied on *natural* interactions with the VR instrument, i.e., interactions that follow real-world physical laws. According to Serafin et al., VR enables the opportunity for creating virtual instruments with *magical* interactions that do not follow real-world physical laws [34].

This paper presents a study investigating two research objectives: whether collaborative MT activities in VR with magical interactions are easily accepted and used by autistic children with severe learning disabilities and intellectual disabilities, and whether they can help to promote social communication between a child and therapist. To address these goals, a VR music looper looking like a train (see Figure 1) was created with two music therapists and then refined with two clinical psychologists. Field testing was then carried out with thirteen autistic children with severe learning disabilities and intellectual disabilities or related neurodevelopmental conditions. To our knowledge, this study is the first to suggest that magical VR instruments for autistic children with severe learning disabilities and intellectual disabilities are promising to support communication.

## 2 METHODS

### 2.1 The Virtual Reality Music Train

These subsections summarize the VR design process that was conducted with two music therapists and two clinical psychologists. A full description is described in a previous paper [29].

**2.1.1 Initial design process.** Before designing the VR intervention, a focus-group interview was conducted with two music therapists. One was a professor teaching an MT master's education with a vast amount of research on autism and MT. The second was a professional music therapist with 13 years of experience working with various clients, including autistic children. Both had tried VR before. The interview aimed at discussing the VR music instrument and environment to be implemented.

Both therapists agreed that no technology could replace an actual therapist. For that reason, their main requirement was entering a VR space with their client and being able to communicate and play the virtual instrument with them. Regarding the environment and avatars, the therapists asked for a "cartoonish" visual style to reduce the social anxiety of the users. Moreover, VR instruments should be easy to play with and require no musical skills.

**2.1.2 Development of the environment.** The VR environment was developed using the Unity3D engine. To allow the therapist and client to speak with each other, a networked connection with voice communication was created using Normcore API. In this environment, users can see the other's avatar movements and what they manipulate.

A VR music looper was designed as both an instrument and social activity inspired by board games, thereby promoting social abilities, such as joint attention. As autistic children often enjoy trains' predictability [16], the looper included a table where a train circulates a railway surrounding a lake, trees, flowers, and a sun slowly rotating in the air (see Figure 1.A). On another table, twelve gate models were placed. The looper included both natural and magical interactions. Users could naturally manipulate the bridges (e.g., take them, throw them). When users put them on the rails, they magically activated a musical sound when the train passed through them. These sounds included marimba, drums, whistles, and "magical" sounds such as whooshes. Additionally, a control panel displayed natural interactions to control the locomotive's speed with a lever, the sound volume using plus and minus buttons, and the frequency of the sounds using a rotating knob (see Figure 1.A). Another natural interaction consisted of a virtual whistle that allowed users to play a whistling sound effect when moving the controller toward the HMD. Whistling resulted in the locomotive emitting a horn sound effect while magically changing the color of the smoke from its chimney. A simplistic, colorful avatar was designed whose mouth moved during verbal communication (see Figure 1.B). Finally, on one wall, a red exit button to quit the application and a green tidy-up button to reset the location of the gates and the whistle were added.

**2.1.3 Adaptation for a day hospital.** In order to test the application in a real-world context, three focus-group interviews were conducted with two clinical psychologists working at a day hospital in

Paris. A day hospital is a clinical institute for children with neurodevelopmental conditions and severe learning disabilities [25]. The objective was twofold: validate the suitability of the application for a day hospital setting, and adapt the design with respect to requirements for this specific setting. The two psychologists were autism experts who had been working at a day hospital for more than three years, knew the target group well, and used digital tools as part of daily interventions (e.g., video games, tablets, robots).

Both psychologists were enthusiastic about using the application. Based on their comments the following changes were made. To give children more agency, three colored buttons were placed on the walls (see Figure 1.A), which could be pressed to change the color of the user’s avatar. Once a user grabbed a gate, the color of the gate’s flag and visual feedback would magically change to the current color of its avatar. A nose and a pair of eyes were added to the avatars to make them look more expressive (see Figure 1.B). Considering sensory issues in autism, the size of all objects was increased, as well as the weight of the gates. The scale of the room was also decreased to make everything accessible at arms’ reach. At last, some high-pitch sounds that may be distressing for some children were replaced by low-pitch ones.

## 2.2 Evaluation at a day hospital

**2.2.1 Participants.** The two clinical psychologists who participated in the design process recruited thirteen autistic children with severe learning disabilities and intellectual disabilities, or related neurodevelopmental conditions, from the day hospital in Paris, in agreement with the clinical team. Children were between 7 and 13 years old (MA:10.46, SD:1.51). Including children from 7 was not considered to be an issue as Newbutt et al. [26]’s study suggested that HMDs could be used from 6 years old for autistic children, provided that a protocol is devised to ensure their safety. Therefore, such a protocol was made in collaboration with the clinical team, as detailed in the next paragraph. Four children were verbal (P1, P2, P3, P6), six had limited verbal abilities (P4, P5, P7, P8, P12, P13), and three had minimal to no verbal abilities (P9, P10, P11). All had ID, their intellectual quotient being inferior to 70. P2 and P6 had some school inclusion times, while others were in the day hospital full-time, where they were also receiving adapted teaching, due to significant social and cognitive difficulties. This low number of children was due to our inclusion criteria, which required them to have a neurodevelopmental condition according to the International Statistical Classification of Diseases and Related Health Problems (ICD-10) [27], intellectual disabilities, and no epilepsy. As similar numbers of participants are used in other VR studies for autism [2, 14, 35], due to the population being hard to reach, it was deemed suitable to address our research objectives. Table 1 summarizes their conditions.

**2.2.2 Protocol.** The children participated in at least one VR session, during which they interacted with the psychologists or another child. The two psychologists were always present as well as one psychology intern. Children’s educators were sometimes present, when interested or for reassurance, following the clinical rules of the day hospital. Sessions were child-directed and lasted fifteen minutes. All sessions were filmed. The psychologists filled out a three-part semi-structured questionnaire taking five to ten minutes after each

session. Indeed, according to them, children could not answer by themselves due to their conditions. In the first part, six questions asked if the child was tired, anxious, or happy before and during the experiment. Then, nine questions inquired about the overall child’s VR experience, as described in Table 2. After that, six questions addressed acceptability and usability issues, inspired by previous studies [6, 9]. Questions focused on: the acceptability of the HMD, disturbance when removing it, easiness of using the system, and the required levels of support to move, focus, and interact with the system. At last, the psychologists could add additional observations. Each question used Likert scales and optional comments. The levels of the Likert scales went from 0 to 4 in the first and third parts, as the criteria were inspired by 5-level Likert scales used in the SUS scale [9] and Bauer et al. [6]’s study. The levels of the Likert scales went from 0 to 5 in the second part, as the criteria were inspired by various studies which adopted different evaluation metrics [11, 30, 37]. As a result, we decided to use 6-level Likert scales to avoid having a neutral option and have the same metric for all questions in this second part.

The clinical staff of the day hospital ensured ethical validation of all procedures and testing.

**Table 1: Profiles of autistic children. Condition corresponds to the ICD-10 classification.**

P	Age	Sex	Condition (ICD-10)
1	10	M	Pervasive developmental disorder, unspecified (F841)
2	11	F	Mixed specific developmental disorders (F83)
3	10	M	Atypical autism due to symptomatology (F84.11)
4	10	M	Childhood autism (F84.0)
5	12	M	Childhood autism (F84.0)
6	7	M	Atypical autism due to symptomatology (F84.11)
7	12	M	Atypical autism due to symptomatology (F84.11)
8	12	M	Childhood autism (F84.0)
9	11	M	Other childhood disintegrative disorder (F84.3)
10	12	F	Other childhood disintegrative disorder (F84.3)
11	9	M	Childhood autism (F84.0)
12	11	M	Pervasive developmental disorder, unspecified (F84.9)
13	9	F	Childhood autism (F84.0)

**2.2.3 Data analysis.** All data collected were anonymized by affecting identifiers to the children. To facilitate the data analysis by our team, the first author translated the psychologists’ free comments to the questionnaire into English. The two first authors then reviewed the questionnaire’s answers to check for discrepancies between the ratings and the comments. They then looked at the videos to take notes about critical incidents and better understand the observed discrepancies. Due to the low number of participants and their strong idiosyncrasies, the ratings were analyzed using descriptive statistics while considering practitioners’ comments. Comments were mainly analyzed using *deductive content analysis* [13], which consisted in analyzing the data with respect to the questionnaire’s categories (e.g., acceptability, usability). *Inductive content analysis* [13] was also used to pay attention to other insights, consisting of unexpected observations being absent from our initial categories.

**Table 2: Questions about children’s experiences with VR. The MT literature references that inspired the choice of questions and their wordings are mentioned in the column called “Ref”. Some questions were also advised by the psychologists (noted ‘Ps’). The ‘+’ and ‘-’ signs indicate if the questions ask about positive or negative aspects.**

Index	Question	Ref
A(-)	The child displayed stereotyped movements.	Ps
B	The child displayed body awareness.	Ps
C	The child could maintain focus on the activity.	[11]
D	The child was engaged in the activities.	[11, 37]
E	The child displayed an understanding of the cause-and-effect relationship in the activity.	[11]
F(-)	The child appeared overstimulated.	[11]
G(-)	The child displayed stress or anxiety.	[11], Ps
H	The child had the ability to react with nonverbal communication.	[11, 37]
I	The child was verbalising pertinent (fitting) to the interaction.	[30, 37]

### 3 RESULTS

#### 3.1 Acceptability and usability

This subsection summarizes children’s experiences in terms of acceptability and usability based on questionnaires filled by the two psychologists during the VR sessions. The results from the respective answers to the questionnaire are summarized in Figure 3.

Of the thirteen children, eleven accepted wearing the HMD: nine very easily, and P11 and P13 only for a short time. In particular, P11 could wear the HMD after one of the psychologists wore it. P13 quickly tried the HMD but lifted it to keep seeing the physical world and did not seem to be immersed in the VR environment. However, two participants (P4 & P12) refused to wear the HMD. P4 said “no” a few times when the psychologist suggested him to wear it, but he was interested in looking at the VR environment through the computer screen. Still, he managed to look inside the HMD once. The psychologists highlighted that he usually needs more time when doing new activities. P12 seemed scared about the HMD, although he was amused to see his educator wearing it.

Among the eleven children who wore the HMD, four received the highest rating of four out of four (4/4) regarding how easy it was for them to use it, five could use it but with lower ratings (2/4 or 3/4), while P1 and P13 received very low ratings (1/4). Low usability for P1 and P13, respectively, draws from bugs occurring during the P1’s experience and from P13’s interest in her look with the HMD rather than in the VR experience. P2 and P5 needed minimal verbal or physical guidance from the psychologists to move around, focus, or use the instrument (0/4 to 1/4 on at least one of these features). On the contrary, nine needed much guidance (3/4 to 4/4 on at least one of these features) (see Figures 2.C and 2.D), three of whom became more autonomous toward the end: P9 needed less support to explore, P6 moved around alone, and P10 picked up one bridge by herself. However, P11 and P13 struggled to use the controllers and HMD simultaneously. P11 refused the controllers but often

tried to touch things with his hands, and P13 sometimes grabbed the controllers without using them to interact. Finally, P1 and P7 were somewhat annoyed when removing the HMD, as they wanted to keep playing. Indeed, P1 wanted to keep experimenting as some bugs (e.g., lags, not seeing his hands) prevented him from properly exploring the VR space, and P7 was so enthusiastic that he did not want to stop.

Among the eleven children who wore the HMD, five experienced no negative effect (0/5) (the rating being understood as a mean of the answers to the questionnaire about sensory overstimulation, stress, and stereotyped behaviors), as shown in Figure 4. P1 and P13 had nearly no negative effects (0.33/5): P1 was a bit stressed when some bugs happened, and the psychologists had difficulties to understand what P13 was experiencing. P5 (1.33/5), P6 (1/5), and P7 (1/5) had some negative experiences, not corresponding to stress or anxiety but rather to a slight over-arousal. In particular, this led P5 to do some repetitive vocalizations (1.33/5), and P7 to be in a rush to test everything (1/5). However, the psychologists added that P6 was stimulated “as he should be”. Some negative experiences were only reported for P11 (2.33/5), with some stress and repetitive movements before wearing the HMD. While refusing to wear the HMD he was agitated, making mouth noises and jumping, he was way calmer once the HMD was on his head.

#### 3.2 Verbal and non-verbal communication

Out of the eleven children who wore the HMD, six socially communicated a lot (more than 4/5 for verbal or non-verbal communication), two somewhat communicated (between 2/5 and 3/5), and three communicated just a little<sup>2</sup> (see Figure 5). Among the children who communicated the most, five verbally described what they experienced or spoke with the psychologists (e.g., to express their joy). Moreover, P10, who is non-verbal, growled toward the end of the session, showing her will to share her experience, and waved to the psychologist’s avatar (see Figure 2.B). The psychologists were also surprised by P8, who interacted a lot with the avatar and the adults in the room, as he is usually solitary when discovering an activity. In addition to replying to questions, he initiated conversation, for instance, when saying to everyone, “Did you see it ?” after performing some action in VR. Then, P5 and P7, who had a moderate level of communication, replied to questions but did not communicate much since they were busy discovering the VR environment. For instance, P5 hugged the psychologist’s avatar but was described as being “in his own world”, speaking with his imaginary language to himself (see Figure 2.A). P7 socially interacted a lot but without language, although he is verbal. Regarding the three children who communicated the least: P9 did many things with guidance and said goodbye at the end, P11 had some physical and eye contacts, and P13 did not seem to be involved at all.

#### 3.3 Attention and engagement

Among the eleven children wearing the HMD, ten were focused and engaged, and P13 had the lowest engagement score (see Figure 6). Among those engaged, six were fully engaged (5/5), being very happy and interested: laughing, smiling, and saying that they

<sup>2</sup>Even if ID9 and ID13 both have ratings of 2/5 for non-verbal communication, they were classified as communicating just a little based on practitioners’ comments.



Figure 2: Key events that occurred during the sessions. (A) P5 hugging the psychologist’s avatar in VR. (B) P10 waving to the psychologist in response. (C) Psychologist showing P10 how to pick up the whistle and bridges. (D) P6 laughing with the psychologist after managing to throw a bridge with physical guidance. (E) P9 touching the floor with his controller and hand.

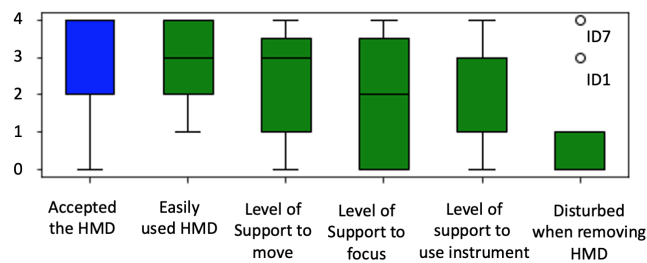


Figure 3: Quantitative ratings from the questionnaire about children’s acceptability and usability. The boxplot in blue concerns all children and boxplots in green only include the eleven children who accepted to wear the HMD.

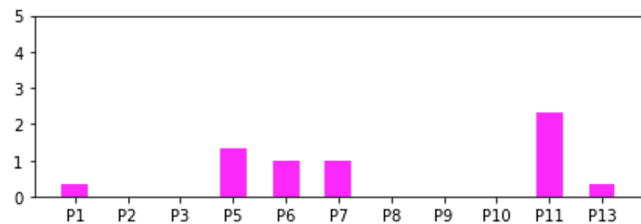


Figure 4: Quantitative ratings from the questionnaire about children’s negative experiences. On the ordinate axis, the scores represent the negative experiences children had, understood as the mean of the ratings related to sensory overstimulation, stress, and stereotyped movements.

enjoyed the experience and commenting on it (depending on their verbal abilities). For instance, P6 laughed after throwing a bridge with the psychologist’s help (see Figure 2.D), and said, “Wow, it was so great !!” when leaving the room after the experience. P5 and P7 also asked to continue using the HMD (e.g., wearing it again), and P3 seemed happy which was something that rarely happened

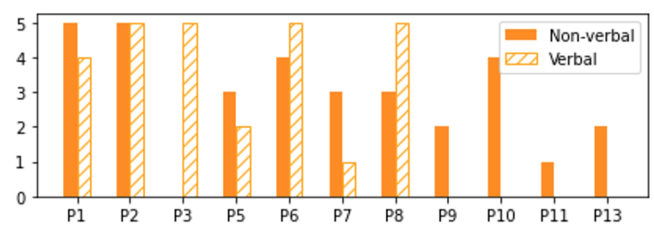


Figure 5: Quantitative ratings from the questionnaire about verbal and non-verbal communication. The verbal or non-verbal conditions of children is detailed in subsection 2.2.1.

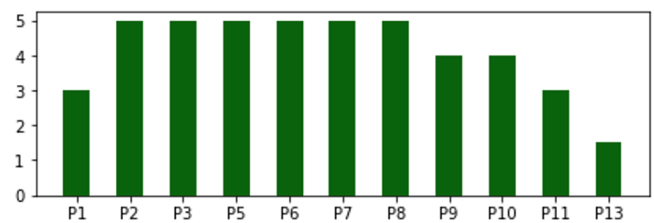
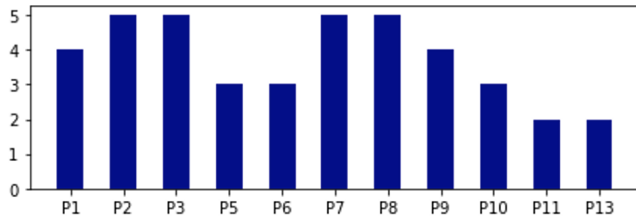


Figure 6: Quantitative ratings from the questionnaire about attention and engagement.

according to the psychologists. Then, P9 and P10 seemed highly engaged but could express it less due to their minimal verbal abilities. Indeed, at the session’s end, when the practitioners asked P9 “Did you like it ?” and “Will you do it again?”, he answered yes to both questions. P10 also made lot of growling noises, which usually show engagement, communication, and pleasure. At last, P1 and P11 seemed moderately engaged (with ratings between 2/5 and 3/5). However, P1 faced some bugs during the sessions, making getting involved difficult. P11 non-verbally asked to try VR again after removing the HMD, and the psychologists remarked that his discovery was “very moving.” At last, P13 was the only child not interacting with the virtual environment and the application, being

more interested in her look with the HMD than in the application. This was observed by her often walking towards the physical mirror in the room and looking at herself. Nevertheless, her non-verbal condition prevented us from collecting further information about this disengagement.

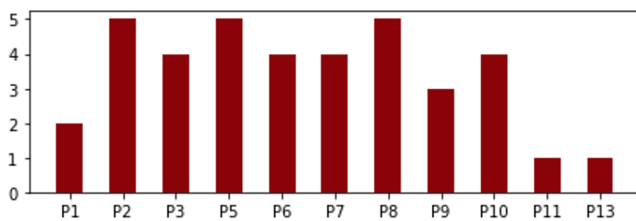
### 3.4 Body awareness



**Figure 7: Quantitative ratings from the questionnaire about children's body awareness.**

Six children had a very positive body awareness (rating superior to 3/5), and five had moderate awareness (rating between 2/5 and 3/5) (see Figure 7). The former were able to move nearly without repetitive movements. In particular, P1 and P7 explored their body in different ways (e.g., crouching on the floor), P7 moved very fast, and P8 opened his mouth to look like he was blowing when using the whistle. The latter displayed different behaviors. P5 and P11 managed to move in space, but P5 did some repetitive vocalizations, and P11 was agitated before wearing the HMD. P6 and P10 remained quite still while observing the VR space. P13 moved after being equipped with the HMD, then lifted the HMD and looked in the mirror. From then, she always kept an eye on the real room while wearing the HMD, and looked back twice in the mirror.

### 3.5 Understanding



**Figure 8: Quantitative ratings from the questionnaire about children's understanding.**

Seven children understood how to use the application - three very well and four well - two had a moderate understanding (rating between 2/5 and 3/5), and two had a low understanding (rating inferior to 2/5). Children with a good understanding can be divided into two groups: P2, P3, P5, P6, P7, and P8 exhibited a quick understanding, and P10 (who usually needs guidance to act) succeeded in grabbing the whistle and bridges after many attempts. In particular, P8 performed every interaction and loved using the whistle, and

P6 managed to listen to psychologists' advice while being excited each time he discovered new forms of interaction. Regarding the two children with a moderate understanding, P9 could interact a little, but the psychologists remained unsure about his overall understanding, and P1 was hindered by some bugs. The lack of understanding of others resulted from different causes: P13 did not really try, and P11 would have needed more sessions due to his condition. Indeed, wearing the HMD was already an achievement for P11. At last, four children tried to explore what was in the real room and in the virtual space, to understand the difference and for reassurance: P8, P9, P11, P13 tended to lift the HMD, and P9 touched the real floor with his controllers and real hand (see Figure 2.E).

### 3.6 Other insights

Two unexpected insights appeared in psychologists' comments through their answers to the questionnaire. First, P8 and P10 were disturbed when wearing the HMD and accidentally hitting the psychologist who was wearing a HMD, as the psychologist's avatar was not at the same position as the psychologist in real life. Both children removed the HMD at this moment. To reassure himself after putting back the HMD, P8 also said "Look, do you see me?" to the psychologist, who answered, "Yes, I see you." Moreover, psychologists were interested when children tested the limits of the system. For instance, P5 went outside of the interaction space boundaries several times, and P8 and P9 threw bridges instead of putting them on the rails. According to psychologists, this capability to "break the system" is beneficial as it allows children to express themselves in alternative ways.

## 4 DISCUSSION AND CONCLUSION

This paper addressed the use of musical activities with VR magical instruments for autistic children with severe learning disabilities and intellectual disabilities, in terms of acceptability, usability, and social interaction. To that end, a collaborative VR music looper looking like a train was designed in collaboration with two music therapists and then adapted for a children's day hospital with two clinical psychologists. Field testing was then carried out with thirteen children with autism or related neurodevelopmental conditions. Below, our findings are discussed, followed by limitations and future perspectives. To our knowledge, this is the first study that suggests that magical collaborative VR instruments for autistic children with severe learning disabilities and intellectual disabilities are promising to support communication.

Most children accepted to wear the HMD, except for two who were respectively anxious or needed more sessions due to their condition. No adverse effects appeared with the HMD. Three children were slightly over-aroused, but it was not overwhelming. Moreover, P11 was agitated before wearing the HMD but significantly calmer once he agreed to wear it. Among the eleven children who wore the HMD, two used the VR application with minimal guidance from the psychologists and nine with much guidance (e.g., psychologists wearing the HMD before them). This finding echoes the findings from Garzotto et al. [14]'s VR study and Bauer et al. [6]' AR study with children with neurodevelopmental conditions and ID, where children with the most severe forms of disability required much guidance to wear the HMD and interact. In our study, two children

also had difficulties wearing the HMD and controllers simultaneously. Considering widespread sensory issues in autism and related neurodevelopmental conditions, this finding is not surprising and prompts further adapting the equipment according to children's sensory needs, as previously encouraged by Parsons et al. [28]. Finally, three body awareness levels were observed: eight children could easily navigate the VR space, P6 and P10 remained still while observing the VR space, and P13 moved while keeping an eye on the physical space.

Three communication levels related to children's understanding and engagement were observed: communicating a lot, moderately communicating, and communicating very little. The first level concerns five children (P2, P3, P6, P8, P10) who communicated a lot verbally (e.g., P8 said to everyone "Did you see it?") or non-verbally (e.g., P10 growled), who were fully engaged and managed to interact with the VR environment. The second level concerns P5 and P7, who understood how to interact and were highly engaged. However, this led them to be in a rush to explore everything, therefore replying to questions but not initiating conversations, except for expressing their joy (e.g., P5 hugged the psychologist a few times). The third category concerns P9, P11, and P13. All communicated minimally and relied a lot on the psychologist to explore (e.g., P11 non-verbally asked to try VR again). P11 had understanding issues due to his condition, and psychologists were unsure of his engagement. P9 was engaged, but psychologists were unsure of his understanding. P13 did not seem interested and had a low level of understanding. P1 can be considered an outlier as he communicated a lot (e.g., hugs, request to wear the HMD again) but faced some bugs (e.g., not seeing the psychologist's avatar) that hindered his understanding and engagement.

This study also displays some limitations. First, the heterogeneity of children's conditions and their idiosyncrasies prevent us from generalizing our results to other children. Further testing should thus be carried out to cross-validate our findings. As our study was performed in a day hospital, to be more ecologically valid [28], some environmental conditions could not be controlled, which may have influenced children's behaviors (e.g., when other children shouted in the corridors). Therefore, new methodologies should be devised to decrease the impact of such external factors on the findings. After that, our findings mainly account for practitioners' views due to children's minimally verbal conditions and ID. Future work may consider creating methodologies enabling to also collect children's views, such as with drawings or pictograms, as previously proposed by Spiel [36]. To devise such methodologies, our questionnaire could be discussed through participative design sessions in collaboration with autism stakeholders. At last, the translation from French to English of the psychologists' free comments may have led to some inaccuracies.

Future perspectives consist of comparing the effect of using magical and natural VR music instruments with autistic children regarding their social communication and interaction abilities. Indeed, contrary to our study, the two previous studies that investigated the use of VR music instruments for autistic children used natural interactions and did not present positive evidence concerning an increase in social abilities [10, 35]. However, differences in settings and methodologies between these studies and ours prevent us from concluding that VR magical interactions are best suited for autistic

children. Nonetheless, drawing upon Serafin et al. [34], we argue for using VR to facilitate magical experiences that could not happen in the physical world rather than replicating existing music practices since the original ones often work well. Future studies could investigate the effect of using various proportions of magical interactions on the social interaction abilities of autistic children. For instance, some research endeavors could focus on widening access to existing music practices by facilitating the required interactions using VR magical interactions, e.g., facilitating the access to a xylophone by using a VR replica with magical interactions. Others could focus on creating VR magical instruments that do not exist in the real world, but still include some natural interactions, e.g., an instrument that does not exist in the physical world but uses the metaphor of having different keys, such as with a xylophone.

Future developments of this work also include the following research endeavours. First of all, conducting studies with more children by collaborating with other clinical institutes is desired. Second, we plan to place the psychologist and the child in different physical locations to reduce the child's concerns for accidentally hitting the psychologist while wearing the HMD. Third, the fact that two children faced difficulties using the HMD and controllers simultaneously, or tried to touch VR objects with their hands, encourages to use hand tracking solutions. Lastly, as two children did not accept to wear the HMD, an asymmetric interaction [19] that enables interaction with VR instruments through another medium (e.g., tablet, projector) could help to better cater to their needs.

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