VIBROTACTILE MEMORY: A CASE STUDY OF TIMBRE PERCEPTION TRAINING IN CHILDREN WITH COCHLEAR IMPLANTS USING A VIDEO GAME

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ABSTRACT

This paper presents a preliminary study investigating the effectiveness of a computer game designed for enhancing timbre perception in children with cochlear implants. The game focuses on instrument recognition and incorporates vibrotactile feedback through the PlayStation 5 DualSense controller. A case study was conducted involving a 7-year-old participant diagnosed with hearing loss due to auditory neuropathy who uses both a cochlear implant and a hearing aid. Training sessions were conducted over a two-week period, with assessments performed before and after the training thanks to a modified version of the Timbre Perception Test. Despite incorporating vibrotactile feedback and tracking participant progress, the study did not observe significant improvements in timbre perception. Factors such as the short duration of the training period, the difficulty of the game, and potential boredom may have influenced the outcomes. The study highlights the need for further research to refine the training intervention, including extending the duration, enhancing engagement, and conducting larger-scale studies with diverse participant groups.

1. INTRODUCTION

Cochlear implants (CIs) are surgically implanted neural prostheses designed to restore hearing in people with profound hearing loss (HL) [1]. Until recently, researchers and companies focused mainly on optimizing these devices for speech, obtaining good results in reestablishing language comprehension [2]. These devices, however, still present challenges for music appreciation. Music, in fact, is a highly complex phenomenon with many factors that can influence its enjoyment and access for hearing aids (HA) and CI users [3–5]. The hardware, software, and physical limitations of CIs result in a reduced frequency range, incapability of distinguishing sounds' consonance and dissonance, limited dynamic range, and difficulty in recognizing instruments (timbre) [6]. Consequently, music enjoyment and the emotions that it can elicit are directly affected, most often resulting in limited fruition. In addition, musical background, degree of success of the surgery, as well as the presence of other pathologies, have an effect on the hearing experience, making every user's sound experience unique.

These general considerations apply to young recipients too, but some additional aspects have to be considered when children are taken into account. Early cochlear implantation has been shown to yield long-term positive effects, providing children with speech capabilities comparable to their normal hearing (NH) peers before the age of four [7]. After age four, young recipients of CIs develop speech slower than NH individuals, making personalization of learning goals a key aspect of training [8]. Ad-hoc training is even more important when the child suffers from auditory neuropathy (AN), a pathology that implies disrupted neural activity that impairs timing perception, low frequencies' perception, temporal integration, gap detection, sound localization among other things [9]. However, children with HL diagnosed in recent years that are fitted with HA and CI before one year of age, may perform differently from previous generations.

Emerging evidence shows that music training improves music perception skills and experience [6, 10, 11], together with psychosocial well being and quality of life [12]. One of the novel techniques to possibly improve musical listening performance is the use of vibrotactile feedback [13]. Vibrotactile feedback refers to the mappings between audio and vibrations that can help to emphasize specific features such as pitch [14, 15]. Another common approach that improves learning experiences for children is the gamification of the training activities [16, 17]. This strategy can guide youngsters with hearing loss towards improving their musical skills [18], especially when HL is due to auditory neuropathy.

Gamification has demonstrated its effectiveness as a tool for enhancing engagement and motivation across various domains, ranging from business to marketing [19]. It has also shown positive impacts on the learning process, improving engagement and knowledge acquisition [20]. Consequently, gamification appears to be a promising approach for boosting participation in training activities among individuals with hearing impairments. However, it remains a relatively new area of inquiry that has yet to be thoroughly explored [21].

In this paper, we introduce a computer game for musical training of children with cochlear implants, with the aim to improve timbre perception through instrument recognition. The game presents different levels of difficulty and features vibrotactile feedback conveyed through the PlayStation 5 controller DualSense [1] . We report a preliminary case study [22] to collect information about user interaction and efficacy to train the timbre perception.

In Section 2 we present the methodology applied for this case study, including the process and design choices made to create the training video game; in Section 3 we showcase the data retrieved from this experiment and finally in Section 4 we analyze the results and draw some considerations related to the whole case study.

2. METHODOLOGY

2.1 Participant

The participant was 7 years old at the time of the experiment. At the age of 4, she received a cochlear implant in her left ear, and she uses a hearing aid in her right ear (bimodal). She has been diagnosed with AN, a condition that can pose challenges in the transmission of signals from the auditory nerve to the brain's auditory cortex. No assessment of the actual hearing capabilities of the subject has been performed for the scope of this project. We did not characterize the user's perception of vibrotactile stimulation; given the participant's young age, we assumed they have ideal sensitivity capabilities, as most degradation occurs with aging or due to traumas [23] (e.g., heavy-machinery use). The participant has been recruited through the Center for Hearing and Balance from the Rigshospitalet of Copenhagen with approval from the parents and the clinicians.

2.2 Design

In the following sections, we present the project's design process and the experiment.

2.2.1 Participatory Design

We applied the principles of *participatory design* [24, 25] involving the end user in the process to open a dialogue to gather ideas and feedback throughout the development. The child, together with the parents and the audio-verbal therapist contributed to the process through an official meeting and some more informal gatherings. During the first meeting, we collected information about the preferred video games from the child as well as clinical practices and training tools already available. In the follow-ups, we mainly included the clinician to receive feedback about the experiment as well as the interface.

[1] Sony Playstation DualSense Controller https://www.playstation.com/en-dk/accessories/dualsense-wireless-controller/ — Last access May 22, 2024

2.2.2 Experiment Design

We designed an experiment that features a video game aimed at training children to improve their timbre perception through listening to musical instruments. The experiment includes an initial assessment of timbre perception, a training period using the video game, and a final assessment of timbre perception. In addition to sound feedback, vibrotactile feedback was incorporated to convey musical information through the sense of touch. The hardware setup comprised a laptop equipped with loudspeakers and a controller to provide both vibrotactile feedback and input capabilities. In Figure 1 the simple setup is depicted.

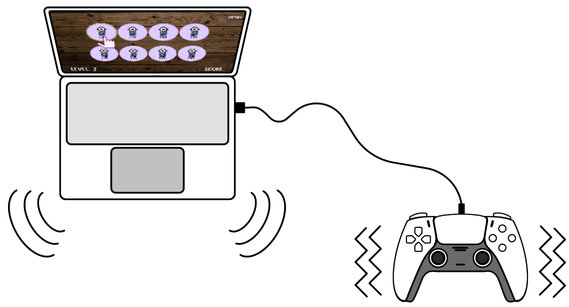

Figure 1. Setup for the training experience.

The experiment extended over a two-week period, with the participant conducting the training activity at home three times a week under the supervision of her parents. The training tool systematically tracked the progress of each participant, facilitating a comprehensive analysis of their performance. Ultimately, we conducted interviews with both the child and their parents at the conclusion of the training period to gain insights into their overall experience and gather feedback on potential enhancements to the prototype.

To assess the efficacy of our intervention, a modified version of the Timbre Perception Test (TPT) [26] was administered both before and after the training in the clinic together with the researchers and the audiologist. The modifications involved scaling the parameters to create a more pronounced difference in the controls, ensuring they were easily audible to the participant.

2.3 Assumptions

Given a single participant and the specific design of the test, we did not formulate hypotheses but instead made some assumptions regarding our expectations concerning the training activity that involved the child with AN:

1. Increasing the training duration will lead to a reduction in the required interaction, measured by the number of clicks, with the cards.

2. Incorporating vibrotactile feedback will improve the ability to discriminate between the cards.

2.4 Training Environment

While creating the training game, we drew inspiration from the classic memory card game, where players take turns flipping pairs of cards to find matching pairs. In our design, we incorporated the same mechanics, but rather than requiring the player to focus on images, we asked them to concentrate on sounds, with particular attention to the timbre of the instrument being played. Once a card is selected, the corresponding sound (and eventually vibration) is played through the laptop's loudspeakers. Only when a matching pair is found, the cards turn, revealing the image of the instrument playing. This approach is borrowed from auditory verbal practice, where sound is provided before vision; thus, the patient is induced to focus first on sound, while visual feedback is given only at a later stage to reinforce the association [8] aiming to enhance both listening capabilities in terms of timbre quality and auditory memory.

We developed the game using the Unity game engine (*ver. 2021.3.11f1*) [27] in a 2D environment. User interaction is made possible through the use of the DualSense controller from Sony. This choice led us to face the problem of feeding the user with a synchronized and coherent vibrotactile signal with the audio. The controller, when connected with a USB cable, behaves as both an input device and vibrotactile feedback. To provide both sound and vibrotactile feedback on independent streams, we opted for controlling the audio and haptic stream through FMOD for Unity [28]. This allows to simultaneously use the integrated sound card of the host laptop and the controller's internal sound card. In Figure 2 we can observe a screenshot of the video game. In the bottom side of the screen, level and scores are reported. From the main menu of the game it is also possible to check the progress of the game and play again the completed levels for further training.

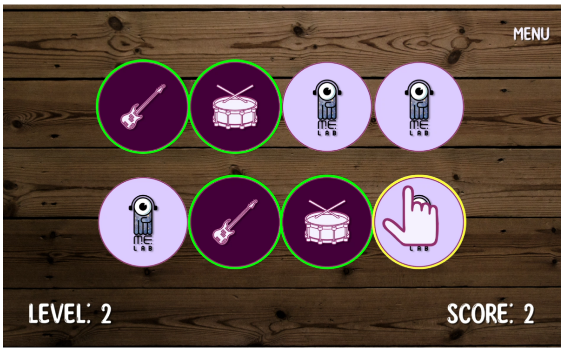

Figure 2. View of the memory game.

2.4.1 Level Generation

The game consists of 16 levels with increasing difficulty. The parameters that vary between the levels include the number and similarity of instruments, as well as the melodies played. Instrument similarity is defined in terms of timbre, where, for instance, a violin is very similar to a viola but remarkably different from a trumpet. Table 1 illustrates how the levels are structured in the game. It's important to note that each level has two different versions—one with haptic feedback and one without. This explains why we report only 8 levels in Table 1 while in the game there are 16. These versions run consecutively, though this detail is not included in the table for the sake of readability.

Level	# Instr.	Similarity	Melody
1.1	4	Different	Different
1.2	5	Different	Different
2.1	4	Different	Same
2.2	5	Different	Same
3.1	4	Similar	Different
3.2	5	Similar	Different
4.1	4	Similar	Same
4.2	5	Similar	Same

Table 1. Level's difficulty structure

In order to prevent any bias, the instrument position and type, and the melodies are randomly assigned to each level and re-calculated at every run.

2.4.2 Data Acquisition

With the aim in mind of tracking the progress of the participant, we implemented a saving system that records the content of each level (i.e., instruments and melodies), the number of clicks per card, and the time it took to complete the level. All this information is stored in separate `.json` files saved in a hidden folder of the host computer's file system to prevent data manipulation from the end user.

2.5 Stimuli and Instruments

To exert the highest degree of control over the musical stimuli present in the experiment, we chose to generate all the recordings from MIDI files. This involved using a set of four AI-generated melodies [2], one ascending and one descending scale, and two famous excerpts (Eine Kleine Nachtmusik and Piano Sonata No. 16 "Sonata Semplice," both composed by Mozart), totaling eight melodies. All recordings are played at 100 BPM and last for two bars, covering a range from A3 to F5 (220 - 698.5 Hz). The MIDI files were employed to feed a set of audio plug-ins based on either sampled or physically modeled instruments to achieve high-quality audio and fidelity. The instruments selected for the experiment are listed in Table 2, grouped by timbre similarity.

Instrument	Category	Instrument	Category
Xylophone	1	Violin	3
Piano	1	Trumpet	4
Guitar	1	Trombone	4
Bass	2	Flute	5
Cello	3	Sax	5
Viola	3	Clarinet	5

Table 2. Instruments categories grouped by timbre similarity

The sound stimuli were generated by loading the MIDI files into Reaper [29], a Digital Audio Workstation (DAW), along with the virtual instruments shown in Table 2. The

[2] Magenta Studio Generator — `https://magenta.tensorflow.org/studio` — Last access May 22, 2024

individual audio files were then exported at 44.1 kHz and 16 bits. All the stimuli were normalized at -12 dB to maintain an equal perceived loudness. These same files were used for both the audio and vibrotactile feedback. The experiment was conducted feeding the vibrotactile actuators with unprocessed audio signal. This choice was driven by the type of training task: since we focus on timbre and musical instrument recognition, we wanted to preserve the frequency spectrum and the envelope of the instruments, following the approach used by Russo *et al.* [30]. In future iterations we will develop other training activities that will include melodic contour identification, and we will use different mapping techniques such as the one used in [15].

2.6 Vibrotactile Input

Humans' mechanoreceptive system is capable of perceiving vibrations up to approximately 1 kHz ([23]) and therefore choosing actuators able to cover this frequency range is crucial. In literature, it is possible to find several prototypes available such as vests, gloves, and furniture ([31]). These solutions are not suitable for our project, since the target group requires rugged devices that are easy to use and feature plug-and-play behavior. Consequently, we opted for a commercially available gaming console controller that children might be familiar with. In addition, these devices can be brought at home and connected to any laptop, giving a good degree of flexibility. Recently, Sony released the PlayStation 5 with the DualSense controller (2020) that features high quality vibrotactile feedback conveyed through voice-coil actuators. The working principle of this technology is similar to the loudspeaker, and thus shares a comparable performance in frequency range.

3. RESULTS

3.1 Video Game's Data

As introduced in Section 2.4.2, we tracked how many times the user interacted with the cards by clicking on them and listening to the sound. In Figure 3, the total number of clicks per session can be seen. The number shown on top of each bar indicates the level in the video game. The bars with the green outline represent the levels with 5 pairs of cards, while the ones without represent 4 pairs of cards. Additionally, there are green and white lines representing the optimal number of moves for 5 and 4 pairs of cards, respectively, where the optimal number represents the expected number of flips (clicks in our case) with a player presenting a perfect memory as demonstrated by Velleman *et al.* [32]. The optimal moves for n pairs of cards are calculated as following:

$$(3 - 2\, ln\, 2)\; n + 7/8 - 2\, ln\, 2 \approx 1.61 \times n$$
$$n = 4 \rightarrow opt.moves \approx 6.44$$
$$n = 5 \rightarrow opt.moves \approx 8.05$$

In figure 3 we can notice that the interaction between the cards for both levels with 4 and 5 pairs of cards are approximately twice the optimal moves reported in the formulas above.

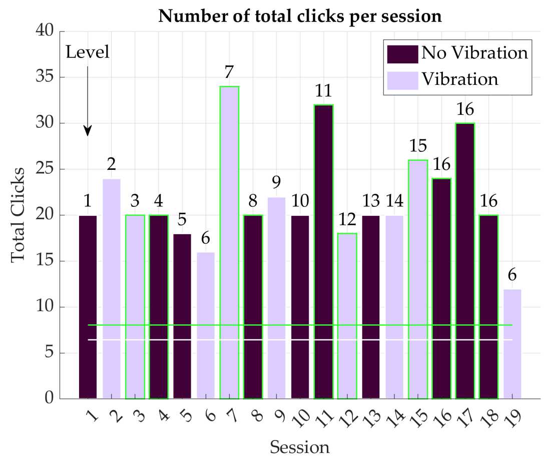

Figure 3. Total amount of clicks on the cards per every level. The levels with green outline are the ones with two extra cards. The white and green lines indicate the optimal moves for 8 and 10 cards respectively.

Observing Figure 4, there is no recognizable patter or trend that could suggest an effect of the vibrotactile feedback or total training time on the average number of clicks per card. The average number of clicks per card among all sessions is 2.42.

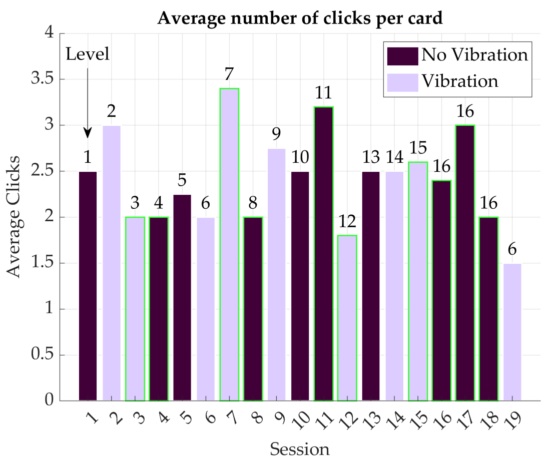

Figure 4. Average amount of clicks on the cards per every level. The levels with green outline are the ones with two extra cards.

In Figure 5 the amount of time elapsed to complete each level is reported. We can observe that the average duration for levels 11 to 16 (excluding the 14th session) is 6 minutes and 8 seconds. This means that participants took between 1 minute and 13 seconds and 1 minute and 32 seconds to find a correct pair, depending on whether the level presented 4 or 5 pairs of cards.

Figure 6 shows the score deviation between the target sound and the answer from the participant. The values represent the number of steps from the slider used in the TPT interface. Running a t-test on the difference between the

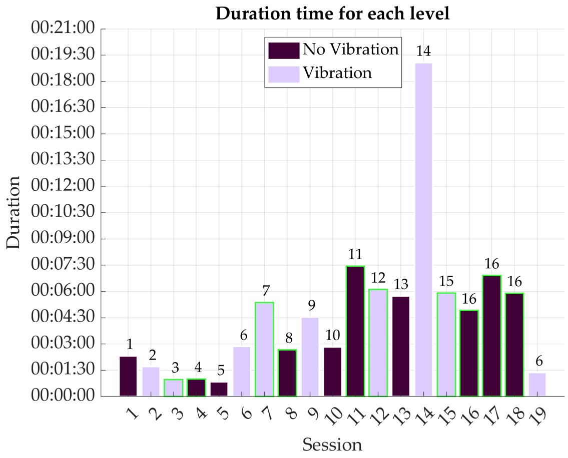

Figure 5. Time elapsed to complete each level.

answer and the target values, we found a p-value of 0.2466 showing no significant difference between the pre- and post-training. For more information we suggest referring to the manuscript [26].

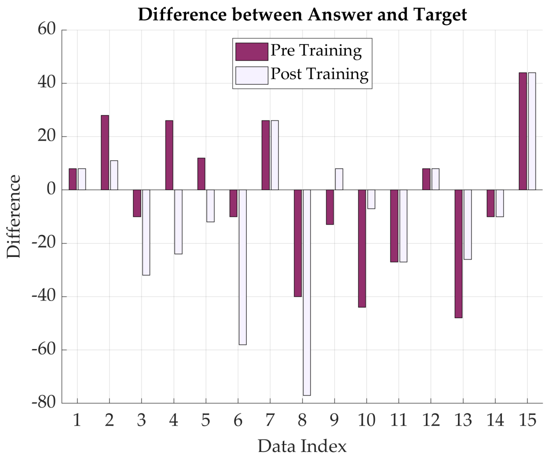

Figure 6. TPT before and after training comparison.

3.2 Interview

To prevent any possible bias, we requested the auditory-verbal therapist to hold a brief interview with both parents and the child in the following session after the training. This approach capitalizes on the established trust between the parties and the familiarity between the child and the therapist. The therapist was given prior instructions to pose targeted questions and guide the discussion to gather relevant information. The conversation was conducted in Danish.

The child reported facing boredom during the training and would not like to repeat the training experience. The parents agree that the game "[...] seemed to be another training". On the other hand, they stated that the game made their child think about the sounds, and she might have learned about the musical instruments. They had to supervise her during all the sessions also because she found a way to cheat, pressing the cards randomly until finding the matching pair. They think it could be suitable for younger recipients too. Finally, they suggest including a more effective rewarding system to improve engagement, and they also think it would be meaningful to be able to listen again to the instruments even after finding the correct pair.

4. DISCUSSION

The findings of this study suggest that the video game intervention designed to enhance timbre perception in children did not produce the expected improvements in participant's performance on the Timbre Perception Test (TPT). Despite the incorporation of vibrotactile feedback, which was intended to provide additional sensory information and enhance participant's ability to discriminate between sounds, the intervention did not yield significant results. This raises questions about the effectiveness of the training approach and potential factors influencing its outcomes.

Several factors may have contributed to the lack of observed improvement in timbre perception following the training intervention. Firstly, the relatively short duration of the training period, conducted over a two-week period with sessions held three times a week, may not have been sufficient for the participants to develop meaningful improvements in their auditory skills. Secondly, this duration did not allow for gathering enough data; we aimed to have more repetitions of the same levels to perform significant data analysis. The difficulty of the game and potential boredom with its repetitive nature could have impacted engagement and motivation, thereby limiting the effectiveness of the intervention as well as the production of data. This is a crucial aspect in the case study as it demonstrates how the current design includes gamification elements in the training activity without being successful. The child, in fact, reported that she usually plays mainstream video games with her friends or alone, and thus we can assume that these games are her comparison term when talking about entertaining activities. The current design features basic gamification mechanisms and, as stated by the parents, could maybe be suitable for younger children in the age range between 4 and 5.

Another point of discussion is the difficulty of the task: from Figure 5, we can observe that the average duration for levels 11 to 16 (excluding the 14th session) is 6 minutes and 8 seconds. This means that participants took between 1 minute and 13 seconds and 1 minute and 32 seconds to find a correct pair, depending on whether the level presented 4 or 5 pairs of cards. Thus, we can conclude that these levels were significantly more difficult than the first ten, indicating a greater challenge in finding similar instruments. This is congruent with our expectations since the harder level presents instruments with similar timbre, thus more challenging to distinguish. In the future, we will reconsider the complexity of the task, making the difficulty increase more gradually and extending the number of levels to follow a gentler learning curve. Level 14 can be considered an outlier, as the completion time is three times longer than the closest levels in difficulty. It can be assumed that the session was not closed before a break, leaving the timer running until the resumption of the session.

From the graphs in the Results Section 3, no effect of vibrotactile feedback on both the average number of clicks and duration time is apparent. One hypothesis could be that the activity was extremely demanding for the auditory channel, leaving no space for attention on the tactile one. Another possibility is that the child did not fully grasp the connection between the feedback and the sound due to their young age. Alternatively, it could be interpreted that the vibrotactile feedback is not capable of conveying relevant information for musical timbre. This interpretation contrasts with the findings of Russo *et al.* [30]. However, it's worth noting that their study utilized a completely different setup (two voice-coils on a chair), presented the vibrotactile stimuli without sound and involved an older group of participants.

The TPT allowed us to measure the timbre perception of the participant but did not test the learning experience in terms of recognition of the specific instruments presented in the study. In fact, the parents of the child reported that the child might have learned about the instruments thanks to the training video game, but this has not been proven.

The findings of this study underscore the need for further research to refine and optimize the training intervention for timbre perception. Future iterations could focus on extending the duration of the training period to allow for more comprehensive skill development, but only with variations in the game design to increase engagement and motivation. For instance, the game could be part of a suite of different mini-games aimed at training musical skills of children with AN. The design will be put under revision to improve both the dynamics and the interaction with the aim of making the game more appealing to the target group.

It is important to acknowledge the limitations of this study, including the small sample size and the lack of a control group for comparison. As mentioned at the beginning of this paper, the study has to be considered as a case study that requires further validation. Allowing the participant to train at home ensured that the activity could be performed in an ecologically valid environment. However, this approach involved some compromises, such as the absence of researcher supervision, leading to uncertainty about the participant's interaction with the controller. Although the controller's design suggests a specific method of interaction and handhold position, we could not guarantee that the participant held the device optimally. Therefore, the participant's grip on the device might have affected the vibrotactile feedback contribution. Additionally, the use of a single participant group and the specific design of the training intervention may limit the generalizability of the findings. Future research should aim to address these limitations by conducting larger-scale studies with diverse participant groups and incorporating control conditions to more rigorously evaluate the effectiveness of the intervention.

5. CONCLUSIONS

In conclusion, while the initial findings of this study did not demonstrate significant improvements in timbre perception following the training intervention, they provide valuable insights into the challenges and considerations involved in developing effective auditory training interventions for children. By addressing the limitations and exploring alternative approaches, future research has the potential to enhance our understanding of auditory perception and improve the effectiveness of interventions aimed at developing auditory skills in children with CI and AN.

Acknowledgments

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