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Virtual Reality pitch ranking in children with cochlear implants, hearing aids or normal hearing

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1. Introduction

1.1. Pitch ranking abilities in children with hearing loss

When listening to music, one uses the hearing to identify all musical elements such as pitches, musical intervals, melodies, chords, rhythms, and timbre [1]. To determine the notes in a melody, it is critical to have the ability to distinguish and recognize musical pitches and their relationships. Subtle pitch changes play an important role in music perception, and major chords and harmonies, which may signal positive emotions, differ by one semitone from minor chords and harmonies which may signal negative emotions [2,3]. The pitch contour of a melody – its pattern of changes in pitch direction i.e. up or down, is perceptually noticeable for children with normal hearing (NH) and 5-year-old children can successfully identify, in other words pitch rank, upward and downward shifts of 4, 2, 1, 0.5, and 0.3 semitones i.e. a note not being on pitch, and these abilities improve from 5 to 8 years of age at which point they reach adult levels. The accuracy of pitch ranking decreases as the size of the shift i.e. number of semitones decreases [4].

Pitch ranking abilities may be challenged when the hearing is impaired. Even though medical and technological treatment with hearing technology i.e. hearing aids (HA), bone anchored hearing system (BAHS), bimodal system (BMS), or cochlear implants (CI) have enabled children with hearing loss (HL) to reach high levels of listening and spoken language, hearing technology like CI does not provide full access to the dynamic range and fine spectral information of musical pitches and their up- or downward shifts of semitones.

Children with HL using HA, CI or BMS have poorer abilities in pitch ranking compared to their age equivalent peers with NH [5]. Children with electrical stimulation i.e. CI or BMS, perform significantly lower than children with acoustic hearing i.e. HA or NH, and all groups of children score significantly higher in a pitch ranking task with a difference of 12 semitones than with a semitone difference (SEM.DIF.) of 3 semitones [6].

In the Nordic country of Denmark 80% of children with HA, CI, or BMS reach age equivalent listening and spoken language [7], but a recent study showed that Danish children with HA or CI do not have age equivalent abilities in recognising musical timbres i.e. the sounds of the different musical instruments [8], and they have significantly lower levels of singing on pitch abilities, music listening enjoyment and general exposure to music than their peers with NH [9]. However, pitch ranking abilities in Danish children with HA or CI have never been assessed, and the overall essence of their music perception is therefore still understudied.

1.2. Virtual Reality in assessing pitch ranking abilities in children with HA, CI or NH

Improvements in technology and public interest in virtual reality (VR) provide an opportunity to utilize it in different areas of research. VR has potential as a practical research tool to manipulate the visual display of a typical testing environment to match the real-world of the study participants i.e. assessing speech perception in children in a VR classroom environment [10]. VR can simulate to a certain extend the complexity and variability of communication in real life. Visual cues have shown to have a positive effect on detection, discrimination, and localization i.e. speech in noise [11], and speech perception [12].

VR has also surfaced as a tool in assessing auditory abilities in patients with HL i.e. word recognition while walking [13], hearing in noise test with or without visual information [14], annoyance caused by sound of traffic or speech, or background noise in simulated street or cafeteria settings [15].

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Yet, VR has never been used in assessing pitch ranking abilities of adults or children with HA or CI even though it holds great clinical potential to do so. To establish the usefulness of such a test setting, it is important to compare the results of such a VR pitch ranking task between children with HA or CI to children with NH.

1.3. Purpose of the study

This current study aimed to develop a VR tool to compare the pitch ranking abilities between children with CI, HA or NH and to discuss the potential benefits by using this technology in a clinical test setting. Furthermore, the study explored if pitch ranking performance was affected by clinical or musical background factors.

In this study, the visual environment simulated through VR was depicting a helicopter cockpit that could fly up or down and the acoustic conditions were pairs of piano tones in high and low spectral ranges with decreasing semitone difference i.e. SEM.DIF. with the pitch going up or down. It was hypothesized that the SEM.DIF. and spectral range would affect the performance of pitch ranking, and that VR would create an engaging test setting keeping the attention of the study participants and help them understand the pitch direction going up or down represented with the helicopter going up or down. The results of this study would, in theory, offer a clinical insight into the music perception abilities of children with HA or CI and potential influential factors thus offering recommendations for professionals and parents around the child. Finally, this study provides an example of how VR could be used in a paediatric clinical auditory test setting.

2. Material and methods

The study has a cross-sectional comparative design and was part of a PhD in speech & language pathology. The participants were also involved in two other studies emerging from the Ph.D. project: A timbre recognition study [8], and a survey study assessing the music background and music habits of the study participants [9]. The authors have no conflicts of interest to declare. Informed consents were collected from all the participating families and the study was ethically approved by the Region Hovedstaden of Denmark.

2.1. Participants

A total of 26 children were enrolled in the study: 15 children with bilateral HL i.e. one group of 10 users of bilateral CI and one group of 5 users of bilateral HA, and 11 children with NH. One child with CI (*'CI – 4'*) was not testable during the pitch ranking task and was excluded from the study and analysis after mutual decision between the parents and the speech and language pathologist in charge of the testing procedure. Hence a total of 25 children participated: 9 with CI (age range: 8.0–15.0 years, mean: 11,1), 5 with HA (age range 7.1–9.1 years, mean: 8.0), and 11 with NH (age range: 7–13 years, mean: 10.1). A detailed description of the groups of children has previously been presented [8] and their characteristics are summarized in Table 1 in terms of age at test, age at HA start or CI activation, degree of hearing loss at diagnosis, degree of hearing loss at test, etiology of hearing loss, type and name of hearing technology device, type of schooling and duration of AVT intervention.

2.2. Musical background factors

Data about formal music experience and music listening was collected for a previous study [8] by using the Music Questionnaire (MQ). This questionnaire was a Danish translation and cultural modification of The Role of Music in Families Questionnaire (RMFQ) [16]. Data about formal music experience was used to calculate a Formal Music Experience score as done in a previous study [5] based on duration (in terms of years), multiplied by its frequency divided by the total number of categories of music experiences. Data about music listening was used to categorize Weekly Music Listening i.e. '0 h. pr. week/never', '1–2 h. pr. Week', '3–5 h. pr. Week', '6–8 h. pr. Week', '9–11 h. pr. Week', and '12–14 h. pr. Week'. The means of the answer intervals are used to derive the group mean hours of Weekly Music Listening as can be seen in Table 1 together with Formal Music Experience scores for all study participants.

2.3. Development of a VR tool for pitch ranking

The current study focuses on the clinical aspects of the pitch ranking task i.e. comparing the performance between children with HA, CI and NH. For that purpose, the use of VR was chosen to increase the children's attention to the task and evaluate its usefulness as a paediatric test tool. The following description of the pitch ranking task including Apparatus, Auditory stimuli, Visual stimuli, Experimental Design, and Procedure of the VR pitch ranking task, was first presented in a master thesis at the Danish Technical University (DTU) [17].

2.3.1. Apparatus

The task took place in the Audio-Visual Immersive Lab (AVIL) at the DTU. The participants sat on a chair located in the middle of the room. The auditory signal was presented from a loudspeaker located in front of them (KEF LS50, Maidstone) at a sound level of 67 dB at 1 KHz. The visual signal was presented through Virtual Reality glasses (HTC Vive Virtual Reality system). Three Vive Trackers were used to calibrate the real environment (RE) with the virtual environment (VE). The spatial position and rotation were tracked with an infrared ray-tracking system. Unity3D (Unity Technologies) with SteamVR plugin was used for the development and presentation of the visual stimuli [18]. The behavioural response was measured through an external joystick (Logitech Extreme 3D Pro joystick).

2.3.2. Auditory stimuli

Each trial consisted of two different groups of tones presented consecutively (each group of tones consisted of a tone repeated twice. The first and last 20 ms. of each complex tone were ramped out by a Tukey window. Then, before and after the stimuli onset and offset, a pause of 25 ms. was added to avoid possible artifacts created by the onset and offset of the sound. All the stimuli were normalized by its Root Mean Square and loudness balanced following the Loudness ITU Standard Recommendation ITU-R BS-1770-1. It applied a filtering based on Revised Low frequency B weighting, based on equal loudness contour curves. The reference was set at 67 dB SPL at 1000Hz, as the loudness level in phons of a 1000 Hz pure tone was defined to be equal to its sound pressure level in dB SPL [19]. The duration was chosen to be set to 1 s. based on the benefit of higher duration for F0DL for unresolved harmonics [20]. Each trial lasted around 4 s. The participants were asked to judge if the second group of tones was higher in pitch than the first group of tones (upward direction) or lower than the first one (downward direction). The task was divided into a training and a testing session. For the training session, the difference between both groups of tones was of 12 semitones. Two spectral areas were selected: one centred at low frequencies (FO at 110–220 Hz) and another centred at high frequencies (F0 at 739.99–1480 Hz). For the testing session, the difference between the groups of tones i.e. semitone difference (SEM.DIF.) was gradually decreased from 12 to 1 semitone. The direction was randomized, maintaining the same amount of upward and downward directions, see Appendices 1-4. The total task consisted on 48 trials as presented in Table 2.

2.3.3. Visual stimuli

The visual environment showed a cockpit of a helicopter and clouds moving towards the participant giving the sensation of flying forwards. When moving the joystick, the helicopter would move either above or below the clouds.

A training session was provided prior to start with the visual help of a

Table 1
Characteristics of the study participants. Previously presented in Kepp et al. [8]

ID	Sex	Age at test (years)	Hearing age	Age at first hearing aid (years, months)	Age at Cl activation (average:years, months)	Degree of hearing loss at diagnosis (dB)	Degree of hearing loss at test (dB)	Aetiology	Type and name of bilateral hearing technology	Duration of AVT intervention (years)	Hours of weekly music listening	Form al music experience
HA 1	Boy	8.6	6.6	1.4	–	41–60	41–60	Unknown	HA, Oticon Safari	2.0	3–5	0.0
Cl 2	Girl	8.0	4.0	0.5	4.0	41–60	>81	Unknown	Cl, Cochlear N6	1.0	3–5	0.0
Cl 3	Girl	13.0	9.4	0.3	3.6	26–40	>81	Pendred's Syndrome	Cl, Cochlear N6	2.0	3–5	4.5
HA 5	Girl	9.1	8.3	0.7	–	41–60	61–80	Unknown	HA, Unspecified	0.0	3–5	0.0
Cl 4	Boy	9.0		1.4	1.9	>81	>81	CMV	Cl, Cochlear N7	5.0	No data	No data
Cl 6	Girl	11.8	9.0	1.5	2.0	61–80	>81	Unknown	Cl, Cochlear N6	0.5	3–5	1.0
Cl 7	Boy	8.0	7.9	6.0	0.11	>81	>81	SoxlO Gene mutation	Cl, Cochlear N7	5.0	0	0.8
Cl 8	Boy	12.0	9.7	1.0	2.3	41–60	>81	Pendred's Syndrome	Cl, Cochlear N6	1.0	6–8	0.0
HA 9	Boy	7.8	6.0	1.0	–	41–60	41–60	Unknown	HA, Phonak Sky V90-P	3.0	3–5	6.0
HA 10	Boy	7.1	6.9	0.1	–	61–80	61–80	Unknown	HA, Oticon OPNl	4.0	3–5	0.3
Cl 11	Boy	12.7	11.0	0.3	1.0	>81	>81	Unknown	Cl, Cochlear Kan sol	5.0	<2	12.0
Cl 12	Girl	9.0	8.1	0.6	0.9	>81	>81	CMV	Cl, Cochlear N7	5.0	<2	2.3
HA 13	Girl	7.6	3.4	3.6	–	41–60	41–60	Unknown	HA, Oticon Sensei Pro	0.0	<2	2.0
Cl l4	Girl	15.0	13.1	1.0	1.9	>81	>81	Unknown	Cl, Cochlear N7	2.0	6–8	0.8
Cl 15	Boy	10.1	5.1	0.6	4.9	41–60	>81	Unknown	Cl, Cochlear N7	1.0	<2	0.8
NH 1	Boy	12.0	–	–	–	–	–	–	–	–	3–5	10.S
NH 2	Girl	10.0	–	–	–	–	–	–	–	–	12–14	11.0
NH 3	Boy	13.0	–	–	–	–	–	–	–	–	3–5	4.5
NH 4	Girl	12.0	–	–	–	–	–	–	–	–	6–8	3.0
NH 5	Boy	7.0	–	–	–	–	–	–	–	–	6–8	6.0
NH 6	Girl	10.0	–	–	–	–	–	–	–	–	3–5	18.0
NH 7	Girl	9.0	–	–	–	–	–	–	–	–	3–5	3.0
NH 8	Girl	12.0	–	–	–	–	–	–	–	–	3–5	0.0
NH 9	Boy	12.0	–	–	–	–	–	–	–	–	6–8	0.0
NH 10	Boy	7.0	–	–	–	–	–	–	–	–	<2	2.3
NH 11	Boy	7.0	–	–	–	–	–	–	–	–	<2	2.3

Table 2
Presentation order of the pitch ranking task.

Presentation order of pitch ranking task
6 trials with decreasing SEM.DIF. from 12 to 7 semitones for Fo in High Frequencies (Appendix 1)
6 trials with decreasing SEM.DIF. from 12 to 7 semitones for F0 in Low frequencies (Appendix 2)
6 trials with decreasing SEM.DIF. from 12 to 7 semitones for F0 in High frequencies (Appendix 1)
6 trials with decreasing SEM.DIF. from 12 to 7 semitones for F0 in Low frequencies (Appendix 2)
6 trials with decreasing SEM.DIF. from 6 to 1 semitone for F0 in High frequencies (Appendix 3)
6 trials with decreasing SEM.DIF. from 6 to 1 semitone for F0 in Low frequencies (Appendix 4)
6 trials with decreasing SEM.DIF. from 6 to 1 semitone for F0 in High frequencies (Appendix 3)
6 trials with decreasing SEM.DIF. from 6 to 1 semitone for F0 in Low frequencies (Appendix 4)

bird flying up or down according to the direction of the pitch. The bird disappeared after the first 6 trials. During the training and the task there were no indications of correct or incorrect response after each trial, but a message saying 'Godt gået!' which means 'well done' in Danish was depicted regularly, and a message saying to let go of the joystick: 'Slip Joysticket' was shown if needed.

Supplementary video links show examples of what a study participant with CI is seeing in the VR glasses during the VR pitch ranking training session and the VR pitch ranking task:

Supplementary video related to this article can be found at https://doi.org/10.1016/j.ijporl.2022.111241

2.3.4. Experimental design

A Two Alternative Force Choice (2AFC) procedure was used where the participants were asked to judge if the pitch difference was in upward or downward direction. To accelerate the test process and keep up the motivation, a timeout of 4 s. after the offset of the sound was set. If the child did not respond in that time, the next stimuli would be presented, and the time-outed trial would be discarded from the analysis.

2.4. Procedure of the VR pitch ranking task

The procedure was explained to each child before entering the AVIL, and the eye-distance of each child was measured to adjust the lenses of the VR glasses. The child sat on a chair in the middle of the AVIL and had a seat belt fastened to prevent falling from the chair. The procedure was explained again with the concept of pitch. This was achieved by showing sung examples, making comparisons between female and male voice pitch either as animals (e.g. bear or bird), or as body positions (e.g. downward pitch explained as moving from tip toes to squatting position). Once the child expressed understanding of the pitch concept, he or she was instructed to push or pull the joystick according to the direction of pitch. A pilot test with a child with NH aged 7 years old done before the study commenced confirmed that the task was clinically suitable for that age.

2.5. Data analysis

Descriptive statistics were summarized as means for the continuous variables and as frequencies and percentages for the categorical variables.

The numbers of correct responses for the high frequency and low frequency ranges for each child were depicted in a graph together with group mean of number of correct responses. The mean value was compared between the groups of children with CI and NH by using a two-sided independent samples Chi *t*-test.

No statistical comparisons were made between the group of children with HA and the other two groups due to the small number of study participants (N = 5).

The distribution of number of correct responses categorized in 5–9, 10–14, 15–19, and 20–24 correct responses was compared by using a Fisher's Exact test. Generally, the Fisher's Exact test was used instead of the chi-squared test, if more than 20% of cells had an expected count below 5.

The effect of number of semitones was depicted with percentage of correct responses in a figure to visualize group differences. A two-sided independent samples Chi *t*-test was done to compare performance i.e. percentage of correct responses in the group of children with CI and in the group of children with NH.

Associations were assessed between pitch ranking performances and the following clinical and musical background factors: sex of the child, age at test, age at HA start, age at CI activation, type of hearing technology i.e. CI or HA, years of AVT therapy, hours of music listening, and formal music experience. The analysis was done for a group of hearing loss i.e. CI and HA users combined into one group, and the group of NH. The Pearson's chi-square test was applied because of its robustness with respect to the distribution of data. P-values below 0.05 were considered statistically significant. Analyses were performed using the SAS software 9.4 (SAS Institute Inc., Cary, NC, USA).

3. Results

3.1. Number of correct responses in pitch ranking

Fig. 1 shows the number of correct responses for each child in the pitch ranking task. Each child is represented by 2 bars with one for high frequency and the other for low frequency sounds.

The performance of pitch ranking in high and low frequency ranged from: CI: 8 to 22 & 6 to 22, HA: 12 to 19 & 8 to 22, NH: 9 to 24 & 17 to 24 (high and low frequencies respectively). The group means of number of correct responses are shown to the right side of the figure: CI group: 15,7 and 15,9, HA group: 15,4 & 17,6, NH group: 19,5 & 21,1 (high and low frequency respectively).

The difference between the performance of the children with CI and the children with NH was significant in the low frequencies (P = 0,0161) but not in the high frequencies.

Table 3 shows the distribution of number of correct responses categorized in 5–9, 10–14, 15–19, and 20–24 correct responses in both high and low frequencies for each group. Half of the children with CI (N = 5; 56%) had between 15- 19 correct answers in both high and low frequencies, and the group with HA were represented with 3 children (60%) in 15–19 correct responses and 2 children (40%) in 10–14 correct responses in the high frequencies and with a more diverse distribution in the low frequencies with 2 children (40%) having 20–24 and 15–19 correct responses and 1 child (20%) having 5–9 correct responses. Most of the children with NH had high performance with 20–24 correct answers in both high and low frequencies (N = 7; 64% and N = 8; 73% respectively). No statistically significant differences were found but it is noteworthy that the difference between the distribution of responses of children with CI and the children with NH was approaching significance in the low frequencies (Fishers Exact P = 0,0598).

3.2. Effect of Semitone Difference on group performance

The group mean percentage correct responses pr. number of semitones betweem the piano tones in the high frequencies is shown in Fig. 2 and in the low frequencies in Fig. 3. The group of children with CI were overall below or around chance level when having a SEM.DIF. of 4 or less semitones and their performance seemed to improve when having a SEM.DIF of 5 semitones in the tasks with high and low frequencies. The group of children with HA were around chance level when having a SEM.DIF. of less than 3 semitones in the low frequency range of the task, whereas they were well over chance with the high frequency tones. The

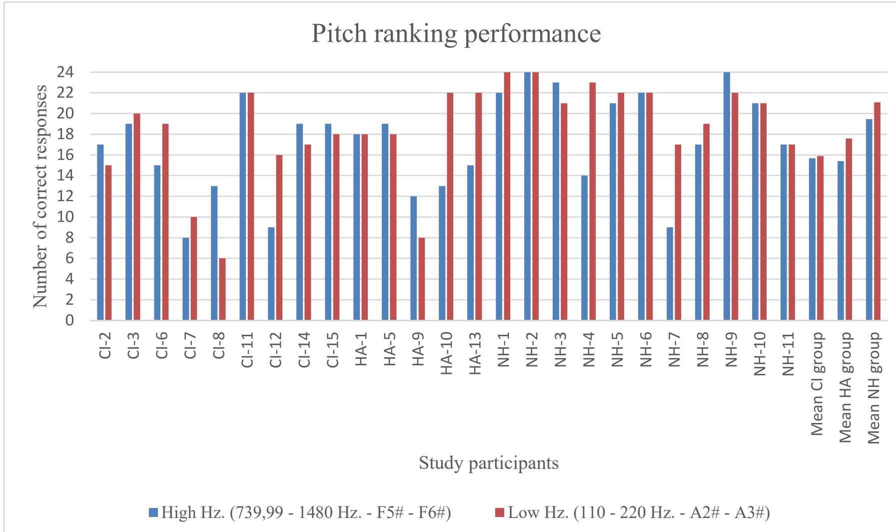

Fig. 1. Mean average pitch ranking performance among the individual study participants and among the three groups of participants with CI, HA, and NH.

Table 3
Categorization of Pitch Ranking Performance in high and low frequencies for the CI, HA, and NH group.

	High frequencies			Low frequencies		
	CI group N (%)	HA group N (%)	NH group N (%)	CI group N (%)	HA group N (%)	NH group N (%)
20 - 24 correct responses	1 (11)	0	7 (64)	2 (22)	2 (40)	8 (73)
15 - 19 correct responses	5 (56)	3 (60)	2 (18)	5 (56)	2 (40)	3 (27)
10 - 14 correct responses	1 (11)	2 (40)	1 (9)	1 (11)	0	0
5 -9 correct responses	2 (22)	0	1 (9)	1 (11)	1 (20)	0

mean % correct responses between the group of children with CI and the group of children with NH were statistically different in both the high frequencies (P = 0,0031) and low frequencies (P = 0,0025).

3.3. Association between pitch ranking performance and clinical and musical background factors

Analysis found a statistically significant association between the distribution of number of correct responses categorized in 5–9, 10–14, 15–19, and 20–24 correct responses in low frequency pitch ranking and Hours of weekly music listening (P = 0,0054).

4. Discussion

4.1. Pitch ranking performance

The group of children with CI had significantly less correct responses in the low frequencies than the children with NH. It is worth noticing that the difference between the group of CI and NH was approaching significance in the low frequency piano tones. Maybe this could be explained by the fact that CI systems are predominantly designed to give access to high frequency sounds to improve speech intelligibility even though almost all children with CI had 22 active electrodes in their CI devices, and therefore theoretically would have access to sounds from app. 125 Hz. Low frequency pitch perception has not previously been a specific target in the clinical rehabilitation of children with HL, but the

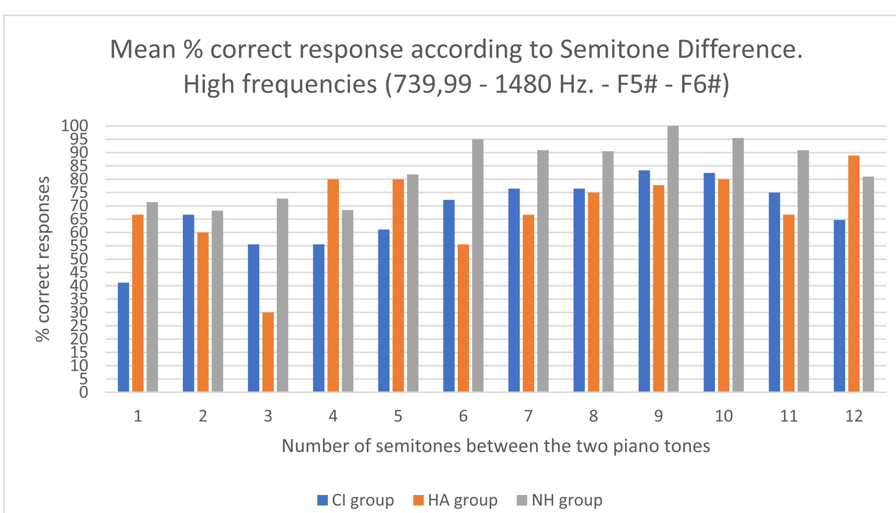

Fig. 2. Mean % correct Response pr. number of semitones between the pairs of piano tones in the high Frequencies for the CI, HA, and NH group.

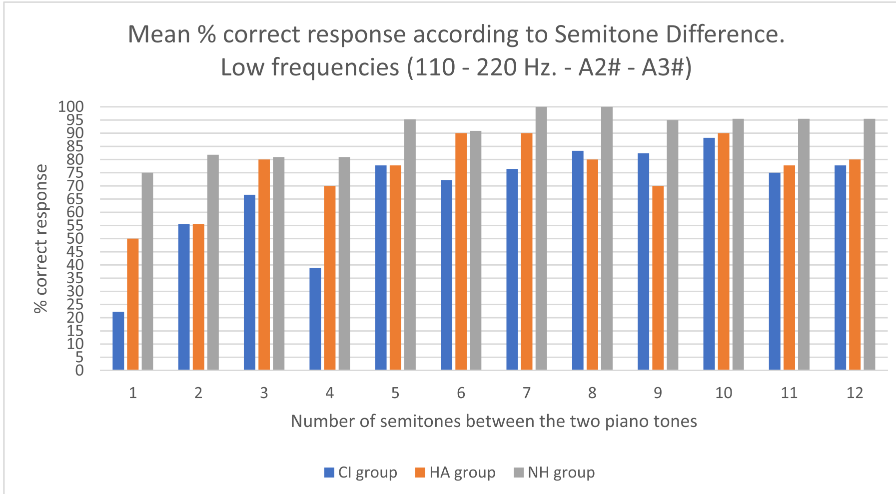

Fig. 3. Mean % correct Response pr. number of semitones between the pairs of piano tones in the low Frequencies for the CI, HA, and NH group.

general rising interest in music perception in patients with hearing technology may change this.

It was hypothesized that the children with HA would be better at pitch ranking the lower frequencies than the higher frequencies due to their low-frequency acoustic hearing and this was confirmed in the study. They seemed to benefit from their acoustic hearing and performed close to children with NH.

Children with NH were hypothesized to perform equally regardless of spectral ranges i.e. high or low frequencies. However, this was not found as the group performed better in the low frequencies than in the high frequencies. This could be due to the higher harmonic density present at low frequencies of the F0, that although theoretically less useful for CI users, may have benefited the children with NH [17]. It is noteworthy that children with CI versus children with NH performed totally opposite one another. This observation has clinical consequence and is important to bear in mind when planning musical training for children with CI.

4.2. Association of pitch ranking in low frequencies and Semitone Difference

This study found that the group mean performance of pitch ranking pr. number of semitones between the piano tones was statistically different between the group of children with CI and the group of children with NH in both the high and low frequency ranges. A study assessing pitch ranking using sound stimuli of a sung vowel with F0 from 98Hz to 740Hz [6] showed that children with CI had lower mean accuracy of pitch ranking (78% for a SEM.DIF. of 6 semitones and 67% for a SEM.DIF. of 3 semitones) than the children with HA (89% for a SEM. DIF. of 6 semitones and 79% for a SEM.DIF. of 3 semitones). These findings are very similar to the group performance of the children in this current study: CI group = 73% for a SEM.DIF. of 6 semitones and 67% for a SEM.DIF. of 3 semitones and HA group = 90% for a SEM.DIF. of 6 semitones and 80% for a SEM.DIF. of 3 semitones. This is noteworthy as the groups of CI and HA are characterized by different background factors i.e. unilateral CI vs. bilateral CI, degree of hearing loss, mean age, and levels of former participation in music training. However, both studies have small sample sizes, and more studies of pitch ranking in children with CI and HA could establish, whether these findings are representative for the population.

In pitch ranking with high frequencies the group of children with HA had a lower group accuracy when there were 7 or 6 semitones between the piano tones than when there were 5 or 4. This could be due to the presentation order of the sound stimuli i.e. going from a SEM.DIF of 12 to 7 semitones to a SEM.DIF. of 6 to1 semitones would theoretically increase the difficulty of the task which could have affected some children.

The children with NH in this current study performed with 71% accuracy with a SEM.DIF. of 1 semitone which was the most challenging part of the task. Another study found that 83% of 8-year-old children with NH ranked pitch at 880 Hz significantly better than chance level i.e. 9 out of 12 correct and the percentage increased to 93.3% in 11-year-old children [4]. However, that study used lower SEM.DIF than 1 semitone i.e. 0.1 semitone, which may have contributed to more pitch ranking training of the children. Furthermore, they were also scored under or above chance level, whereas this current study scored performance according to correct or incorrect responses.

The general decrease in performance at a SEM.DIF. of 11 and 12 semitones between the piano tones could be due to a lack of training effect as the presentation order of the sound stimuli started with a SEM. DIF. of 12 semitones and gradually decreased to 1 semitone at the end of the task.

4.3. Association between pitch ranking performance and clinical and musical background factors

This study found that there were great individual differences in the pitch ranking performance within the group of children - particularly in the group of CI users. Some children performed below chance level, but some children had remarkable performances with 10, 11 or even 12 correct responses. Individual differences could be due to the level of daily music listening which in theory could train the ability to perceive and distinguish pitches.

Even though pitch ranking performance was not statistically affected by Formal Music Experience score, it is noteworthy that the child 'CI-11' had high levels of pitch ranking performance in both high and low frequencies and a high score of Formal Music Experience i.e. many years of playing a pitch producing instrument. On the contrary, 'CI-7', and 'CI-8' had pitch ranking performances below chance levels and both had no formal music experience. Larger sample sizes could establish whether formal music experience affects pitch ranking abilities.

This study suggests that the potential benefits of listening regularly to music and participating in formal music activities should be emphasized in the clinical rehabilitation practice of children with CI.

4.4. Evaluation of the VR tool for pitch ranking

Overall, all children agreed that the VR setting was fun and engaging and none expressed dislike towards the setting. The recruitment of study participants was remarkably quick as the VR concepts seemed intriguing for many families.

However, many found the task boring and too long and recommended feedback after each trial to confirm that they had understood the task and to keep up motivation. A participatory study developing a VR task for assessing speech-in-noise and spatial music abilities in children found that the variety of immersive scenarios should cover age and interests, and that feedback should be included to ensure positive reinforcement [21]. These aspects would be worth considering for future VR tasks as timeliness and gamification might increase motivation in children.

An important experience gained from the current study was that the visuals were too distracting for a child with CI i.e. 'CI-4'. The child became too focused on the visual prompts of the bird in the training session and did not understand that it disappeared after the first 6 training trials. This caused confusion and the child could not proceed with the task. Some patients with HL may be inclined to mainly direct their attention on visual stimuli which must be considered when developing VR test settings for audiology testing.

Observations of the children during the task revealed that the task was cognitively challenging for some of the study participants. The concept of a piano tone being higher or lower in pitch was difficult to comprehend - regardless of hearing status. It is certainly challenging to grasp the rationale behind high or low pitch if one has never been presented with the concept. The speech and hearing pathologist in charge of the testing made use of body language or analogies of female and male voices to demonstrate high and low pitches. The visualization of the helicopter going up or down according to the up- or downward direction of the pitch seemed to help some children, and VR has previously been useful in giving listeners significantly more information for judging the musical pitch intervals than in non-virtual environments [22].

The use of VR can result in disagreement between the sensory systems of balance i.e. when using VR in a seated position, the visual system senses the motion of the visual display, whereas the vestibular system senses a relative lack of motion. This disagreement between systems may result in perceptual motion sickness in some adults [23] and some children [24]. In this study, no children reported symptoms of such nor were any discomfort observed in the children during or after the task. This is in line with a previous study that found that the use of VR did not increase symptoms of perceptual motion sickness or other discomfort in most children that participated in a speech understanding task with talkers in multiple locations [10].

5. Conclusion

In general VR seemed useful in assessing pitch ranking in children regardless of hearing status and this study argues that VR holds great potential for testing or training of auditory abilities i.e. localization [25, 26] or music perception tasks.

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Appendix Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijporl.2022.111241.

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