EXPLORING IMMERSION AND SPATIAL AUDIO PERCEPTION IN CONCERTS FOR HEARING-IMPAIRED AND NORMAL HEARING AUDIENCES

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ABSTRACT

In this paper we present the results of an investigation performed during a concert designed specifically for individuals with a hearing impairment. We remixed a popular song for the Ambisonic concert hall at The Royal Danish Academy of Music. 23 participants at the concert filled out an immersive and spatial audio perception questionnaire and seven of them participated in individual interviews. Results show that spatial audio perception is better for individuals with normal hearing as opposed to individuals with hearing impairment, but there is no significant difference regarding the sense of immersion. The investigation also underlines the challenges of running scientific experiments in concert settings.

1. INTRODUCTION

With devices like cochlear implants (CI) and hearing aids (HA), most hearing impaired (HI) individuals can achieve good speech intelligibility, whereas music perception remains problematic [1]. However, most HI report that music continues to be a part of their life and that they respond emotionally to music [2].

The fact that longer reverb time and echoey rooms affects music enjoyment for HI negatively [3] [4] makes concertgoing problematic. And since instrument discrimination is difficult for HI, the auditory complexity of a concert experience can lead to a decreased music enjoyment [5]. The hearing impairment and the general social aspects of concertgoing can be difficult to overcome, which means that many HI tend to avoid music listening other than at home [6].

A lot of research has investigated how to improve music perception for HI [7], but there has only been a few studies of concert attendance [8]. Since concertgoing and listening together is an important factor of the general quality of life [9], this is an area that begs further research. It was shown that a widely spread spatialization of speech and noise improves speech intelligibility for HI [10]. So, it could be speculated that an immersive reproduction of music could impart a higher degree of instrument segregation and enjoyment for HI, especially in a concert setting.

In this paper, we investigated how hearing impaired individuals experience immersive music delivered as part of a concert experience.

Specifically, the research presented here is placed at the intersection of music appreciation for hearing impaired individuals, immersion studies and concert research. From the perspective of music appreciation, we seek a better understanding of how individuals with hearing impairment experience music during a social event such as a concert. From the perspective of immersion studies, we aim to better understand the concept of immersion and how it can be measured for hearing impaired individuals. From the perspective of concert research, this is an emerging topic discussed in the next section.

1.1 Concert research

In recent years, there has been a trend to increase the ecological validity of empirical work in music cognition research [11, 12]. One of the areas where this trend has been seen is in the combination of concerts and scientific activities [13, 14]. The empirical methods used in such settings range from self-reports, sometimes continuous [15], measurement of inter-subject correlations [16], and capturing motion through mobile phones [17]. Another interesting research direction is the study of the effect of room acoustics in the emotional response to music [18].

In some research institutions, sophisticated performance- or concert halls specialized for concert research have been created, such as the Livelab at McMaster University in Hamilton, Canada [1] and the ArtLab at the Max Planck Institute for Empirical Aesthetics in Frankfurt, Germany [2].

In [8], the authors describe the execution and evaluation of a concert specifically designed for individuals with CI. In particular, six pieces were commissioned with a focus on individuals with CIs. The concert was evaluated through focus group interviews. In the interviews, spatialization was identified as an important element by both normal hearing and individuals with hearing impairment. The paper also presented some considerations regarding the familiarity of the music the audience was exposed to, and whether they could develop appreciation through increased exposure. It is well known from the literature that the familiarity of music is important to increase its enjoyment [19] especially for the HI [20].

In [21], a research program is proposed to evaluate music

[1] https://livelab.mcmaster.ca
[2] https://www.ae.mpg.de/artlab/information.html

listening in classical concerts. The paper acknowledges how concerts and concert listening experiences have already been acknowledged as worthwhile research topics by a multitude of disciplines. However, a more thorough, systematic, and transdisciplinary research is still needed. One important aspect stressed in the paper is that concert curators need to form an essential part of a research team, since the research inquiries need to fit as part of the artistic experience. Moreover, it is pointed out how a research program that investigates the concert frame and its components can only be performed in interdisciplinary teams.

Overall, as stated in [22], concerts can be considered a presentational musical field, where participants are divided into performers and audience, as opposed to the participatory musical field, where participants move between being performers and being audiences. This means that concerts are an interesting venue of research where ecological validity is maintained, but with the advantage that the roles of the individuals involved are rather well defined.

1.2 Measuring immersion

Researchers from different domains, from virtual reality to games and to musical experiences proposed several definitions of the term immersion and how to measure it.

In the field of virtual reality, one of the prominent researchers, Mel Slater, defined 'immersion' as an objective property of a system. Higher or lower immersion depends on the extent to which a virtual reality system can support natural sensorimotor contingencies for perception [23, 24].

In [25], Hyunkook Lee examines the definitions of various concepts related to immersion and integrates them into a general conceptual model of immersive experience. The paper considers the concept of immersion as well as related concepts such as presence and involvement, in order to create some rigor and organization of the existing definitions proposed in the literature.

An attempt to define immersion in the context of audiovisual experiences is also provided in [26]. Taking into consideration the multitude of research and definitions regarding immersion, the authors define the term as *a phenomenon experienced by an individual when they are in a state of deep mental involvement in which their cognitive processes (with or without sensory stimulation) cause a shift in their attentional state such that one may experience disassociation from the awareness of the physical world.*

In the context of musical experiences or audio-visual experiences, most research examines the influence of sound delivery methods in enhancing immersion [27, 28]. Such explorations are mostly performed in laboratory settings, with one subject at the time, and with the different conditions randomized.

In [29] (part 1 and part 2) different spatial audio reproduction methods were evaluated and it was found that expert listeners and inexperienced listeners use very different languages to describe the sense of immersion.

When looking at methods to measure immersion, Rumsey observes how there has been a unwillingness to break free from the concept of reference stimuli [30]. Rumsey states that there may be advantages to adopting some form of reference-free evaluation. He observes that there is still the open question of defining immersion carefully enough, pointing at the different attempts undertaken. He also mentions that non-experienced listeners may not have the same preference patterns as experienced ones in this context, and that additional low-slung loudspeakers can improve the results in certain cases.

In [31], immersion is defined as a psychological state characterized by perceiving oneself to be enveloped by, included in, and interacting with an environment that provides a continuous stream of stimuli and experiences.

In order to measure immersion in musical settings, a recent questionnaire has been developed [31]. The questionnaire was developed to understand whether there is a relationship between the increasing spatiality of sounds and the listener's emotional response.

In this paper, by using an adaptation of the questionnaire presented in [31] and [32], we investigated immersive music experiences in a concert setting and understanding whether immersion and spatial characteristics perceived differently by hearing impaired and normal hearing users.

2. CONTEXT OF THE RESEARCH

This research is a part of a larger cooperation between the Multisensory Experience Lab at Aalborg University [3], The Royal Danish Academy of Music (RDAM) [4] and Copenhagen Hearing and Balance Center (CHBC) at Rigshospitalet [5]. Through concerts and other events, music for hearing impaired is investigated.

This paper is based on a concert-event that took place on October 1st 2023 in New Hall at RDAM. For the concert, a band (drums, electric bass, grand piano and voice) played eight songs (*What a wonderful world, Lyse nætter, Jeg har elsket dig så længe jeg kan mindes, To lys på et bord, Imagine, Den gamle skærslippers forårssang, Forårsdag* and *Papirsklip*). The repertoire was chosen to put together a programme of familiar songs with a broad appeal for the Danish audience, which was expected to have a high average age (at the event the average age was 57,6 years).

In order to help the audience feel comfortable, the event started with a sing-along song. This is in line with the Danish tradition of singing together at concerts and social events. The event also ended with a sing-along song. The first sing-along song was *Septembers himmel er så blå*, and the final one *Nu falmer skoven trindt om land*. Both songs are very familiar to a Danish audience.

The concert also involved a test of melodic contour identification (MCI) [33], where participants were asked to identify different melodic contours (rising, falling or arching). There was also tryouts of a haptic bench, which is a bench with footrest, where vibrating actuators are mounted and configured to support the listening experience of the voice and bass in the music.

[3] https://melcph.create.aau.dk

[4] www.dkdm.dk

[5] https://www.rigshospitalet.dk/english/departments/centre-of-head-and-orthopaedics/department-of-otorhinolaryngology-head-and-neck-surgery-and-audiology/Centres-and-Units/Pages/Copenhagen-Hearing-and-Balance-Centre.aspx

Figure 1. Image from the concert

To investigate the sense of immersion for the audience, one song was played back through an Ambisonics system in the hall. The music played at the event, was a studio recording of a band playing the Danish folksong *Der er ingenting i verden så stille som sne* (There is nothing in the world as quiet as snow). It is a "live in the studio" multi-track recording with overdubbed lead/backing-vocals and a few extra instruments. The playback of the immersive song was in the programme after the fourth band-song.

Since the event had a strong focus on listening and was investigating listening capabilities, there were no assistive listening devices, texting or sign interpreter. Out of the approximately 45 people in the audience, 23 took part in the research, by filling out questionnaires in realtime.

3. DESIGN OF THE AMBISONIC HALL AT THE ROYAL DANISH ACADEMY OF MUSIC

The Ambisonics system in New Hall at RDAM was established in 2019. It has 44 loudspeakers (Dynaudio LYD5), arranged in a dome around the audience, and four subwoofers (Dynaudio SUB6) on the floor. (see Table 1, Figure 3 and Figure 4. All loudspeakers/sub's are fed from a DAD AX32 converter. The speakerdome is arranged in five rings with two loudspeakers in the top above the center.

Ring	Number	Height (cm)
Floor	1-8	40
Panel	9-20	160
Above panel	21-28	260
High	29-34	320
Top	35-38	360
Zenith	39-40	400
Subwoofers	41-44	Floor
Stereo pair	45-46	260
Extra front	47-48	40

Table 1. The speakers' configuration in the Ambisonic concert hall at The Royal Danish Academy of Music.

The loudspeakers are permanently installed in the hall and designing the setup required both perceptual, technical, practical and architectural considerations. For instance, it was not possible to mount loudspeakers at the floor even though it would have been optimal to ensure the possibility of placing sounds anchored at ground level.

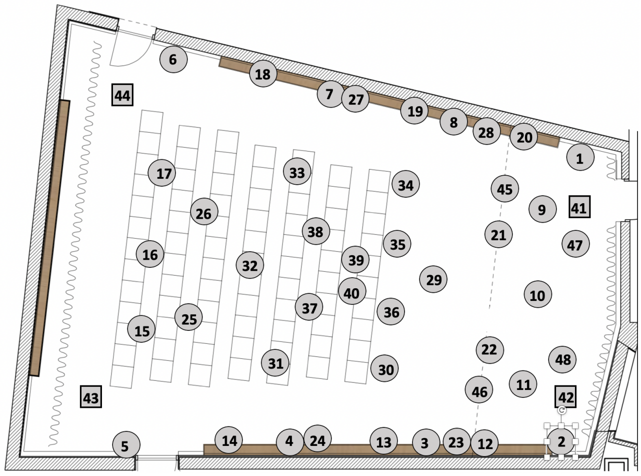

Figure 2. Speakers' placement in the hall. See the list in Table 1.

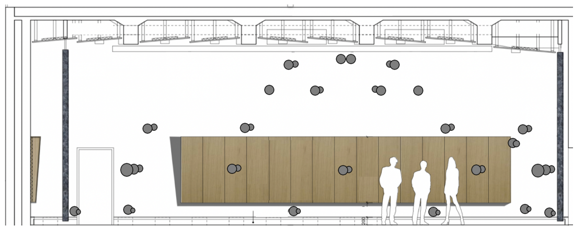

Figure 3. Speakers' placement in the hall. Side view.

The hall is trapezoidal and the ceiling not high enough to accommodate a perfect sphere, so loudspeakers are individually processed to mimic the optimal placement. This is achieved through delay, attenuation and equalization from the SPQ speaker management card in the DAD AX32.

New hall at RDAM is built for concert experiences rather than laboratory research. The acoustics are variable with an RT60 from 1,0s to 1,2s and designed for small classical ensembles. For this event the room was damped to an RT60 of 1,0s. Even though this is a short reverb for a concert space, the room acoustics are still an active player in the musical experience. From a scientific point of view, this increases the challenges because the distribution of sound is uneven according to where the listener is located in the hall. These differences especially play a role, when running experiments with a combined diverse audience.

The same room has been simulated visually and acoustically in [34], where a virtual reality simulation (VR) was proposed. This was done in order to provide virtual accessibility when the room was closed due to COVID-19 restrictions. In this case the sonic component is delivered through headphones with a custom made Ambisonic to binaural rendering engine.

4. METHODOLOGY

4.1 Mixing for the Ambisonic Room

For the audio mix, standard equalizing (FabFilter Q3) and dynamic compression (FabFilter C2) was applied to optimize the sound of the individual sources before placing them in the three dimensional space. To get a clearly focused placement, most instruments were played through only one single loudspeaker. To give the audience a clear immersive experience, it was chosen to create an enhanced spatial experience with the instruments located far apart in stead of recreating a naturalistic placement of the instruments on the front stage area. The whole mix was spread, as individual channel-based sources, across the 3D soundscape as shown in Fig. 5 and Fig. 6.

The audio-mix was played from an Apple MacMini running ProTools to the loudspeakers via a MADI-connection from an RME MadiFace to the DAD AX32 converter.

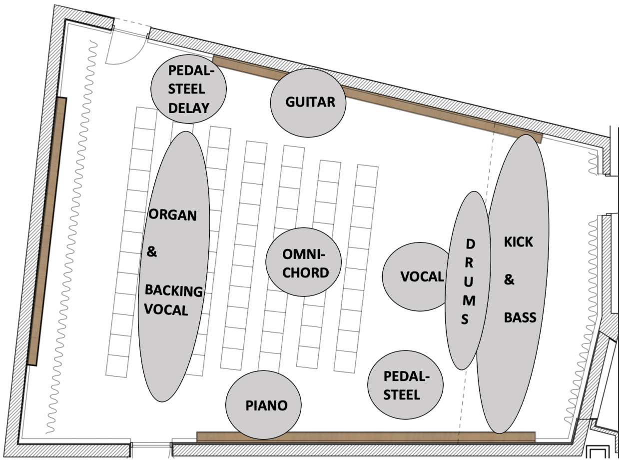

Figure 4. Placement of the sound sources in the immersive mix.

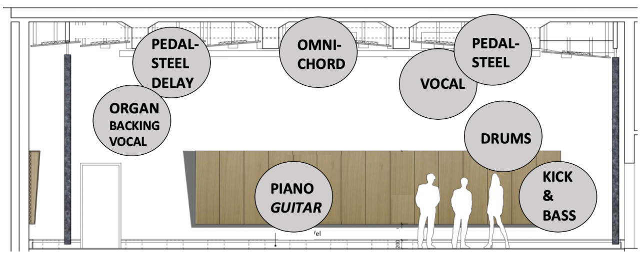

Figure 5. Placement of the sound sources in the immersive mix. Side view.

4.2 Questionnaire development

We prepared a questionnaire in order to measure how participants experienced the immersive mix, both from the perspective of the challenges usually experienced by HI, the general music appreciation and immersion characteristics. The questionnaire is based on a list of statements which the participants rated from 1 to 6 in relation to how strongly they disagreed or agreed.

The questions related to immersive characteristics were adapted from the immersive music questionnaire [31]. Questions related to music appreciation with a focus on challenge for hearing impaired were extracted from [32].

All questions were translated to Danish. We opted for a short questionnaire which is preferable, in many cases, since it avoids the adverse effects associated with an extended time of completion [35]. This is especially the case when the majority of the audience is represented by individuals with hearing impairment, that are known to be easily subject to fatigue [36]. We therefore limited the questionnaire to the 11 questions shown in the first column of Table 4. The questions related to music appreciation (questions 1-4), ability to discriminate instruments and their location (questions 5 and 6) and immersion (questions 7 to 11). The questionnaires were handed out on paper to the participants.

4.3 Interviews

One week after the concert, seven of the HI were interviewed individually about their experience. The interviewees are all a part of a larger study investigating the effect of music training on concert perception (awaiting submission). The interviews were carried out as semi-structured telephone interviews [37] [38], had an average duration of 20.5 minutes and concerned all the elements of the concert, including the immersive playback. All interviews were recorded and the analysis was carried out afterwards.

5. PARTICIPANTS AND THEIR HEARING PROFILE

The concert was an open public event. Of the approximately 45 individuals who participated only 23 data entries were considered eligible in the questionnaire. Some participants either did not answer more than one or two questions and some did not answer at all.

Participation was voluntary, and participants were not compensated. The recruitment process utilized various channels, including:

1. Danish CI social media groups.
2. Local and regional hearing associations (høreforening).
3. Local and regional centers for *Education and Communication* (Center for Specialundervisning for Voksne, Roskilde og København).
4. The *Center for Hearing and Balance* at the local hospital (Rigshospitalet).
5. Personal invitations.

While entering the concert hall, each participant was assigned an animal to replace their name, for respecting anonymity and asked to fill out the demographic informations as well as their hearing profile. They were also asked if they played or had played any musical instrument, how many concerts per year they attended, and to what degree they felt part of a shared musical experience when attending a concert. The replies can be found in Table 2.

Animal	Gender	Age	Hearing profile	Music	Concerts / year	Musical partaking
Alligator	F	35	2CI	No	1-2	some
Penguin	M	64	2CI	No	20	high
Hyena	F	66	2CI	no	5-8	high
Goat	M	68	2CI	no	4-5	some
Shrimp	F	?	2CI	piano (5 years)	10	high
Squirrel	F	74	1CI	guitar	1-2	some
Rhinoceros	F	74	1CI	no	0	some
Duck	M	67	1CI	no	0	not at all
Trout	M	78	1CI, 1 HA	clarinet	1	some
Bee	F	33	1CI, 1 HA	plays and sings	rarely	high
Raven	F	67	1CI, 1 HA	piano teacher	12-14	some
Rabbit	F	28	2 HA	no	one	some
Ladybug	F	26	2 HA	violin	5-10	high
Turkey	M	50	2 HA	guitar	0-1	some
Salmon	M	?	2 HA	no	10	some
Whale	F	78	N	klaver	2	high
Beaver	F	?	N	10	2	high
?	F	59	N		5	high
Bear	M	38	N	singing	2-3	high
Eagle	F	53	N		20	high
Scorpion	F	38	N	no	5-6	high
Snail	F	43	N		4	high
Panda	F	52	N		1-2	high

Table 2. The profile of the participants to the concert who filled the questionnaire described.

Profile	Number	Age (mean $\pm$ std)
2CI	5	58 ± 16
1CI	3	72 ± 4
1CI,1HA	3	59 ± 23
2HA	4	35 ± 13
NH	8	52 ± 14

Table 3. Summary of the profiles of the participants to the concert who filled the questionnaire described.

6. RESULTS

Table 4 shows the results of the answers to the questionnaire question by question in terms of mean and standard deviation for hearing impaired (column 2) and normal hearing listeners (column 3).

6.1 Analysis of Questionnaire

For analysis, we divided the participants in a group of hearing impaired individuals (n= 15), and a group of normal hearing (n= 8). The hearing impaired group included individuals with two cochlear implants (2 CI), one cochlear implant and deaf on the other ear (1 CI), one cochlear implant and one hearing aid (1 CI, 1 HA), and two hearing aids (2 HA) (see Table 3).

The mean and standard deviation of the answers from all participants can be seen in Table 5. From the table it can be noticed that the ratings by NH is generally higher for all the items to individuals with hearing impairment.

Due to the lack of normality, non-parametric tests were necessary for comparing item distributions in this dataset. A Wilcoxon rank-sum test showed a significant difference in the enjoyment of the music (question 1, $p < 0.05$), the appreciation of the overall soundscape (question 4, $p < 0.05$)), the ability to localize sounds (question 5, $p < 0.05$)), the ability to distinguish between different instruments (question 6, $p < 0.05$)), and the sense of being captivated by the listening experience (question 8, $p < 0.05$)). This is confirmed by the literature on hearing impaired individuals in social settings, where it is known that they have difficulties in localizing and distinguishing between many sound sources, also in musical settings [39].

Figure 6 visualizes the results of the questionnaire as boxplots. It can be seen that the HI had difficulties in perceiving directional cues and in instrument segregation (question 5-6), while they still enjoyed the playback (question 1-4). Also, the large deviation within the HI group compared to NH is clearly shown.

6.2 Analysis of Interviews

Interviewees all reported to have enjoyed the immersive playback and most of them felt somehow surrounded by sound, compared to listening to the band performance, which took place on the front stage.

The sensation of being surrounded by sound did, however, not lead to any perception of direction from the individual instruments. One single interviewee (a dual CI-user) reported very good perception of direction and instrument discrimination, which underlines the finding that there is a large deviation within the HI-group, while replies from NH is more homogeneous.

A CI+HA-user reported to have very good stereo-

Question	HI	NH
1) The piece was very enjoyable.	4.71 ± 1.37	5.87 ± 0.35
2) The melodies were very enjoyable.	5.07± 1.14	5.75 ± 0.46
3) The rhythms were very enjoyable.	5.03 ± 1.07	5.75 ± 0.46
4) The overall soundscape was very enjoyable.	4.92 ± 1.07	6 ± 0
5) I can tell where all the sounds were coming from.	3.00 ± 1.57	5.12 ± 0.83
6) I can distinguish different instruments.	4 ± 1.51	5.75 ± 0.46
7) I felt that the music surrounded me.	5.27± 1.19	5.87 ± 0.35
8) The listening experience captivated me.	4.8 ± 1.31	5.87 ± 0.35
9) My listening experience was similar to a live concert.	4.09 ± 1.44	5 ± 1.3
10) The music seemed detached from the loudspeakers.	4.09 ± 1.29	4.25 ± 1.388
11) The music resounded from everywhere.	4.63 ± 1.36	5.5 ± 0.75

Table 4. Questions asked to the participants and their mean and standard deviation (1-6 Likert scale) for hearing impaired (HI) and normal hearing (NH).

perception when streaming directly to the CI/HA for home-listening, while spatial perception in a real room was very bad. In spite of the live acoustics of the hall, interviewees of this study reported a high enjoyment of the music. Investigating the influence on concert hall acoustics on music enjoyment of HI is thus a relevant area of further studies.

7. DISCUSSION

Playing the immersive music production confirmed several challenges experienced by individuals with hearing impairment, such as the difficulty of segregating and localizing instruments. However, these results need to be considered with caution, given the relatively low number of participants that filled out the questionnaire.

Despite the relatively short questionnaire, some of the participants left some questions unanswered, reducing the amount of data collected. This is true both regarding their demographics, ability to play an instrument or even the questions regarding immersion.

It is worth noticing that the qualitative interviews that took place a week after the experience confirmed the data from the questionnaire.

Overall, we encountered different challenges when running scientific experiments during a concert experience. Especially when considering that the majority of the audience were hearing impaired and elderly individuals.

One challenge is the uncontrolled environment of a concert hall (as opposed to the controlled settings of a laboratory. Another challenge is how to balance between a scientific experiment and a musical experience pleasant for the audience. The audience was invited to a concert with a special focus on hearing impaired individuals. It was therefore just as important to focus on creating a concert experience as it was to have the scientific experiment as a goal.

It was also important to make sure that the scientific experiment proved beneficial to improve the quality of life of this particular population, and not a mere scientific inquiry that only satisfies the curiosity of the researchers.

For these reasons we kept the number of questions in the questionnaire rather limited (11 questions), selecting the ones we found most relevant to measure immersion and music appreciation. Concert research makes it hard

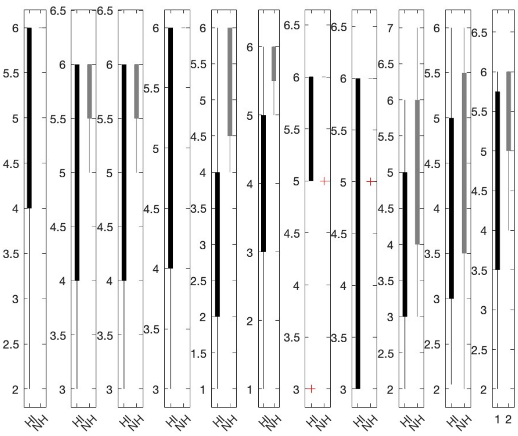

Figure 6. Box plots for the 11 questions for hearing impaired (HI) and normal hearing (NH). The boxplots clearly indicate the large deviation in the answers from the individuals with hearing impairment as opposed to those with normal hearing.

to perform traditional scientific experiments. For example, it could have been interesting to investigate the effect of different strategies of spatialization on immersion, or the overall effect of changing one variable in the spatialization. That would have required playing the same piece of music more than once in a randomized order. While this is a proper scientific methodology, it would have introduced a high level of fatigue in the audience involved. An alternative approach could have been to invite two groups of participants to two different concerts, but that would have required a much larger sample population in order to provide some statistically valid conclusions.

It would also have been interesting to triangulate the questionnaire's results and the qualitative interviews with captured objective data such as physiological data. This would have required some rather intrusive hardware and it is important to stress that the involved audience came to the event to listen to music, not to participate to a scientific experiment.

In future studies, we could consider other ways of data collection, for example through mobile phones. This would require the development of a user friendly app suitable for the target audience. Data collection during concerts was done for example in [17], and the experience showed some limitations, despite addressing populations without reported impairments.

Although all individuals brought a smartphone, it would have required some additional technical support to use it as an additional measuring device.

It is well known that the listener's position, with respect to loudspeakers, creates precedence effect [40], nobody reported on that in the questionnaire. And only one participant reported in the interview, that the listening position had been close to the loudspeaker playing the guitar.

One item for further discussion is the choice of the music at the concert. As previously mentioned, in another concert for individuals with cochlear implants, some dedicated pieces of music were commissioned [41].

In the research presented in this paper we decided to choose a rather familiar song for different reasons. First of all, in previous focus group interviews it was clear that individuals with hearing impairment are interested in reaching a level of music appreciation which is similar to normal hearing for any kind of music, and they are not interested in having music specifically composed for their hearing devices. This is related to the importance of music as a social interaction and gathering, regardless of the ability of the listeners.

Individuals with hearing impairments do not want to be placed in an isolated category. Moreover, as previously mentioned, there is some previous evidence on the correlation between the familiarity of a musical experience and the appreciation [19], [20].

8. CONCLUSION

In this paper we described an experiment run as part of a concert experience for individuals with hearing impairments. The goal of the experiment was to investigate how individuals with hearing impairment experience immersive music compared to normal hearing individuals.

The results of the experiment confirm existing knowledge, for example the difficulty in localizing/discriminating instruments and that there is a large deviation in the listening capabilities of the HI. It is a positive sign that individuals with hearing impairment seem to enjoy music almost as much as the normal hearing.

The experiment showed several methodological challenges involved when running ecologically valid experiments. For example, the listening experience took place in a concert hall as opposed to a traditional laboratory setting. The audience at the concert included mostly elderly individuals with hearing impairments, which introduced additional challenges when measuring their experiences.

In the future, we plan to investigate other methodologies for measuring audience experience at similar events, for example combining questionnaires and interviews with physiological data such as heart rate and motion measurements.

9. ACKNOWLEDGMENT

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