

# How do Deaf and Hard of Hearing people listen to Music Instruments?

## Subjective Evaluation and Acoustic Features

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**Abstract**—Many Deaf and hard-of-hearing (DHH) people enjoy music, mostly songs. One of our research purposes is to increase music accessibility for DHH individuals and broaden their musical experiences to include instrumental music. To investigate how DHH people experience instrumental music and enjoy it without barriers, we conducted two experiments to determine the relationship between the ease with which people can listen to instrumental music (listenability) and the acoustic features of the music. We used short clips of 95 timbres (19 instruments with 5 pitches) in one experiment. In another experiment, we used around 20 seconds of two-part musical pieces played by 10 timbres from a combination of two instruments. We calculated 12 acoustic features for each sound stimulus and obtained correlation coefficients between listenability and each acoustic feature. We found that: 1) only the acoustic feature of entropy is commonly related to listenability between single instruments and combinations of two instruments, and 2) the listenability of two-part performances depends on the instruments playing the melody part, which cannot be applied to all the instruments we used, though. With the limitations in the experiments, such as the number of participants, the number of musical pieces, and the kinds of timbres, we have learned that the listenability of musical pieces with timbres from a combination of instruments cannot be fully described by acoustic features alone; other musical elements, such as melody and harmony, must also be considered. Furthermore, and more importantly, to improve the accessibility of instrumental music for DHH people, we must study the relationship between their auditory characteristics and listenability, and develop music recommendations for DHH people.

### I. INTRODUCTION

Thanks to the performance of hearing support devices, access to music, which is a non-verbal sound, has also improved. In a questionnaire on music activities, 50 out of 57 D/deaf and Hard-of-Hearing (DHH) respondents answered that they listen to music. In addition, 50 out of the same number of respondents answered that they sing. It seems that listening to music and singing are activities that a certain number of DHH people engage in. Oshima describes how DHH young people learn songs, practice singing, and are enthusiastic to sing songs [1]. In the same questionnaire, on the other hand, for the question of whether they play musical instruments, only 26 people said they did. We also work with DHH university students, since all our students are either D/deaf or hard of hearing, to improve their music accessibility and give them

better listenability in music. One of the benefits of improving music accessibility is that it enables them to discover music they have not had access to before and to expand their world of music, which is one of our research aims. To do this, we investigated which instrumental sounds are easy to listen to with subjective evaluation and acoustic features.

A profoundly deaf student who likes to listen to music conducted an experiment on listening to instrumental sounds based on her own experience that some timbres of instruments are more straightforward to listen to while others are not in music class, and that there are timbres she likes and sounds she dislikes [2]. Based on her work, we conducted an online experiment to understand the subjective evaluation of listenability and the preference for 19 instruments of five different pitches [3]. Since the evaluation was performed on every instrument, we wanted to understand the listenability when combining several instruments to play music, as in actual music scenes.

In this paper, we put our research questions as follows.

- What are the acoustic features of timbres for DHH people to give them listenability?
- Are the acoustic features of timbre by each instrumental sound related to music performed by timbres of combining two instruments?

According to the ASA definition, timbre is the attribute of auditory sensation that enables a listener to distinguish two sounds with the same loudness and pitch (ANSI S1.1-1994). In this study, we use an operational definition: timbre is defined as the information derived from either a single instrument or from the combination of two instruments. Then, we describe our two experiments for each question and the results from those experiments. We also discuss the relationship of acoustic features between timbres from each single instrument and the combination of instruments.

### II. RELATED WORKS

There are several tips on teaching music to children with hearing loss. Related to the timbre, “Take the student’s lead on which instrument they would like to learn.” is desired [4]. “Understanding how your student’s loss relates to the span of his musical instrument can be illuminating. Ask your student to

bring his audiogram to the lesson. Together, you can compare his loss to the frequencies on his instrument.” [5]. In her survey of musical instrument lessons for children with hearing loss, LaLonde showed that some instruments are good for them for reasons, such as the harp being good because the strings are close to the ears [6]. Among the current musical education situations for children with hearing loss, mapping the loss to the student’s instrument and finding good reasons to choose an instrument [6] are essential to give children with hearing loss good music experiences.

In their Timbre Perception Test for hearing people [7], Lee and Müllensiefen described that attack time and spectral centroid are the most salient timbral properties to be acknowledged by researchers these days. While the spectral flux or deviation is considered the third property, it is open to debate. Marozeau et al. found that the perception of timbre differences occurs independently of different fundamental frequencies, namely different pitches [8]. Gfeller et al. experimented with Cochlear Implantees (CIs) and people with hearing (NH) regarding timbre understanding by the fundamental frequency. They stated that CI differs from NHs in the fundamental frequency range [9], although it was not clear why CIs are unable to identify timbres and instruments. An experiment to create artificial timbres from the envelope and spectral information of sounds revealed that CIs use the envelope to identify timbres [10]. Kong’s experiment also showed similar results that bimodal and bilateral CIs use the temporal envelope as a primary cue for timbre perception [11]. Since timbre affects music perception, Galvin et al. conducted experiments on melodic contour identification with different timbres. They found the effect of timbres on melodic contour identification [12], and melodic contour discrimination is affected by the masking of other timbres [13].

Using multimodal stimuli, especially tactile information, is a way to give music accessibility to DHH people. Verma et al. showed the possibility of tactile input to understand timbres by people with hearing loss [14]. Though only a few intend to support DHH in sound acquisition, Paisa surveyed current tactile devices for listening to music [15]. Myllar Balloons or Sound Hug conveys information about music with colors of light and vibration. Without such technologies, DHH students in music classes touch instruments or speakers while hearing students appreciate music performance.

Most of the research related to music, such as music activities or music perception, is targeting DHH with CI users such as [16], [17], [18], and [19]. Though all our students are D/deaf or hard of hearing, they wear CIs, hearing aids, or a combination or do not even use devices. Therefore, we do not intend to get some results from only a subset of students depending on what devices they use but to understand them as a whole. In the same context, we don’t intend to divide students into groups; we do not get results from the two groups of D/deaf and hard of hearing.

### III. EXPERIMENTS

For the two questions above, we conducted two experiments.

- ExS: it is for understanding the relationship between the listenability (ease of listening) by DHH people and acoustic features. Participants listened to the timbre generated from a single instrument to give a subjective evaluation of the listenability of each timbre.
- ExM: it uses two instruments to play music to understand the relationship between the listenability of music by DHH people and acoustic features. Participants listened to music played by two instruments, tapped along to the beat, and gave a subjective evaluation of their confidence in tapping to each music.

Both experiments were approved by the Ethics Committee of the authors’ institution. As described below, both were conducted online. Though this way of conducting experiments raises the problem of reliability of the experiments in general, we wanted to find out how DHH listen to sounds under the everyday listening environment, not in the lab. environment.

#### A. ExS for acoustic features of timbre from a single instrument

As described in Hiraga [3], we experimented with ExS wholly online. Participants used their own devices, either PC, tablet, or smartphone, with any speakers, anytime and anywhere. The timbres used in this experiment were classical guitar, electric guitar, harp, cello, violin, piano, clavinet, horn, trombone, trumpet, tuba, bassoon, clarinet, flute, recorder, accordion, harmonica, shamisen, and sou. The shamisen and sou are traditional Japanese plucked string instruments. We selected these instruments according to the past experiment designed and conducted by the profoundly deaf student [2]. We prepared 95 timbres using the Sibelius music notation tool to make musical scores of four consecutive quarter notes of the five pitches (C3, G3, C4, G4, and C5). Some sounds are not possible in the actual acoustic musical instruments, such as C3 by the violin. Musical scores are exported to audio files at 90 beats per minute (BPM) with one of the above-described instrument sounds. The generated audio file (.wav) was a single channel with a sampling rate of 44.1 kHz and 16 bits per sample. From the sampling rate and the BPM, we extracted the first note from the audio file to get a short sound clip of a length of 667ms. All audio files were normalized.

Altogether, 31 DHH people (male 11, age range 18–22) participated. Regarding the frequency of listening to music, 19 answered daily, seven a few days a week, and five a few days per month. Their hearing prostheses and number of timbres are shown in Table I with another experiment.

We implemented ExS as a web-based experiment environment with Gorilla [20]. Participants first adjusted their hearing level, took a simplified hearing test (mimicking the actual hearing test, a sine wave at seven frequencies is presented and the participant is asked to report the loudness heard), and evaluated their listenability on the seven levels (-3: not at all, 3: very well). We asked participants to experiment three times on three different days.

TABLE I  
NUMBER OF PARTICIPANTS AND NUMBER OF TIMBRES USED IN THE TWO EXPERIMENTS.

	Participants						Timbres
	HA2 <sup>a</sup>	HA1 <sup>b</sup>	CI2 <sup>c</sup>	CI1 <sup>d</sup>	BM <sup>e</sup>	None	
ExS	21	4	1	3	1	1	95
ExM	7	4	0	1	0	1	10

<sup>a</sup> Hearing aids in both ears.

<sup>b</sup> Hearing aids in one ear.

<sup>c</sup> Cochlear implants in both ears.

<sup>d</sup> Cochlear implants in one ear.

<sup>e</sup> Bimodal (hearing aid in one ear, cochlear implant in another ear).

#### B. ExM for acoustic features of timbres from the combination of instruments

ExM is a tapping test, along with beats, by listening to music. We assumed that the listenability of music affects the tapping correctness, and listenability relies on timbres.

Based on the results from Nakahara's experiment [2], we chose four instruments: accordion (abbreviated as ACC), recorder (REC), piano (APF), and shamisen (SHM), which are often used in Japanese music classes, and Japanese traditional instrument (shamisen) introduced in the class. We used them for the melody and accompaniment parts of four musical pieces. We used the ten combinations of instruments: ACC\_ACC, ACC\_APF, APF\_APF, REC\_ACC, REC\_APF, REC\_REC, SHM\_ACC, SHM\_APF, SHM\_REC, and SHM\_SHM. The description of XXX\_YYY represents that XXX plays the melody part and YYY plays the accompaniment part. We excluded some combinations, such as APF\_REC, because it is unlikely to play the recorder as the accompaniment part for the piano.

We asked a professional composer to compose two musical pieces and their variations (altogether four musical pieces) of a 4/4-time signature consisting of 16 measures with two parts (melody and accompaniment). In the experiment, we used the first half of the 8 measures. These four musical pieces were composed with the Sibelius score notation software and exported to audio files at three BPMs of 90, 100, and 110. By generating audio for the melody part and the accompaniment part, the music file was made by combining these two audio files. The generated audio file (.wav) was a single channel with a sampling rate of 44.1kHz and 32 bits per sample. All audio files were normalized. Figure 1 shows the first four measures of one of the four musical pieces.

Altogether, 13 DHH people (male 9, age range 19–23) participated. Regarding the frequency of listening to music, 9 answered daily, four a few days a week, and three a few days per month. Their hearing prostheses and number of timbres are shown in Table I.

We implemented ExM using Presentation Mobile. Participants downloaded Presentation Mobile on their smartphones and participated in it from their homes. We gave instructions online to participants; then, they listened to four sets; each set



Fig. 1. The first four measures of a musical piece.

consisted of 10 music performances of 10 timbre combinations. We asked them to tap their smartphones along with the beat of music performances. After each piece of music, we asked them to evaluate the confidence of the tapping on the five levels (1: very confident, 5: not at all confident).

Instead of using the whole audio data, we extracted the audio data from 250 ms before and 250 ms after for the 32-beat time. Then, we calculated 12 acoustic features for each timbre combination for 32 beats and obtained the average. Thus, we obtained 12\*10 data. For the analysis, we used the audio data of one of the four musical pieces at a tempo of 90. The subjective evaluation was derived from the confidence in tapping. For each timbre, we calculated the average of the participants' confidence in tapping.

## IV. RESULTS

We used MIRtoolbox on Matlab [21] to retrieve 12 acoustic features related to timbre: attack time, attack slope, zero crossing, roll-off, brightness, centroid, spread, skewness, kurtosis, flatness, entropy, and irregularity. The calculated values were rescaled to [-1, 1].

#### A. Linear correlation coefficient between ease of listening and acoustic features

Among these features, the following are found to be related to the listenability of either ExS or ExM. Conventionally, the absolute values of correlation coefficients over 0.4 are interpreted as moderate or strong [22].

- the shorter attack time (the duration from the start of the sound to the onset peak) (ExS).
- the larger entropy that includes a wide range of frequencies. Spectral entropy encodes the distribution of power in the frequency domain based on Shannon entropy (ExS and ExM).
- the smaller irregularity. Irregularity shows how large the amplitude varies between adjoining partials (ExS).
- the smaller attack slope which measures the steepness of the amplitude increase at the beginning of a sound (ExM).
- the larger roll-off. Roll-off shows the frequency value under which 85% of energy is contained (ExM).
- the larger spread. Spread shows the standard deviation of frequencies (ExM).
- the larger flatness (ExM).

Table II shows the values of the correlation coefficient between listenability in ExS and confidence in ease of tapping in ExM. Green cells show the values equal to or larger than 0.4, while red cells show the values equal to or less than -0.4.

TABLE II

RESULTS OF AUDIO FEATURES AND SUBJECTIVE JUDGMENT. LINEAR CORRELATION COEFFICIENT VALUES. EXS FOR EASE OF LISTENING, EXM FOR EASE OF TAPPING. GREEN CELLS SHOW THE VALUES EQUAL TO OR LARGER THAN 0.4, WHILE RED CELLS SHOW THE VALUES EQUAL TO OR LESS THAN -0.4.

Acoustic features	ExS	ExM
attack time	-0.47	-0.10
attack slope	0.17	-0.44
zerocross	0.27	-0.14
roll-off	0.26	0.48
brightness	0.36	0.31
centroid	0.28	0.39
spread	0.18	0.50
skewness	-0.28	-0.30
kurtosis	-0.34	-0.24
flatness	-0.03	0.65
entropy	0.40	0.46
irregularity	-0.43	-0.28

TABLE III

VALUES OF ACOUSTIC FEATURES OF FOUR SINGLE INSTRUMENTS (AVERAGE VALUES OF FIVE PITCHES). VALUES ARE RESCALED IN [-1, 1] WITH ALL 19 INSTRUMENTS.

	ACC	APF	REC	SHM
attack time	0.10	-0.79	0.68	-1.00
attack slope	-0.77	0.29	-1.00	0.99
zerocross	-0.17	-0.69	-1.00	0.29
rolloff	-0.15	-0.05	-1.00	0.73
brightness	0.06	-0.10	-1.00	0.81
centroid	-0.06	-0.12	-1.00	0.75
spread	-0.09	0.23	-1.00	0.53
skewness	-0.20	-0.38	1.00	-0.79
kurtosis	-0.39	-0.58	1.00	-0.86
flatness	-0.75	0.40	-0.95	1.00
entropy	0.08	0.52	-1.00	1.00
irregularity	0.04	0.80	0.49	-0.39

### B. Acoustic features and ease of listening

1) *ExS*: For the timbre analysis, we used an array of 12 \* 95, where 12 is the number of audio features, and 95 is the number of timbres (19 instruments by five pitches). Average values of acoustic features of four instruments used in *ExM* are shown in Table III.

The recorder timbre has the least listenability for all five pitches. The timbres give the best listenability varied among wind instruments (bassoon, tuba, and trombone), which we did not expect [3](Table IV).

2) *ExM*: After obtaining the twelve acoustic features, we rescaled them in the range of [-1, 1] for comparison. Table V shows the twelve acoustic features for each of the ten timbre combinations. Figure 2 shows the average values of the confidence of tapping for the 10 timbres.

## V. DISCUSSION

### A. Listenability of timbres: a single instrument vs. a combination of timbres

Since we used different subjective evaluations of the listenability of a single instrument and confidence of tapping for the music played by the combination of timbres, it is not straightforward to compare the two subjective evaluations. On the other hand, it is not suitable to ask participants, “How was

TABLE IV

RESULTS OF AUDIO FEATURES AND SUBJECTIVE JUDGMENT. BSN: BASSOON, CGT: CLASSICAL GUITAR, CLN: CLARINET, CVN: CLAVINET, FLT: FLUTE, REC: RECORDER, SHM: SHAMISEN, BSN: BASSOON, EGT: ELECTRIC GUITAR, TUB: TUBA, TRB: TROMBONE, TRP: TRUMPET, VIN: VIOLIN

Audio feature	min	max	easiness in listening to	
			min	max
C3	attack time	CVN	FLT	
	irregularity	FLT	VIN	REC BSN
	entropy	REC	SHM	
G3	attack time	SHM	FLT	
	irregularity	FLT	CGT	REC TUB
	entropy	REC	SHM	
C4	attack time	CVN	FLT	
	irregularity	FLT	APF	REC TUB
	entropy	REC	SHM	
G4	attack time	SHM	FLT	
	irregularity	FLT	CLN	REC TRB
	entropy	REC	EGT	
C5	attack time	SHM	FLT	
	irregularity	TRP	REC	REC TRB
	entropy	REC	SHM	

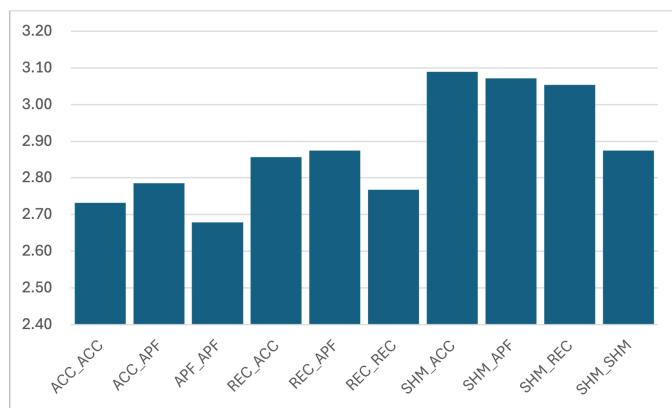


Fig. 2. The average values of confidence of tapping for the ten timbre combinations.

the listenability of the music?” after they listened to a piece of music because the length of the performance is more than 20 seconds. The participant’s evaluation of listenability may vary during that length of performance. Therefore, participants subjectively answered the “confidence of tapping” question, which they could judge from their tapping task. We assumed that if participants could listen to the music piece, then tapping would be easy, and here we compare the listenability of the timbre of a single instrument and the confidence of tapping of the timbre of combined instruments.

From Table II, we can see that the entropy is the only common feature related to the listenability of timbres of a single instrument and those of two instruments. Timbres with the larger entropy values involve the wider frequency range, which may affect the better listenability for DHH people.

Regarding the confidence of tapping, we assumed that the timbres combinations with higher listenability were easier to listen to and, therefore, easier to tap. However, in actual music, we also hear melody and rhythm, which are musical elements

TABLE V  
VALUES OF ACOUSTIC FEATURES OF TEN TIMBRE COMBINATIONS. VALUES ARE RESCALED IN [-1, 1].

	ACC_ACC	ACC_APF	APF_APF	REC_ACC	REC_APF	REC_REC	SHM_ACC	SHM_APF	SHM_REC	SHM_SHM
attack time	-0.94	-0.98	1.00	-0.88	-1.00	-0.98	-0.16	-0.57	-0.58	-0.96
attack slope	0.70	0.69	-0.57	0.76	1.00	1.00	-0.60	-0.39	-0.40	-1.00
zerocross	0.90	1.00	-0.78	-0.85	-0.90	-1.00	-0.10	-0.14	-0.95	0.70
rolloff	0.00	0.12	-0.42	-0.75	-0.70	-1.00	0.31	0.48	0.23	1.00
brightness	0.20	0.46	-0.41	-0.78	-0.74	-1.00	0.16	0.46	0.02	1.00
centroid	0.04	0.21	-0.52	-0.76	-0.77	-1.00	0.20	0.40	0.01	1.00
spread	0.21	0.29	-0.41	-0.77	-0.75	-1.00	0.47	0.61	0.47	1.00
skewness	-0.46	-0.63	-0.12	0.64	0.37	1.00	-0.43	-0.75	-0.27	-1.00
kurtosis	-0.65	-0.76	-0.33	0.49	0.16	1.00	-0.54	-0.80	-0.27	-1.00
flatness	-0.67	-0.63	-0.65	-0.90	-0.87	-1.00	0.28	0.50	0.20	1.00
entropy	0.08	0.01	-0.03	-0.52	-0.75	-1.00	0.57	0.68	0.16	1.00
irregularity	-0.30	0.56	0.19	0.51	1.00	0.48	-1.00	0.20	0.30	-0.73

TABLE VI  
COSINE SIMILARITIES BETWEEN TIMBRES BY A SINGLE INSTRUMENT AND THOSE OF TWO INSTRUMENTS. ABSOLUTE VALUES OVER 0.50 ARE SHOWN IN RED (NEGATIVE) OR GREEN (POSITIVE), AND THOSE BETWEEN 0.50 AND 0.25 ARE SHOWN IN LIGHT RED (NEGATIVE) OR LIGHT GREEN (POSITIVE).

	ACC_ACC	ACC_APF	APF_APF	REC_ACC	REC_APF	REC_REC	SHM_ACC	SHM_APF	SHM_REC	SHM_SHM
ACC	-0.05	-0.10	0.89	0.12	-0.01	0.05	0.19	-0.11	0.13	-0.05
APF	0.03	0.02	-0.65	-0.44	-0.43	-0.48	0.42	0.61	0.27	0.48
REC	-0.16	-0.23	0.88	0.58	0.50	0.60	-0.44	-0.69	-0.42	-0.60
SHM	0.11	0.16	-0.87	-0.50	-0.43	-0.52	0.36	0.62	0.28	0.52

TABLE VII  
COSINE SIMILARITIES BETWEEN TIMBRES BY A SINGLE INSTRUMENT. POSITIVE VALUES ARE SHOWN IN RED AND NEGATIVE VALUES ARE SHOWN IN GREEN.

	ACC	APF	REC	SHM
ACC	-	-0.59	0.68	-0.74
APF	-0.59	-	-0.82	0.88
REC	0.68	-0.82	-	-0.97
SHM	-0.74	0.88	-0.97	-

other than timbre.

### B. Acoustic similarity between timbres by a single instrument and timbres of the music

We calculated the cosine similarities between vectors of five acoustic features of timbres by the single instrument and by the combination of two instruments (Table VI). The five acoustic features are those that have moderate to strong correlation coefficients found in ExM. Table VII shows the cosine similarities of five acoustic features between four timbres each from a single instrument. The four instruments could be divided into two groups of (1) accordion and recorder, and (2) piano and shamisen.

When the melody part is played by the recorder, the accompaniment part is played either by accordion, piano, or recorder. This is the same as when the melody part is played by the shamisen. Focusing on the rows of REC and SHM in Table VI, green cells showing the larger cosine similarities are when the melody part is the same as either the recorder or the shamisen.

The cosine similarities shown in green and red cells in the row of APF are similar to those of SHM (Table VI). This might be because the piano and shamisen are in the same group. On the other hand, it is hard to interpret the four cells

in the column of APF\_APF. ACC and ACC\_ACC have a small value of cosine similarity. We need to pursue what makes the acoustic features of timbres different between timbres from a single instrument and timbres of the combination of a single instrument.

### C. Limitations

We understand the limitations in interpreting the two experiments because the experiments were conducted online, and the number of participants was small. Though online experiments cannot control devices and the environment in the online experiments, we prefer this environment to the lab experiment because our setting mimics the environment where DHH people listen to music every day. Since the listenability of music by DHH people varies person by person, and even the same person listens to music differently according to their health condition. Therefore, we asked participants to repeat the experiment even though it is impossible to get statistical testing from our experiments. From the point of view of the sound contents used in the experiment, we are unsure about the meaning of using the artificial sound, especially since there were no authentic sounds, such as C3 in a violin. Furthermore, though we used the confidence of tapping for the listenability in ExM, we will seek a more suitable listenability judgment method for timbres by prural instruments. Even with this lack of rigor in the experiment, the results from these experiments are necessary for our future work.

### D. Future work

In ExM, listenability was determined solely by acoustic features. We found that timbres with high entropy values gave DHH better listenability. Since this is not enough to explain the listenability, we will consider other musical elements, such

as melody contour, harmony, and beat strength, in relation to the listenability of music for DHH.

In cases of hearing impairment, hearing ability is often described from an audiogram and shown with dBHL value. However, the shape of an audiogram varies depending on the measurement frequency, referred to as auditory characteristics. Thus, the hearing ability does not clearly indicate whether someone's listenability is better in low-frequency or high-frequency bands. Since musical instruments have a wide frequency range, it may be difficult to judge the listenability of music without knowing an individual's auditory characteristics. It is also difficult to say whether a particular instrument or piece of music is easy for DHH individuals to listen to. For this reason, we collected individual audiograms and will perform a qualitative analysis of the listenability of many pieces of music for each DHH person. This will help us understand the acoustic features of music timbres and each DHH person's listenability toward music recommendations for DHH people.

#### REFERENCES

- [1] C. Oshima, R. Hiraga, H. Yamamoto, and K. Nakayama, "A qualitative research study to clarify why deaf and hard of hearing people enjoy singing," in *Proc. HCIH 2025*, 2025.
- [2] Y. Nakahara, R. Hiraga, and N. Kato, "A subjective evaluation of music beat recognition with different timbres by hearing-impaired people," in *Proc. ICCHP*, vol. 10896, 2018, pp. 207–210.
- [3] R. Hiraga, K. Yasu, and Y. Shiraishi, "Audibility and preference of musical instrument by people with hearing loss," in *Proc. IEEE SMC*, 2025, pp. 961–966.
- [4] "How to make music activities accessible for deaf children and young people." (accessed: 07.09.2025). (), [Online]. Available: [https://www.musicmark.org.uk/wp-content/uploads/ndcs\\_how\\_to\\_make\\_music\\_activities\\_accessible.pdf](https://www.musicmark.org.uk/wp-content/uploads/ndcs_how_to_make_music_activities_accessible.pdf).
- [5] N. M. Williams. "Teaching music to students with hearing loss." (accessed: 07.09.2025). (), [Online]. Available: <https://nafme.org/teaching-music-to-students-with-hearing-loss/>.
- [6] K. M. LaLonde, "Teaching music to hearing impaired," *Minot State University ProQuest Dissertations & Theses*, vol. 10684252, 2017.
- [7] H. Lee and D. Müllensiefen, "The timbre perception test (tpt): A new interactive musical assessment tool to measure timbre perception ability," *Att., percep. & psychophys.*, vol. 82, no. 7, 2020.
- [8] J. Marozeau, A. Cheveigné, S. Mcadams, and S. Winsberg, "The dependency of timbre on fundamental frequency," *The Journal of the Acoustical Society of America*, vol. 114, pp. 2946–57, 2003.
- [9] K. Gfeller, S. Witt, M. A. Mehr, G. Woodworth, and J. Knutson, "Effects of frequency, instrumental family, and cochlear implant type on timbre recognition and appraisal," *Annals of Otology, Rhinology & Laryngology*, vol. 111, no. 4, 2002.
- [10] J. Heng, G. Cantarero, M. Elhilali, and C. J. Limb, "Impaired perception of temporal fine structure and musical timbre in cochlear implant users," *Hear Res*, vol. 82, no. 7, 2011.
- [11] Y.-Y. Kong, A. Mullangi, and J. Marozeau, "Timbre and speech perception in bimodal and bilateral cochlear-implant listeners," *Ear and Hear*, vol. 33, no. 5, pp. 645–659, 2012.
- [12] J. J. Galvin III, Q.-J. Fu, and S. Oba, "Effect of instrument timbre on melodic contour identification by cochlear implant users," *J Acoust Soc Am.*, vol. 124, no. 4, 2008. DOI: 10.1121/1.2961171.
- [13] J. J. Galvin III, Q.-J. Fu, and S. Oba, "Effect of a competing instrument on melodic contour identification by cochlear implant users," *J Acoust Soc Am.*, vol. 125, no. 3, 2009. DOI: 10.1121/1.3062148.
- [14] T. Verma, S. C. Aker, and J. Marozeau, "Effect of vibrotactile stimulation on auditory timbre perception for normal-hearing listeners and cochlear-implant users," *Trends in hearing*, vol. 27, 2023.
- [15] R. Paisa, N. C. Nilsson, and S. Serafin, "Tactile displays for auditory augmentation—a scoping review and reflections on music applications for hearing impaired users," *Front. Comput. Sci.*, vol. 5, 2023.
- [16] J. Boyer and J. Stohl, "Meludia – online music training for cochlear implant users," *Cochlear Implants Intl*, vol. 23, no. 5, pp. 257–269, 2022.
- [17] B. A. Swanson, V. M. Marimuthu, and R. H. Mannell, "Place and temporal cues in cochlear implant pitch and melody perception," *Front Neurosci*, vol. 13, no. 476511, 2019.
- [18] O. Macherey and A. Delpierre, "Perception of musical timbre by cochlear implant listeners: A multidimensional scaling study," *Ear and Hear*, vol. 34, no. 4, pp. 426–436, 2013.
- [19] K. Gfeller, R. Mallalieu, A. Mansouri, *et al.*, "Practices and attitudes that enhance music engagement of adult cochlear implant users," *Front Neurosci*, vol. 13, no. 470544, 2019.
- [20] A. L. AnwyI-Irvine, J. Massonnié, A. Flitton, N. Kirkham, and J. K. Evershed, "Gorilla in our midst: An online behavioral experiment builder," *Behavior research methods*, vol. 52, pp. 388–407, 2020.
- [21] O. Lartillot, P. Toivainen, and T. Eerola, "A matlab toolbox for music information retrieval. data analysis, machine learning and applications," in *Studies in Classification, Data Analysis, and Knowledge Organization*, 2008, pp. 261–268.
- [22] H. Akoglu, "User's guide to correlation coefficients," *J Emerg Med.*, vol. 18, no. 3, 2018. DOI: 10.1016/j.tjem.2018.08.001.