Tactile Beat Perception with SANSync: Comparative Study of Participants with Deafness and Hearing Participants

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Abstract – **This work presents SANSync, a system designed to support inclusive music participation by delivering real-time tactile beat cues to deaf users. The system consists of a station device that extracts beat-timing sequences from audio or video and wirelessly transmits them to wristbands, which convert the signals into synchronized vibration pulses. To evaluate its effectiveness, 30 participants (15 deaf and 15 hearing) completed a beat synchronization task, tapping in time with vibration cues across three songs at different tempi (72, 108, and 129 beats per minute).**

Hearing participants achieved higher synchronization accuracy and consistency, with hit rates of 78.37% at a 10% tolerance window and 92.07% at 15%. Deaf participants showed more variability, with corresponding hit rates of 57.63% and 70.89%, but notably, about half performed at a level comparable to hearing participants. These differences are attributed to limited rhythmic experience and communication challenges during first-time use. With training, performance among deaf participants is expected to improve significantly, highlighting SANSync's potential as an affordable pathway toward inclusive, shared musical experiences.

Keywords – deafness, accessibility, assistive devices, inclusive music, affordable technology.

I. INTRODUCTION

Deaf individuals face a wide range of challenges in their daily lives, stemming not only from communication barriers but also from societal structures that are often designed with hearing populations. Everyday activities such as accessing healthcare, education, or public services often become disproportionately challenging when accommodations are insufficient or awareness is limited. These barriers also influence employment opportunities, access to information, and participation in community life, underscoring the need for inclusive design and greater recognition of sign language in public spaces [1].

Beyond everyday difficulties, deaf individuals often face a deeper problem of social exclusion. Even with new technologies, many are still left out of full participation in society. True inclusion requires more than just physical access – it also needs clear communication, mutual understanding, and respect for Deaf culture and sign language. Closing these gaps is important for building a more inclusive and diverse society.

One area that is often overlooked is access to music. Often seen as an experience centered on sound, music is generally assumed to be inaccessible to deaf individuals. As a result, they are frequently excluded from musical events and cultural spaces. However, Deaf communities have developed rich and creative ways to engage with music through vibrations, visual cues, and movement. In Thailand, some schools for deaf students already include cultural dance performances as part of their activities, often without relying on technology. In these performances, music is experienced through body movement, rhythm, and visual coordination, showing that musical appreciation does not depend only on hearing.

Deaf individuals experience music through low-frequency vibrations, performers' movements, and visual effects such as lights in rhythm with the beat. Technologies like vibrating platforms, tactile devices, and visual displays further enhance these experiences [2], [3]. Deaf artists, including sign language performers and dancers, contribute by using visual storytelling and rhythmic movement, expanding how music can be expressed and shared [4].

Inclusive events that combine sign language, visual effects, and vibration-based technologies create shared spaces for both deaf and hearing participants. These environments foster connection, cultural exchange, and mutual understanding, helping to reduce social barriers [5]. While music cannot address all structural causes of exclusion, it can play a valuable role in promoting inclusion and redefining accessibility [6].

Music perception refers to the way people sense, interpret, and understand music. It involves recognizing core elements [7] such as tempo (the pace or speed of the music), rhythm (patterns of duration and accent), pitch (the perceived highness or lowness of sound), melody (an organized sequence of pitches), harmony (the simultaneous sounding of pitches), timbre (tone color or quality, e.g., piano vs. violin), and dynamics (variations in loudness and intensity). Additional dimensions often discussed include texture (the layering of musical lines), form (the structural organization of sections), articulation (the manner in which notes are executed), orchestration (the distribution of material across instruments), and lyrics (the meaning carried by words in songs).

For hearing individuals, this process is primarily auditory, while for deaf and hard-of-hearing individuals it can occur through vibration, visual cues, and tactile feedback [8]. Advances in technology continue to broaden these multisensory experiences, making music more accessible to diverse audiences [9]. Various technologies have been developed to enhance music experiences that can benefit deaf individuals. The following are the reviews of current technologies that support musical engagement within the Deaf community.

- Visual Music Representations

Visual systems use colors, shapes, lights, or animations to represent music elements such as pitch, dynamics, or timbre.

  - Sound Visualization Tools like Music Animation Machine [10] allow users to “see” music in real time.

- Tactile and Haptic Feedback Systems

  These systems convert audio signals into vibrations that users can feel on their skin.

  - SubPac [11] is a wearable device that provides low-frequency vibrations to the back or chest.
  - VibroGlove [12] are research-based wearable prototypes that map specific frequency bands to different body locations.
  - Projects like Emoti-Chair have shown that haptic devices can significantly improve beat perception and emotional engagement in deaf users [13],[14].

- Vibrotactile Floors and Environments

  Room-scale setups use vibrating floors or chairs that enable users to feel music through their entire body.

  - FeelTheMusic [15] installations and Soundbeam [16] environments have been used in inclusive concerts and music therapy.
  - Experiments with vibrotactile stages in clubs (e.g., Deaf Rave [16]) show that shared vibration can foster a collective experience of music.

- Collaborative and Participatory Music-Making Tools

  Tools that enable deaf and hard-of-hearing individuals to co-create music have also been developed. Beat Blocks [18] allows intuitive, rhythm-based creation with visual and haptic feedback.

- Sign Language Integration with Music

  Some performances combine sign language with music to communicate lyrical and emotional content.

  - Signed music videos, such as those by ASL interpreters or deaf performers [19], have gained popularity and foster inclusion.
  - Recent study [20] investigates how synchronized signing and rhythmic body movement help convey the musical structure.

However, most of these technologies remain limited in accessibility. Some are prohibitively expensive, while others exist only as research prototypes. Earlier devices were also difficult to design and operate, as they attempted to convey multiple musical elements – such as pitch, dynamics, and timbre – simultaneously, making them overly complex and less user-friendly. Moreover, many were not designed to facilitate shared experiences between deaf and hearing individuals.”

In this study, we introduce SANSync, a simple and low-cost device designed to enable **shared music experiences** between deaf and hearing individuals. The system is based on tactile feedback and focuses on delivering two fundamental musical elements – tempo and rhythm – to users in real time. Our central idea is that when deaf participants can follow, anticipate, and synchronize with beats with sufficient time resolution, they are able to actively participate in music-related activities such as dance, alongside their hearing peers. Unlike prior approaches, SANSync operates wirelessly and in real time, transmitting beat information while the music is being played. Its broadcasting design allows dozens of users to connect simultaneously, enabling both deaf and hearing participants to share and enjoy the same musical experience together.

The remainder of the paper is organized as follows. Section II describes the development of the SANSync device. Section III presents the experimental setup and results. Section IV discusses the findings and concludes the paper.

II. SANSYNC DEVICE DEVELOPMENT

Our device, named SANSync[1] (derived from “Sinoatrial Node Synchronization”), evokes the metaphor of the human heartbeat aligning with musical rhythm. It is designed to detect and identify beat sequences and generate real-time vibration pulses on a wearable device for deaf users. While hearing individuals experience the song acoustically, deaf individuals wearing SANSync perceive the rhythm through tactile vibrations in the same shared space. The idea is to enable mixed groups of hearing and deaf individuals to enjoy the same music together and to interact socially, potentially participating in joint activities such as dancing or playing musical instruments.

A. System Components

The SANSync system consists of two connected components: a station device and multiple wearable wristbands.

1. Station Device (PC):

   The station is a personal computer running a Python-based program with three main functions. First, it supports loading and playback of standard MP3 and MP4 files, ensuring compatibility with widely available media so that users can easily access their own music collections. Second, it performs beat detection by analyzing the audio track with open-source signal processing libraries such as *madmom*, *librosa*, *sounddevice*, and *soundfile*. Among these, *madmom* plays a central role in beat tracking, applying machine learning algorithms to achieve reliable detection even in complex musical passages [21]. Finally, once beats are identified, the program plays the music or video while simultaneously broadcasting beat-timing data over Wi-Fi in the 2.4 GHz band using the low-latency UDP protocol. Each beat is encoded as a compact two-byte message, minimizing processing overhead and ensuring near-instantaneous delivery to all receivers.

2. Wearable Wristbands:

   The wristbands are lightweight devices built around the M5StickCplus V2 ESP32 module (see Fig. 1), a versatile microcontroller with integrated Wi-Fi

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[1] While inspired by the sinoatrial node – the heart’s natural pacemaker – SANSync is not a medical or physiological application, but a technological framework for synchronizing musical beats with tactile feedback.

capability. Each wristband connects to the same Wi-Fi network as the station and continuously listens for transmitted beat packets, verifying the source of each message to avoid false triggers. Once verified, the signal is decoded and converted into a pulse-width-modulated (PWM) output that drives a compact vibration motor attached to the wristband. The motor delivers tactile pulses directly to the user's wrist, precisely synchronized with the music's rhythm. This design enables deaf users to feel the beat in real time while hearing users experience it through sound. Portable, wireless, and easily scalable, the wristbands can be deployed for group use without complicated setup.

Fig. 1. M5StickCplus V2 ESP32 module with vibration motor hat

B. *How SANSync Works*

The overall working principle of SANSync is illustrated in Fig. 2. When a user selects a song or music video, the PC-based station loads the file and performs real-time beat analysis. By combining machine-learning beat detection with efficient audio processing libraries, the system extracts rhythmic patterns and converts them into digital timing sequences. Unlike traditional music-visualization software, which focuses only on graphics, SANSync transforms rhythm data into wireless haptic feedback, bridging sensory channels between hearing and touch.

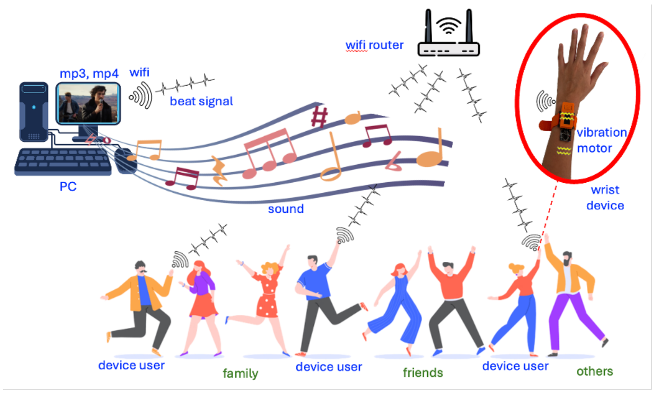


Fig. 2. Working concept of SANSync.

Once beat sequences are extracted, they are transmitted concurrently with playback, ensuring that every detected beat is aligned with the ongoing audio or video. The choice of UDP over Wi-Fi is deliberate: unlike TCP, UDP avoids acknowledgment delays and packet buffering, allowing the system to achieve millisecond-level synchronization. The use of 2-byte encoding further minimizes data load, making the transmission robust even with multiple wristbands connected simultaneously. Under low-traffic Wi-Fi conditions, the typical one-way latency is around 2 to 10 ms. This delay is negligible compared to human perception thresholds for rhythm synchronization.

On the receiver side, each wristband acts as a tactile music interface. Upon decoding the signal, it instantly generates PWM pulses to activate the vibration motor. The tactile feedback is strong enough to be clearly perceived, but short enough to capture the rhythm without masking subsequent beats. This provides a natural, rhythmic sensation that mimics the temporal feel of the music.

A key advantage of SANSync is its scalability and inclusivity. A single station can support 20–30 wristbands within a radius of about 30 meters, depending on the Wi-Fi router's specifications. This enables shared group experiences, where hearing participants enjoy the sound while deaf participants feel the rhythm together. Unlike earlier prototypes, SANSync avoids complexity by focusing only on the beat element of music, making the system more intuitive, affordable, and practical for real-world use.

III. Experimental Setup and Results

To evaluate the effectiveness of our device for rhythm synchronization with music, we conducted preliminary experiments, the details of which are presented as follows

A. *Objective*

The experiment aims to evaluate how effectively deaf individuals can detect the beats and anticipate the tempo of music through vibrational feedback via using synchronized beat vibrations generated from our device. The results will be compared with a control group of hearing individuals to determine relative perceptual effectiveness.

B. *Participants*

To ensure adequate statistical power and representativeness, the study include a total of 30 participants, divided equally into two groups:

Group A (Deaf participants): 15 individuals with profound hearing loss with no known tactile sensory impairments. To exclude the effects from under-developed rhythm detection and motor timing [22], the recruited participants are selected from the ages 15 years and older.

Group B (Hearing participants): 15 individuals with normal hearing ability, matched in age and gender distribution to Group A.

Sample size selection is based on prior studies [22] in sensory perception involving between 10–20 participants per group, which have demonstrated sufficient power for preliminary comparative analysis. If variability in responses is high, a follow-up study with a larger sample size may be conducted.

C. *Apparatus*

Participants will use the SANSync system to receive the transmitted beat. The device will be placed on the palms or forearms, where tactile sensitivity is optimal.

D. *Procedure*

The experiments were conducted with one participant at a time. For both groups, each participant was exposed to three identical one-quarter-note music tracks at different tempi: slow (72 BPM), medium (108 BPM), and fast (129 BPM). To ensure consistency, the selected tracks maintained an almost constant BPM throughout. The beats generated by the station device were defined as the "ground truth" and served as the reference for analysis. To eliminate the influence of visual cues, participants received only vibration feedback from a SANSync wearable device, without access to the accompanying music video. In addition, no audio playback was provided, ensuring that the experience was purely tactile. Participants completed a 'beat synchronization task' by tapping on a table in time with the vibration pulses received from the SANSync wristband, producing approximately 60–80 taps per trial. Because participants occasionally produced fewer or extra taps due to mistaps, only trials with tap counts within approximately the same range as the 40 ground-truth beats were retained for analysis. Tapping data were recorded using a sound recorder, and the timing sequences were extracted from the audio files with a peak detection algorithm. These sequences were then compared against the beat-timing sequences generated by the SANSync station device. Performance was evaluated in terms of two key metrics: timing accuracy (closeness of taps to the target beats) and consistency (variability across repeated taps).

Ethics Statement. The study posed minimal risk and, under the policies of our institutions and the Deaf school, did not require formal approval; all participants gave voluntary consent under teacher supervision.

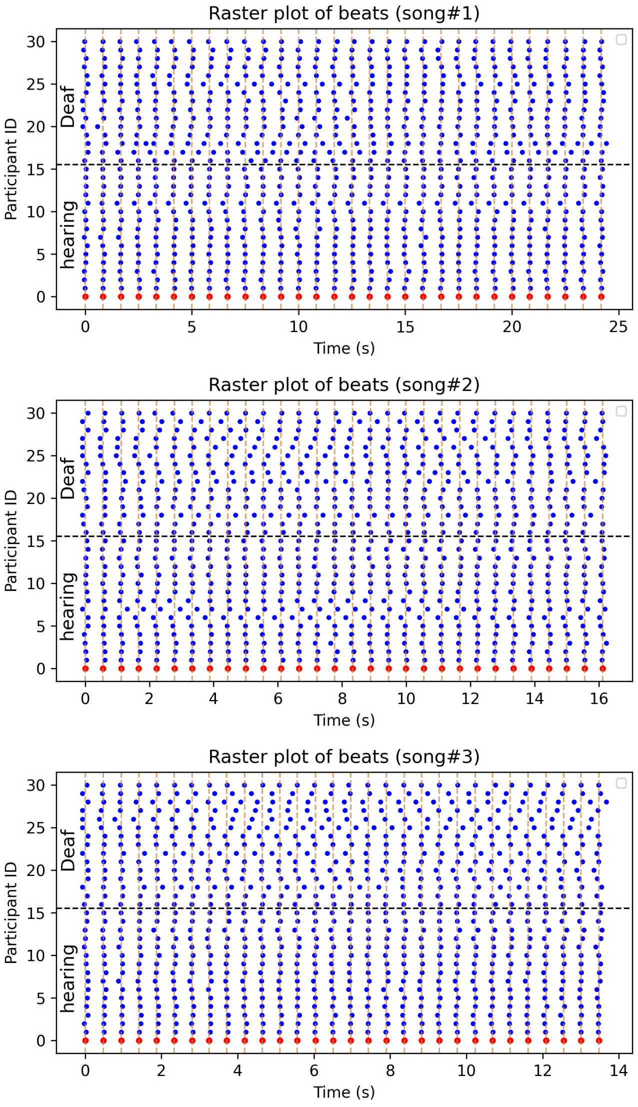


Fig. 3. Participant's taps -- blue vs. ground truth beat -- red. Participant from #1 to #15 are hearing and from #16 to #30 are deaf. (Top) song#1 72 BPM (Middle) song#2 108 BPM, (Bottom) song#3 129 BPM.

E. Results

To evaluate participants' ability to synchronize with the musical rhythm, timing accuracy was measured by computing the absolute and relative differences between each tap and the corresponding ground-truth beat. Group-level performance was summarized using the mean absolute error and standard deviation in terms of percentages of beat intervals. Figure 3 presents raster plots of participant taps (blue) compared with the ground-truth beats (red) across three test songs. The top half of the figure corresponds to deaf participants, while the bottom half corresponds to hearing participants. For clarity, the time axis was aligned such that each trial starts at zero seconds. As shown, hearing participants exhibited more consistent performance, with their tap distributions more evenly aligned with the ground-truth beats, whereas deaf participants demonstrated greater variability.

For further analysis, a small time tolerance window was defined to determine whether a tap was sufficiently close to the ground-truth beat; taps falling within this window were registered as "hits". Figure 4 presents the relationship between hit rate and timing variability across all data collected for the three songs, with results shown separately for deaf participants (top) and hearing participants (bottom). When the tolerance window was set to 10% of the beat interval (equivalent to 46–83 ms), the two groups performed very similarly, although hearing participants showed slightly higher accuracy (Fig. 4a). This result suggests that a 10% tolerance is already too strict to be reliably achieved, even for hearing participants. As shown in Fig. 4b, when the tolerance was relaxed to 15% of the beat interval, group differences became more apparent. Hearing participants demonstrated greater consistency than deaf participants, with a higher proportion of accurate repeated hits and a smaller standard deviation. This outcome was also consistent with our impressions noted during the sessions.

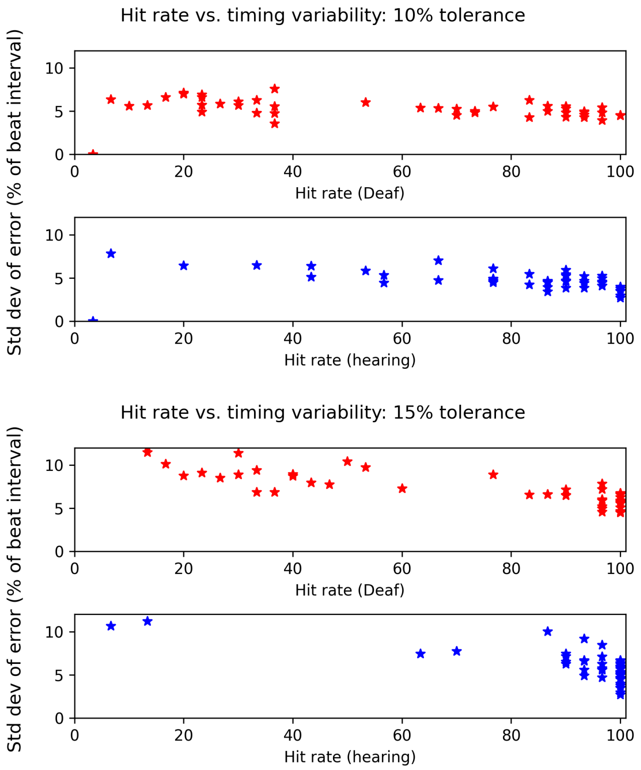


Fig. 4. Overall hit rate v.s. standard deviation of percentage of error. (Top) within 10% of beat interval (Bottom) within 15% of beat interval

In the next step of analysis, we selected the results using a 15% tolerance of the beat interval, which allowed clearer comparison between the two groups. Figure 5 presents heat maps of timing errors for each song, where the horizontal axis represents beat indices and the vertical axis represents the participant IDs assigned in the experiment. The top half corresponds to deaf participants, and the bottom half to hearing participants. Negative values (red) indicate advanced timing, positive values (blue) indicate delayed timing, and white spaces denote missed hits. Variability along the horizontal axis is not critical, as the starting point of observation may shift between trials.

For hearing participants, the heat maps across all three songs show broadly similar patterns. This suggests that tempo changes (72, 108, and 129 BPM) did not substantially affect their ability to maintain consistent synchronization with the beats. The timing errors remained relatively stable, with only minor variations in advance or delay.

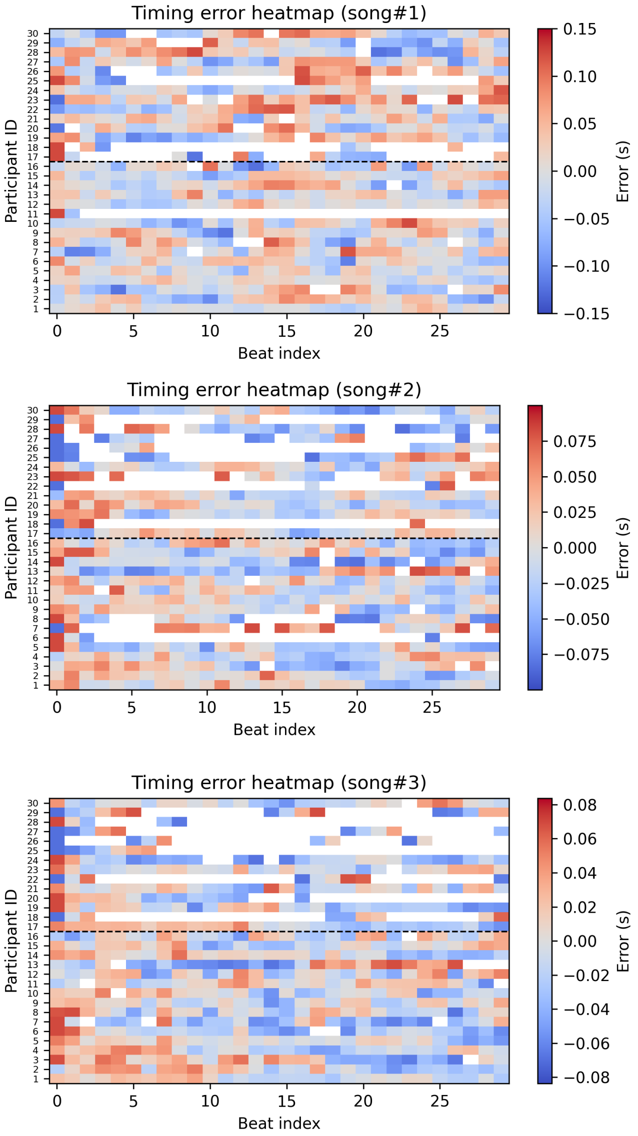
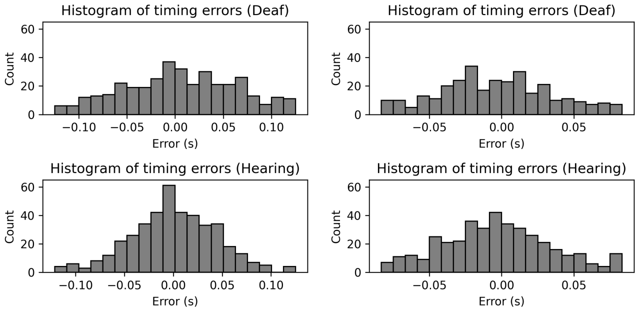


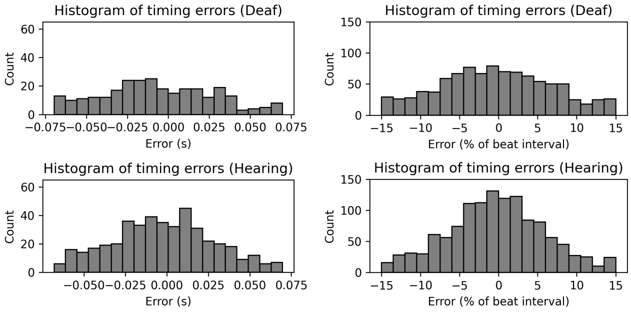
Fig. 5. Timing error heatmaps. Red tone color indicates time advance. Blue tone color indicates time delay. White spaces indicate mishits. (Top) song#1 72 BPM (Middle) song#2 108 BPM, (Bottom) song#3 129 BPM.

For deaf participants, it is worth noting first that a subset, approximately half, performed at a level comparable to hearing participants, suggesting individual differences in adaptation to tactile rhythm cues. However, overall, their performance displayed greater variability across songs. Synchronization was relatively stable at slower speeds but at faster tempi the rate of mistaps, as well as both advanced and delayed responses, increased noticeably. This pattern indicates that higher beat rates introduce greater difficulty in maintaining accurate tactile synchronization, likely due to the reduced interval between successive beats, which provides less time for processing and response. The increase in mishits with tempo also reflects the challenge of sustaining rhythmic consistency over faster musical passages.

Figure 6 shows the histogram of errors for each song (Fig. 6a to Fig. 6c) and also across all data collected for the three songs (Fig. 6d). Tables I summarizes synchronization performance under tolerance windows of 10% and 15% of the beat interval. At the stricter 10% criterion, hearing participants achieved an overall hit rate of 78.37%, compared with 57.63% for deaf participants. The mean error for both groups was relatively small, but deaf participants showed larger variability, as indicated by higher standard deviations. Performance declined most noticeably for deaf participants at the fastest tempo (129 BPM), where the hit rate dropped to 48.00%.



a) song#1 72 BPM b) song#2 108 BPM



c) song#3 129 BPM d) all 3 songs

Fig. 6. Histogram of timeing errors. Top part for deaf and Bottom part for hearing participants. a) song#1 72 BPM, b) song#2 108 BPM, c) song#3 129 BPM. d) across all data collected for the three songs.

When the tolerance was relaxed to 15%, hit rates increased substantially for both groups. Hearing participants reached an overall hit rate of 92.07%, while deaf participants improved to 70.89%. Despite this improvement, standard deviations remained higher for deaf participants, indicating greater inconsistency in tapping accuracy. Importantly, the gap between groups widened at higher tempi, reflecting that faster rhythms were more challenging for deaf participants to track through tactile feedback.

Overall, these results suggest that while hearing participants consistently maintained higher accuracy and lower variability, a subset of deaf participants demonstrated performance approaching that of hearing participants for all tempi. The tolerance analysis highlights both the potential and the limits of tactile beat perception: moderate tempo and less stringent timing windows yield better alignment, but increased tempo amplifies variability, especially among deaf participants.

TABLE I. SYNCHRONIZATION PERFORMANCE

Hit registration (within)	**10%**		**15%**	
Song #1 (72 BPM)	**Hearing**	**Deaf**	**Hearing**	**Deaf**
Mean error (% of beat interval)	0.76	0.91	0.34	0.80
STD error (% of beat interval)	3.95	5.17	5.40	6.94
Hit rate (%)	85.78	66.22	92.00	81.56
Song #2 (108 BPM)	**Hearing**	**Deaf**	**Hearing**	**Deaf**
Mean error (% of beat interval)	-0.77	-1.65	-0.56	-0.81
STD error (% of beat interval)	5.18	4.94	6.50	7.26
Hit rate (%)	70.44	58.67	87.11	69.91
Song #3 (129 BPM)	**Hearing**	**Deaf**	**Hearing**	**Deaf**
Mean error (% of beat interval)	-0.48	-1.43	-0.53	-1.71
STD error (% of beat interval)	4.94	5.73	6.23	7.78
Hit rate (%)	78.89	48.00	97.11	62.44
All songs	**Hearing**	**Deaf**	**Hearing**	**Deaf**
Mean error (% of beat interval)	**-0.48**	**-1.43**	**-0.53**	**-1.71**
STD error (% of beat interval)	**4.94**	**5.72**	**6.23**	**7.78**
Hit rate (%)	**78.37**	**57.63**	**92.07**	**70.89**

IV. DISCUSSIONS AND CONCLUSIONS

The results reveal a clear performance gap between deaf and hearing participants, with hearing participants showing higher synchronization accuracy and consistency. This difference can be explained by two main factors. First, many deaf participants have limited exposure to structured rhythmic patterns, unlike hearing participants who are accustomed to rhythm through auditory experience. This lack of familiarity may have made it harder for them to interpret and anticipate SANSync's tactile cues. Second, communication barriers during first-time use made task instructions less clear, leading to misunderstandings and greater mistap rates.

Nevertheless, about half of the deaf participants performed at a level comparable to hearing participants, showing that tactile rhythm perception is achievable even without auditory input. These limitations should therefore not be viewed as inherent, but rather as differences in exposure and initial instruction. With structured training and repeated practice, it is plausible that deaf participants could improve substantially, potentially matching or surpassing hearing participants. SANSync provides a consistent and learnable tactile feedback channel, which can become more intuitive with experience and help users strengthen associations between tactile cues and motor responses.

In summary, this study demonstrates SANSync as a low-cost system capable of enabling inclusive music engagement. While hearing participants achieved higher accuracy overall, deaf participants showed clear potential, particularly at slower tempi. The present results should be regarded as a baseline under first-time use, and future long-term training studies are needed to examine how training can further enhance performance. These findings highlight SANSync's promise as a tool for inclusive music-making, offering both immediate accessibility and long-term opportunities for skill development.

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