Designing Gestures for Digital Musical Instruments: Gesture Elicitation Study with Deaf and Hard of Hearing People

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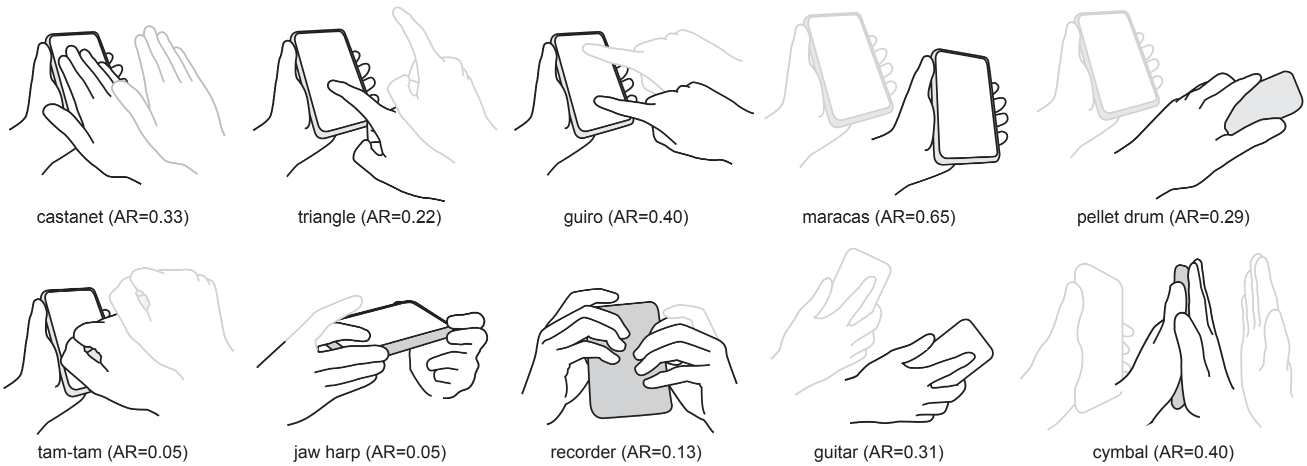

Figure 1: Most frequent gesture proposals for each referent. (AR = agreement rate)

ABSTRACT

When playing musical instruments, deaf and hard-of-hearing (DHH) people typically sense their music from the vibrations transmitted by the instruments or the movements of their bodies while performing. Sensory substitution devices now exist that convert sounds into light and vibrations to support DHH people's musical activities. However, these devices require specialized hardware, and the marketing profiles assume that standard musical instruments are available. Hence, a significant gap remains between DHH people and their musical performance enjoyment. To address this issue, this study identifies end users' preferred gestures when using smartphones to emulate the musical experience based on the instrument selected. This gesture elicitation study applies 10 instrument types. Herein, we present the results and a new taxonomy of musical instrument gestures. The findings will support the design of gesture-based instrument interfaces to enable DHH people to more directly enjoy their musical performances.

CCS CONCEPTS

• **Human-centered computing → Empirical studies in accessibility**.

KEYWORDS

Deaf, hard of hearing, music, mobile, gesture elicitation study

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1 INTRODUCTION

Musical activities have been reported to provide a wide range of cognitive, social, emotional, and physical benefits [64]. Similarly, smartphones already provide users with opportunities to incorporate musical activities into their daily lives. Owing to the release of digital audio applications for mobile devices and desktop music, anyone can experience the process of creating music and virtually playing an instrument. Although deaf and hard-of-hearing (DHH) people can enjoy music in various ways [24], they typically find it difficult to enjoy digital musical instrument applications. When DHH people play real instruments, they typically feel the sound and rhythm from the vibrations transmitted from the instrument and their own body movements. However, this is not possible with smartphone digital musical instrument applications because they cannot currently provide the same depth of vibrations as that provided by a real instrument. Furthermore, most applications are controlled using a touch screen, rendering it difficult to employ the body in ways beneficial to music appreciation. Previous research has helped DHH people play musical instruments using sensory substitution devices that convert sound into light or vibrations [52]. However, such approaches assume that a traditional instrument is available, and special hardware is required. As a result, a gap remains between DHH people and their daily musical satisfaction. To fill this gap, this study focuses on augmenting smartphone digital musical instrument applications accordingly.

In our previous work [26], we developed a smartphone-based musical instrument prototype for DHH users based on motion gestures, enabling users to feel the music through smartphone vibrations. This concept has been well received by DHH users. However, the design space remains ambiguous, and there is a lack of taxonomical and control parameters. This paper describes the empirical results of a gesture elicitation study (GES) of the physical expressions displayed when using a smartphone as a musical instrument. In our experiment, given the opportunity to obtain vibrational feedback through the smartphone from gestures, participants were asked to identify the most suitable motions to accompany the music. This work provides a quantitative and qualitative characterization of these gestures and a user-defined gesture set and taxonomy. Furthermore, design implications are summarized.

2 RELATED WORK

2.1 Music and DHH People

DHH people can and do enjoy music [16, 49]. A detailed study on how DHH people relate to music was conducted by Darrow et al. [6]. Glenny [23] and Roebuck [55] are DHH people who work as professional musicians. Beethoven, who is famous for his many masterpieces, suffered from hearing loss as well [11]. These examples suggest that people who are born deaf or have lost their hearing during life can still enjoy music. Few organizations are working toward making music more enjoyable and accessible to DHH people. "Music and the Deaf" [1] encourages DHH people to participate in musical activities. A musical activity called the "White Hand Chorus" [2] values the participation of children who are hearing and speech impaired or autistic. These projects also contribute to bringing DHH people closer to music. This study aimed to create digital musical instruments that can be enjoyed by DHH people using only existing devices. Therefore, it is expected to facilitate the daily musical enjoyment of DHH individuals.

2.2 Accessible Digital Musical Instruments (ADMIs)

To make music-making available to a more diverse population, ADMIs are gaining interest in the field of computerized music applications [27]. Previous research has resulted in systems that allow people with neurodevelopmental [38, 47, 54] and mental disorders [48], as well as motor [2, 3] and visual disabilities [32, 46, 50, 63, 78] to enjoy music. However, ADMI research for DHH people is scarce; the review by Ilsar et al. [27] reported that only four ADMIs for DHH people have been developed as of 2020.

Music and speech are fundamentally different in their wave forms; thus, it is difficult to enjoy music with hearing aids designed for speech [5]. Additionally, cochlear implants make it easier to listen to human conversations; however, they are not yet suitable for music [41]. Researchers have worked to improve such devices by designing accompanying music training programs and games [18, 37, 81]. However, melody and timbre identification remains difficult [9, 19]. Several approaches allow DHH users to perceive music without relying on their ears via sensory substitution [35].

Numerous sensory substitution systems have been developed to convert auditory information into visual [15, 17, 31, 42, 53, 68, 79, 81] and tactile cues [28–30, 33, 43, 51, 52]. Sensory substitution systems faces the perennial problem of the difficulty of designing intuitive mappings [52].

This study is not an approach that allows DHH people to imitate the way hearing people enjoy music. The main objective was to create an application that allows DHH people to enjoy making vibrations such that they can appreciate the nuances of timbres and melodies.

2.3 Creating Music with Mobile Devices

Owing to their widespread use worldwide, mobile phones have the potential to help people overcome cultural and economic barriers. In 2004, Tanaka proposed a system for creating music with mobile devices [62], and development communities have emerged [20].

Since the development of the pocket Gamelan [59] in 2006, wherein a mobile phone is used with music by moving it around, several projects [13, 22, 36, 56, 57, 70, 71] dedicated to realizing musical interaction in this way have emerged. Smartphone music applications have enabled multiplayer performances. Notably, the Stanford Mobile Phone Orchestra [45] was founded in 2007, followed which an ensemble at the University of Michigan was founded [12]. However, to the best of our knowledge, there are no examples of DHH people being involved in these activities.

Several mobile music projects address the importance of tactile feedback [21, 25, 61]. Unfortunately, haptic feedback tends to be monotonous on smartphones and does not directly provide the depth of musical structure required for DHH people. In our approach, instead of using a smartphone's haptic sensations as an adjunct to music, we use them for purposes of musical expression. In summary, several smartphone sensory output methods are being applied to solo and group musical performances, and the inclusion of DHH people in these activities is required.

2.4 GES Method

The GES method is used to design gesture-enabled user interfaces that reflect the behavioral preferences of end users. In doing so, researchers and designers seek to identify the gestures that correspond to certain system operations (i.e., referents). Often, designers devise different gestures that correspond to all referents. However, by involving the end user in this process, we expect to build a gesture set that is easier to remember and use. In this study, the pleasing nature of movement is a novel application of a GES.

The GES was first introduced by Wobbrock et al. in 2005 [73]. Since then, GESs have been realized using various systems, and 216 peer-reviewed papers were compiled in 2020 [66]. GES has been applied to various contexts including driving [44, 77], drone operations [10, 60], and augmented-reality scenarios [1, 67, 72].

[1] https://matd.org.uk/
[2] https://www.elsistemajapan.org/whitehands

In addition to freehand types [69, 75, 76], smartphone [14, 34, 80] and smartwatch gestures [4, 8, 39] have been studied. Our research addresses the musical instrument context for DHH users, noting that GES methods have been underutilized among the ASSETS community, and we hope this study will inspire them.

3 EXPERIMENT

3.1 Participants

We recruited 11 participants (five females, five males, and one "other") through email and social media channels (see Table 1). The eligibility criteria required DHH individuals with an iPhone 8 or a newer model, for which we designed the stimuli and study. This hardware limitation was necessitated by the requirement of the smartphone's Core Haptics engine and framework, which is a linear resonant actuator that provides customized vibrational feedback at fine levels of detail. The criteria did not include any musical experience. The participants were 25.4 years old on average (SD = 5.39, range = 19-38). Eight participants were profoundly deaf, and the others noted hearing difficulties that interfered with their daily lives. Participants were paid ¥860 for a 1-h study period. The experiment reported in this study was approved by the authors' university's ethics committee.

3.2 Study Application

We created an iOS application using Xcode and Swift. The application first intakes the user consent to participate and verifies the presence and functionality of the Core Haptics engine of the Apple smartphone. When launched, image buttons appear with the names of 10 musical instruments, as shown in Fig. S1. When the user makes a selection, haptic feedback is provided.

The 10 instruments used as stimuli were representative of the four main Hornbostel–Sachs musical classification hierarchy elements (i.e., idiophone, membranophone, chordophone, and aerophone)(see Fig. S1). The reason for this was to investigate how gestures were different depending on the category of instruments. This hierarchy was included such that the gestures could be coded and analyzed heuristically.

The vibrational pattern of each instrument was designed empirically to capture the characteristics of the instrument and make it easy to distinguish (see Appendix A for details).

3.3 Experimental Process

The study was conducted remotely using Zoom, owing to the COVID-19 pandemic and Japan's social-distancing restrictions. The iOS application was delivered to participants through TestFlight [3]. The experiment began with demographic questions. Prior to the experiment, participants were asked about their preferred communication channel (i.e., text chat or verbal), and we proceeded according to their preferences.

First, the participants were provided instructions on how to use the application. After they confirmed that all 10 instruments were working properly, they were asked to identify the instruments with which they were unfamiliar. Thereafter, they were presented with the referents and asked to invent gestures for the given instruments as the vibrations were created. They demonstrated the gestures over Zoom. To mitigate ordering effects, the referents were presented in a random order (Appendix B).

Following the study by Ruiz et al. [58], the participants were instructed to treat their smartphone as a "magic brick" that could recognize any gesture they might wish to perform. Hence, they were less influenced by the sensing and recognition technologies in creating the gestures. After demonstrating their gestures for each referent, the participants were asked to evaluate those gestures using a five-point Likert scale of questions [7]: (1) Goodness of fit: "The gesture I performed is a good match for its purpose," (2) Ease of use: "The gesture I performed is easy to perform."

Additionally, the experimenter(s) delved into how the participants produced the gesture and why they selected it. Although many GESs have employed a think-aloud protocol, it was difficult to apply this method as some preferred to communicate via text chat. Therefore, we asked them the questions immediately after they demonstrated their gestures, resulting in a more concise taxonomy.

3.4 Data Analysis

We evaluated user gesture preferences using the agreement rate (AR) for each referent obtained using the formula provided by Vatavu and Wobbrock [65] (see Appendix C) and the thinking time in seconds required by participants to propose a gesture for a given referent after being asked.

4 RESULTS

4.1 User-Defined Gesture Set

With 11 participants and 10 referents, 110 total gestures were created and clustered into groups of similar types according to the criteria described in Appendix D. Of the 110 gestures obtained, 55 were distinct. Fig. 1 summarizes the ARs and most frequently proposed gestures for each referent. The mean AR value was 0.27, which is a typical value compared with those reported in previous studies. The ARs for jaw harps and tam-tams were 0.05, and this value is considered small [65]. In contrast, similar gestures were proposed for maracas, with an AR of 0.65.

4.2 Correlation Analysis

The mean AR across all referents was 0.27 (SD = 0.18). The highest rate was obtained for maracas, and the lowest rate (0.05) was obtained for the tam-tam and jaw harp (see Fig. 1). The average thinking time was 62 s (SD = 59.1), goodness of fit was 4.02 (SD = 0.91), and ease of use was 4.12 (SD = 0.94).

Three pairs of significant correlations among the metrics are shown in Fig. S2. We found a significant negative correlation between ease of use and thinking time (Pearson's $r_{(N=10)} = -0.63,\ p = 0.05$; see Fig. S2 (a)). We also found a significant positive correlation between goodness of fit and AR (Pearson's $r_{(N=10)} = -0.66,\ p = 0.03$) and ease of use and AR (Pearson's $r_{(N=10)} = -0.63,\ p = 0.05$; see Figs. S2 (b) and S2 (c)).

4.3 Gesture Taxonomy for Musical Instruments

Several GES taxonomies have been developed, including surface gestures [74] and mobile interaction types [58]. Taxonomies provide

[3]https://developer.apple.com/jp/testflight/

Table 1: Demographics of the DHH participants for the GES.

ID	Age	Gender	Hearing loss	Onset age	Hearing device	Musical Experiences
P1	23	Male	Unknown	9 years	None	piano
P2	38	Female	Profound	3 years	Hearing Aids	chorus, piano
P3	29	Female	Profound	Birth	Hearing Aids	chorus, percussion, piano
P4	26	Male	Profound	1 year	Hearing Aids	chorus, drum, melodica, recorder, xylophone
P5	28	Other	Profound	Birth	Hearing Aids	chorus, clapping, piano, xylophone
P6	21	Female	Profound	2 years	Hearing Aids	chorus
P7	21	Female	Unknown	16 years	None	accordion, chorus, piano, recorder, xylophone
P8	25	Male	Profound	Birth	None	drum, flute, melodica, piano, recorder
P9	19	Male	Profound	1 year	Cochlear Implants	chorus, koto, piano, recorder
P10	21	Female	Unknown	2 years	Hearing Aids	chorus, recorder
P11	28	Male	Profound	Birth	Hearing Aids	chorus, piano

a means of understanding design spaces and, in this case, explaining and analyzing music appreciation gestures. Our taxonomy is the first developed for DHH gesture-based instrument performance, and it is manually classified into three dimensions of Nature, Form, and Function. Each dimension is further classified into smaller categories (see Fig. 2). The classification of all instruments together and those of each instrument are shown in Figs. S3 and S4, respectively.

The Nature dimension classifies gesture-meaning relationships. For the instruments, 70% of the gestures were classified as Motion and 22% were Vibration, accounting for 92% of the Nature ratings. Motion accounted for more than 60% of all instruments, apart from the jaw harp. The highest percentage of Vibration classifications was observed with the tam-tam (36%) and jaw harp (55%), which were the instruments with the lowest ARs.

The Form dimension distinguishes whether the smartphone's position changes and whether the position of the hand not holding the smartphone moves. Overall, Smartphone, Hand, and Both accounted for 86% of the total. Thus, most gestures were accompanied by user arm movements. Both was the most common gesture for cymbals (64%) and maracas (45%), as both are commonly played by holding objects of the same shape in both hands.

The Function dimension classifies the way in which a smartphone is observed. The instruments with most gestures classified as Non-sonorous are tam-tam (55%), guitar (55%), triangle (45%), and guiro (36%). These four are played by holding and moving non-soronous objects, such as a percussion mallet for the tam-tam and triangle, pick for the guitar, and stick for the guiro, with one hand. The instruments played by moving sonorous objects have a high percentage of gestures classified as Sonorous: castanets (100%), cymbal (64%), maracas (82%), and pellet drum (91%).

5 DISCUSSION

5.1 Interpretation of Quantitative Analysis

5.1.1 Subjective ratings and thinking time. There was a negative correlation between ease of use and thinking time. This can be interpreted in two ways. First, when participants spend more time thinking about a task, they may come up with gestures that are more flexible and easier to demonstrate. Second, corresponding gestures are quickly imagined when the musical instrument is easy to play.

5.1.2 Subjective ratings and agreement rate. There was a positive correlation between goodness of fit and agreement rate and between ease of use and agreement rate. It can be interpreted that the gestures that most participants produce tend to be easy to perform and suitable for the task.

5.2 Future Work

5.2.1 User Studies for Playing to the Rhythm. The objective of this study was to use gestures to play music and not to select which instrument to play. To this end, this study aimed to define the gestures as preliminary to playing a piece of music to a rhythm. For example, when learning how to play the drums, a series of steps is normally applied (e.g., hold the drumsticks, hit the drums, and play to a rhythm). Of these, holding the drumsticks and hit the drums are the gestures we investigated, as they precede rhythmic playing. Future work should include experiments with playing to a rhythm using gestures.

5.2.2 Cultural differences. Previous research [40] has discussed user-defined gestures while focusing on cultural differences. Hence, some differences may appear between Deaf and other cultures. For example, P3 mimicked a gesture that meant "sutra" in sign language, associating the vibration of a wooden fish used in a Buddhist temple with that of the cymbal. Future research should include GESs for playing musical instruments with hearing people and other user groups, as it may provide deeper insights into inclusion.

5.3 Implications for Gesture Designs and Implementations

5.3.1 Instruments Played with Both Hands. The instruments played with the same object in both hands were cymbals and maracas. In the Form dimension of cymbals and maracas, Both accounted for 64% and 45%, respectively. When playing a musical instrument application, one hand holds the smartphone as the other creates sound. This form is asymmetric and considerably differs from the actual instrument. Nevertheless, our participants preferred to perform the same movement with both hands. Other instruments played with both hands include wooden clappers and several types of drums. For those, it is recommended that the hand not holding the smartphone be able to move as well. In that case, the hand not holding the smartphone would have difficulty receiving vibrotactile sensations.

Table 2: Taxonomy of gestures for musical instruments based on 110 gestures.

Dimension	Category	Description
Nature	Motion	Gesture that mimics the motion of playing a real instrument.
	Vibration	Gesture that indicates something associated with the feel of vibration.
	Abstract	The mapping between instruments and gestures is arbitrary.
	Name	Gesture that indicates something associated with the name of the instrument.
Form	Smartphone	User moves the smartphone.
	Hand	User moves the hand that is not holding the smartphone.
	Both	User moves the smartphone and hand that is not holding the smartphone at the same time.
	Pose	User performs the gesture keeping the smartphone and hands at one location.
Function	Sonorous	The smartphone serve as a sonorous object.
	Non-sonorous	The smartphone serve as a non-sonorous object, such as hand and stick.
	Others	The smartphone serve as something other than the above two cases.

Notably, P3 stated that he would like to feel the vibrations with both hands.

5.3.2 Hand Poses are not Important in Motion Gestures. Participants did not insist on hand poses when demonstrating gestures that were not classified as Pose in the Form dimension. For example, all those who demonstrated the gesture of tapping the smartphone with a finger said that it was acceptable to tap it with another finger. When devising the gesture of swinging downward with the smartphone, P1 said, "I hold my smartphone this way, but I think other users should hold their smartphone in the way they prefer.' Motion gestures for playing a musical instrument should include various hand poses. Additionally, when developing a motion gesture recognizer, diverse hand poses should be assumed.

5.3.3 Association from Vibration. Gestures falling into the Vibration category were created by imitating daily actions that evoke pleasant feelings. The participants failed to agree on any gestures in the Vibration category. For example, P7 associated the vibration of the tam-tam with the motion of hitting a ball in tennis, whereas P3 associated it with the motion of accelerating a motorcycle. Designing a gesture based on vibrations may result in low agreement; hence, other design methods (e.g., Motion, Abstract, and Name in Nature dimensions) should be prioritized.

5.3.4 Influence of Daily Smartphone Usage. As mentioned in Section 3.3, participants were instructed to assume that the smartphone was a magic brick that could recognize any gesture. However, several participants were inspired by their daily use of smartphones. For example, when creating a gesture for the triangle instrument, P7 mimicked the action of capturing a picture with a smartphone such that the position of the smartphone would be stable. Because smartphones are devices that are used on a daily basis, the way they are manipulated has been optimized to ensure user comfort. Thus, it is recommended that gestures be designed to not disrupt the comfortable holding of the smartphone in normal situations, such as when holding it vertically or horizontally or when capturing pictures.

5.3.5 Smartphone Cases and Accessories. There are ring-type accessories on the market that attach to the back of a smartphone to make it easier to hold by inserting a user's finger through it. P7 and P8 emphasized that such accessories would allow certain gestures to be executed more safely. Some gestures are difficult to perform with notebook-type smartphone cases. When employing gestures that include vigorous movements, it may be safer to encourage the user to install a ring-type accessory or remove the notebook cover.

5.3.6 Referents with Low Agreemnet.

Unknown instruments: jaw harp. No participants were familiar with the jaw harp. With other instruments, participants often created gestures that imitated how they imagined they would play the real one. However, this approach did not work with the jaw harp. It is likely that the resulting gestures were diverse for this reason.

Instruments that can be played with only one hand: tam-tam. The agreement rate of the tam-tam was 0.05; however, all other idiophones had values greater than 0.2. This may be attributed to the fact that the real tam-tam does not require the performer to hold the sonorous object, and that it can be played with one hand. All other idiophones are two-handed instruments; thus, the roles of the hand holding the device and the other hand are easily fixed. Because this is not the case with the tam-tam, the gesture parameters appear to have been distributed in various ways depending on the smartphone being held by one or both hands, and whether it was moved vertically or horizontally.

6 CONCLUSION

We conducted a study that elicited motion gestures from 11 DHH participants based on 10 different musical instruments, using their smartphones as instruments. Based on the commonalities of user-defined gestures, we created the first taxonomy of gestures for DHH people such that developers of musical-instrument-emulating smartphone applications will have design guidelines. Our findings provide several implications that will eventually help DHH people enjoy various instruments on a daily basis.

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A DESIGN OF VIBRATIONAL FEEDBACK

Core Haptics provides two pattern types: transient (i.e., short and fixed duration) and continuous (i.e., customizable duration). The intensity and sharpness can be finely controlled to provide fine attenuation of intensity, frequency, and tempo. The vibrational patterns of the instruments were determined empirically using [4], a graphical user interface tool used to generate haptic feedback. Haptrix for the Mac operating system provides graphically transient and continuous parameters with time variations. The vibration patterns were iteratively designed, tested, and improved in a laboratory environment with multiple researchers.

We designed the vibration profile of each instrument following the pattern guidelines provided by Apple [5] in the Apple Haptic and Audio Pattern file format, which can be rendered using the Core Haptics framework.

B RANDOMIZE PROCESS

At the beginning of each experiment, variables were assigned to the 10 instruments, shuffled into a uniform distribution, and presented to the participants.

C AGREEMENT RATE

The agreement rate (AR) for each referent can be obtained using Vatavu and Wobbrock's formula [65]:

$$AR(r) = \frac{\sum_{i<j} \delta_{i,j}}{n \cdot (n-1)/2}$$

$$\delta_{i,j} = \begin{cases} 1, & \text{i-th and j-th participants are in agreement over referent } r \\ 0, & \text{otherwise} \end{cases}$$

where n is the number of participants.

D GESTURE GROUPING CRITERIA

(1) Tapping on a smartphone is considered the same gesture, even when using different or multiple fingers. For example, "tapping with the index finger" and "tapping with the index and middle finger at the same time" are the same.
(2) The hand(s) used for gesturing are distinguished. For example, if a smartphone is held in the right hand, touching the screen with the right-hand thumb is different from touching the screen with the left-hand thumb.
(3) Proximity of the smartphone to the body is distinguished. For example, striking a stationary smartphone with one's moving hand is different from striking a stationary hand with a moving smartphone.
(4) The contact locations on the phone include the touch screen, back, and sides. It is inconsequential where on the screen the participant taps.

E OTHER INSTRUMENTS PARTICIPANTS WOULD LIKE TO PLAY

After the experiment, participants were asked if there were any other instruments they would like to play on their smartphones. The following instruments were suggested: cello (P2); drum (P9, P10, P11); flute (P7); handbell (P3, P4); harp (P6, P11); metallophone (P6, P9); piano (P7, P9); sampler (P1); tambourine (P2); trombone (P7); trumpet (P6); violin (P2, P6, P9, P10); and xylophone (P6, P9, P11). P5 stated that he would like to see the inclusion of rare and unusual instruments that are unavailable on the market.

Few participants who wanted to make use of samplers and other electronic music handlers. This study focused on simple, typical acoustic instruments and did not cover instruments that produce electronic music (e.g., synthesizers), which many smartphone users can currently access. Therefore, exploring the designs of those instruments will be an interesting challenge in future.

[4] https://www.haptrix.com/
[5] https://developer.apple.com/design/human-interface-guidelines/ios/user-interaction/haptics/