Multi-touch Exploration and Sonification of Line Segments

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ABSTRACT

We present SoundLines, a mobile app designed to support children with visual impairments in exercising spatial exploration skills. This is achieved through multi-touch discovery of line segments on touchscreen, coupled with sonification feedback. SoundLines is implemented as a game in which a kitten is guided to find its mother cat by tracing the line connecting them on touchscreen.

User study with 4 visually impaired adults assessed the app accessibility and the feasibility of multi-touch exploration, compared to single-touch. While there were limited differences between single- and multi-touch modalities, results indicate that proprioceptive sensing is predominant in multi-touch exploration and that audio feedback provides benefits mostly in single-touch exploration.

CCS CONCEPTS

• **Human-centered computing** → *Empirical studies in accessibility*; *Accessibility systems and tools*; *Touch screens*; *Auditory feedback*; • **Social and professional topics** → **People with disabilities**.

KEYWORDS

Visual impairment, multi touch interation, spatial understanding.

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1 INTRODUCTION

The ability to comprehend spatial information is comparable between people with visual impairments or blindness (VIB) and sighted people [14]. However, the lack of experience in accessing spatial information makes spatial understanding challenging for people with VIB [11] and in particular children [16]. Indeed, spatial information is commonly conveyed through visual representations and seldom available in an accessible format for people with VIB [6].

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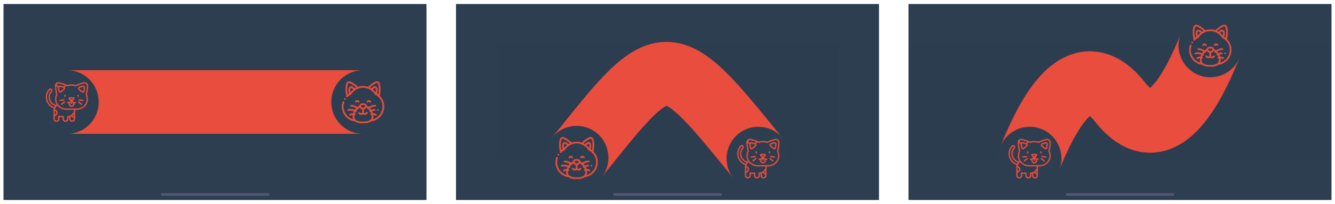
Embossed paper, thermographic print and 3D models [5, 20] are used by people with VIB to access spatial representations. To explore such materials, a common strategy is using both hands to assess the overall structure of the examined object, acquire relative positions between the explored parts, and thus build a mental model of the object [22]. However, tactile materials take time to model and often require special instruments and sighted operators to be created. Furthermore, the amount of information they can convey depends on their size, and once created they cannot be changed [7].

Touchscreen interface can also provide spatial information to people with VIB through proprioceptive sensing, acquiring the positions of the elements on the screen area by touch, while information about the explored parts is conveyed with audio feedback [3]. This approach is useful from grade school [9] to higher education [2]. However, to the best of our knowledge, existing solutions use single-touch exploration, which is limiting when assessing spatial relations between different elements, and it is in contrast with the multi-touch approach used for exploring physical objects [22].

To investigate multi-touch interaction on touchscreen, we developed *SoundLines*, a mobile game that children with VIB can use to exercise spatial exploration skills. The game's goal is to help a kitten reach the mother cat by following the line connecting them with a finger on a touchscreen, while guided through sonification. *SoundLines* implements two exploration modalities. In single-touch modality, the mother cat and the kitten are found in sequence and then connected, all with one finger. In multi-touch modality, the mother cat is found with one finger; then, while holding the first finger on the screen, the kitten is found and then guided towards the mother cat with another finger. Three sonification modalities are available while tracing the line: volume modulation, pitch modulation and period modulation. Exploration can also be performed without sonification, relying only on proprioceptive sensing.

We performed a study with 4 adults with VIB to assess the feasibility, effectiveness and preference of different exploration and sonification modalities. Although most participants showed preference for single-touch exploration, there are no significant differences between single- and multi-touch modalities considering task completion time, accuracy, and number of errors. The only exception is volume sonification, for which single-touch modality is faster. We did not detect effects of different sonifications on the multi-touch exploration, which may indicate that in multi-touch modality the participants rely more on proprioceptive exploration and less on auditory feedback. Instead, in single-touch modality, participants were more accurate when period modulation is used, which was also the preferred sonification modality for most participants.



(a) Straight Line (b) Curved Line (c) Broken Line

Figure 1: Screenshots of completed *SoundLines* exercises with different types of line.

2 *SOUNDLINES* SYSTEM

The goal of our system is to provide children with VIB, who are most impacted by the lack of accessible spatial information [16], with a means for exercising with spatial concepts. To this end, the following system design guidelines were defined together with two experts in accessibility and education for children with VIB.

(D1) Enable inclusive usage by children with and without VIB.
(D2) Stimulate prolonged usage through engaging interactions.
(D3) Allow caregivers to supervise children while playing.
(D4) Explore usage with single- and multi-touch interaction and diverse sonification modalities.

2.1 Gamification

As suggested in prior literature [4], we developed the app as a game in order to be engaging for children (D2). The game is structured as a series of quick rounds. In each, the child explores the touchscreen in search for two randomly positioned elements: a kitten and a mother cat. Then, the child guides the kitten to reach the mother cat by following the line that connects them. The line can be straight, curved or broken (see Figure 1), and it should be traversed without exiting its boundaries, defined by the line's width w (see Figure 2).

Figure 2: Elements of a line to be sonified.

The cats and the line are announced through audio and displayed visually, allowing also sighted children to play (D1), and caregivers to supervise the child's interaction with the system (D3). To support the children in playing the game autonomously, before each round, instructions on how to play the game, including the exploration and the sonification modalities used, are displayed visually and read through the system's text to speech functionality (D1).

2.2 Interaction Design

We designed two exploration modalities: single-touch and a multi-touch exploration (D4). In single-touch exploration, the user scans the touchscreen area with one finger, using proprioceptive sensing to understand the position of the explored elements, while auditory feedback provides information about the touched elements [2].

In multi-touch exploration, we replicate a technique commonly used by people with VIB for the exploration of tactile materials: multi-touch exploration with one static hand and one moving hand [22]. In this approach, one finger is used as an anchor for an element of interest, while a second finger explores other elements. Proprioceptive sensing conveys the spatial relationship between the explored elements and the element anchored by the static finger. Auditory feedback is also possible as a reinforcement cue, and it can be provided in the same way as in the single-touch exploration, since only one finger moves at a time.

2.3 Sonification Modalities

To support the task of following a line connecting two elements on touchscreen, *SoundLines* translates spatial information into non-speech audio [12] (D4). We sonify the distance d between the user's finger and the centre of the line connecting the cats, normalized to the width of the line w (see Figure 2). The distance ranges between 0 when the user's finger is on the line centre and 1 when it is exiting the line. We adopt the following sonification modalities:

Volume modulation [23]: A pure sine wave sound ($440Hz$) is played continuously. Its volume varies between 0 (no sound), when $d = 0$, and 1 (maximum volume), when $d = 1$. Thus, it is louder when the finger is about to exit the line.

Pitch modulation [2]: A pure sine wave sound is played continuously. Its frequency ranges between $250Hz$, when $d = 0$, and $650Hz$, when $d = 1$, resulting in a higher pitched sound when the finger is about to exit the line.

Period modulation [13]: A ping sound of a duration of $0.1s$ is played repeatedly. The time between two sounds ranges between $0.5s$, when $d = 0$, and $0s$, when $d = 1$. Similar to car parking sensor sounds, this sonification results in more frequent sounds when the finger is about to exit the line.

Additionally, we also consider the following condition:

No sonification: The user can only rely on proprioceptive sensing for exploration. This condition can only be used for straight lines, for which the direction to follow is known.

3 USER STUDY

We performed a preliminary user study which consisted in a series of tasks performed with *SoundLines* and a follow-up questionnaire. Due to the early stage of the prototype, the study focused solely on assessing the app accessibility and the robustness of our approach, and therefore it did not involve children but adult participants [17].

3.1 Participants

We recruited 4 participants (see Table 1), two with severe low vision and two blind [15]. All participants had prior experience with mobile devices and assistive technologies. All but *P*4 also had prior experience with sonification interaction (*e.g.*, graph sonification [8]).

Table 1: Participants' demographic information.

ID	Sex	Age	Visual Impairment		Sonification
			Condition	Onset	experience
P1	F	42	Blind	birth	Yes
P2	M	24	Severe Low vision	birth	Yes
P3	M	31	Blind	12 years	Yes
P4	M	57	Severe Low vision	4 years	No

3.2 Experimental Setting and Apparatus

The experiment was conducted in a university lab. We used an iPhone X device with VoiceOver screen reader, attached to a table to avoid undesired movements. Over-ear headphones were used to ensure a clear audio. Participants could adjust screen reader speed and volume. We modified *SoundLines* to include only straight lines, positioned randomly on the screen, since our goal was not to examine task performance, but assess the feasibility of our approach.

3.3 Procedure

The participants were first introduced to the experimental setting, presented with a description of the study and their demographic information was collected. We then performed a training phase to familiarize the participants with the apparatus, the sonifications and exploration modalities used. The training consisted of 8 tasks constructed as combinations of the 2 exploration and the 4 sonification modalities. All training tasks were performed with horizontal lines in the center of the screen. The test task sequence was scripted to avoid effects of order. The sonifications were ordered through a Latin square design, while the exploration modalities were alternated. Line types (horizontal, vertical, diagonal) and their positions on the screen (up, down, left, right and center) were randomly ordered and they were not considered as a factor to be tested. In total, participants performed 56 tasks each: 8 training tasks, plus 2 repetitions for 24 testing task combinations. Before each task, in addition to verbal instructions, earcons [21] corresponding to the task sonification modality were used as reinforcement.

We collected the following metrics for each task, using a remote data collection library developed in-house [1], and we analyzed how exploration and sonification modalities affected task performance:

Errors - Number of times the finger leaves the line.
Time - Total duration of the exploration (including restarts).
Distance - Average distance from the line centre.

Afterwards, the participants were asked to complete a questionnaire which assessed ease of use, ease of understanding, pleasantness and participants' overall preference regarding the exploration and sonification modalities. The complete study protocol, earcons used, and full results are available online[1].

[1]https://soundlines.netlify.com/

4 RESULTS

Besides *P*4, who completed only one task repetition due to lack of time, participants completed all assigned tasks and questionnaires. *P*1 and *P*4 had some difficulties due to system gestures sometimes being triggered during exploration. Specifically, in single-touch modality, starting the exploration from the top screen edge would sometimes trigger system notifications. Instead, in multi-touch modality, moving fingers in a circular motion would sometimes trigger the rotor gesture. After noting this we advised the participants that these issues might occur and assisted them when needed.

4.1 Task Results

Table 2 shows task results (as avg±stdev), grouped by exploration and sonification modality. Statistically significant differences were assessed between measurements using Friedman test and Wilcoxon Signed-Rank test [19] as post-hoc. Results show that participants were quicker in following the line with volume modulation in single- rather than multi-touch exploration ($z = 44$, $p < .05$). However, this did not result in more accurate line-following or fewer errors. There were no other significant differences between single- and multi-touch modalities. Instead, with single-touch exploration, the average distance scores were found to be significantly different across sonifications ($\chi^2 = 8.37$, $p < .05$). Specifically, period modulation had lower scores with respect to other sonifications ($p < .05$).

Table 2: Task results by exploration & sonification modality

Sonification	Interaction	Errors	Time (s)	Distance (px)
Volume	**Single**	0,9±1,1	23,2±18,6	27,3±11,0
	Multi	2,6±5,6	82,1±120	29,0±12,0
Period	**Single**	1,9±4,0	40,7±44,7	19,7±13,2
	Multi	1,2±2,8	41,8±44,0	22,7±15,1
Pitch	**Single**	1,2±2,6	36,3±47,5	26,4±13,7
	Multi	1,2±2,1	52,4±93,8	27,2±12,7
None	**Single**	1,6±3,2	45,6±57,3	25,6±10,2
	Multi	1,4±2,8	46,0±62,6	27,7±13,5

4.2 Questionnaire results

Period modulation was also the preferred sonification for most participants, in particular considering ease of understanding and overall preference (see Table 3). However, preferences varied for pleasantness, and some of the participants were undecided. Instead, all participants but *P*1 preferred single- to multi-touch exploration.

Table 3: Exploration (EM) and sonification (SM) preferences

Question	P1	P2	P3	P4
Preferred EM	multi	single	single	single
EM easiest to understand	multi	single	single	single
EM easiest to perform	multi	single	single	single
Preferred SM	period	/	period	/
SM easiest to understand	period	period	volume	/
Most pleasant SM	pitch	period	volume	/

5 DISCUSSION

We discuss key findings and limitations of our user study.

5.1 Single-touch Vs. Multi-touch

Limited differences between single- and multi-touch exploration emerged. On the one hand, single-touch modality, coupled with volume modulation resulted in a faster exploration. On the other hand such differences did not impact the exploration metrics, that is the precision in following the line or the number of errors. This may indicate that both modalities are similarly effective for touchscreen spatial exploration tasks.

We expected the questionnaire results to show a stark preference towards multi-touch exploration because it is more similar to physical object exploration, and it also allows to maintain a reference point while exploring, thus facilitating the understanding of relationships between elements. Instead, most participants reported a preference for single-touch exploration. We attribute this result to the fact that the participants were more used to this modality, as it is adopted by screen readers on mobile devices. The undesired activation of system gestures may have also contributed to worsen the perception of the multi-touch modality.

One limitation of our work is that it considers only one of the possible multi-touch interaction approaches. Our design enables the use of an anchor point as a proprioceptive reference to an element on the screen while exploring other elements. Since only one finger is moved at a time, concurrent audio feedback is not required. Other designs might involve simultaneous movement of multiple fingers on the screen, with associated concurrent auditory feedback. Such design has been used for multi-touch typing feedback [10], but it has not been tested for touch screen exploration.

5.2 Sonification Feedback Effects

During single-touch exploration, specific sonification modalities improved the exploration process. Indeed, distance score improved when period modulation was used. Instead, we did not observe improvements on multi-touch exploration due to different sonification modalities. One explanation is that, in the multi-touch modality, the participants were primarily guided by proprioceptive sensing during the exploration. This was possible because the two elements on the screen were connected with a straight line, which could be followed relying solely on proprioception. We expect the users to rely more on the sonification feedback during multi-touch interaction when curved or broken lines are used.

5.3 Applicability to Different Trajectory Shapes

The proposed exploration and sonification modalities will have to be evaluated with different line shapes to verify their applicability and performance. Additionally, different exploration and sonification modalities will need to be assessed as they might be more appropriate to convey more complex and curved shapes. For example, for curve lines, sonifying the curvature might provide better support rather than the current approach of sonifying the distance from the line center. Similarly, to explore broken lines, exploration modalities using multiple anchor points or a strategy for exploring a sequence of points could be explored in the future.

5.4 Study Participants

One limitation of our evaluation procedure is the fact that it was performed with a small number of adult participants. This choice was made because our initial focus was to assess the feasibility of the approach and the accessibility of our system, aimed at improving the interaction design and detecting possible limitations [17]. After this preliminary evaluation, our goal is to improve the app, publish it, and involve representative participants [18], that is children, for an in-depth study of the system. Clearly, such studies will focus on different aspects of the app than the conducted study. One challenge will be tuning the app interface to different physical characteristics of the users (*e.g.*, adapting line thickness to children fingers). We will also assess whether the app is perceived to be engaging by the children, and whether their level of digital literacy and familiarity with mobile devices is sufficient to use the system.

5.5 No-bezel Touch Screen Accessibility

Mobile devices are moving away from physical buttons, towards no-bezel touchscreens, replacing button interactions by system gestures performed by swiping from the device edges. While visually pleasing, this change introduces new accessibility issues. For example, people with VIB commonly use screen edges as a proprioceptive cue for starting touchscreen exploration. As a result, participants movements performed during exploration would sometimes be detected as system gestures, interrupting the exploration process. We believe that this issue impacted the participants' preference scores as well as the quantitative results of our study. For the proposed approach to be used in the future, a method to disambiguate such gestures will be needed, or the system gestures will need to be deactivated while multi-touch exploration is in progress.

6 CONCLUSION AND FUTURE WORK

This paper presents *SoundLines*, an edutainment mobile app for supporting children with VIB in exercising spatial exploration skills. This is achieved through proprioceptive sensing, stimulated with single- or multi-touch interaction on a touchscreen, coupled with diverse sonification feedback modalities as reinforcement cues.

Preliminary tests with adult participants did not highlight functional differences between single- and multi-touch exploration. However, single-touch exploration was found to be faster when the volume modulation is used. This suggests that sonification feedback may be more effective for single- rather than for multi-touch interaction. We speculate that this is due to higher attention dedicated to proprioceptive sensing in the case of multi-touch exploration.

As future work, we will design a new iteration of the *SoundLines* system addressing the limitations of the current approach, in particular the confusion of exploration movements with system gestures. We will also experiment with different exploration modalities, such as simultaneous exploration with two hands, which is commonly used for tactile exploration [22]. We will run additional user studies and longitudinal experiments with children participants to understand their performance during touchscreen exploration activities.

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