



SENSE-braille: Children's Multisensory Experiences with Auditory-Haptic Activities

Journal:	<i>British Journal of Visual Impairment</i>
Manuscript ID	BJVI-25-0017.R1
Manuscript Type:	Research Article
Keywords:	visual impairment, blindness, multisensory, braille, sensory sensitivity
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Abstract

This research investigated sensory preferences and experiences of individuals with visual impairment and blindness, when interacting with a novel multisensory device for braille learning. The device comprised an enlarged braille cell, in which interacting with each button elicited a sound, haptic vibration, or an auditory-haptic stimulus. Children, adolescents, and adults with blindness or visual impairment placed their fingertips on the device to perceive braille letters. Parents rated their children’s auditory and tactile hyper- and hyposensitivity. All participants reported enjoyment, competence, and confidence during device interaction. Participants with blindness favoured auditory-haptic and auditory modalities, while participants with visual impairment also liked the haptic-only modality. Children with blindness who scored high on hyposensitivity revealed higher hypersensitivity scores within the auditory and haptic modalities, while children with visual impairment showed cross-modal hyper-and hyposensitivity correlations between tactile and auditory modalities. Multisensory enrichment of braille learning, applications, and diagnoses are discussed to outline future research.

Word count: 150

Keywords: visual impairment, blindness, multisensory, braille, sensory sensitivity

Introduction:

Braille letters consist of small, raised dots arranged in a 2x3 cell with a height of ~0.5 mm, and a diameter of ~1.5 mm (UK Association for Accessible Formats, 2020). Learning to read braille requires sensory, motor, and cognitive abilities to perceive the dots, understand the spatial configuration and transform the perceived spatial layout into letters (Martinello & Wittich, 2022). Studies have indicated that individuals with blindness and visual impairment who use braille develop stronger spelling skills compared to those who predominantly use auditory methods (Papadopoulos et al., 2009). An earlier start and a longer duration of braille learning is also associated with higher braille reading speeds (Lang et al., 2021). Previous research highlights significant advantages of braille literacy for higher employment rates, and educational attainments (Hoskin et al., 2024; see also McDonnall et al., 2024; Ryles et al., 1996). However, the reduced tactile sensitivity in some learners, the length of braille books, and auditory alternatives that are less practice dependent have raised concerns of braille usage (Tobin & Hill, 2015).

Braille readers typically use their fingertips to identify letters using either their right hand, left hand, or both (Papadimitriou & Argyropoulos, 2017). While braille beginners often place both index fingers side by side, a more efficient strategy involves using both hands to perform separate but complementary functions. A range of braille reading strategies exist in terms of specific placement and movements of hands and fingers across and between lines, which depend on factors such as individual preferences, proficiency in braille reading, and physical ability (Bertelson et al., 1985; Davidson et al., 1980; Hughes et al., 2011; Kusajima, 1974; Mangold, 1977; Mousty & Bertelson, 1992; Nonaka et al., 2021; Olson & Mangold, 1981; Wormsley & D'Andrea, 1997; Wright et al., 2009).

Research indicates that braille beginners perceive letters as “textural” rather than “spatial” configurations (Millar, 1997). According to Millar (1997), dot density is crucial for

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braille reading. Instead of coding braille patterns by their outer shape, beginners learn to distinguish single dots as dot density cues are easier to interpret than global shape cues (Millar, 1977; 1986; for further research on tactile perception and braille, please find: Barciero et al., 2023; Bertelson et al., 1992; Boven et al., 2000; Grant et al., 2000; Knwolton and Wetzel, 1996; Legge et al., 1999; Nolan & Kederis, 1969, Ostima et al., 2014; Stevens et al., 1996; Wong et al., 2013). Given that variations in braille size might interfere with the texture characteristics of the letters, it has been recommended to present braille letters in their original size (Millar, 1997; see Barlow-Brown et al., 2019 for further discussion). However, other research suggests that using enlarged braille letters via a pegboard resulted in more effective learning compared to standard braille letters in sighted children with no prior experience in reading braille (Barlow-Brown et al., 2019; Heller & Mitchell, 1985; Newman et al.,1982; Newman et al., 1985).

During braille learning, learners may use a variety of sensory modalities to associate tactile representations of letters with their corresponding meanings (Millar, 1997). For those with intact auditory perception, the sound of the letter needs to be associated with the haptic pattern of the braille letter. Theories suggest that impaired multisensory processing could lead to an overreliance on one sensory modality, which might result in hypersensitivity, while reducing reliance on others, which might lead to hyposensitivity (Hill et al., 2013; Sieman et al., 2020). Hyper- and hyposensitivity might be explained by the interaction between neurological thresholds and self-regulation (Dunn & Daniels, 2002). In this case, the neurological threshold can be defined as the amount of sensory stimulation required to detect a stimulus while self-regulation refers to response regulation to sensory input. For example, a child could react to sensory information without actively modifying or controlling it or actively manage sensory input to meet their needs.

To understand the impact of alterations in the onset of multisensory experiences, Scheller et al. (2021) investigated processes of multisensory integration, such as auditory-tactile integration in children with congenital and late blindness as well as adults with late onset blindness after the age of 8 years together with a sighted control group. Participants were asked to indicate whether two objects either presented in the haptic, auditory or in the auditory-haptic condition, differed in size. As children with congenital blindness and late blindness mainly rely on auditory and haptic information to identify an object, it has been suggested that they would show earlier auditory and haptic integration than sighted individuals. Nine- years old children with congenital blindness showed a higher benefit from integrating auditory-haptic information compared to sighted children. Furthermore, optimal auditory-haptic integration started at a younger age in individuals with early blindness compared to the other groups, whereas optimal auditory-haptic integration was impaired in individuals with late blindness. The authors suggest that cross-modal plastic changes, such as the recruitment of visual brain areas by the remaining sensory modalities, might be one underlying principle of optimal auditory-haptic integration in children with blindness (for visual cortex activity see for example: Amedi et al., 2005; Burton et al., 2002; Liu et al., 2023; Merabet et al., 2005; Pascual-Leone et al., 1993; Sadato et al., 1998).

On the other hand, several findings suggest that sound localization and motor responses can be delayed in children with visual impairment and blindness, as visual information contributes to sensory-motor feedback that supports efficient environmental exploration (Cappagli et al., 2017; 2019). Training with an Audio Bracelet for Blind Interaction (ABBI) which connects to a smartphone and elicits a sound in response to movement showed that spatial accuracy improved in children with visual impairment and blindness after auditory-motor training (Cappagli et al., 2017, 2019).

This finding aligns with research demonstrating improvements in learning outcomes after multisensory training (Mathias & von Kriegstein, 2013) given that multisensory experiences activate a higher number of memory traces compared to unisensory experiences and thus allow more fine-tuned predictions about upcoming items (such as words). Based on this concept, the presentation of Braille letters was enriched with auditory and haptic sensory information in the current experiment.

This paper reports findings of participatory design sessions to develop the multisensory device, such as participant enjoyment and usability. A multisensory device has been developed, consisting of a six-button box arranged in an enlarged 2x3 braille cell (see Figure 1). This emulates the approach used by some teachers who use egg-cartons to teach the spatial concept of a braille cell (Farrand et al., 2024). Each of the buttons could initiate a sound (increasing in pitch from button one to six), a haptic vibration, or the combination of the sounds and vibrations. Participants could feel the haptic vibrations and listen to the sounds by either placing the fingertips on each button, or by pressing each button which initiates a sensory response (see Figure 1b). Children were interviewed about their enjoyment, their perceived competence, and their nervousness (Deci & Ryan, 2000). They were also asked about the modality they mostly enjoyed during device interaction. Parents completed the Glasgow Sensory Questionnaire (GSQ; Robertson & Simmons, 2013) on behalf of their children to analyse sensory sensitivity profiles.

Materials and Methods:

Participants:

Twelve children, adolescents, and young adults with blindness ($M_{age} = 16$ years, age range = 11 – 21 years; $SD = 3.8$; 9 females, 3 males) and 13 children, adolescents, and young adults with visual impairment ($M_{age} = 15$ years, age range = 9 – 21 years; $SD = 3.5$; 6 females, 7

males) placed their fingertips on the buttons of the device and communicated their experiences to the researchers after device interactions. Two teachers with visual impairment also interacted with the device (2 females, 61 years old and the other did not indicate the age). To match the groups of individuals with blindness and visual impairments as much as possible with respect to age and braille experiences, two teacher participants were excluded from the analysis. Participants with blindness had no more than residual light perception whereas individuals with visual impairment could also perceive contrast. This classification has been made based on previous studies including individuals with blindness and/or visual impairment (Föcker et al., 2012; 2015; 2024; Hölig et al., 2014, 2015; Kattner et al., 2024; Röder et al., 2004; Topalidis et al., 2020). Due to ethical guidelines, accessing individual visual acuity data and intelligence measurements would have required separate data-sharing agreements with each school and charity, which were beyond the scope of this study and difficult to obtain. Therefore, analyses involving direct measures of participants' vision and intelligence measures were not possible in this study.

Diagnoses and demographic information for each participant are listed in Table 1.¹

The diagnosis of one participant was unknown. Among the 13 children with visual impairment, two were also diagnosed with autism, and another two were diagnosed with ADHD. Additionally, one participant was suspected to have both autism and ADHD. None of the children were diagnosed with Cerebral Visual Impairment (CVI), although it should be noted that a lack of diagnosis does not necessarily mean that children do not have any CVI (Williams et al., 2021). Three participants had a dual diagnosis of blindness and hearing impairment. They were wearing hearing aids which allowed them to hear typical speech and

¹ Ten sighted individuals also interacted with the device. Given that the sighted group was not a direct control group to the group of individuals with visual impairment and blindness, we did not report the results in the main manuscript, but in the supplementary material.

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music within 1 m. Please note that the decision to include individuals with additional impairments was guided by the fact that many individuals with visual impairment and blindness also have co-occurring impairments and diagnoses (please see Absoud et al., 2011; DeCarlo et al., 2014; Fazzi et al., 2019; Stevenson & Tedone, 2025; Teoh et al., 2021 for further information).

Participants were recruited through conversations with the braille teacher and the Qualified Teacher of Children and Young People with Vision Impairment (QTVI) who recommended specific students for whom the device would be most appropriate or relevant. These were mostly students who were either currently learning braille or who were being considered for braille instruction due to changes in their vision. In the current experiment, all students who received braille instruction - Grade 1 (uncontracted braille) and/or Grade 2 (contracted braille) - including those students who knew a few braille letters, were considered braille readers.

Twenty-three children and adolescents were braille readers, and two children with visual impairment had no braille reading experiences. The mean age onset of braille learning was 6 years (range: 2-11 years, SD = 2.6). Braille reading experiences varied between 2 and 15 years (M = 8.18 years, range: 2-15 years, SD = 3.94 years).

The primary goal of the device interaction was to enhance motivation to learn braille, even among children who had not yet started formal braille learning. Including participants at different stages of braille literacy (e.g., those in the early, pre-braille phase) allows for a more representative sample of the broader population of children and adolescents with visual impairments. This diversity enriches the dataset by offering a wider range of perspectives on the feasibility and usability of the device across different educational stages.

Table 1. Demographics of individuals with blindness and visual impairment.

Vision Status	Diagnosis	Age (years)	Gender
Blind	Leber's congenital amaurosis	13	female
Blind	Microphthalmia	12	female
Blind	Retinitis pigmentosa	11	female
Blind	Bilateral anophthalmia	15	male
Blind	Retinal Detachment	13	male
Blind	Leber's congenital amaurosis	14	female
Blind	Leber's congenital amaurosis	18	female
Blind	Microphthalmia	15	female
Blind	Retinopathy of Prematurity	20	female
Blind	Retinopathy of Prematurity	21	female
Blind	Rare genetic condition	21	female
Blind	Rare genetic condition	21	male
Vision Impaired	Glaucoma	13	female
Vision Impaired	Bilateral retinal folds	11	female
Vision Impaired	Septo-optic dysplasia	20	male
Vision Impaired	Cone rod dystrophy	17	female
Vision Impaired	Unknown	15	male
Vision Impaired	Nystagmus	10	male
Vision Impaired	Glaucoma	16	female
Vision Impaired	Retinitis pigmentosa	16	male
Vision Impaired	Nystagmus	12	female
Vision Impaired	Retinal dystrophy	14	male
Vision Impaired	Microphthalmia	14	male
Vision Impaired	Leber's congenital amaurosis	9	female
Vision Impaired	Optic nerve hypoplasia	21	male

The multisensory device:

The outer casing of the multisensory device was made of polylactide (PLA), a thermoplastic polymer that is biodegradable, renewable and typically used as a filament for 3D printing prototypes. The device shell (Height: 78mm, Width: 215mm, Depth: 50mm) and buttons (Height: 60mm, Width: 11mm) were fabricated by an Original Prusa i3 MK3S+ 3D printer. Object designs were drawn using Autodesk Fusion 360 and AutoDesk Tinker CAD and prepared for printing using PRUSA slicer software (2.7.1). Six Grove haptic motor modules integrated with DRV2605L drivers were used to create the haptic vibrations of the buttons, and six Grove buttons with pull down resistors were used to record button presses. An Arduino Mega 2560 Rev3 was used as a microcontroller board, with a Grove - Mega Shield v1.2 attached. The code created on the Arduino IDE (2.3.2) was uploaded to the microcontroller board. A Grove speaker was used to play auditory sounds.

The haptic vibration controlled by the Arduino through the haptic motors included waveform 14/123 (Strong Buzz-100%, duration; 500ms). The auditory sounds were feedback sounds: 349Hz, and 1261Hz; and auditory sounds associated with each button increased in pitch from button 1 to button 6: button 1: 293Hz, button 2: 329 Hz, button 3: 349Hz, button 4: 391Hz, button 5: 440Hz, and button 6: 493Hz. The device was equipped with two additional buttons: a start button to initiate letter presentation, and a cancel button positioned on the front of the button box, facing the participant (see Figure 1).

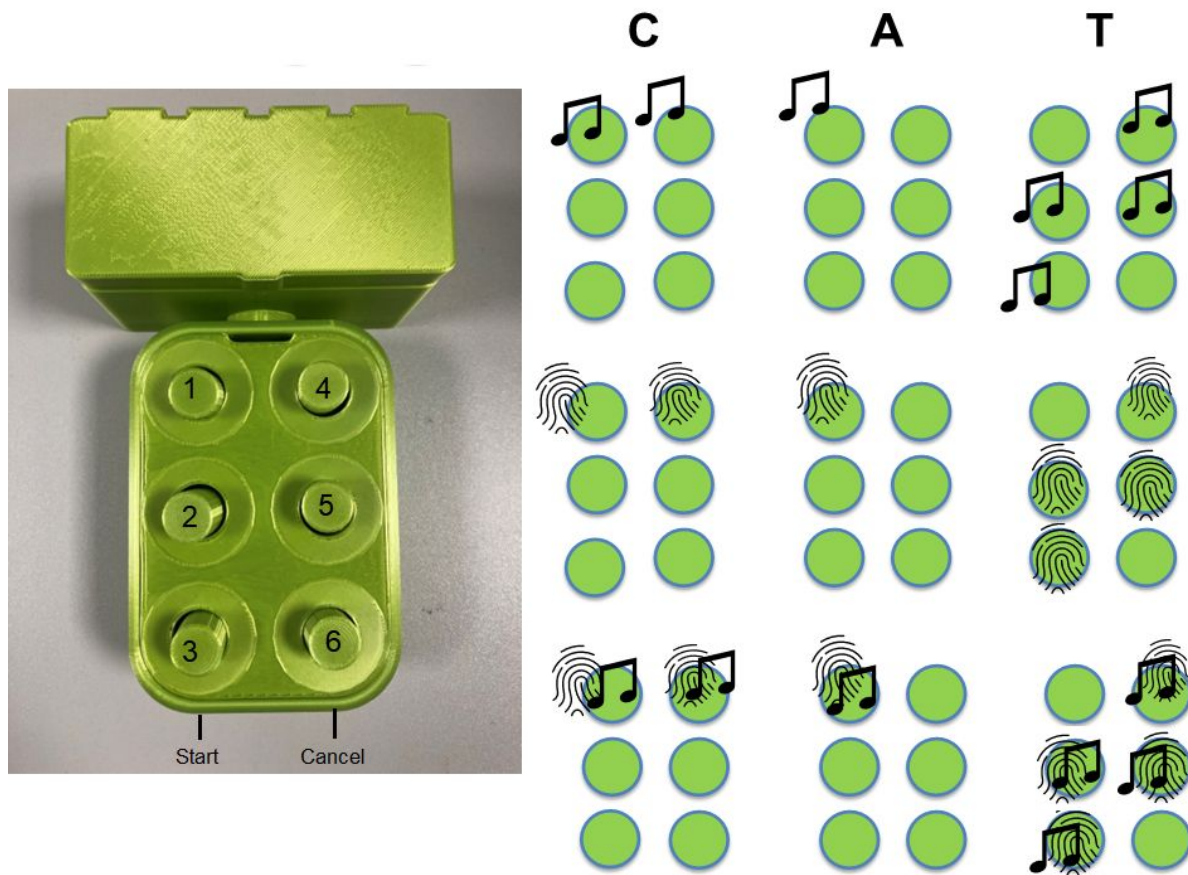


Figure 1. Multisensory Device (left side): A six-button box connected to a box including the Arduino with start and cancel button at the front side. Right side: Serial presentation of the letters CAT in three different modalities (auditory, haptic and auditory-haptic).

Experimental Setting: The multisensory device was placed underneath a small table, behind a curtain (see Figure 2) to record the participants' hand explorations with the device under standardised conditions, e.g., without any visual cues (Lederman & Klatzky, 1987; Gentilucci et al., 1997; Polechoński, & Olex-Zarychta, 2012; Yokosaka et al., 2016). After the initial exploration, the table was removed, and small cushions were provided to support their wrists and to allow children a comfortable hand-position (Figure 2 B).



Figure 2. Experimental setting (A). The multisensory device was placed underneath a small table. Children were asked to place their fingers on the buttons (B), to be able to feel the haptic vibrations. Thumbs were placed on the start and cancel button.

Braille Letter presentation: Letters were presented with increasing difficulty in the auditory-haptic, the auditory or the haptic modality. Presentation started in the auditory-haptic modality as this format represents the salient and modality-enriched form of braille. Afterward, each participant was asked to indicate whether they would prefer subsequent letter presentation in the auditory or the haptic modality. Each letter was experienced through a specific sequence of button vibrations. For example, to experience the letter "T," buttons 2, 3, 4, and 5 vibrated sequentially. Sounds with increasing pitch were presented sequentially from button 1 to button 6. The braille letters were presented in the following order, according to the Hands-On reading scheme (McCall et al., 2011; Royal National Institute of Blind People, 2016; please note that guidelines might vary depending on the nature of visual impairment, and learning experiences):

- a, b, g, i, k, l (level 1)
- c, d, h, o, t (level 2)

e, m, n, p, s (level 3)

f, r, u, x, y (level 4)

j, q, v, w, z (level 5)

According to the Hands-On reading scheme, letters that are more tactually distinct and allow to create simple consonant-vowel-consonant words early on, were introduced first (e.g., bag). Less common letters were introduced at a later stage.

The letter presentation began with the letter A, which included only one haptic vibration, and the letters were grouped into different levels (1–5). A tune was played as feedback for reaching the next level. After each letter presentation, children were asked to identify the letter and they were given the opportunity to identify the letters on a 3D-printed chart specifically designed with smaller braille letter dimensions (dot size: 2mm high, diameter 2mm, see Figure 3). This braille letter size was chosen because a smaller 3D-printed version was challenging to read. Correct and incorrect letter responses were retrieved via the transcriptions of the video-recordings.

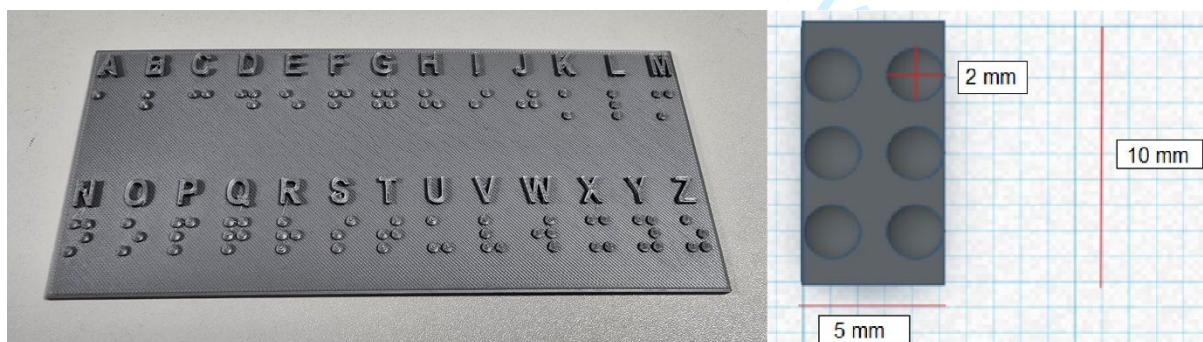


Figure 3. 3D printed braille chart (left side) including smaller braille letters; right side: dot size: diameter: 2 mm and dot height: 2 mm; cell width 5 mm, cell length: 10 mm.

Hand placement: While children were interacting with the multisensory device, **their hand placement was recorded by using a top view of the children’s hand and Go Pro** (Hero 4 session) cameras.

Intrinsic Motivation Inventory (IMI, Deci & Ryan, 2000): Following the interaction with the multisensory device, **the participants were interviewed** about their enjoyment, nervousness, and perceived competence in using the device and **they were asked specific questions** adapted from the Intrinsic Motivation Questionnaire (Deci & Ryan, 2000). **The aim was** to collect responses to all questions, however due to the repetitive nature of some of the questions (I think I am pretty good at the task vs. I felt pretty skilled at this task), some participants were getting bored which resulted in missing data. **Therefore, those questions were selected**, which were answered by more than 84% of the participants ($n \geq 3$) participants, for example: perceived competence: $n = 8$ participants with blindness, $n = 13$ participants with visual impairment, and $n = 10$ sighted participants, supplementary material) and which were relevant to measure enjoyment, perceived competence, and nervousness.

The following items were included in the analysis:

- *While I was doing this activity, I was thinking about how much I enjoyed it*
- *I think I am pretty good at this activity*
- *I did not feel nervous at all while doing this activity*

Glasgow Sensitivity Scale (Robertson and Simmons, 2013): To assess sensory sensitivity in children and adolescents, **parents were asked** to complete the Glasgow Sensory Sensitivity Scale through QuestionPro on behalf of their children. Adolescents aged 18 and older completed the questionnaire themselves. Twenty-three parents and one 18-year- old adult answered the questionnaire. **A parent report was chosen** (as opposed to children’s self-report) as parents might have observed their children’s behaviour across different situations and time

(for further arguments reported in the literature: see Smees et al., 2023). The Glasgow Sensitivity Scale focuses on different sensory experiences in everyday-life situations and consists of 42 items, which can be classified in two main categories: *Hypersensitivity* (21 items) and *Hyposensitivity* (21 items) and which can be further subdivided into seven different modalities (visual, auditory, gustatory, olfactory, proprioceptive, tactile, vestibular). The questionnaire investigates how often the children experience some sensory events in everyday life activities (see examples in Table 2). It is important to note that strong positive correlations have been observed between hyper and hypo sensitivity scores in previous research, both across all modalities but even within modalities (Sapey-Triomphe et al., 2018). The Glasgow Sensory Questionnaire includes seven sensory modality categories. For data analysis, the auditory and haptic modality items were selected because the device interaction required the children to engage with both auditory and tactile (haptic) sensory input (instead of olfactory or vestibular information). Table 2 indicates a more detailed description of these items.

Table 2. Items of the Glasgow Sensory Sensitivity Scale.

Hypersensitivity	
Auditory	
Item 6	Do you find certain noises/pitches of sound annoying?
Item 25	Do you dislike loud noises?
Item 31	Do you react very strongly when you hear an unexpected sound?
Tactile	
Item 1	Do you dislike the physical sensation you get when people hug you?
Item 15	Do you dislike having a haircut (for example, because little bits of hair go down your back)?

Item 22	Do you cut the labels out of your clothes?
Hyposensitivity	
Auditory	
Item 9	Do you like to listen to the same piece of music/part of a DVD over and over again?
Item 14	Do you find it difficult to hear what people are saying?
Item 33	Do you really like listening to certain sounds (for example, the sound of paper rustling)?
Tactile	
Item 16	Do you notice that you have hurt yourself but did not feel any pain?
Item 27	Does your body ever feel ‘numb’ - like you can’t feel anything against your skin?
Item 39	Do you find that you are able to go outside without a coat or a jacket when other people think that it is too cold?

Results:

1. Hand placement and letter identification

Participants’ hand movements were video-recorded to analyse their interactions with the device and to identify any typical hand movement patterns (Gentilucci et al., 1997; Lederman & Klatzky, 1987; Polechoński, & Olex-Zarychta, 2012; Yokosaka et al., 2016). Seventeen out of the eighteen users, began interacting with the multisensory device using both hands, moving their fingertips across the buttons. One child without any braille experience used only their right hand. Sixteen out of the eighteen users started using the device independently, without any additional support, e.g., pressing start and cancel buttons.

After an initial exploration phase, all users were asked to place their fingertips on the buttons to sense the haptic vibrations. Out of 25 children, 15 children could identify the letters in most cases correctly (>70%), 4 children had difficulties to identify the letters (e.g., because they experienced that the haptic vibrations were too strong or they had difficulties to put the fingertips on the device), and 2 children showed evidence for both correct and incorrect responses. Four data sets were missing. While all children had the opportunity to identify the letter on the braille chart, children who were experienced with braille would just articulate the letter.

2. Modality Preferences

After interacting with the device, each participant was asked to indicate their preferred modality for engaging with the multisensory device. To investigate which modality was chosen most often a chi-squared test was applied to compare the distribution of preferred modalities - the auditory-haptic, haptic and the auditory modality - across all participants. This distribution was also compared between individuals with blindness, and visual impairment. Results indicated that there was no significant difference in modality preferences ($\chi^2(2,25) = 5.84, p = .054$; Auditory-haptic: $n = 14$; auditory: $n = 6$, haptic: $n = 5$, see Figure 4). The preference pattern between individuals with blindness and visual impairment slightly differed (see Figure 3): Individuals with blindness selected mainly the auditory-haptic modality ($n = 8$) and the auditory modality ($n = 4$) whereas individuals with visual impairment selected all modalities: the auditory-haptic modality ($n = 6$), the haptic modality ($n = 5$) and the auditory modality ($n = 2$) ($\chi^2(2,27) = 7.858, p = .020$; Likelihood Ratio).

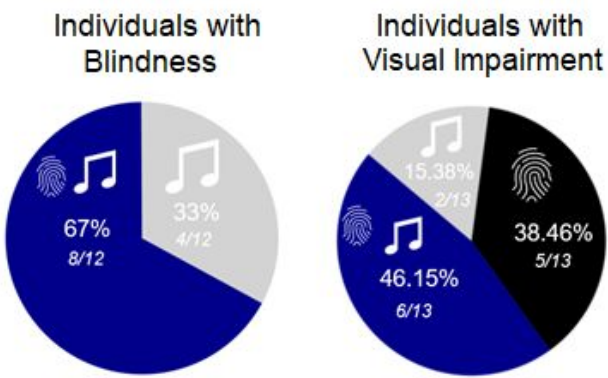


Figure 4. Modality preferences in individuals with blindness and visual impairment. Dark blue = auditory-haptic modality, grey = auditory modality, and black = haptic modality.

3. Enjoyment, Nervousness and Perceived Competence (adapted from IMI, Deci & Ryan, 2000)

Following device interaction, participants were asked to rate their enjoyment during the task, their nervousness, and their perceived competence on a scale between 1-7 (see Figure 5).

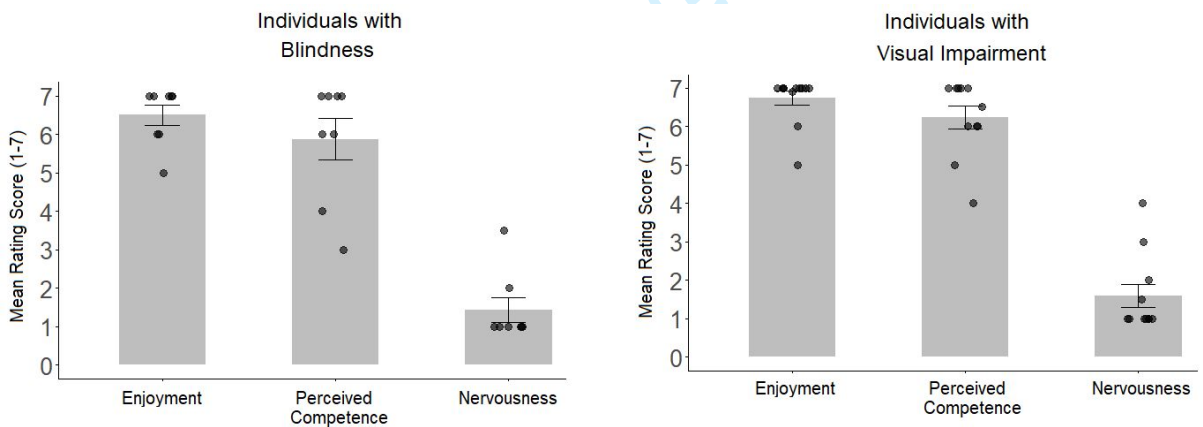


Figure 5. Reported Enjoyment, perceived competence, and nervousness in participants with blindness, and visual impairment. Single black dots indicate individual rating scores.

Given that the data were not normally distributed, the Kruskal Wallis test was applied to investigate whether the groups significantly differed in *Enjoyment*, *Perceived Competence*

and *Nervousness*. Groups did not significantly differ in reported *Enjoyment* ($H(1) = .446, p = .504$), *Perceived Competence* ($H(1) = .049, p = .825$), and *Nervousness* ($H(1) = .203, p = .652$). All participants rated *Enjoyment* ($MD = 7, SD = .67$) and *Perceived Competence* ($MD = 6.5, SD = 1.23$) higher compared to the *Nervousness ratings* ($MD = 1, SD = .94$); furthermore participants rated their *Enjoyment* higher than their *Perceived Competence* (*Enjoyment* – *Nervousness*: $W = .000, p < .001$; *Enjoyment* – *Perceived Competence*: $W = 3.0, p = .034$; *Perceived Competence* – *Nervousness*: $W = .170, p < .001$).

4. Glasgow Sensory Sensitivity Scale:

Next, the participants' sensory sensitivity scores were analysed, and this pattern was compared between participants with visual impairment and blindness (see Figures 6 and 7). Parents ($n = 15$) completed the Glasgow Sensory Sensitivity Scale on behalf of their children ($n = 9$ children with visual impairment; $n = 6$ children with blindness). One young adult with blindness completed the questionnaire by themselves. Thus, the data sets of $n = 7$ participants with blindness ($M_{age} = 14$ years, age range = 12 – 18 years; $SD = 1.97$; 5 females, 2 males) and $n = 9$ children with visual impairment were included in the data analysis ($M_{age} = 13$ years, age range = 9 – 17 years; $SD = 2.51$; 6 females, 3 males). First, it was tested whether individuals with blindness and visual impairment significantly differed in sensory sensitivity scores. Therefore, the items of the Sensory Sensitivity Scale were grouped into auditory and tactile *Hyper-* and *Hyposensitivity*. The Mann-Whitney U-Test did not reveal any significant differences between participants with blindness and visual impairment when comparing hyper and hypo-sensitivity scores within the auditory and the tactile modality (all p 's $> .1$, see Table 3).

Table 3. Sensory Sensitivity Scores of the Auditory and Tactile Modality. Means (M) and standard error (SE) for each condition and group.

Group	Auditory Hyper	Auditory Hypo	Tactile Hyper	Tactile Hypo
Individuals with Visual Impairment (n = 9)	M: 9.22 (SE: 0.62)	M: 6.88 (SE: 0.63)	M: 4.89 (SE: 0.51)	M: 5.11 (SE: 0.51)
Individuals with Blindness (n = 7)	M: 8.86 (SE: 0.74)	M: 7.86 (SE: 0.74)	M: 5.86 (SE: 0.77)	M: 6.29 (SE: 0.89)

To further understand how sensory sensitivity relates within and between different modalities, Spearman correlations were used to analyse whether hyper- and hyposensitivity ratings correlated within and across modalities, separately for children with blindness and those with visual impairment (see Figures 6 & 7). For example, children who might have a higher sensory sensitivity in one modality, might also show higher sensitivity in another modality. As can be seen from Figures 6 & 7, the pattern differed in individuals with blindness from individuals with visual impairment: In individuals with blindness, higher hypersensitivity scores were also correlated with higher hyposensitivity scores, particularly within the auditory and tactile modalities. In contrast, the pattern was more mixed in children with visual impairment, possibly reflecting greater variability in modality preferences within this group. For example, auditory hypersensitivity scores correlated with tactile hyposensitivity scores.

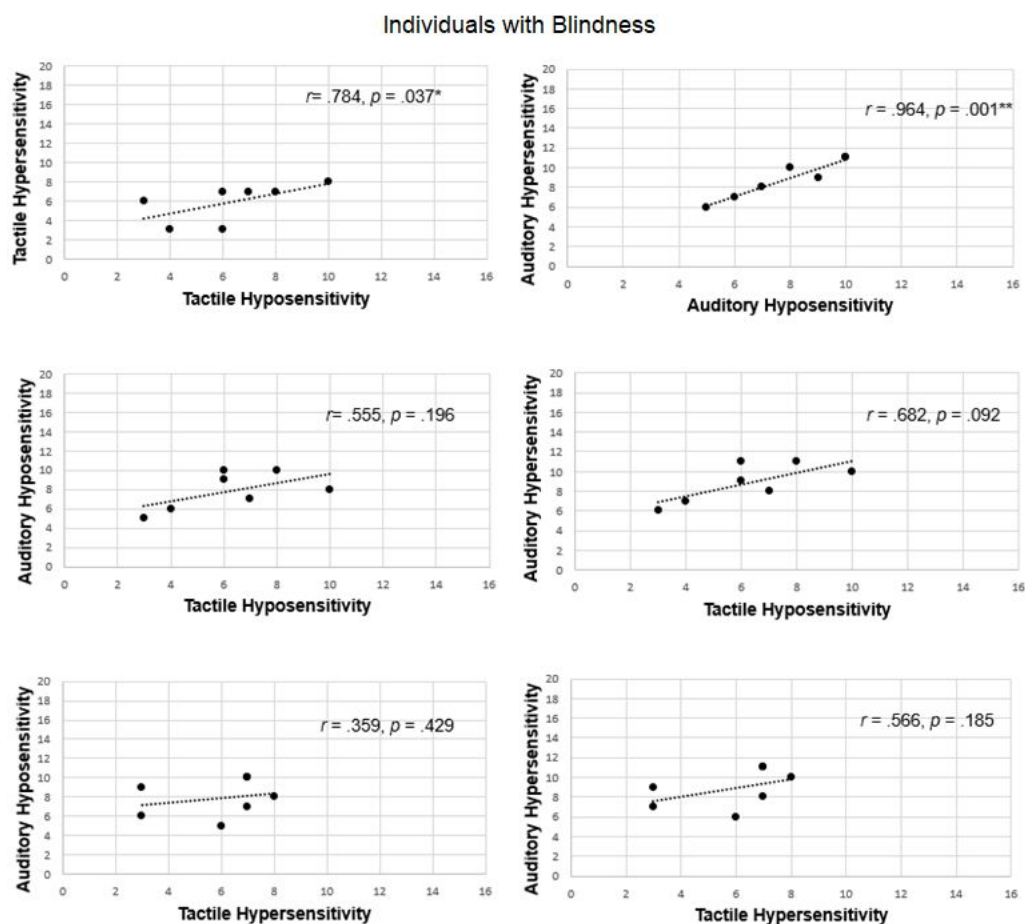


Figure 6. Correlation between auditory and tactile hyposensitivity and hypersensitivity scores in individuals with blindness.

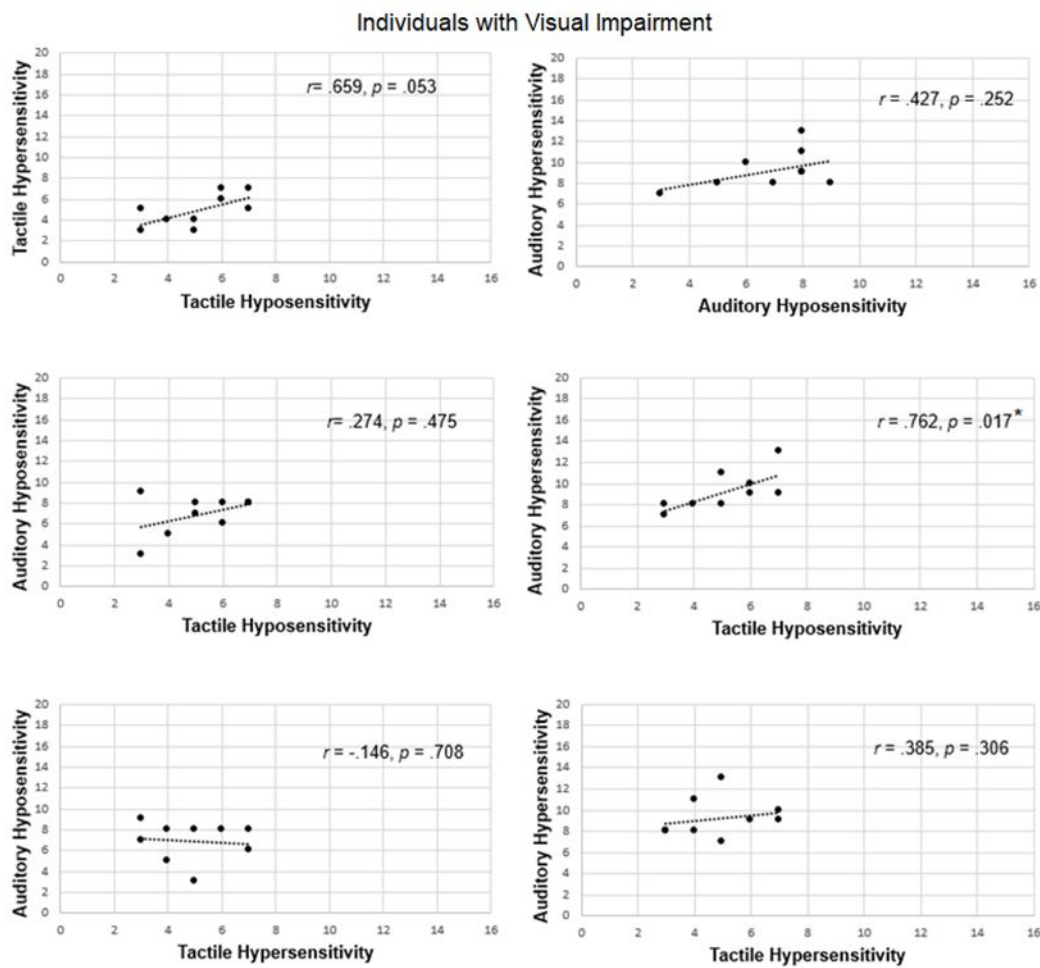


Figure 7. Correlation between auditory and tactile hyposensitivity and hypersensitivity scores in individuals with visual impairment.

Discussion:

The primary aim of this research project was to investigate participants' enjoyment and usability of a newly created multisensory device in participatory design sessions.

Even though the modality preferences did not significantly differ, 14 out of 25 participants selected the auditory haptic modality, which might have reached significance with a higher sample size. This initial finding further aligns with our aim to enrich braille learning with the combined auditory-haptic settings in future research. According to the intersensory redundancy hypothesis, the time-synchronous presentation of information across different modalities can facilitate stimulus detection and attention to stimulus properties (Bahrick & Lickliter, 2000; Bahrick, Lickliter, & Flom, 2004). Previous research has also shown that learning can be improved after the presentation of multisensory compared to unisensory cues in sighted children (Broadbent et al., 2017, 2020). Multisensory-enriched instruction has been shown to improve literacy gains (Scheffel et al., 2008; Warnick & Caldarella, 2016) and to support language and mathematics learning through gesture-based approaches in sighted individuals (Andrä et al., 2020; Mathias et al., 2022; Morrett & Chang, 2015; Zhen et al., 2019).

The idea of implementing auditory-haptic information into learning devices also fits to the idea of enriching complex mathematical graphs with auditory-tactile features. Users are usually "haptically overloaded" as these graphs often contain complex patterns that require a detailed haptic exploration, and complex sequences of those graphs need to be memorised (see Ramôa et al., 2023). One alternative solution is the usage of Tactom Readers which are 2D graphic readers and braille pin matrix displays (see Ramôa et al., 2023). More recently, researchers have included acoustic feedback besides spoken explanations and showed that users were able to find more details with the new auditory features (Ramôa et al., 2023).

Thus, auditory-haptic information might be efficient not only in braille learning but also in other applications such as identifying tactile graphics and maps.

The preferred modality pattern differed between children with blindness and visual impairment: while individuals with blindness preferred the auditory-haptic (67%) and the auditory modality (33%), children with visual impairment indicated their preferences for auditory-haptic (46.15%), auditory (15.38%) and the haptic modality (38.46%). While a higher sample size is required in future studies to confirm those findings, one factor which might explain these group differences could be related to the prevalence of the autism diagnosis in some children with visual impairment. Children with autism show different sensory patterns, compared to children without autism, and research has indicated “diminished” multisensory integration abilities (Stevenson et al., 2014). Even though CVI was not diagnosed in the current sample, previous research indicated that individuals with CVI might have difficulties to integrate different sensory modalities and may have specific sensitivity profiles (Lueck et al., 2021).

To further understand sensory sensitivity patterns in children with visual impairment and blindness, we also asked parents to indicate Sensory Sensitivity Scores on behalf of their children. While sensory sensitivity ratings did not differ between groups, the sensitivity ratings correlated within the tactile and the auditory modality as well as across different modalities in children with visual impairment, while in individuals with blindness, the sensory ratings only correlated within one modality. This finding matches previous results using the Glasgow Sensory Sensitivity Score in children who either scored high or low on the autism questionnaire (AQ, Sapey-Triomphe et al., 2018): This study showed positive correlations between auditory hyper and hyposensitive scores in individuals with low AQ scores; however, these correlations were absent in the tactile domain. On the other hand, individuals with high AQ scores showed correlations between hyper and hyposensitivity

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3 scores within both, the auditory and the tactile modality. In the present study, findings
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5 indicate that these correlations also occur between different modalities in children with visual
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7 impairment.
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10 11 *Limitations and outlook:* 12

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14 While this study included various exploratory approaches to understand the interaction with
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16 the device, future research requires a larger sample size (including braille beginners) to
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18 investigate whether the device is effective for braille learning. This would also allow for a
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20 more detailed investigation of how different subgroups interact with the device—for
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22 example, children with visual impairments and co-occurring diagnoses, and those without co-
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24 occurring diagnoses. Future studies should also include different cognitive measurements,
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26 such as IQ in children to better understand cognitive requirements to interact with the device
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28 as well as exact measures of visual acuity and visual functions.
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33 Additionally, we aim to investigate whether multisensory braille letter presentation might
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35 facilitate braille learning compared to haptic braille learning.
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38 39 *Conclusion* 40

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42 To conclude, participants enjoyed interacting with the newly created multisensory device
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44 which emphasises its potential as an engaging tool for braille learning. Differences in sensory
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46 sensitivity profiles might be linked to modality preferences and the importance of
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48 customising braille presentation to meet individual needs and sensory preferences. Future
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50 research should further investigate the connection between sensory sensitivity profiles and
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52 modality preferences of braille letter presentation in visually impaired and blind individuals.
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Figure Captions:

Figure 1. Multisensory Device (left side): A six-button box connected to a box including the Arduino with start and cancel button at the front side. Right side: Serial presentation of the letters CAT in three different modalities (auditory, haptic and auditory-haptic).

Figure 2. Experimental setting (A). The multisensory device was placed underneath a small table. Children were asked to place their fingers on the buttons (B), to be able to feel the haptic vibrations. Thumbs were placed on the start and cancel button.

Figure 3. 3D printed braille chart (left side) including smaller braille letters; right side: dot size: diameter: 2 mm and dot height: 2 mm; cell width 5 mm, cell length: 10 mm.

Figure 4. Modality preferences in individuals with blindness and visual impairment. Dark blue = auditory-haptic modality, grey = auditory modality, and black = haptic modality.

Figure 5. Reported Enjoyment, perceived competence, and nervousness in participants with blindness, and visual impairment. Single black dots indicate individual rating scores.

Figure 6. Correlation between auditory and tactile hyposensitivity and hypersensitivity scores in individuals with blindness.

Figure 7. Correlation between auditory and tactile hyposensitivity and hypersensitivity scores in individuals with visual impairment.

Table legends:**Table 1.** Demographics of blind and visually impaired individuals.**Table 2.** Items of the Glasgow Sensory Sensitivity Scale.**Table 3.** Sensory Sensitivity Scores of the Auditory and Tactile Modality. Means and standard error for each condition and group

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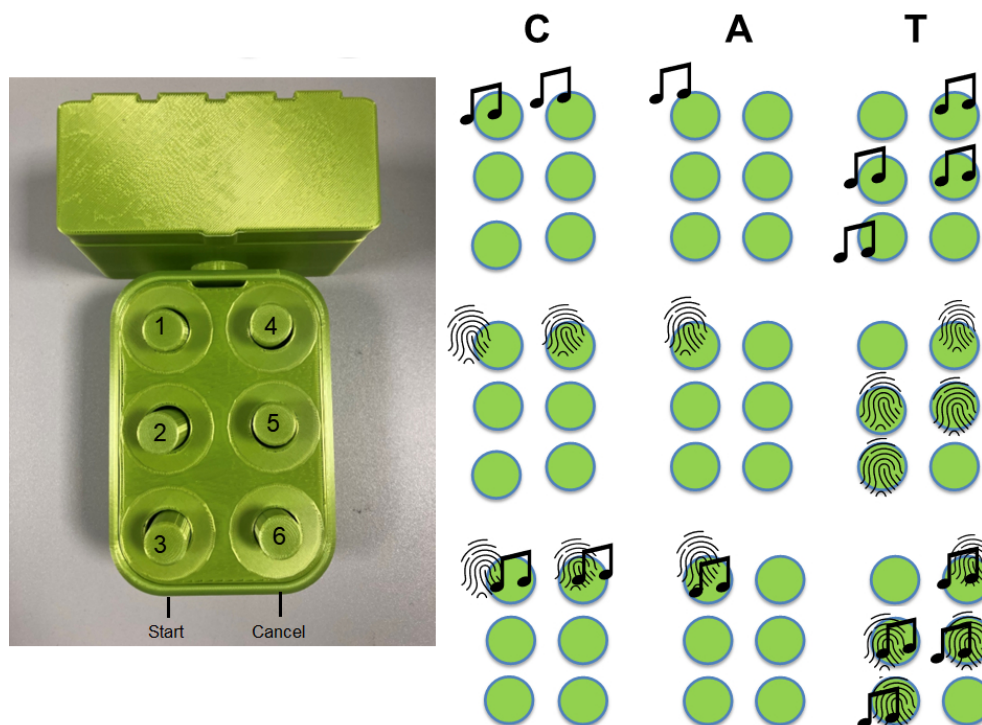


Figure 1. Multisensory Device (left side): A six-button box connected to a box including the Arduino with start and cancel button at the front side. Right side: Serial presentation of the letters CAT in three different modalities (auditory, haptic and auditory-haptic).

202x148mm (120 x 120 DPI)



Figure 2. Experimental setting (A). The multisensory device was placed underneath a small table. Children were asked to place their fingers on the buttons (B), to be able to feel the haptic vibrations. Thumbs were placed on the start and cancel button.

159x58mm (120 x 120 DPI)

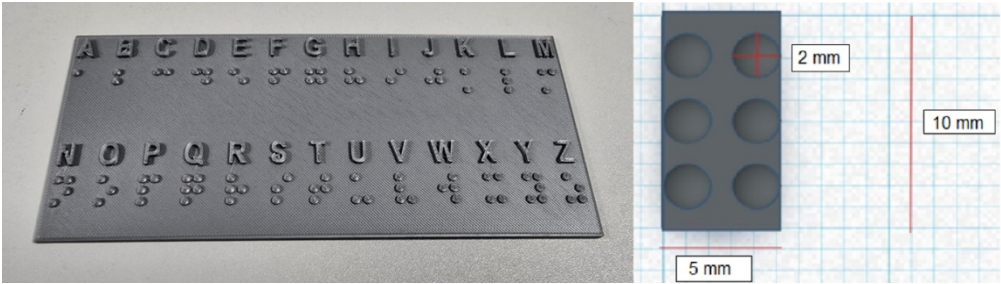


Figure 3. 3D printed braille chart (left side) including smaller braille letters; right side: dot size: diameter: 2 mm and dot height: 2 mm; cell width 5 mm, cell length: 10 mm.

159x44mm (220 x 220 DPI)

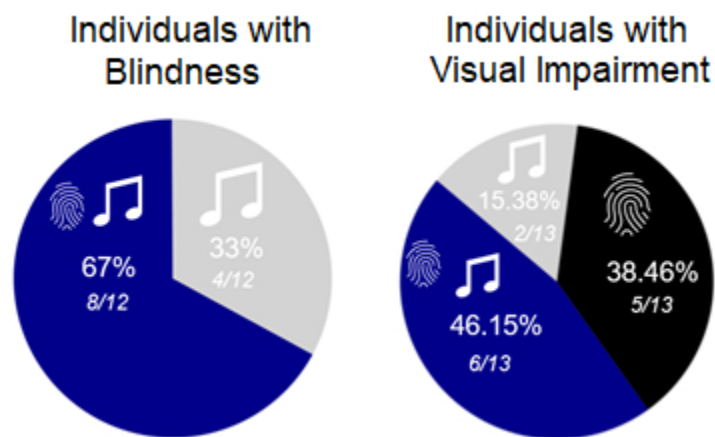


Figure 4. Modality preferences in individuals with blindness and visual impairment. Dark blue = auditory-haptic modality, grey = auditory modality, and black = haptic modality.

66x40mm (144 x 144 DPI)

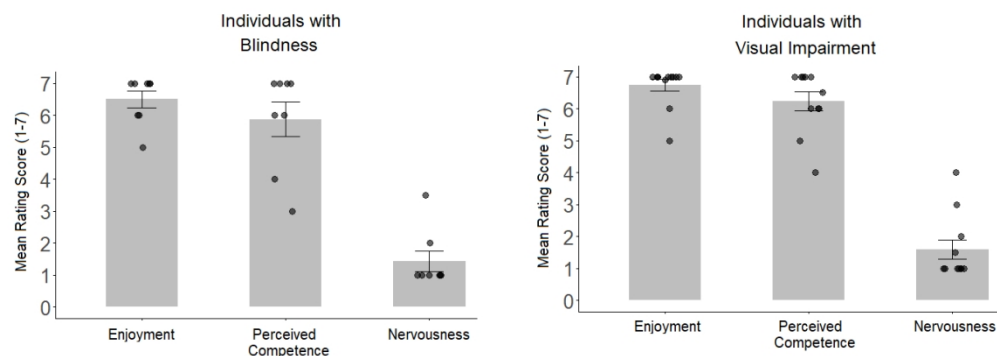


Figure 5. Reported Enjoyment, perceived competence, and nervousness in participants with blindness, and visual impairment. Single black dots indicate individual rating scores.

240x86mm (144 x 144 DPI)

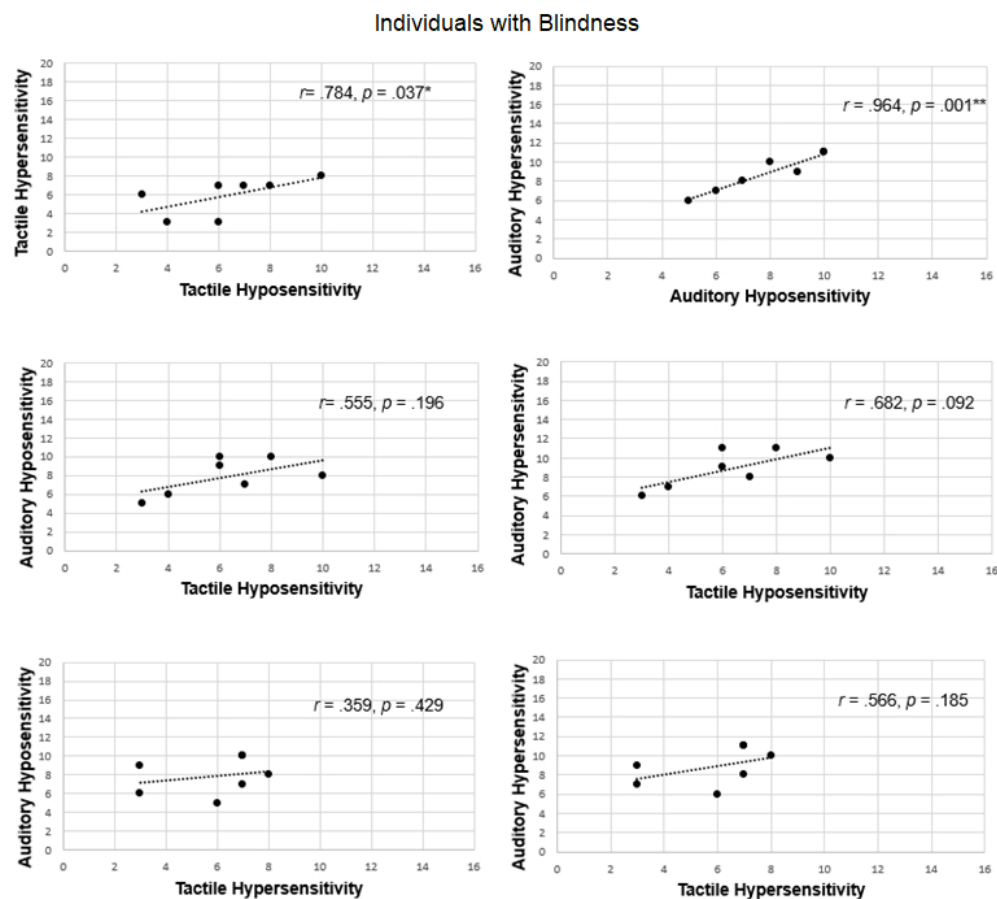


Figure 6. Correlation between auditory and tactile hyposensitivity and hypersensitivity scores in individuals with blindness.

135x125mm (144 x 144 DPI)

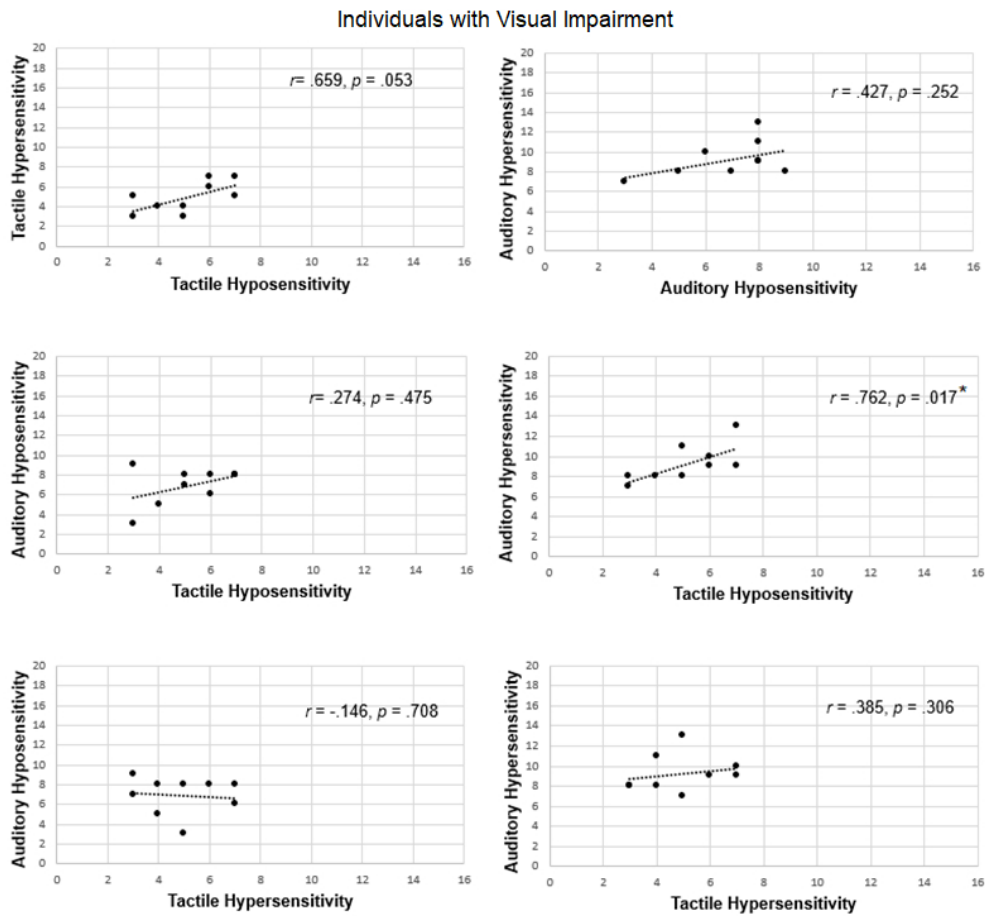


Figure 7. Correlation between auditory and tactile hyposensitivity and hypersensitivity scores in individuals with visual impairment.

139x132mm (144 x 144 DPI)

Table 1. Demographics of blind and visually impaired individuals.

Vision Status	Diagnosis	Age (years)	Gender
Blind	Leber's congenital amaurosis	13	female
Blind	Microphthalmia	12	female
Blind	Retinitis pigmentosa	11	female
Blind	Bilateral anophthalmia	15	male
Blind	Retinal Detachment	13	male
Blind	Leber's congenital amaurosis	14	female
Blind	Leber's congenital amaurosis	18	female
Blind	Microphthalmia	15	female
Blind	Retinopathy of Prematurity	20	female
Blind	Retinopathy of Prematurity	21	female
Blind	Rare genetic condition	21	female
Blind	Rare genetic condition	21	male
Vision Impaired	Glaucoma	13	female
Vision Impaired	Bilateral retinal folds	11	female
Vision Impaired	Septo-optic dysplasia	20	male
Vision Impaired	Cone rod dystrophy	17	female
Vision Impaired	Unknown	15	male
Vision Impaired	Nystagmus	10	male
Vision Impaired	Glaucoma	16	female
Vision Impaired	Retinitis pigmentosa	16	male
Vision Impaired	Nystagmus	12	female
Vision Impaired	Retinal dystrophy	14	male
Vision Impaired	Microphthalmia	14	male
Vision Impaired	Leber's congenital amaurosis	9	female
Vision Impaired	Optic nerve hypoplasia	21	male

Table 2. Items of the Glasgow Sensory Sensitivity Scale.

Hypersensitivity	
Auditory	
Item 6	Do you find certain noises/pitches of sound annoying?
Item 25	Do you dislike loud noises?
Item 31	Do you react very strongly when you hear an unexpected sound?
Tactile	
Item 1	Do you dislike the physical sensation you get when people hug you?
Item 15	Do you dislike having a haircut (for example, because little bits of hair go down your back)?
Item 22	Do you cut the labels out of your clothes?
Hyposensitivity	
Auditory	
Item 9	Do you like to listen to the same piece of music/part of a DVD over and over again?
Item 14	Do you find it difficult to hear what people are saying?
Item 33	Do you really like listening to certain sounds (for example, the sound of paper rustling)?
Tactile	
Item 16	Do you notice that you have hurt yourself but did not feel any pain?
Item 27	Does your body ever feel ‘numb’ - like you can’t feel anything against your skin?
Item 39	Do you find that you are able to go outside without a coat or a jacket when other people think that it is too cold?

Table 3. Sensory Sensitivity Scores of the Auditory and Tactile Modality. Means and standard error for each condition and group.

Group	Auditory Hyper	Auditory Hypo	Tactile Hyper	Tactile Hypo
Visually Impaired (n = 9)	M: 9.22 (SE: 0.62)	M: 6.88 (SE: 0.63)	M: 4.89 (SE: 0.51)	M: 5.11 (SE: 0.51)
Blind (n = 7)	M: 8.86 (SE: 0.74)	M: 7.86 (SE: 0.74)	M: 5.86 (SE: 0.77)	M: 6.29 (SE: 0.89)

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The sighted group ($n = 10$; $M_{age} = 55$ years, age range = 37 – 71 years; $SD = 12$; 7 females, 3 males) consisted of 8 braille teachers, QTVIs, and braille technicians. QTVI stands for Qualified Teacher of Vision Impairment.

Seven teachers taught grade 1 and grade 2 braille, experiences varied between 2 and 28 years. The braille technician could read grade 1 and grade 2 braille by sight. Two participants with visual impairments were qualified braille teachers and were proficient in teaching both grade 1 and grade 2 braille as well.

This approach allowed us to gather their expert perspectives on whether the device would be suitable for teaching braille in the classroom and if they might incorporate it into their lessons. During the interaction with the device, teachers were asked whether they could perceive the haptic vibrations on their fingertips compared to previous interactions. It is important to note that in earlier iterations (prior to this research project), participants could not always sense the haptic feedback due to technical issues with how the device delivered the feedback. Therefore, understanding whether the teachers could experience the haptic, auditory-haptic, and auditory feedback, as well as their ability to perceive the letters, was a key objective.

Following their interaction with the device, the teachers were also asked whether they would recommend incorporating it into their lessons. Please note that our research project focused on children with visual impairment and blindness, and our aim was to understand how they interact with the device. In future research, we aim to understand how sighted children would interact with the device to build more inclusive learning environments. Additionally, we interviewed teachers and technicians to gather expert input on improving the device and optimising its use in the classroom.

Modality preferences and Enjoyment, Competence and Nervousness ratings in sighted individuals

As the sighted group in our study consists mainly of teachers and technicians and cannot be compared with children with blindness and visual impairment, we report the results separately. Six out of 10 sighted individuals preferred the auditory-haptic modality, followed by both the haptic ($n = 2$), and the auditory modality ($n = 2$). However, the preferences for different modalities did not significantly differ ($\chi^2(2,10) = 3.2, p = .202$). Sighted individuals rated *Enjoyment* ($MD = 7, SD = 1.1$) and *Perceived Competence* ($MD = 5, SD = 1.4$) higher compared to the *Nervousness* ratings ($MD = 3, SD = 1.66$); however there was no difference between *Enjoyment* and their *Perceived Competence* (*Enjoyment* – *Nervousness*: $W = .000, p = .004$; *Enjoyment* – *Perceived Competence*: $W = -1.187, p = .235$; *Perceived Competence* – *Nervousness*: $W = 2.527, p = .012$).

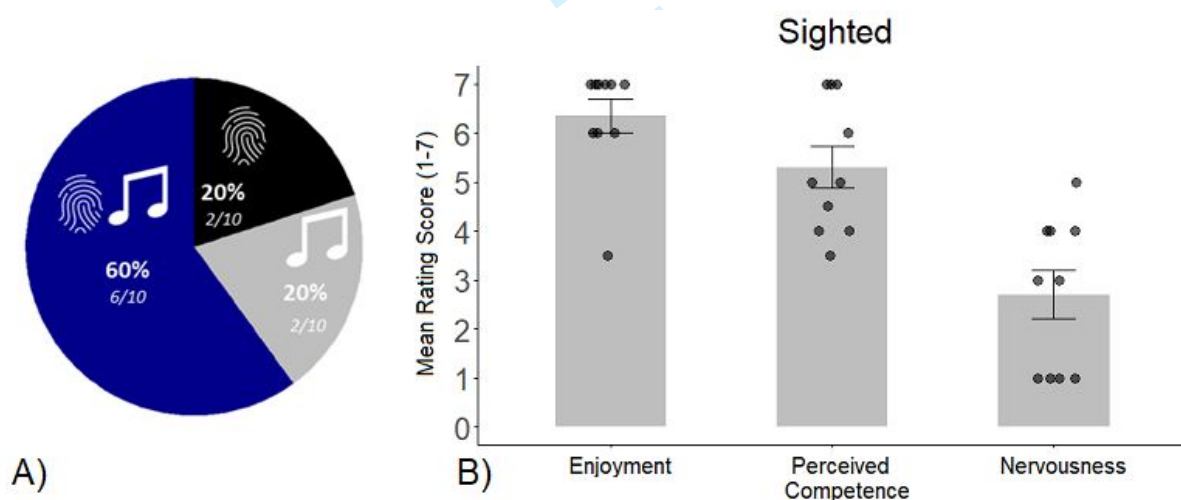


Figure 7. A-B. A) Modality preferences in sighted individuals. Dark blue = auditory-haptic modality, grey = auditory modality, and black = haptic modality. B) Reported Enjoyment, Perceived Competence, and Nervousness in sighted individuals. Single black dots indicate individual rating scores.