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Methodical testing of tactile cartographic signs in isolation and in context

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ABSTRACT

To date, the ways of testing tactile signs lack systematization. Hence, the aim of our research was to methodically evaluate the legibility of the proposed set of tactile signs. Our solution is based on the sign theory, in which signs have relations with reality, other signs, and users. We employed a two-step procedure by first assessing signs in isolation to verify the ease of decoding and differentiation of signs within the same geometry type, and then evaluating their correct interpretation in context – on a map with signs in different geometries. We validated our approach using signs designed for historic garden maps that formed our case study. We tested these signs across three matrices (for point, line and area signs). Most of the signs were correctly recognized by the study participants in the first attempt. Any illegible signs were redesigned and reevaluated in context using seven pseudomaps. At this stage, minor issues related to single signs arouse, primarily due to inappropriate pseudomap design rules rather than sign geometries themselves. Based on participants' feedback, we refined the signs again, and finally obtained a standardized set of 52 legible signs, intended for 3D-printed tactile maps using the DLP technique. Our analysis confirms that the proposed signs are legible, regardless of the user's skills and characteristics.

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Sustainable Development Goals
SDG 10: Reduced inequalities

1. Introduction

Tactile maps convey visual information to people with visual impairments (PVI) about spatial objects, their mutual relationships, and meaning through touch and vision (Lynch, 1960). PVI exists within the same social and educational space as sighted individuals and cannot be excluded from the social discourse on visual phenomena (Śmiechowska-Petrovskij, 2021). These maps are vital for the autonomy of PVI and serve as a source of knowledge, preventing their informational and educational exclusion (Czerwińska, 2017). However, the effective use of such maps heavily relies on PVI's access to accurate, legible, and affordable tactile representations.

Current studies on tactile cartography focus on analyzing tactile perception in relation to tactile reading (Perdue & Lobben, 2016), testing design solutions (Cole & Robinson, 2023; Jehoel et al., 2005), tactile signs design (Brittell et al., 2018; Gual-Ortí et al., 2015), text, and information frameworks (Engel & Weber, 2021), technological advancements (Barvir et al., 2021; Touya et al., 2018), and even automatic tactile map generation (Götzelmann & Pavkovic, 2014; Jiang et al., 2024; Taylor et al., 2016; Wabiński, Mościcka, et al., 2022). However, numerous maps designed during the aforementioned research remain unused due to their illegibility to PVI (Brulé et al., 2020). Several publications outline best practices for developing tactile maps (BANA and the CBA, 2010; The N.S.W. Tactual and Bold Print Mapping Committee, 2006). The standardization and parameterization of tactile signs, considering the peculiarities of tactile perception and visual impairments are also addressed (Cole, 2021; Gill & James, 1973; ISO, 2013, 2019; Prescher et al., 2017). Maintaining the legibility of tactile maps remains their crucial aspect.

Ensuring maps' legibility requires verifying the assumptions made in developing maps with participation of PVI, which so far have focused on three types of issues: comparing production techniques (Jehoel et al., 2005; Perkins, 2002), testing signs legibility and assessing the distances between signs (BANA and the CBA, 2010; Jehoel et al., 2005, 2006; Perdue & Lobben, 2016), and evaluating maps' utility for orientation (Holloway et al., 2019; Papadopoulos et al., 2018). Various methods

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of checking the legibility of tactile signs have so far been practiced in sessions with PVI, including measuring reading time of signs on a matrix/map, noting erroneous indications, opinions, or preferences (Brittell et al., 2018; Wabiński, Śmiechowska-Petrovskij, et al., 2022). The tasks in such research mainly rely on symbol arrays – matrices/maps made in various techniques, without proper verification of the signs in context (Lee, 2019). In testing materials and production techniques, the number of signs used was usually small (up to 10). Past studies have most commonly verified only one type of signs at once (e.g. only point signs) (Jehoel et al., 2005; Prescher et al., 2017). Legibility testing has most often consisted of evaluating individual signs (Lawrence & Lobben, 2011), rather than identifying them on maps (Gual-Ortí et al., 2015).

Previous research aimed at testing materials involved various groups of testers, yet their selections lacked proper justification. Some tests included only groups of students or schoolchildren (Espinosa & Ochaíta, 1998; Ungar et al., 1994), although the maps' purpose did not concern education. Many studies have often involved both PVI and sighted individuals (De Oliveira et al., 2016; Jehoel et al., 2005). These diverse approaches and the lack of emphasis on methodical studies of signs legibility resulted in challenges obtaining objective and reproducible results, prompting researchers to develop their own procedures. Despite acknowledging limitations and drawbacks of the existing approaches primarily related to adapting testing procedures and selecting materials, signs, and tasks (Brittell et al., 2018; Perdue & Lobben, 2016), no research has yet been conducted on how to address these issues.

As demonstrated by the literature review, the study of tactile signs lacks systematization and methodological coherence. Different handling procedures were practiced, depending on the specific purpose. This led to a selective approach in the choice of materials, tactile signs and tasks. These practices were limited to identification tasks on abstract materials only, examining signs in isolation, disregarding their interrelations, and limiting research to a single type of geometry (e.g., Lambert & Lederman, 1989; Prescher et al., 2017). Researchers highlight these limitations, suggesting the necessity of conducting research with a broader perspective, but they seldom undertake it themselves (Brittell et al., 2018; Perdue & Lobben, 2016).

Considering this, our research aims to **methodically evaluate the legibility of tactile signs**. To ensure the most objective and reproducible results, we proposed a solution incorporating two vectors: subjective and personal. Subject-matter embedding involves basing the methodology of tactile sign legibility testing on sign theory, considering the crucial role signs play in cognition and communication. Our two-step procedure involves evaluating signs first in isolation within the same geometric categories and then assessing them in context, surrounded by other signs on maps. Personal embedding of the proposed methodology involves selecting PVI with diverse sociodemographic characteristics to validate the methodology. This ensures a solution for a broad audience, where tactile sign legibility relies solely on their intrinsic properties independent of testers' characteristics.

In this paper, we aim to answer the following **research questions**:

- **How does the two-step testing procedure support the development of legible tactile signs?**
- **How does the selection of testers impact the results of sign legibility?**

The methodical procedure strengthens empirical data and enhances the evaluation of tactile signs. It focuses on the geometric properties (shape, texture, and dimensions) influencing their haptic recognition and distinguishability, rather than relying on testers' characteristics. This standardized approach has the potential to be universally applicable, irrespective of the way tactile maps are produced.

2. Materials and methods

2.1. Methodological basics

The basis of the adopted methodology assumes that the same rules apply for tactile signs and maps as for traditional maps and cartographic signs. Pierce's sign triad (Atkin, 2010; MacEachren, 1995), serves as the methodological foundation for studying tactile cartographic signs. Peirce's framework identifies three key semiotic elements: the sign (representamen, carrier of meaning), object (element of reality), and interpretant (meaning). Using a system of such signs, a map communicates information that conveys content to the viewer. The system of cartographic signs is thus equated with the map language, governed by the laws of semiotics, capturing three types of relationships:

(1) **Semantic** – concerning the **relationship between signs and the reality** to which the signs refer, that is, the assignment of signs to their corresponding meanings;
(2) **Syntactic** – concerning the **relationships between signs**, i.e., for example, the mutual distribution of

signs or the correspondence of their distribution on the map with their distribution in reality;

(3) **Pragmatic** – concerning the **relationship between signs and map recipients**, encompassing communication, understanding, sign convention meaning.

Therefore, the methodical testing of tactile signs was assumed to include examining the correctness of the semiotic relationships within the cartographic sign system. The principles of testing, covering the two-stage procedure – including testing tactile signs in isolation and in context – as well as preparatory and summary stages, constitute a comprehensive methodology for testing tactile signs. The process is outlined in Figure 1.

In the existing literature, there are no examples of research specifically addressing the correctness of semiotic relations through an iterative approach that verifies tactile signs both in isolation and in context. Unlike previous studies, our approach assumes a comprehensive assessment of sign legibility, encompassing an extensive set of signs with precisely defined geometric parameters. Furthermore, we advocate for diverse testers to evaluate the legibility of these signs, paving the way for a more robust and universally applicable methodology.

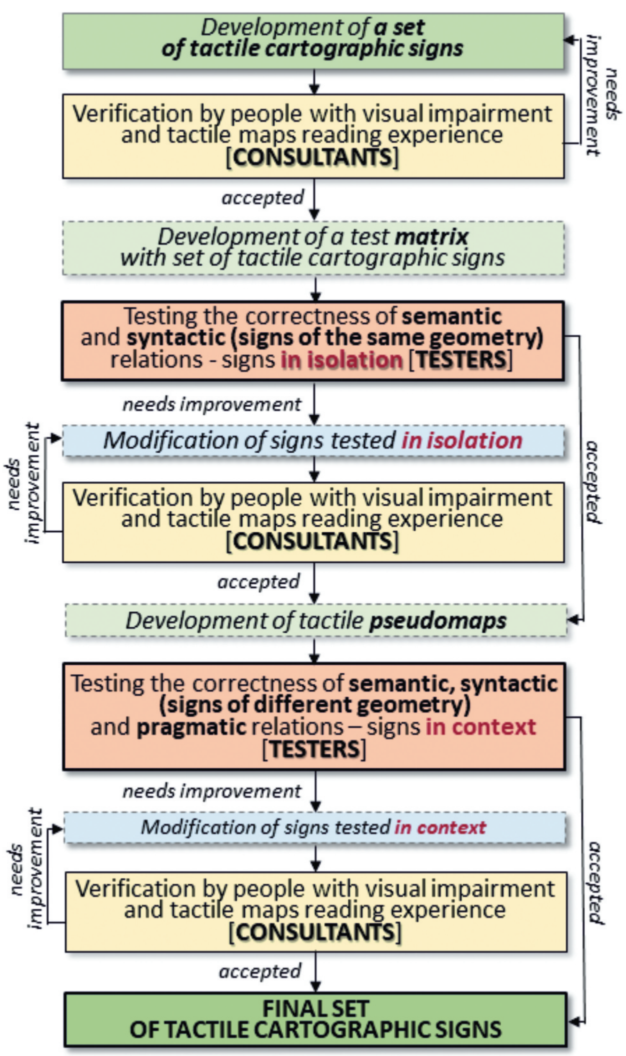

Figure 1. The course of the process of testing tactile cartographic signs (own work).

The proposed procedure evaluates a set of tactile signs, encompassing all signs on the final map. The set's extent depends on the map's subject and purpose. The set of designed tactile signs should consider users' perceptual capabilities, requiring appropriately sized signs with adequate spacing (Wabiński, Mościcka, et al., 2022). Geometric parameters of the signs, such as their shapes, textures and dimensions should align with the planned production technique, because different printing techniques may yield varying textures and sharpness, affecting tactile perception. The signs should take the simplest possible shapes, yet remain associated with the depicted objects (Nolan & Morris, 1971). Prioritizing signs, whose utility has been confirmed by PVI in prior studies is advisable.

The optimal sample size cannot be precisely defined due to the limited population of PVI and challenges in obtaining a diverse sample. According to Siegel and Castellan (Siegel & Castellan, 1988) 15 study participants are enough to perform both asymptotic procedures of nonparametric tests and human factors validation testing. Faulkner (Faulkner, 2003) also supports this, stating that 15 participants can identify at least 90% and an average of 97% of problems with a verified product. The test results should provide insights into the legibility of signs based on their geometric properties. Therefore, the group of testers should be as diverse as possible in terms of sociodemographic characteristics, i.e., age, gender, level of education, moment of vision loss, specifics of visual disability, and the range of skills and techniques in tactile cognition. While gender typically does not impact the results of testing tactile signs and maps (Nolan & Morris, 1971), differentiating respondents by gender is advisable for equality. Additionally, we recommend conducting dependency analyses between the test results and all these features (Dwivedi et al., 2017; Food and Drug Administration, 2016; King & Minium, 2003). The choice of statistical tests has to be determined by the size of the sample of testers, the scale of measurement of the variable (quantitative, qualitative) and variable distribution. For small samples, where the tested variables will not meet the assumption of a normal distribution, or with qualitative variables, non-parametric tests should be used. With a diverse group of testers, evaluation results should focus on sign properties rather than individual testers' characteristics.

2.2. Testing signs in isolation

In the proposed procedure, the first stage assesses the legibility of tactile signs independently, testing point, line, and area signs separately in a process called testing in isolation. This allows examination of the ease of decoding signs and their assignment to meanings (semantic relations), as well as the differentiation of signs within content categories (syntactic relations between signs of the same geometry).

To implement the above, stimuli matrices were prepared, separately for point, line, and area signs, based on a previously developed set of tactile signs. The signs on these matrices should be randomly arranged in rows and columns, and duplicated to increase the tasks' difficulty. In order to eliminate potential confounding variables, the order in which the matrices are presented to testers should be predetermined, so that particular geometries are tested both at the session's beginning (participant unfamiliar with the tactile material) and end (tired participant). The legend should be available to the test subject near the matrix or on a separate board and should explain all the signs shown on the matrix.

Using the matrix, the test subject performs tasks prepared by the instructor, identifying signs in the matrix rows. The researcher calls out the sign (its meaning), which must be located correctly. The test subject can repeatedly check the legend. While performing tasks, instructors record the number of errors (incorrect assignment of a sign to its meaning or failure to find a sign in a given row within a 30 second time limit), and also the number of times each sign was selected instead of the sign asked for (mistaken with other).

In addition, situations when the subject refers to the legend more than once or repeats browsing the row, should be noted (protracted responses). It was assumed that the number of errors should not exceed 1, and the number of protracted responses should be no more than 2 if the sign was confused with another, or more than 3 if no errors were made, for a sign to be considered correct. Such high requirements result from the need to ensure high legibility of signs, as they are intended for various audiences.

Before the study, we adopted the criterion, according to which problems with reading more than 50% of signs would result in repeating the entire test session. All the modified signs should later be rechecked by consultants (2–3 PVI experienced in working with tactile maps). Only after accepting all the signs tested in isolation, it would be possible to evaluate signs in context.

An essential study phase involves subjects freely discussing the tested tactile signs, going beyond instructed tasks. The interview should include at least:

- Open-ended supporting questions about semantic and syntactic relationships, e.g. Which characters are easy to distinguish? Which characters were similar to each other?
- The possibility of free speech with encouragement to express general opinion on matrices, signs, legends, printing technique, test procedure, and to propose potential improvements.

Test subjects might offer valuable comments, opinions, or conclusions about specific signs, regardless of task performance. These comments should be collected during interviews at the end of each testing session. Survey results should always be considered when modifying signs after each survey session.

2.3. Testing signs in context

In the second stage, we propose to evaluate the legibility of tactile signs considering the influence of other signs, including those with different geometries, by testing them on maps in a process called testing in context. This allows us to examine the correctness of:

- semantic relations, i.e. the ease of assigning meaning to a specific sign amidst other signs in the environment;
- syntactic relations between signs with different geometries. At this stage, design of a map impacts the legibility and distinguishability of characters, especially in terms of the spacing between signs;
- pragmatic relations, considering the relationships between signs and map recipients, related to communication, understanding and meaning conventions of signs. Thus, the study of their correctness involves examining the correct understanding and interpretation of signs depending on the context, that is, their surroundings on tactile maps.

To examine signs in context, signs of various geometries are placed in different configurations on pseudomaps. Pseudomaps, which imitate but do not represent reality, are useful for juxtaposing signs in diverse combinations. The legend, as in standard tactile maps, should explain all the depicted signs.

The study of signs in context should involve two types of tasks:

(1) location tasks, i.e., finding the indicated signs on the maps. The examinee must search the entire map sheet, while errors and protracted responses are recorded;
(2) narrative tasks, i.e., telling the story of what is on the map. Testers' references to signs (whether all or some), accurate recognition of their meaning, and interpretations within the narrative trajectory, are crucial. The process requires finding and distinguishing signs, assigning meaning, all while ensuring a sense of comfort and simplicity. The narrative analysis complements and reinforces the effectiveness of the initial task.

Evaluating the correctness of sign recognition in context is challenging to parameterize. Each sign needs individual consideration, accounting for error frequency and the nature of encountered difficulties – whether due to signs characteristics or immediate surroundings. Distinguishability of signs is influenced by editorial rules in tactile maps development (e.g., minimum horizontal spacing between signs). Additionally, the total number of location tasks may vary due to time limitations.

In the second session, we maintained the identical sign acceptance criteria used during the first session, testing in context provides valuable insights that may also lead to adjustments in established map editing principles.

The results of narrative tasks are qualitatively analyzed using analytical categories: obligatory (signs, mental map, errors, generalized judgments), and optional (map-specific). Test subjects' highlighted phrases and signs indicate the creation of a mental map, capturing spatial relations or movement routes. Components extracted during sessions include errors (misidentified signs or irregularities), and opinions containing generalized judgments about the map's representation. Considering the map's subject and function, other categories should also be distinguished to analyze the constructed narratives. After testing signs in context, interview protocols for testers should follow the same rules as those after testing in isolation.

2.4. Case study

The proposed methodology was tested on one common set of signs developed for tactile maps of gardens in various design styles (Baroque, Renaissance, Romantic, English, Japanese). Each garden style was presented on maps at 2 or 3 levels of detail. Level I (general map) depicts the entire garden composition. Level II (more detailed) highlights the most characteristic part of each garden style. Level III (large scale) focuses on a unique part, specific to each style. The five selected garden design styles offer an overview of the history of garden art. Despite their diverse features, tactile maps representing these styles have not been developed until now.

Signs were designed based on good practices available in the literature and our previous work (Wabiński, Mościcka, et al., 2022). Originally, 60 tactile signs were developed, comprising 30 point signs, 13 line signs and 17 area signs: 16 textures and 1 plain (default) surface, including 11 reserve signs (5 point, 3 line, and 4 area). Before the study session, two experienced consultants with visual impairments reviewed and provided feedback on the pilot set of designed signs, leading to revisions prior to the study's initiation. Appendix 1 presents the list of originally designed signs. The number of signs of particular geometries is based on the tactile map content ranges of historic gardens at different levels of detail (Zwirowicz-Rutkowska et al., 2023), considering the necessary reserve signs.

In cooperation with the Polish Association of the Blind, a recruitment form was distributed and filled out by 86 interested participants for our study. Based on the information provided by the candidates, we selected a diverse group of final testers. Our study participants exhibited almost equal gender representation in both sessions. The majority of testers identified themselves as fully blind (85% in the first session and 89% in the second), with a slight predominance of individuals with adventitious blindness over congenital blindness. Particular age groups were well represented in each session. At least half of the testers in each session had experience with tactile maps and Braille reading. The majority of testers (55% in the first session and 61% in the second), declared a high level of Braille reading experience. Following Section 2.2. guidelines, we prepared three matrices for testing signs in isolation. After replicating the signs, matrices included respectively 120 point signs, 52 line signs and 60 area signs. We converted their geometries into standard tessellation language (STL) and 3D-printed them applying digital light processing (DLP) technique that uses UV laser for selective curing of photopolymer liquid resin. In this technique, the physical object is built layer by layer in an additive process on the printer's build plate (Chaudhary et al., 2022). Figure 2 illustrates a sample matrix.

The first testing session, conducted at the Polish Association of the Blind headquarters over three days in June/July 2022, involved 20 testers, each allotted 60 minutes. The testers were assigned three tasks (tasks 1–3) for recognizing all point, line, and area signs. Appendix 2 contains detailed instructions for tasks 1–3. After the session, each tester completed an annotated

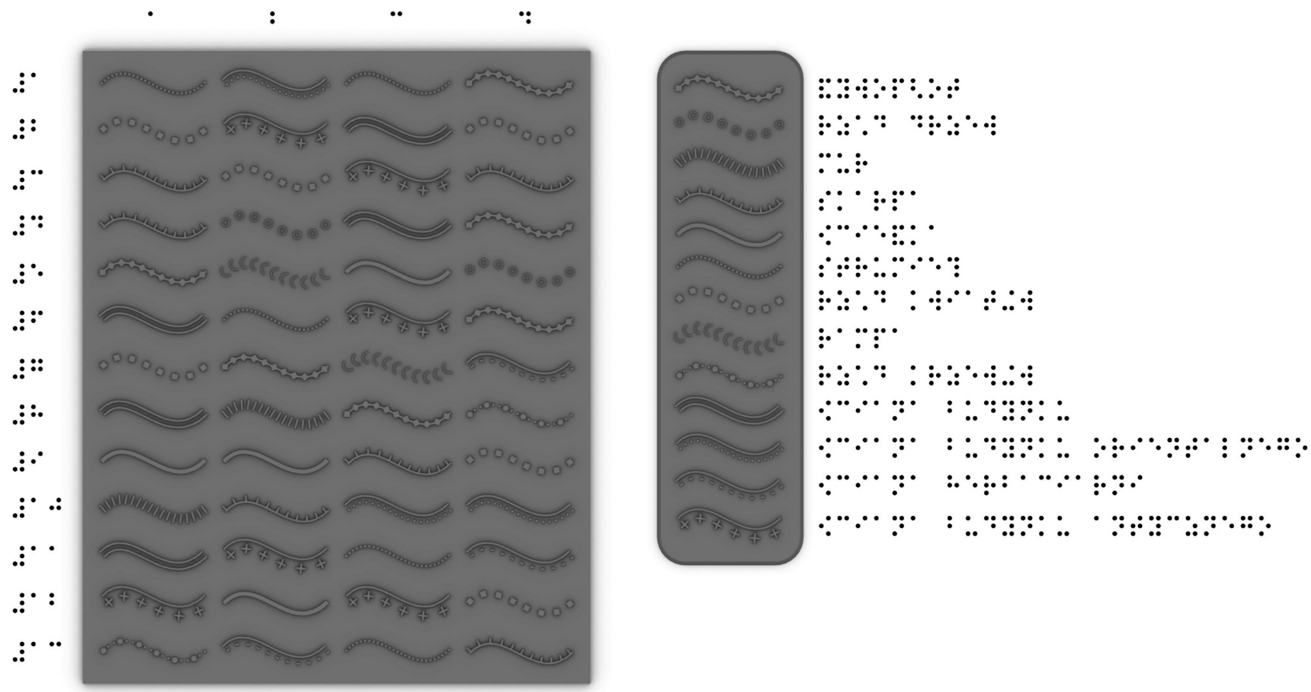

Figure 2. Line signs test matrix with its legend – 2D version (own work).

questionnaire, leading to sign adjustments based on their feedback. The validity of the implemented signs modification was confirmed by two experienced consultants with visual impairments. The proposed symbol set got accepted and was later used in context testing.

Following the guidelines from Section 2.3, seven pseudomaps were prepared for testing signs in context, including:

- three maps of the Baroque and Renaissance gardens (I, II, III level map);
- two maps of the Japanese garden (I and II levels combined, III level);
- one pseudomap each for the English and Romantic gardens (I and II levels combined).

Figure 3 illustrates an example of a pseudomap of a Japanese garden at I and II detail levels combined. The pseudomaps and their legends were 3D-printed using DLP technology.

The pseudomaps were presented to participants in a predetermined order. Eight location-based tasks were designed: finding point, line and area signs on various pseudomaps (tasks 1–7 - one for each of the pseudomaps), and constructing narratives about the maps (task 8 - constructing a narrative). Refer to Appendix 3 for detailed tasks descriptions.

19 testers participated in the second session (one resigned just before the session due to personal reasons), with 17 being the same as those from the first session. The session spanned 3 days in October and November 2022, with a 90-minutes time limit per each participant. After the session, each tester completed a questionnaire, leading to subsequent signs adjustments based on testers' feedback. The validity of the implemented changes was confirmed by the same two consultants as after the first session.

To examine the relationship between test results and testers' characteristics, we employed non-parametric versions of all statistical tests, given that the collected data do not meet adhere to the assumptions of parametric tests, (such as a normal sampling distribution).

Specifically, we applied the Kruskal-Wallis test with Dunn's-Bonferroni post hoc test (Dunn, 1964; Kruskal & Wallis, 1952) and the Mann-Whitney U test (Mann & Whitney, 1947). These tests allowed us to identify significant differences in sign recognition correctness across various conditions, including age, experience in reading tactile maps, Braille reading experience, gender, education level and timing of vision loss. We conducted our data analysis using IBM SPSS Statistics 28.

3. Results

3.1. Results of testing signs in isolation (stage 1)

In the initial testing phase, 11 of the 30 proposed point signs were deemed appropriate for immediate use (cf. section 2.2.). During our analysis, we considered

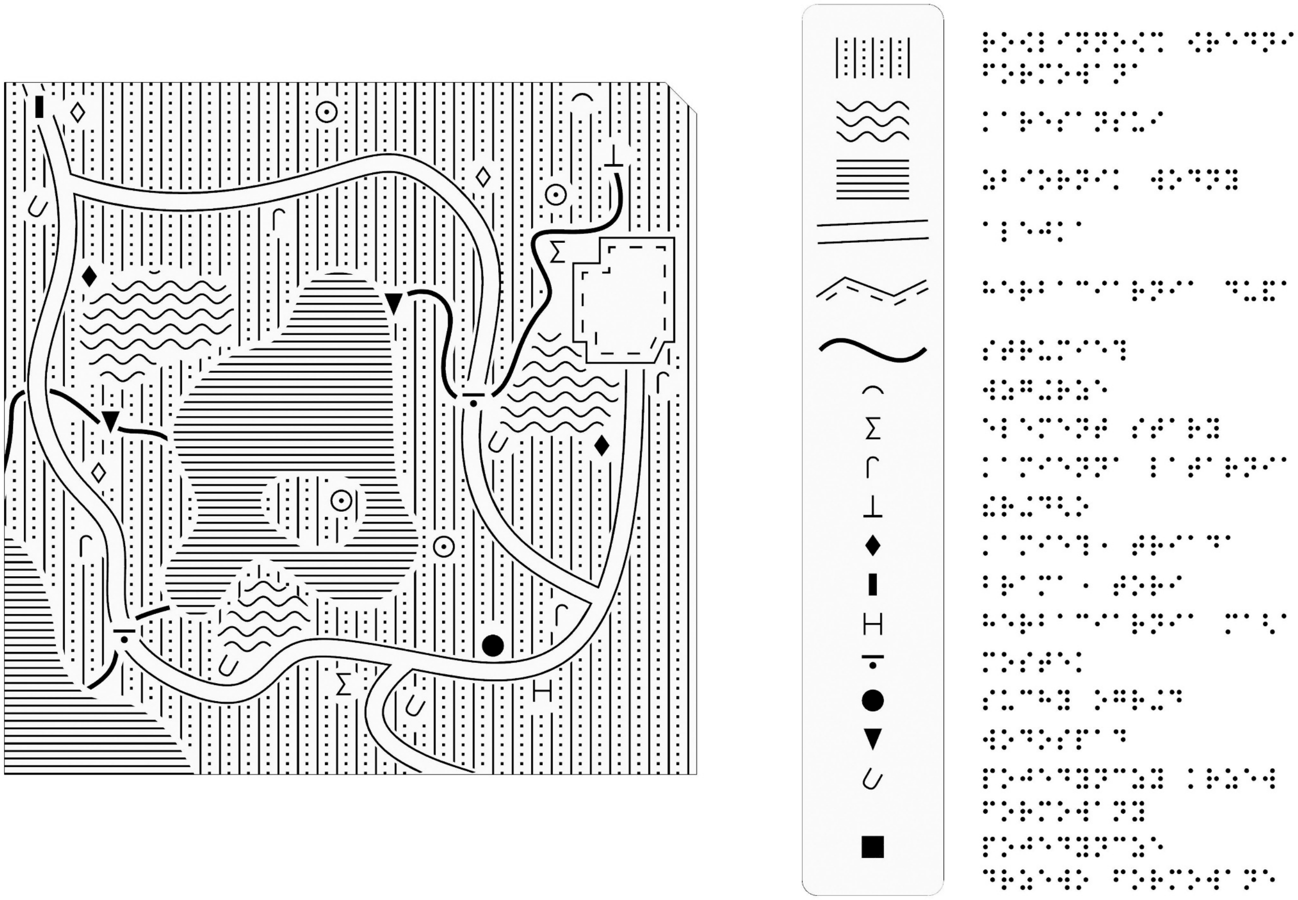

Figure 3. Pseudomap for testing signs in context with legend – Japanese garden (I and II level of detail combined) – 2D version.

situations, where certain signs were not found at all or where different signs in a row were indicated instead of the one we asked for (errors). Additionally, we noted how many times each sign was chosen instead of the intended ones (mistaken with others). We have also documented all instances of protracted responses (Figure 4). The designations of all the signs (point, line, area) correspond to their numbering in Appendix 1.

Some point signs were too similar to each other, often differing only in one haptic variable (Griffin, 2001; McCallum et al., 2005), e.g. rotation only. Such signs

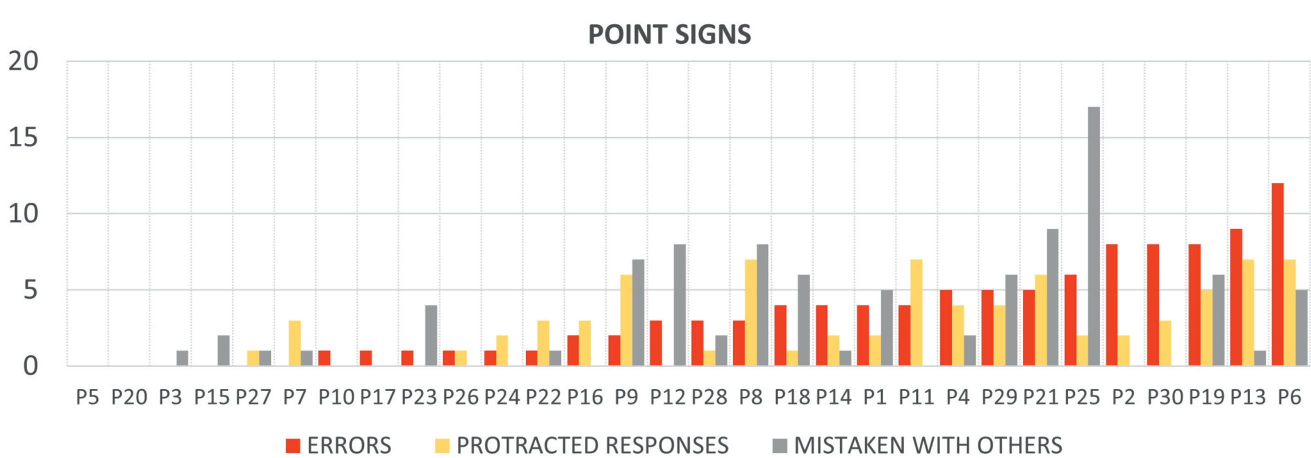

Figure 4. The types of mistakes associated with each point sign with the green box denoting signs evaluated as correct needing no further modifications.

were frequently associated with protracted responses. Table 1 provides a detailed overview of the signs confused by testers. It highlights pairs of signs mistaken with each other in specific cells, shown as a percentage of errors (incorrect indications). Rows in Table 1 represent the signs designated for identification on matrices in location tasks ("asked for"), while columns represent the signs that were mistakenly chosen instead (answer), or were not found at all (pass). Distinct colors in column one indicate the frequency of protracted responses: green represents 0–1 cases, yellow denotes 2–3 cases, and red signifies more than 3 cases. These guidelines also apply to Tables 2 and 3.

Out of the 13 tested line signs, 8 fulfilled our inclusion criteria. With three backup signs included in the original set, only minimal modifications were required. Types of line sign errors are shown in Figure 5, while a more detailed matrix is presented in Table 2.

Area signs caused the most problems for the study participants. Of the 16 area signs designed, only 6 were deemed correct (Figure 6, Table 3).

During the post-session interviews, testers provided feedback on the signs and the usability of matrices, offering insights into design-related issues. Many valuable suggestions were received, aiding in the enhancement of the most problematic signs' legibility.

When asked about the comfort of material usage, participants responded using a 5-point Likert scale. 78% of the responses indicated either "yes" or "definitely yes," while

Table 1. Point signs confusion matrix - percentages of errors (incorrect indications).

asked for \ answer	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	P16	P17	P18	P19	P20	P21	P22	P23	P24	P25	P26	P27	P28	P29	P30	pass
P1																			5%		5%		10%								
P2						5%		35%																							
P3																															
P4									25%																						
P5																															
P6							20%					5%	5%								20%										10%
P7																															
P8																													10%		
P9																					5%										5%
P10																															
P11				5%				5%	5%									5%													
P12																5%												10%			
P13	5%			5%								20%		5%							10%										
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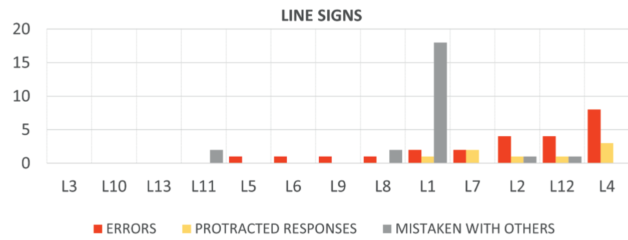


Figure 5. Types of mistakes associated with individual line signs with the green box denoting signs evaluated as correct and not requiring further modifications.

only one tester (5%) reported discomfort, thus affirming the comfort of using 3D-printed materials (DLP technique).

3.1.1. Testers' characteristics and tactile sign recognition in isolation

Dependency analyses revealed no significant performance disparity between individuals with congenital blindness and those with adventitious blindness/low vision (Mann Whitney U test: U = 33.000; $p = 0.205$). However, significant variations were observed concerning the legibility of point signs (U = 21.000; $p = 0.030$, mean rank of congenitally blind: 7.33; those with adventitious blindness/visual impairment: 13,09).

Regarding the correlation between tactile map reading experience and the ability to recognize signs, statistically significant distinctions were found among groups ($\chi2(2) = 7.933$; $p = 0.019$). Those with low experience in using tactile maps performed significantly worse compared to those with average and high skills (Dunn's post-hoc analysis with Bonferroni correction: high-none or low $\chi2(2) = 9.650$; $p = 0.016$; average-none or low $\chi2(2) = 8.083$; $p = 0.97$; Mrank high = 8.10; average = 9.67; none or low = 17.75). No statistically significant differences were detected in recognizing individual sign geometries or Braille reading experience. However, in isolation testing, subjects with intermediate Braille experience outperformed those with low or no experience ($\chi2(2) = 7.304$; $p = 0.026$; Dunn's post-hoc analysis with Bonferroni correction: average-none or low $\chi2(2) = 11.067$; $p = 0.029$; Mrank average = 4.83; none or low = 15.90).

Regarding sociodemographic variables, neither gender, education level, nor age statistically significantly differentiate the ability to correctly read the proposed tactile signs (Table 4).

3.2. Signs modifications after testing in isolation

The main issue reported by the study participants regarding point signs was their small size, making them difficult to differentiate. Consequently, all signs' sizes were increased from 6 to 7 mm. To address the durability concerns of the thin elements, the width of the thinnest components was enlarged from 0.5 to either 0.6 or 0.7 mm.

To enhance legibility, we raised the tiny elements within point signs by 0.2 mm compared to the signs' outline. Since identification of these tiny elements was nevertheless problematic, we have limited the number of such signs. Problematic signs were excluded from the initial set, necessitating the proposal of new sign designs. The original point symbol set consisted only

Table 2. Line signs confusion matrix percentage of errors (incorrect indications).

asked for \ answer		L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13
L1												10%		
L2		15%							5%					
L3														
L4		40%												
L5		5%												
L6		5%												
L7		5%											5%	
L8			5%											
L9		5%												
L10														
L11														
L12		15%							5%					
L13														

Table 3. Area signs confusion matrix - percentage of errors (incorrect indications).

asked for \ answer	A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16	pass
A1				5%						10%		20%					
A2																	
A3	5%			25%													
A4			25%											5%			5%
A5									5%								
A6							10%										
A7			5%														
A8																5%	
A9										5%			25%				
A10	10%		5%									5%	10%	10%			
A11																	
A12																	
A13									25%	5%							
A14				5%						5%							
A15																	
A16													20%	10%			

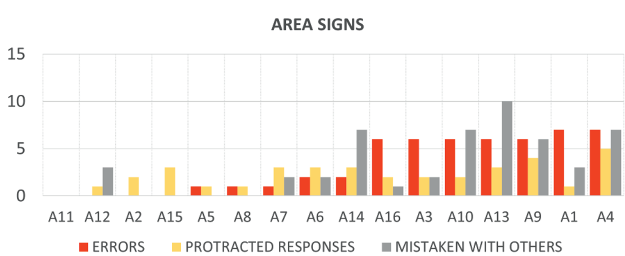


Figure 6. Types of mistakes associated with individual area signs.

of the signs based on outlines, since they had been found more legible in the past studies compared to solid ones (Gill & James, 1973). But to further differentiate them, we have introduced additional haptic variable by proposing also solid signs. Point signs tested along with their modifications are shown in Figure 7.

Modifications to the line signs included enlarging elements of the problematic signs and increasing spacing between elements forming double lines (Figure 8).

Table 4. Analysis of the relationship between sociodemographic variables and the accuracy of recognition of tactile signs in isolation.

Variable	Testing in isolation
Gender[1]	U = 33,000, *p* = 0,194
Education[1]	U = 29,000, *p* = 0,116
Age[2]	χ2(3) = 2,510, *p* = 0,474

[1]Mann-Whitney U Test; [2] Kruskal–Wallis Test.

To improve the recognition of area signs, we differentiated them using multiple haptic variables. Responding to participants' feedback, we adjusted the size of certain texture elements to ensure optimal recognition either individually or as part of the overall texture (Figure 9).

After modifying the signs, we have asked two experienced consultants for feedback, leading to some necessary adjustments, including the exclusion of the four most problematic point signs and two area signs. Additionally, two line signs denoting alleys and main axes of the gardens were introduced for the planned contextual testing.

Following these revisions, we were left with 25 point, 12 line and 14 area signs, each with their corresponding meanings (cf. Tables 5–7).

3.3. *Results of testing signs in context (stage 2)*

Due to time constraints (sessions lasted 90 minutes), the complexity of tasks, as well as in the face of differences in terms of time required to solve them, not all participants could complete every scheduled task – this includes both location and narrative tasks. For this reason, the number of errors and protracted responses were expressed as relative values, depending on the total number of sign-related tasks performed by the testers, when verifying whether a given sign could be considered legible.

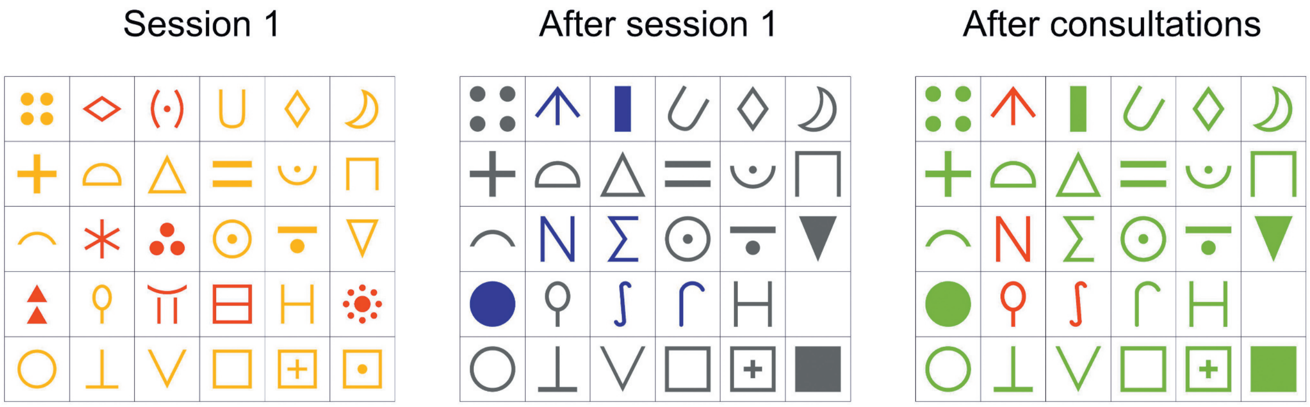


Figure 7. Point signs: red – excluded signs, orange – signs requiring modifications, green – accepted signs, gray – modified signs, blue – new designs.

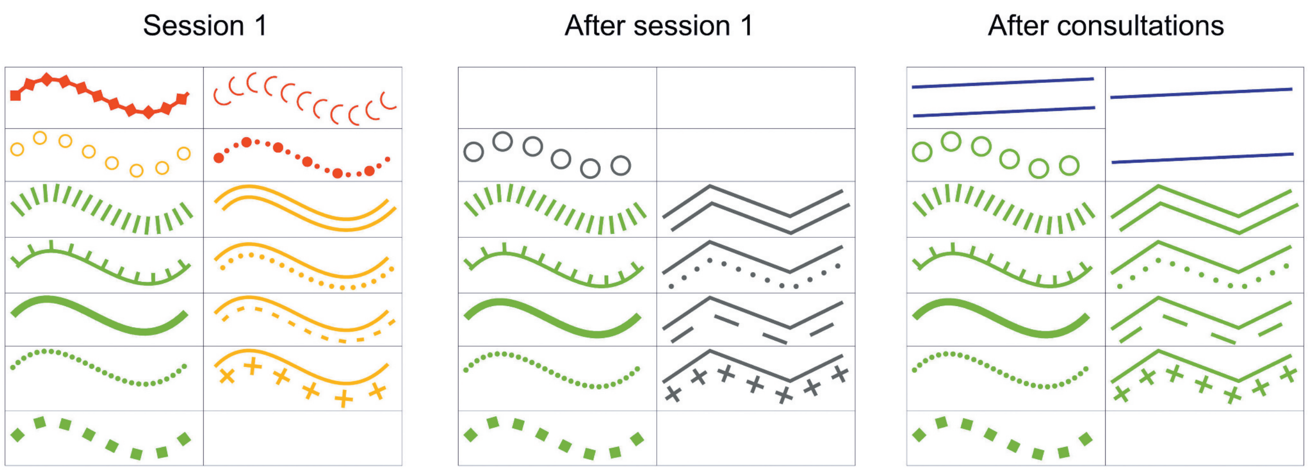


Figure 8. Line signs: red – excluded signs, orange – signs requiring modifications, green – accepted signs, gray – modified signs, blue – new designs.

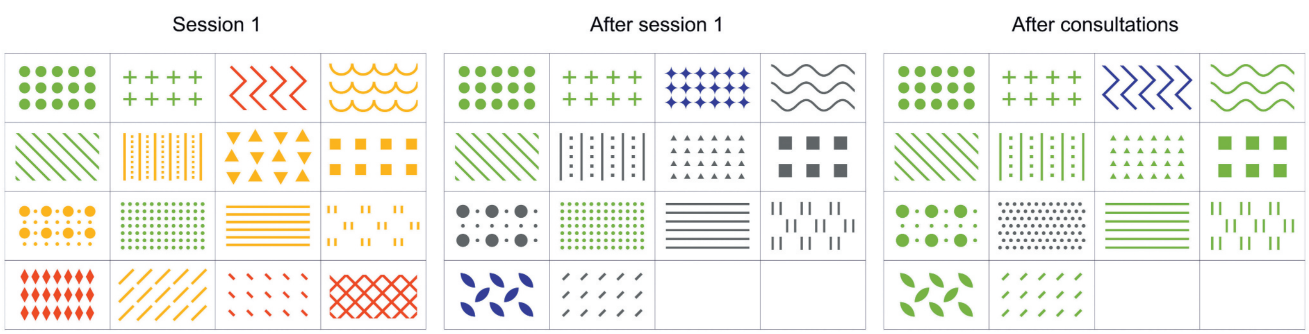


Figure 9. Area signs: red – excluded signs, orange – signs requiring modifications, green – accepted signs, gray – modified signs, blue – new designs.

3.3.1. Results of location tasks

In the location-based tasks, participants were instructed to locate specific elements, e.g.: *locate 5 fountains* or *find an alley that ends by the surface water*. If a participant was unable to locate all 5 fountains or pointed to a different sign than the one representing fountains, we counted this as an error, making it a very strict criterion. Attempts involving multiple signs were assessed as a single attempt. In cases where a sign was not found, it was considered an error.

As not all participants completed every task and that certain signs were repeated across different

Table 5. Results of the location-based tasks – point signs.

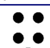
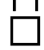
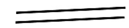
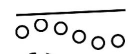
No.	Point Sign	Appearance	Protracted responses [%]	Errors [%]	Total attempts
1	viridarium		0.0%	0.0%	17
2	antique element		0.0%	10.5%	19
3	old element		15.8%	10.5%	19
4	hill		0.0%	5.3%	19
5	ruin, grotto, tomb		0.0%	0.0%	8
6	tree		0.0%	0.0%	37
7	formed tree		0.0%	0.0%	19
8	bower, stage		0.0%	5.3%	19
9	stone lantern		0.0%	0.0%	19
10	spring		15.8%	21.1%	19
11	stairs		14.8%	3.7%	27
12	sculpture		0.0%	0.0%	44
13	stones		5.6%	5.6%	36
14	gate		2.6%	2.6%	38
15	fountain		0.0%	0.0%	38
16	plant support		0.0%	11.1%	18
17	tea house		0.0%	0.0%	19
18	building		2.7%	10.8%	37
19	oriental building		0.0%	0.0%	19
20	antique building		0.0%	0.0%	19
21	bucket plant		11.1%	0.0%	18
22	bridge		23.7%	15.8%	38
23	dry garden		5.3%	26.3%	19
24	waterfall		15.8%	15.8%	19
25	formed shrub		2.7%	5.4%	37

Table 6. Results of the location-based tasks – line signs.

No.	Line Sign	Appearance	Protracted responses [%]	Errors [%]	Total attempts
1	alley		0.0%	0.0%	67
2	main axis		5.6%	5.6%	36
3	row of trees		50.0%	38.9%	18
4	row of flowers		0.0%	15.8%	19
5	shrubs		0.0%	0.0%	18
6	hedge		0.0%	5.3%	19
7	stream		6.9%	6.9%	29
8	wall		13.5%	21.6%	37
9	building wall		15.8%	10.5%	19
10	oriental building wall		15.8%	0.0%	19
11	antique building wall		21.1%	10.5%	19
12	tea house wall		5.3%	15.8%	19

pseudomaps, we tallied the total attempts for each sign type. Subsequently, we calculated the overall number of errors and instances of protracted responses for each sign during the session.

In the case of point signs (Table 5), the majority did not pose significant issues. Merely 2 out of 25 signs exhibited an error rate of 20% or higher, a tolerable outcome given the time constraints.

The signs with highest error rates are characteristic for maps of a Japanese garden, where more unique signs appear compared to other styles. A single pseudomap representing this style (combining levels I and II) featured 12 distinct point signs, which is close to the maximum number of unique symbols (of all geometries) allowed on a single tactile map sheet (Rowell & Ungar, 2003). Based on participants' feedback and the contexts in which these signs caused confusion, we decided to assign different meanings to particular signs to enhance their clarity. For example, the sign initially representing a bridge was hard to distinguish when following a path or a stream and thus, will now depict a dry garden, addressing the previous ambiguity.

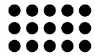
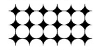
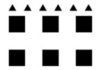
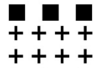
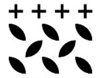
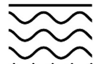
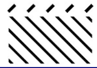
Regarding line signs (Table 6), the results remain acceptable. The two most problematic signs were: a row of trees and a wall. Row of trees only appeared on a Baroque/Renaissance pseudomap (I and II levels), symmetrically positioned along the map sheet's vertical edge. Since most study participants scanned the maps horizontally and focused on the central sections of the pseudomaps, they struggled to identify these features. To resolve this, we incorporated an empty offset around the map sheets in the final designs. The issue with the wall sign, commonly mistaken for double lines representing building walls, was resolved by extruding the building walls to different heights compared to other line signs in the final set.

Regarding area signs (Table 7), the most problematic instances were associated with the Baroque/Renaissance map (III level), with four area signs placed next to each other at the same height. To address this issue in future designs, we will enlarge blank offset between area signs (from 2 to 4 mm). Garden parterres appeared twice in Table 7 to test two possible textures, with the decision made to retain version 2 on the final signs set.

3.3.2. Results of narrative tasks

Due to time constraints, we collected a total of only 37 narratives: Baroque-Renaissance garden (I level) – 7 narratives; Baroque-Renaissance garden (III level) – 7 narratives; English garden – 10 narratives; Romantic garden – 6 narratives; Japanese garden (I and II levels) – 7 narratives. Prioritizing these pseudomaps for narrative tasks was influenced by the highest number of errors encountered in these pseudomaps during the location tasks. This allowed us to assess participants' narrative construction abilities on more complex pseudomaps. Recorded respondent narratives of the gardens

Table 7. Results of the location-based tasks – area signs.

No.	Area Sign	Appearance	Protracted responses [%]	Errors [%]	Total attempts
1	cluster of trees		31.6%	15.8%	19
2	high vegetation		11.1%	5.6%	72
3	medium formed vegetation		4.3%	4.3%	47
4	short vegetation		5.4%	5.4%	37
5	parterre (version 1)		11.1%	27.8%	18
6	parterre (version 2)		17.6%	11.8%	17
7	viridarium		21.1%	5.3%	19
8	flowers		26.3%	47.4%	19
9	herbs		15.8%	10.5%	19
10	lawn		9.3%	5.6%	54
11	surface water		2.1%	2.1%	48
12	dry garden		0.0%	0.0%	19
13	sand		0.0%	0.0%	17
14	gravel		5.9%	0.0%	17

were meticulously transcribed and qualitatively analyzed.

Analysis revealed that respondents primarily constructed narratives by identifying or listing content elements (signs), sometimes without referring to the legend directly. Consequently, similar but not identical terms were used to describe objects, leading to occasional clarification requests. Of the 37 narratives, 27 (73%) included mentioning signs with many signs being generally mentioned, but without decoding their exact meanings. Among the pointed and discussed signs, erroneous references happened in 19% of cases. To illustrate the narrative's features related to the indicated signs, here is an excerpt from a tester (B21) describing a Japanese garden: "*There is a lot of water in general. There is some vegetation, too. There is a lot of water in the middle. And, of course, alleys, which can get you basically all over the garden, and walk, let's say, around this water reservoir. There are also some lamps on the side…*".

In most cases, the map's content elements were not cataloged considering spatio-temporal relations, as exemplified in the earlier quote, but were integrated within the narrative, constructing a mental map of the space. This method involved describing navigation through the garden, specifying the location of objects in relation to geographic directions, or highlighting important landmarks. Such descriptions were present in 43% of the narratives. For instance, in an excerpt from a statement by B16 describing an English garden: "*The alley is crossed by a stream and there is a bridge over this stream, also you can walk along the alley over the stream on this bridge. The alley actually comes to a fork, because one way goes to the left – northwest, and the other to the southeast. Let's go northeast. Near the alley we meet the bower again …* ".

Terms indicating perceived garden style features were present in 24% of the narratives, corresponding to Baroque-Renaissance (3 cases), Romantic (3 cases), English (2 cases) and Japanese (1) styles, for example: "*Then along the main avenue we still have low vegetation on the right and left. Perpendicular to the main avenue there is also a wall and then we have plantings, in the middle of which there are also fountains symmetrical to the main avenue. (…) there are side alleys, which can be used to go right and left from the main avenue – they are symmetrically led, and they also branch off into smaller ones, and next to them there are steps, which differentiate the levels of vegetation.*" (tester B9, Baroque-Renaissance garden, I level).

Some testers formulated generalized conclusions and opinions about garden specifics, not explicitly referencing the assumed garden features but implying a potential correct interpretation with proper preparation prior to the session. An example of this type of narrative can be seen in B5's statement about the Japanese garden: "*This is a much more difficult garden at first glance. For me, it is a big chaos in that there are many alleys that intersect at different angles.*"

Certain narrative excerpts revealed that tactile signs stimulated the creation of surrogate imagery by the subjects based on synesthesia – the activation of associations and sensations coming from visual memory or the sense of hearing, smell, e.g.: “*It reminds me of colors and a large variety of vegetation and buildings, tea house, the old element, also these buildings here, stone lantern, tori gate. It reminds me of colors, something with pink, brown, an accumulation of, well... warmth.*” (B3 tester, Japanese garden).

In post-session interviews, participants rated their material usage comfort on a 5-point Likert scale. 89% responded “yes” or “definitely yes,” while only one tester reported a negative experience. The increase in “hard to say” responses compared to stage 1 could be attributed to the session’s complexity and duration (90 minutes compared to the previous 60 minutes).

3.3.3. Testers’ characteristics and tactile sign recognition in context

For dependency analyses, only complete observations involving participants completing locations tasks on all pseudomaps were statistically analyzed, resulting in the exclusion of two incomplete observations.

Participants with congenital blindness did not outperform the adventitiously blind in overall signs reading ($U = 20.500$; $p = 0.134$), although they demonstrated better recognition of point signs ($U = 12.500$; $p = 0.021$; mean rank of individuals with congenital blindness: 6.06; those with adventitious blindness/visual impairment: 11,61). Similarly, no significant differences were found among groups with varying levels of tactile map reading experience ($\chi2(2) = 2{,}006$; $p = 0{,}367$). The same was true for tactile signs recognition and Braille reading skills (test results Kruskal-Wallis $\chi2(2) = 1{,}464$; $p = 0{,}4817$).

The impact of specific visual impairments on sign reading ability wasn’t tested due to the small sample size of only two participants described as visually impaired. Additionally, while considering sociodemographic variables, neither gender, education level, nor age significantly differentiate the ability to correctly read the proposed signs (Table 8).

Table 8. Analysis of the relationship between sociodemographic variables and the correctness of recognizing tactile signs.

Variable	Testing in context
Gender[1]	$U = 35{,}00$ $p = 0{,}923$
Education[1]	$U = 33{,}500$ $p = 0{,}809$
Age[2]	$\chi2(3) = 1{,}404$ $p = 0{,}705$

[a]Mann-Whitney U Test; [2] Kruskal–Wallis Test.

3.4. Changes of signs after testing in context

Some point signs caused troubles when placed in a context, such as the bridge situated at the crossing of an alley and a stream, resulting in identification issues despite varying heights (Figure 10). To address this, we reassigned specific meanings to the signs, ensuring understanding in future contexts. For the finalized symbol set and their corresponding meanings, please refer to Appendix 4.

Participants encountered difficulties in recognizing all area signs, leading to further adjustments. Since signs were tested in a context during stage 2, we identified pairs of area signs frequently mistaken, despite legibility in isolation. To resolve this, we assigned distinct meanings to these signs, ensuring they are unlikely to appear together on the same map sheet due to their characteristic representation of different garden design styles. We also prioritized the most legible textures for frequently appearing signs, while trying to resemble their real-world counterparts.

Only one sign underwent geometry modifications (lawn in Table 7), altering the arrangement of dots to increase the number of differentiating haptic variables from similar signs, such as clusters of trees.

In response to participants’ feedback, we adjusted the heights of the proposed tactile signs. Double lines were occasionally mistaken for other line signs (alleys), prompting modifications to the 4 signs representing different types of building walls. An additional height level was incorporated into the sign set to mitigate this issue (Table 9).

Figure 10. Troublesome bridge symbol (in red) on the crossing of alley and stream.

Table 9. Tactile signs heights.

Sign type	Original height [mm]	Modified height [mm]
Area	0.5	0.5
Line	1.0	1.0
Building walls (line)	n/a	1.5
Point	1.5 (1.7)*	2.0 (2.2)*

*values in brackets refer to the height of small elements inscribed into point signs.

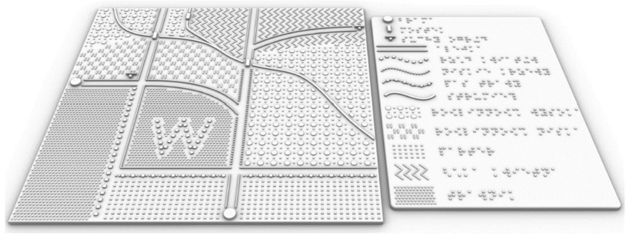


Figure 11. Pseudomap and its legend used during consultations after stage 2.

Since the modifications after stage 2 were rather cosmetic, the entire study session did not need to be repeated. Yet, to verify the efficacy of the changes, we consulted two experienced individuals again. Accordingly, we prepared an additional pseudomap (Figure 11) featuring modified and newly added signs (including a strip of grass and flower meadow), tasking the consultants with location-based challenges.

While the consultants expressed overall satisfaction with the results and the newly introduced signs, they highlighted challenges in distinguishing certain area signs on the pseudomap. This difficulty stemmed from the inclusion of six different area signs, including a default surface – an unlikely scenario in the final garden maps. Increasing the offsets between symbols from 2 mm to 4 mm in subsequent iterations will address this concern. Notably, there were no issues distinguishing neighboring signs placed at different heights.

Moreover, during the study, participants were solely provided with tactile materials. The final maps will incorporate additional Braille and audio descriptions to enhance their comprehension.

4. Discussion

Past studies on testing tactile signs typically employed one-step procedures, with signs being tested only in isolation (Lambert & Lederman, 1989). Moreover, the examined signs rarely had consistent meanings across different maps (Edman, 1992), and tests involved small, homogenous tester groups, often incorporating sighted individuals wearing blindfolds (Espinosa & Ochaíta, 1998; Prescher et al., 2017). However, signs indicated as legible in isolation could be illegible on a map, whereas signs examined by sighted people wearing blindfolds may be unclear to people with congenital blindness, etc. Our two-stage methodology addresses these issues, providing a diverse set of signs with well-defined geometric parameters, ready for use on tactile maps. As not all of the proposed signs were legible in isolation, some needed minor modifications, while others required complete redesign. This underscores the need for an iterative evaluation process.

While studying signs in isolation helps eliminate incomprehensible or indistinct signs, it lacks consideration of contextual factors relevant to map arrangements, when distances and spatial relationships must be considered. Testing signs in context is essential, ensuring legibility in various scenarios. Additionally, contextual testing reveals the map's communicative effectiveness and grammar, enhancing its utility by providing knowledge about the analyzed space and helping to build a mental map of the area. This supports our proposal for a two-stage legibility assessment methodology, and brings **the answer to the first research question**. As a result, we developed a parametrized set of legible tactile signs ready for use on maps.

Examining signs in isolation is an initial step in assessing tactile signs' legibility. It facilitates effective verification and modification without necessitating complete map redesign. This approach allows for multiple test iterations, making adjustments more manageable – modifying matrices or even single signs, instead of complete maps. It streamlines the map design process by refining sign layouts and creating a comprehensive tactile representation of space.

Testing in context revealed that modifications from the initial stage resulted in easy recognition by participants. They were able to comprehend not just individual signs but also the overall context and create narratives within the map content. The satisfactory results surpassed the authors' expectations, suggesting that prolonging the study duration and reducing the number of pseudomaps could have yielded even better results and increased the number of narratives obtained.

Contextual testing revealed previously unnoticed issues during testing in isolation – related to sign legibility, distinctions between different signs' geometries, minimal distances between sign and their placement on maps' edges. Such insights would have been inaccessible without contextual testing. This valuable insight, absent in prior studies, enabled us to establish unambiguous tactile map redaction rules for future use.

Qualitative analysis of the constructed narratives validated the correctness of semantic, syntactic, and pragmatic relations. It highlighted the signs' effectiveness in conveying informational content and their role in aiding the construction of mental maps. Pragmatic effectiveness extended beyond informational content educational value related to garden styles, aiding in understanding unfamiliar surroundings. Even without audiodescriptions, some participants managed to identify garden styles characteristics, demonstrating the signs' effectiveness. These results suggest that testers were comfortable reading the signs, performing tasks, recognizing garden style features, and forming general conclusions about them. It confirms that all types of semiotic relations in the final signs set are correct, and map based on such signs will communicate information to the viewer in a correct way.

In our analysis, we discovered that user characteristics significantly impact tactile signs testing. During stage 1 (testing in isolation), we observed variations in sign decoding based on the moment of sight loss and experience in tactile reading (including Braille and tactile maps). Individuals with congenital blindness performed slightly better at recognizing point signs, as did those with adventitious blindness or visual impairment. Additionally, better performance was observed for those with more experience in reading tactile maps and Braille.

We modified the signs based on these results, particularly by enlarging point signs to improve efficiency of individuals with limited tactile abilities. In stage 2 (testing in context), there were no statistically significant dependencies between experience related to reading tactile maps or Braille and sign legibility correctness. However, users with congenital blindness still performed better in recognizing point signs.

Regarding sociodemographic variables, neither gender, education level, nor age statistically significantly differentiated the ability to correctly interpret the proposed tactile signs in both testing stages.

The selection process of study participants in testing tactile signs legibility is crucial. In our case study, such diversity of testers was achieved. This made it possible to generalize the legibility of the signs, this workmade them legible to a diverse audience. This legibility is based on the signs' geometric features rather than perceptual abilities of readers, which brings **the answer to the second research question**. Our results primarily reflect sign geometric characteristics and not the testers' characteristics, providing a universally comprehensible solution, especially pertinent in garden map development, that are intended for various audiences.

A systematic study yielded a parametrized set of 52 legible signs (see Appendix 4). Considering the constraints of incorporating unique tactile signs on a single map sheet and the preferences of PVI for geometrically simple signs, proposing further designs of legible signs would be challenging. However, given the thorough description of each sign in our set, adaptation for various applications is feasible. Minor modifications might be necessary for alternative production techniques. Swell-paper might be preferred for cheap production of portable maps, while thermoforming may be suitable for producing tactile maps in large quantities. While our research employed 3D printing for rapid prototyping, offering swift and cost-effective corrections, other production techniques may not afford the same flexibility in signs design (Prescher et al., 2017).

This research is a part of a broader project focused on tactile map technology development, encompassing not only signs design but also editorial principles, and cost-effective printing techniques. The same group of testers will also be involved in evaluating printing techniques and the final garden maps. Existing literature lacks studies involving the same group of testers and consultants across a series of sessions in the comprehensive development of tactile maps. The final maps will be enhanced with text and audio descriptions to provide user-friendly products.

5. Conclusions

Signs on tactile maps are subject not only to the constraints of their legibility adapted to tactile perception, but also to the demands imposed on the signs themselves as carriers of information. Our research demonstrates a methodical approach to evaluate tactile signs, ensuring the development of fully functional tactile maps.

This research emphasizes the insufficiency of one-step evaluation for developing legible tactile signs. We propose a two-step evaluation process, analyzing signs both individually and in context, to maximize their legibility and universality. Implementing this methodology on case study maps reveals the necessity of simultaneous development of signs and map editing rules that facilitates development of legible tactile maps. Moreover, involving PVI in sign evaluation enhances the reliability of results, ensuring that final tactile products fulfil the target audience expectations.

The developed set of tactile signs is compatible with one of the 3D printing techniques (specifically DLP). Future research should assess sign legibility with alternative techniques and materials, such as swell-paper. Nonetheless, our testing methodology and the developed tactile signs set contribute to standardization and automation of tactile maps production, enhancing availability of tactile graphics in general.

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Data availability statement

The data that support the findings of this study (assessment forms) are openly available in Zenodo at https://zenodo.org/records/8099368 and https://zenodo.org/records/8099383.

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