École Polytechnique

BACHELOR THESIS IN COMPUTER SCIENCE

Perceptible Transition of Textures on Tactile Maps for Visually Impaired Users

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Abstract

This study explores the use of intuitive geometric tactile patterns as low-cost and accessible multi-sensory tools for visually impaired users. While tactile patterns have long been recognized and widely used for conveying information to Visually Impaired users, there remains a lack of qualitative evaluation regarding the impact of pattern complexity and haptic load estimation. Thus, we have taken the first step by formally evaluating the Perceptible Transition of Textures on Tactile Maps. We hope this will open up new avenues for innovative accessibility ideas using such economically and technologically accessible patterns, with a high social impact.

Keywords Visual Impairments, Tactile maps, Geometric patterns, Haptic perception, Inclusion, Educational documents, Geography, Perceptive haptic distance, Visually Impaired (VI) users

Contents

1 Introduction

This investigation delves into the application of intuitive geometric tactile patterns as a cost-effective and universally accessible multi-sensory tool for VI users. Tactile graphics, defined as raised, textured, or embossed images specifically designed for exploration through touch, provide a means for VI individuals to experience visual information in a tactile format [8]. These graphics are demonstrably critical for successful social integration of VI individuals in areas such as map navigation and supplementary tactile cues during travel. Existing research emphasizes the indispensable role that tactile graphics technologies play in the educational and social spheres of VI individuals' lives [20]. The lack of accessibility is particularly detrimental within STEM disciplines (Science, Technology, Engineering, and Mathematics) where graphics play an important role. While tactile patterns have long been recognized and widely used for conveying information to VI users, there remains a lack of qualitative evaluation regarding the impact of pattern complexity and haptic load estimation. In this study, we have taken the first step by formally modeling and evaluating the Perceptible Transition of Textures on Tactile Maps. We hope this will open up new avenues for innovative accessibility ideas using such economically and technologically accessible patterns, with a high social impact.

1.1 Motivation

Educational Documents for VI Users

Context VI people represent a significant part of the population, there are up to 30 million blind and partially sighted persons in geographical Europe [42]. Despite ongoing efforts to enhance inclusivity for disabled individuals, infographics remain challenging to access for them. According to Brulé et al. [14], children's engagement with educational documents can be improved through the use of reflexive and playful technologies. These technologies should be easy to use, inherently interesting for social and cultural exploration, and foster collaboration between students and teachers. Additionally, the educational documents themselves should be adaptable by teachers to different settings and modifiable by children to fit their individual needs. Additionally, it is recommended to use multiple senses, such as touch and sound, in the design of educational documents. Indeed, mutli-sense stimulation allows to replace the perspective (3D) aspect which must be abandoned in tactile documents as it creates confusion in shape understanding by VI users.

Following this multi-sense recommendation, the link between vision and haptics has been investigated by Bouzbib et al. [12], specifically within the field of Virtual Reality. VR has a close relationship with how VI people perceive the world as it is a space where "users do not perceive their physical vicinity : the outside world is not noticeable". "It quantifies users' involvement and naturalness of interactions through control, sensory, distraction and realism factors". There are two types of indicators related to haptics : tactile (through the skin) and kinesthetic (from proprioception). Haptic solutions are classified by a degree of physicality (use of real objects or not) and a degree of actuation (its reliance on motor-based hardware implementation enabling displacement such as position or shape). Three types of tasks can be done in this setting : exploration (touch the environment and understand its constraints), manipulation (modifying the position and orientation of an object) or edition (modification of an object property such as scale or shape). An example of physical edition interfaces is 2.5D tabletops developed by Siu et al. [37]. They are made of pins raising and lowering themselves, which number defines their haptic fidelity resolution. They are used as desktop interfaces for shape simulation and require bare-hand interactions. It makes them easy to use, allows a free navigation at desktop scale and a bimanual manipulation for exploration.

1.2 Related Work

Geometric Tactile Design

Current research in tactile graphics design emphasizes design principles that prioritize simplicity and familiarity. To illustrate this, Fadhlillah [11] has attempted to introduce a new texture design for tactile pictograms. The texture media can be varied through its form, angle, height, and width, with the latter two relating to the size. The researcher proposed a method for designing textures based on a visual language theory focusing on conveying movement and depth. This method involved translating core concepts like repetition, navigation, and direction into specific textural properties such as form, angle, height or area. The study created and tested a system of textures but yielded inconclusive results, highlighting the limitations VI users face when encountering new design systems without clear meaning. Introducing too many elements can even weaken the effectiveness of graphics-based designs.
In contrast, Zhao et al. [18] have investigated the exploration methods of visually impaired individuals when interacting with raised-line graphics. The study focused on finger behavior, specifically tactile fixations, revealing significant differences in fixation number and duration across graphics, tasks, and using both index fingers. Notably, more fixations occurred on the left hand, while longer durations were observed on the right hand. The study also identified three bimanual exploration strategies, involving fixed right-hand anchor points, alternating hands, and a chaining hands exploration pattern.

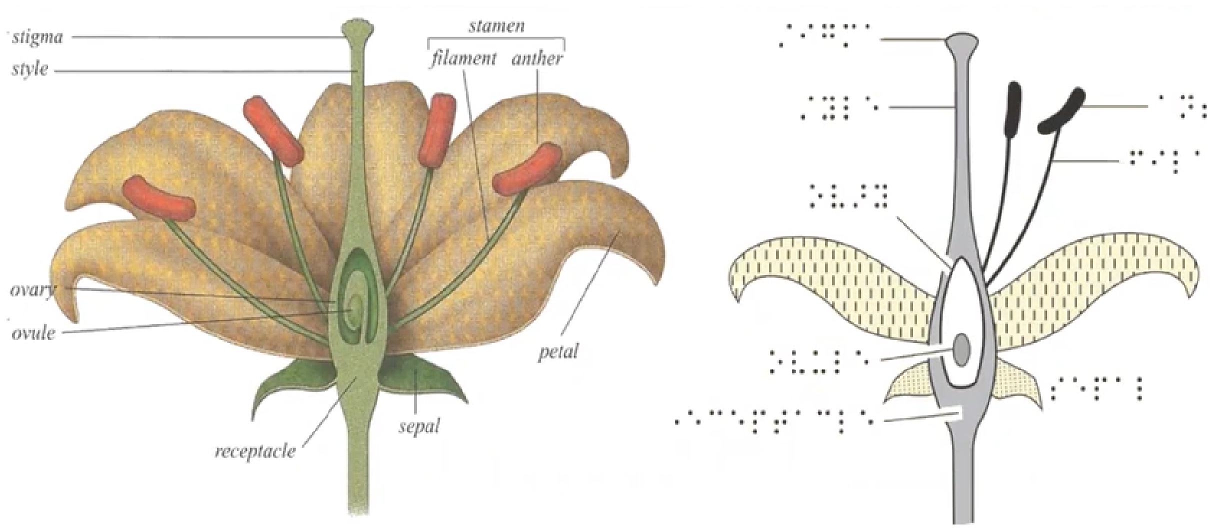

Figure 1: *Translation of a graphic to a tactile representation*

Concurrently, Panotopoulou et al. [45] have identified the key characteristics that allow VI people to perceive shape. Their studies suggest that illustrations for VI audiences should use canonical views from large surface areas, respecting the object's topology (flat vs curved surfaces) and avoiding occlusions which are perceived as mistakes. An example of a canonical view can be seen in Figure 1. Conversely, the study found that precise placement of connection points and exact proportions have minimal impact on shape understanding. Based on these observations, Panotopoulou et al. [45] proposed a multi-projection tactile line drawing method. Their approach takes a 3D object, segments it, applies multi-projection processing and rendering, to result into a line drawing with curved textures (shown in Figure 2). This tactile drawing approach has been shown to improve shape understanding in raised line drawings by VI users.

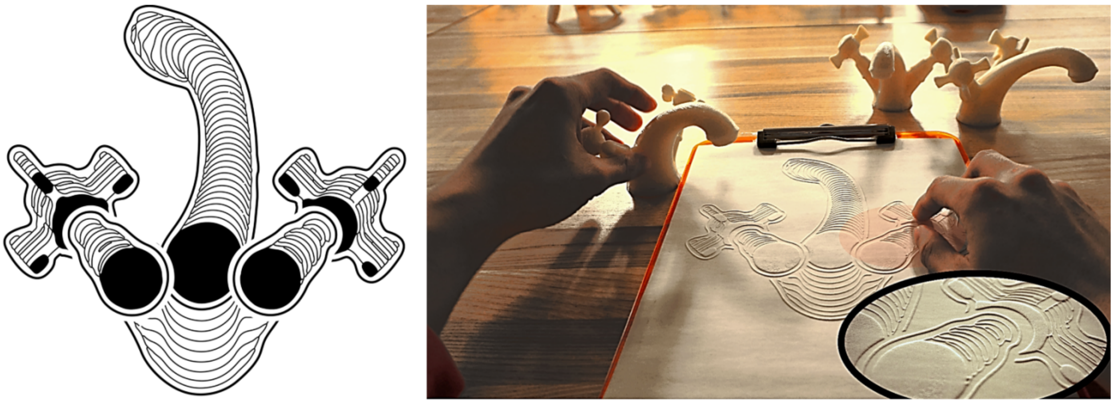

Figure 2: *Implementation of a multi-projection tactile line drawing* [45]

Recently in 2016, Cervenka et al. [46] have come up with a convenient algorithm that converts a conventional map into a simplified black-and-white graphic printed according to the principles of tactile maps. On the publicly accessible website Mapy.cz, a world planisphere is available and users can choose a location to target. Tactile maps are offered in 3 scales: basic $1 : 1,200$ (street resolution), medium $1 : 37,000$ (district scale) or small $1 : 300,000$ (large cities scale). Four types of area symbols are distinguished, namely buildings, water zones, green areas and industrial areas. Their approach regarding map lettering is by implementing it "in two ways in order to enable the cooperation of blind and sighted users with the map. Primarily, streets are marked on the map with abbreviations of three letters based on the street name, which are written in Braille in the street axis. These labels are supplemented by full street names in orange, which does not react to heat treatment in any way and therefore remains only in visual form". As a final step, the generated maps along with their legends, as presented in Figure 3, can be printed on swell-paper and react to heat treatment as explained in Section 2.1. This process has some limitations : maps cannot be generated at a large scale (at country-size for example), and the area symbols are restricted to a set of four patterns (dashes, point grid, structured raster, and raised blocks).

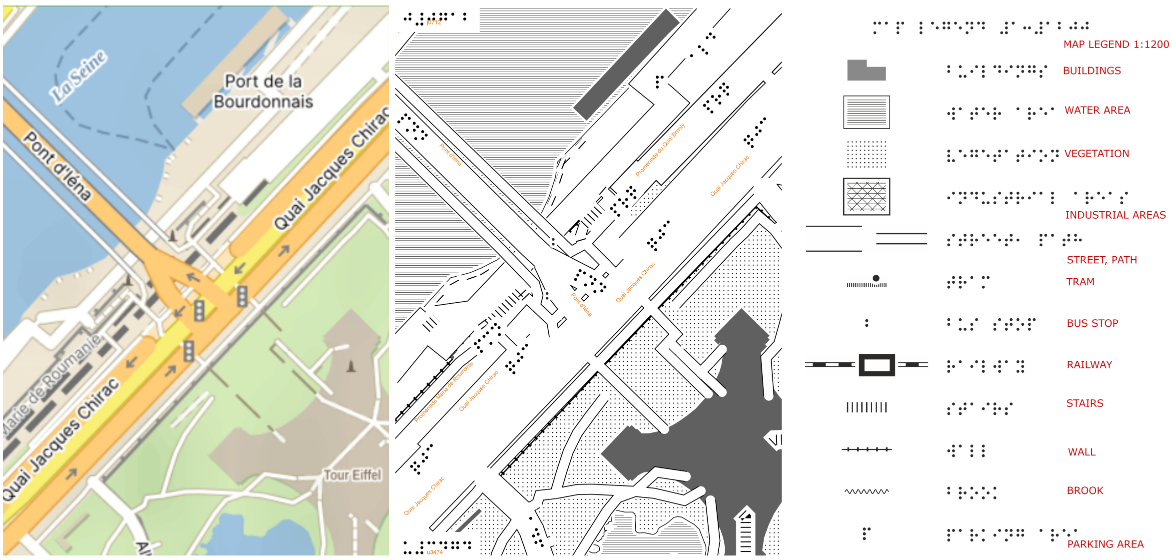

Figure 3: *An example of haptic map generation by the online software mapy.cz* [46] *with the provided legend*

Point Patterns : a particular type of geometric patterns

Point Patterns are particular type of geometric patterns that have diverse applications in Computer Graphics such as such halftoning, stippling, or avoiding aliasing artifacts in ray tracing. Since the early eighties, researchers have been studying different stochastic sampling techniques for point pattern generation.

The Poisson disk distribution is recognized for its superiority in capturing relevant information visually. It exhibits a blue-noise spectrum, ensuring spatial evenness with certain desirable properties, accurately capturing lower-end frequency content and achieving approximate uniformity at higher frequencies. Various sampling techniques have been developed based on this distribution, such as dart throwing by Cook [22], though it is now considered highly inefficient. Some optimizations, like logarithmic algorithms by Jones [32] and tiling-based methods by Shade et al. [31], enhance efficiency by reducing rejections and maintaining spatially-varying density functions. Another approach by Lloyd [36] involves updating point positions through iterations, where a Voronoi diagram is computed for each point, and the point is shifted to the centroid of the Voronoi cell. While effective, this method lacks a satisfactory termination criterion, posing challenges for spatially-varying density point sets. Lloyd's method variant by Balzer et al. [28] ensures equal integrated density in Voronoi cells but comes with high computational complexity. A comparison of all of these methods generating Poisson disk distributions has been made by Lagae & Dutré [9] based on radial statistics and spectral properties and highlighted method-dependent considerations for different uses. A recent promising method by Raanan [33] associates each point with a radially-symmetric kernel function, generating a point sample with blue noise spectral properties in linear time. This approach combines equidistance and randomness, providing an efficient generation of blue noise point pattern.

As mentioned earlier, blue noise point patterns are particularly well-suited for image stippling. It is a technique used in computer graphics and art to represent an image by using a collection of strategically placed points to convey the shape, shading, and details of the original image, as shown in Figure 4. Since blue noise patterns provide the best balance between spatial evenness, natural shading, reduced aliasing and detail control, they are a popular choice for creating accurate representations in high-quality stippled images. Interestingly, research by Yellot [17] suggests that the arrangement of photoreceptors in the extra-foveal part of the human retina possesses blue noise characteristics, which can explain why such distributions are visually appealing and intuitive.

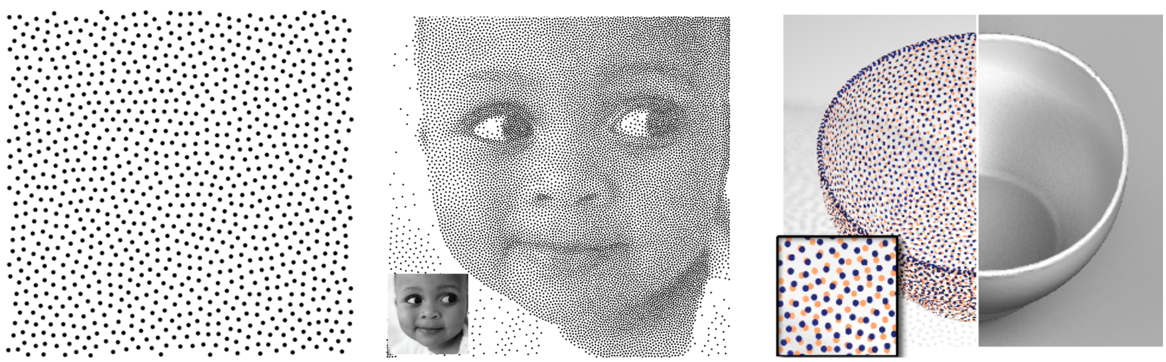

Figure 4: *Left and middle : Blue noise point pattern and image stippling by Raanan* [33]. *Right: a method for blue noise point on a surface (considering both position and normal direction) to improve the reconstruction of the surface from a smaller set of points by Chen et al.* [6]

2 From Design to Fabrication of Tactile Maps

2.1 Different Fabrication Methods

In this study, we are specifically focusing on tactile maps, which are tactile graphics serving a visual representations of environmental or geographical spaces. There exist different methods to create tactile maps, and they all have their limitations as noted by Ducasse et al. [7]:

- Hand-crafting is the most simple method one can use to create tactile maps. It is a rapid and immediate solution for providing access to graphics, particularly those with important spatial layout. Almost any materials can be used to create a composition, for instance magnets on a white-board, tactile drawing boards, or a collage on a smooth paper. The main disadvantages of this method are a lack of durability and no replicability [29].

- Alternatively, one can use a braille embosser to print tactile maps. It is a special type of printer that creates braille output on paper. It operates similarly to a regular printer but instead of using ink cartridges employs small pins to raise specific sections of braille paper, forming raised dots, lines and surfaces. There exist different types of printers such as desktop, high-speed and portable embossers for diverse uses. It is possible to print tactile maps on advanced embossers, provided that a specific software such as TMAP [1] is used to translate map information into a format that is suitable for embossing.

- One of the most common methods for creating tactile maps is heat embossing. This process is straightforward: the map is designed on a computer and then printed on "swell paper" (also known as "microcapsule paper" or "heat-sensitive paper") using a regular printer. Swell paper contains microcapsules of alcohol in its coating. Upon heating the paper in a specialized oven such as Zy-Fuse or Piaf, these microcapsules expand, creating raised relief over the black ink. The resulting raised-line maps, as exposed in Figure 5, are tactile and can be perceived by VI users. They can also serve as visual maps and facilitate collaboration in learning between blind and partially sighted individuals. However, this method has its drawbacks, including the high cost of swell paper and the limited durability of the resulting maps.

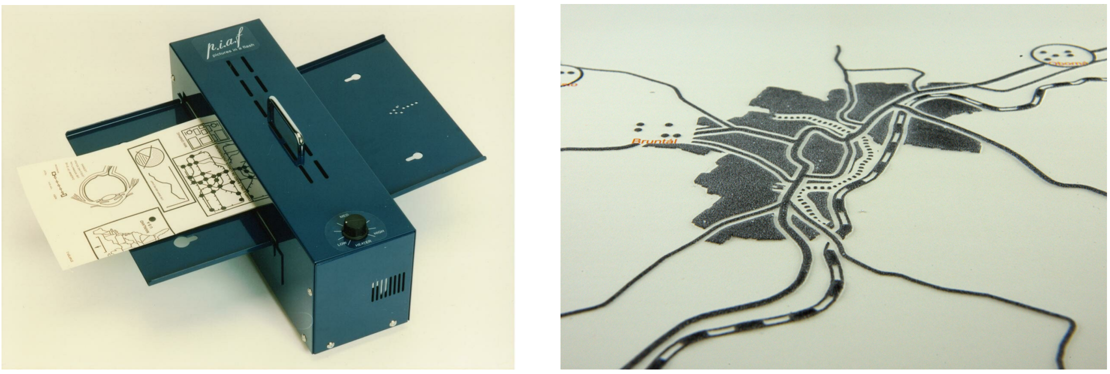

Figure 5: *An oven used for heat embossing and a raised-line tactile map*

- Another technique, known as thermoforming, involves placing a plastic sheet over a master created from various textured materials. When heated in a vacuum, the sheet permanently conforms to the texture of the master. Its key benefit lies in its capacity to create varying relief heights, but inconsistent quality is often found in such documents due to air entrapment or uneven heating.

- Additionally, tactile maps printed in resin are known for their robustness, durability. This method allows a rich tactile complexity and high raised surfaces. However, this method involves using a resin-based 3D printer which is often expensive and long to use.

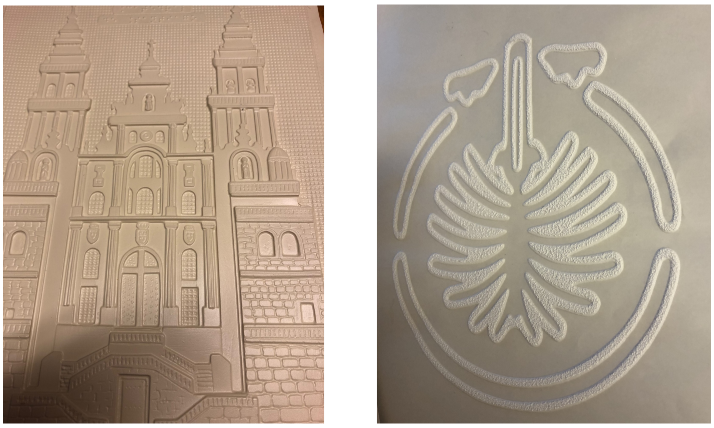

Figure 6: *Left, a thermo-formed tactile drawing. Right : a tactile drawing printed in resin*

While tactile maps are effective educational tools, they come with several limitations and challenges. In addition to being time-consuming and costly, producing tactile maps requires the expertise of a tactile graphics specialists who understand how to present information in a way that can be comprehended by VI users, especially targeting children, as noted by Tatham [10]. Furthermore, Yatani et al. [19] indicate that once the tactile maps are printed, their static nature makes them quickly outdated.

The text displayed on tactile maps also poses challenges. Braille and other text raised-line systems like Moon's alphabet [2] are more relevant than embossed roman-style as they display a greater variation in their lower frequency content, high tangibility (legibility) within a given character space and minimizing space usage, thus offering a better tactile feedback, as observed by Loornis [23]. However, those characters lack of variability in font size, spacing, and orientation, thereby limiting their application in tactile maps. Plus, only a minority of VI individuals are proficient in reading Braille [30]. Thus, maps frequently incorporate legends to prevent overwhelming the map itself with excessive detail, but Hinton [15] pointed out that the frequent transition between the map and legends can disrupt the reading process, so their content and placement near the map should be optimized.

The variety of these common production methods limits the standardization of tactile maps as they require different approaches for map preparation. However, other factors limit the standardization of tactile map design.

2.2 Obstacles to Standardization

The transition from a traditional map to a tactile map raises many challenges. According to Eriksson et al. [25], "in many cases, copying a visual map without revision into a tactile form of the same size would result in a map that is difficult to read because of its being too cluttered ". Expanding map size for detailed reading often obstructs the overall tactile comprehension. Instead, it's common to trim information or distribute it across multiple maps. Due to "differences of perception among individuals with visual impairments and differences between various production methods of tactile maps", the standardization process of tactile map design is not straightforward. Although international standards exist for tactile mapping, for example from the International Organization for Standardization (ISO) [3], the technical approaches provided are usually difficult to use in real-life applications. Wabinski et al. [40] provide a complete review of research and best practices regarding tactile map design. Their study covers various subjects ranging from map composition to more in-depth details about map content. They have interrogated several tactile map designers from all over the world about parameters on symbols to respect in order to ensure haptic readability, such as their minimum size or distance one from the other. The answers revealed that there was no agreement on a common guideline or design rule, highlighting the lack of standardization and cooperation between practitioners from different countries. In particular, information about the maximum number of patterns to use in a single map is scarce. We will come back to this important feature in our problem formalization in Section 3.

2.3 Guidelines on Tactile Symbols : Point, Line, Texture

Based on the comprehensive work of Wabinski et al. [40], our study of tactile symbols relies on the following axis : the choice of tactile symbols (covering their specific aspects as well as their coordination), rules for tactile map composition and numerical specifications regarding the creation of symbols and their arrangement on the map.

Choice of Tactile Symbols

- **Realism and Simplicity.**
  In the development of tactile symbols, ensuring a high degree of realism and comprehensibility for VI users is paramount. This means using shapes that suggest real-world features and keeping symbols true to their real-life counterparts, for example by representing railroads with two parallel lines crossed by shorter lines. Moreover, simplicity ranks as the second most vital principle following legibility, underscoring the importance of keeping representations unambiguous and as straightforward as possible.

- **Universal and Custom Symbols.**
  Certain symbols are common across all production methods, for instance "simple geometric forms such as squares and circles for point symbols, solid and dashed lines with various spacing and area symbols consisting of solid lines at different angles". While Regis & Nogueira [34] suggested a system of point symbols for tactile world maps (see Figure 7), their adoption by map designers has been limited, leaving the representation of specific features like oceans and tropics inconsistent. For more specific symbols, according to the production method, there exist diverse sets of recommended symbols along with, if applicable, their meaning . We refer to Nolan & Morris 's study [5] for generic symbol recommendations for thermo-forming and heat embossing methods.

- **Characteristics of Point Symbols and Line Symbols**
  Point symbols, defined by their form, size, solid-outline, and continuity, should remain unfilled with a single outline for improved legibility, as suggested by Nolan & Morris [5]. Bris [24] indicates that point symbols should be different from the symbols used to form textures on the same map, even with distinct sizes. Specific types of point symbols called icons are designed to orient users and convey specific information. They are positioned consistently on the page such that they are easily memorable and functional, for instance compass-point-north icons are always located in the lower-left corner and provide guidance on geographic orientation.

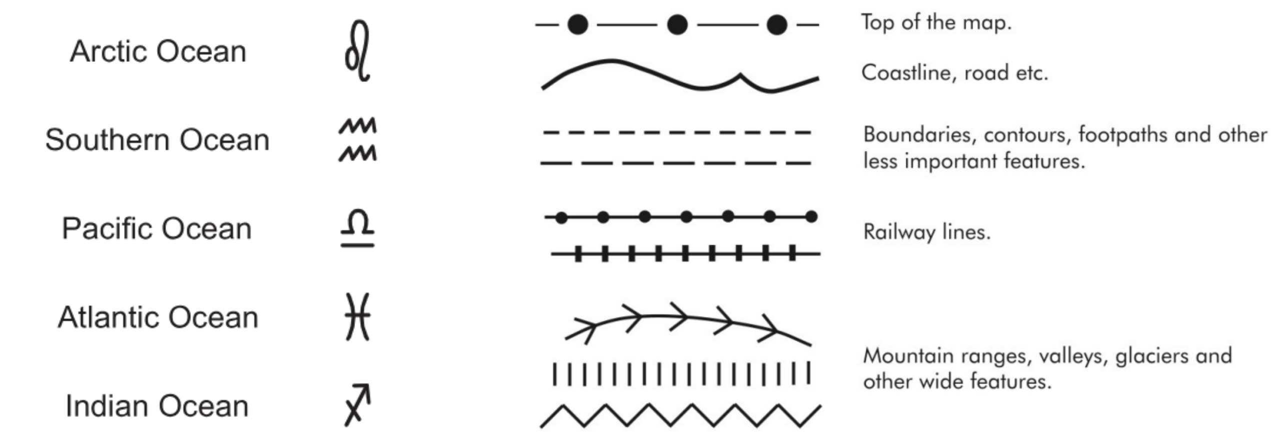

Figure 7: *Left: suggestion of standardization of point symbols for tactile world maps* [34] *Right : line symbols and applications* [39]

Line symbols, which may appear in any direction in tactile maps, are discriminable by the following features : continuous-interrupted, smooth-ragged, single-double, or thick-thin. An example of line symbols with their recommended applications by the NSW Tactual and Bold Print Mapping Committee [39] is shown in Figure 7. To effectively distinguish lines embedded within textures, Barth [21] notes that employing a minimum of two contrasting attributes is imperative. Easton & Bentzen [4] recommend using broken or dotted single lines for "faster exploration and better memory representations".

- **Characteristics and Applications of Area Symbols.**
  - The NSW Tactual and Bold Print Mapping Committee [39] has identified multiple parameters characterizing area symbols : style (geometry of texture elements, including regularity and continuity), pitch (distance between pattern elements), and thickness (width of pattern elements) as shown in Figure 8. From a specific pattern, other patterns can be created by varying at least one characteristic listed before, but for instance rotation should be combined with another variation to avoid confusion.
  - Different tactile patterns serve various purposes [38]. A solid-rough pattern effectively conveys depth. Dot or coarser patterns are ideal for larger areas but should avoid overwhelming the diagram, however their effectiveness diminishes with small shapes. Horizontal-line patterns are best suited for broad, flat shapes with rectangular or square features, while vertical-line patterns emphasize the verticality of a shape. Basket-weave patterns come into play when filling large shapes and representing solid objects. In contrast, solid patterns are limited to small areas. They are best used when other patterns are unsuitable or to highlight important shapes.

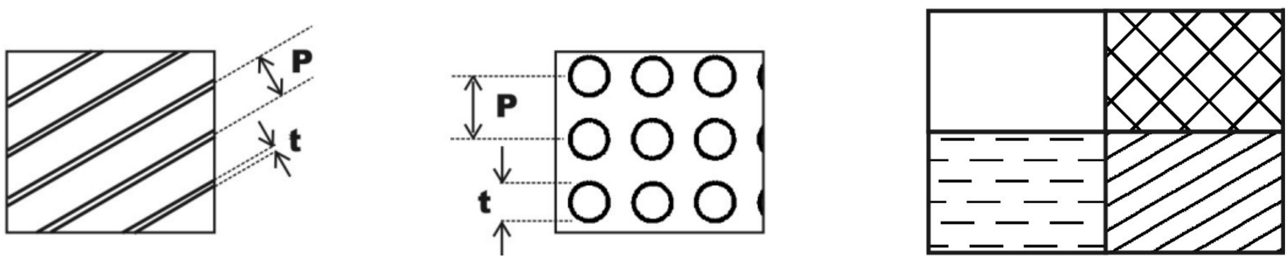

Figure 8: *On the left, pattern characteristics identified by* [39] *: style, pitch "P" and thickness "t" ; on the right, a selection of tactile patterns : empty, basket-weave, horizontal broken lines and dashes*

Map Composition and Numerical Parameters.

- **Legend and Labels.**
  - A legend describing all of its symbols and Braille abbreviations should be placed near the map, and both should be framed by thick lines to delimitate their content.
  - Labels should be put only if necessary and in abbreviated form if taking up too much space, with their meaning listed in a legend. Using Braille labels is often the easiest way to describe a feature, as mentionned earlier in Section 2.1. Such labels generally require horizontal placement, with street descriptions following their course being the only exception.

- **Scaling and Number of Features.**
  - Choosing the right scale for representation and adjusting the size of the map accordingly is crucial for tactile map design. Heller & Ballesteros [35] state that if a tangible map is too small, there will be problems with resolving fine detail while a too large scale would lead to difficulties to get an overview of the map.
  - In order to maintain legibility of tactile maps, less features should be shown than on a visual map. Töpfer & Pillewizer [43]'s formula $n_f = n_a * \sqrt{\frac{M_a}{M_f}}$ helps determine the maximum number of objects n_f displayable on a smaller scale map M_f, considering the original number n_a and scale denominators M_a, M_f. It ensures that information density stays manageable for touch perception. More specifically, it is agreed that a single map should include no more than 10-15 point symbols.

- **Numerical Parameters for Symbols.**
  - Wabinski et al. [40] have combined the recommended parameters for area, point and line symbols from different sources (and precising the production method used when possible) in a useful document, underscoring the significant differences in values across guidelines. An example of their recommendation summaries is shown in Figure 9. Cases in point are an optimal point symbol size varying from 3 to 13 mm or a maximum number of 5 height levels on a single map adviced by Bris [24]. Indeed, Wabinski et al. [47] have found that height differentiation of tactile symbols of all kinds can be used to improve tactile maps legibility.
  - Jehoel et al. [41] have attempted through a series of studies to determine the optimal elevation of tactile features on maps. As a result, they suggested an optimal elevation of 0.16 mm, which is significantly lower than what existing tactile maps and design guidelines would predict. Thermo-formed plastic is commonly over 1 mm, swell paper is around 0.5 mm and Braille embossers produce dots at elevations of 0.25 to 1.0 mm according to Gill & Silver [16]. Thus, the elevation of tactile maps varies depending on the production method used but all exceed the optimal value, so tactile map features may not need to be as elevated as they commonly are.

Table 4. Heights.

Parameter	Values and sources
Minimum height difference between symbols	0.04–0.08 mm (Jehoel *et al.*, 2009)
	0.5 mm (Bris, 2001)
Maximum number of height levels on a single map	5 (Bris, 2001)
Recommended heights for symbol types	Braille: 0.5 mm, line and area: 1 mm, point: 1.5 mm (Wiedel and Groves, 1969)
Minimum symbol height	0.2 mm (Jehoel *et al.*, 2006)
	0.4 mm (Bris, 2001)
	0.5 mm or 0.3 mm for smooth symbols (ISO, 2016)
	0.75 mm (Jesenský, 1988)
Optimal symbol height	0.3–1.5 mm (ISO, 2019)

Figure 9: *An extract of numerical parameters collected by* [40] *, this table focusing on heights*

3 Methodology

Based on our performed bibliographic analysis, while there is a consensus that the number of patterns in a single map should be limited, there has been insufficient exploration into determining the precise maximum number. One notable exception is a paper by Wieckowska et al. [26] suggesting to use "four different textures, including the smooth background" without providing detailed information on the underlying experiments. In a visit to INSHEA [27], discussions with experts, namely Mathieu Gaborit [13] working with real users with visual impairments, led to the recommendation of using a maximum of five different textures per tactile map, including the smooth one. Motivated by a formal validation of such statement, and given the absence of concrete evidence regarding the optimal number of textures, we provide a formalization of the context through two main research questions.

Toward a formal validation of expert recommendations

Regarding area symbols, the recommendations in Section 2.3 present their characteristics, the most common ones; and give advice to discriminate them from point symbols or lines, and specific numerical values to respect. However, these guidelines focus solely on one texture at a time, providing very little information about how to combine them in a meaningful and optimal way. The first lack of information is about the choice of the most relevant area symbols to represent environments. There is also a lack of guidance on how to combine different textures and about the haptic charge of using different patterns in a tactile map. From these observations and focusing on the context of tactile maps printed on swell paper, we derived two key research questions.

- $Q1$ **: Identifying the most representative patterns for tactile maps**
- $Q2$ **: Estimating the haptic perceptible distance between tactile patterns**

3.1 Representative patterns for tactile maps (Q1)

We categorized different groups of environment elements, commonly present in geographic maps:

- Water Areas. Divided into three main categories based on their movement.
  - Waving water: large bodies of water with surface waves, including seas and oceans.
  - Flowing water: continuously moving water from higher to lower elevations, such as rivers and streams.
  - Still water: bodies of water with little to no surface movement, including lakes, ponds, and marshes.
- Natural Lands. Categorized by prominent features such as landform and vegetation.
  - Low elevation land: plains, valleys
  - High elevation land: mountains, hills
  - Vegetated land: forests, grasslands, green areas within urban areas
  - Non-vegetated land: dry plains, deserts, ice
- Urban Areas. Separated according to their dominant land use, often host point symbols for prominent places, so should allow point symbols above to be discernable
  - Residential area
  - Commercial or academic area
  - Historical area
- Peri-Urban Area :
  - Industrial area : dedicated to large-scale production, manufacturing, and processing of goods including factories, warehouses
  - Agricultural area : can be divided into arable (for growing crops like corn, wheat, and vegetables) and livestock agricultural area (dedicated to raising animals for meat, milk, eggs)

Based on this categorization, we have collected a set of geometric patterns that may be used to represent each of these categories, see Figures 10, 11, 12, 13. This set will be further reviewed by experts from the INSHEA [27], while considering different practical aspects such as the cultural interpretation based on the localisation of the user study, as well as the technology-based constraints and already adopted conventions or standard patterns (known as trames in French). This expert guided sampling procedure will lead to an approved set of geometric patterns representing the four types of environments.

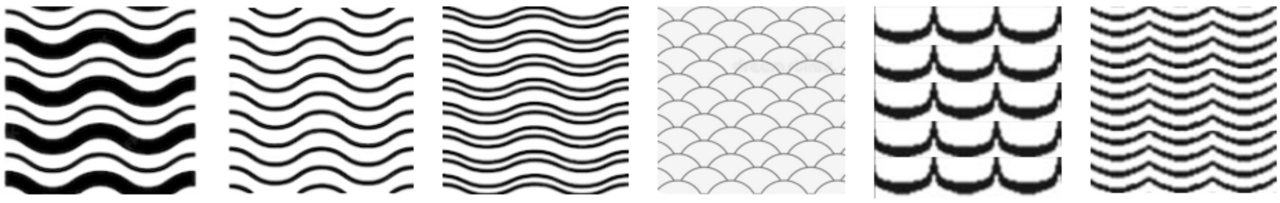

Figure 10: *Set of patterns for water areas*

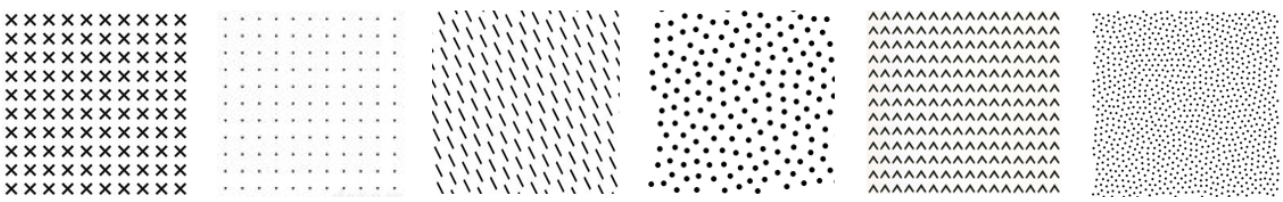

Figure 11: *Set of patterns for natural lands*

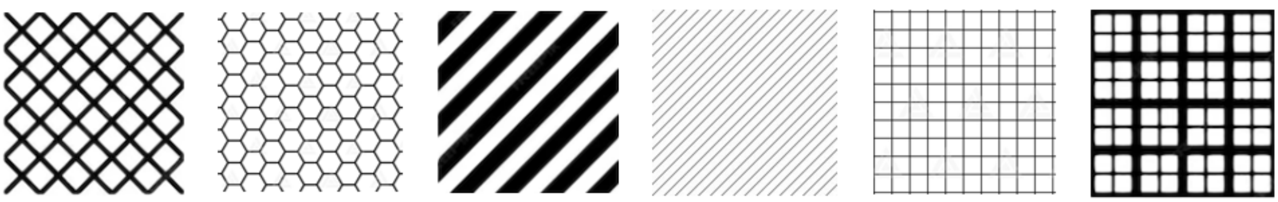

Figure 12: *Set of patterns for urban areas*

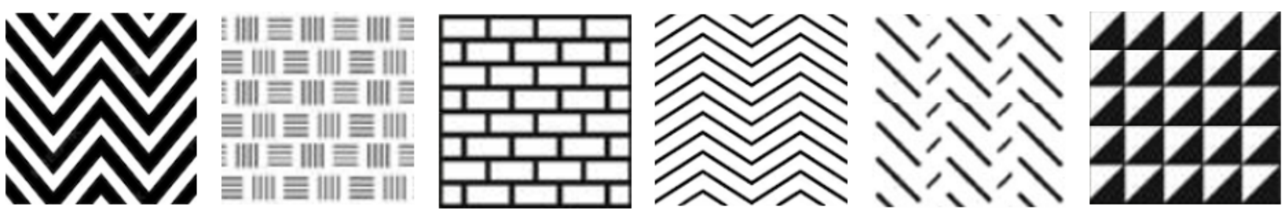

Figure 13: *Set of patterns for industrial areas*

3.2 Formalizing the Perceptible Transition in Tactile Textures (Q2)

After sampling the set of representative patterns, we need to formally analyze how they are perceived through touch. However, to the best of our knowledge there is currently no established standard haptic measure applicable to our study. To address this gap, we propose a formal framework for estimating the similarity or dissimilarity in haptic perception between the patterns. This framework includes a new concept of "perceptible distance" and a "Tactile Domino setting" to formalize our analysis and validation process. The effectiveness of this approach is planned to be further supported by feedback from real users (detailed in Section 3.3).

Haptic perception distance As a first step toward a formal analysis of haptic perception of tactile patterns, we present a model which leads to a relative comparison of haptic perception over our data set of patterns P. For this, we will perform a set of experiments to compare the haptic perception of different tactile patterns. This model builds on a so-called Haptic Distance between pairs of patterns $p_1, p_2 \in P$, denoted by $HD(p_1, p_2)$. This underlying metric of our model is never calculated using specific values. Instead, our focus lies on relative distances, allowing us to compare the haptic contrast between pairs of patterns in the creation of tactile maps.

Relative distances are estimated through a set of experiments, in which the users are asked to sort the pairs of tactile patterns based on the perceived haptic contrast. More formally, we define a total order $\preceq$, on the set of pairs of patterns belonging to our data set, denoted by PxP. Comparison on haptic perception of pairs of patterns can be then formalized through this order, for example $(p_1, p_2) \preceq (p_1, p_3)$ where p_1 is the hat pattern, p_2 the point pattern, p_3 the basket-weave pattern in Figure 14.

Sampling process across patterns categories Based on some preliminary experiments (mainly with sighted people), we sub-sampled each category of our data base, in a way that the haptic contrast between representative patterns of each category are maximized, following the same ordering strategy.

Tactile Domino setting We derived from the sample a set of so-called "Tactile Dominos" of two patterns allowing to compare the perceptible contrast between pairs. The dimension of these dominos will be revised by experts recommendation in a way that the haptic perception is facilitated for VI users. The patterns are vertically arranged to eliminate any potential bias in haptic perception resulting from the user's right or left hand according to their exploration methods of raised-line graphics, as mentionned earlier in Section 1.2. Furthermore, users will be explicitly instructed to employ both hands when perceiving each pattern.

3.3 User Study : Validation on transition perception

Solutions developed in research laboratories to aid VI individuals sometimes lack of practical usefulness when applied to real-world settings. It is therefore necessary to invite them to take an active role in research by getting their feedback on whatever solutions developed. In the following section, we describe the user study that will be conducted to answer $Q2$.

Transition boundary setting In our study we focus on the area textures and will simply employ the standard recommendations for the line symbols to represent boundaries as well as the recommended gap (also called "safe white bound" to highlight the change of region; namely 5 mm or 3 mm for highly contrasting symbols according to Wieckowska et al. [26]). However, the shape and choice of the boundary (curved, linear, or none for patterns allowing one edge to define the space as in Figure 17) might naturally have an impact on the perception of the transition between the tactile patterns. To evaluate this correlation between the geometric pattern types and the boundary shape, we included study points 5 and 6 investigating the effect of boundaries on perceptible transitions of textures.

Final set of experiments Each study point was designed in a way that one of our hypotheses or statements is analysed and addressed without any bias. We are planning to decompose the user study in two phases.
PHASE 1 : Between the two pairs of textures, which one has the greatest contrast of textures ?
PHASE 2 : Associate each environment specification to one or more textures from the provided set.

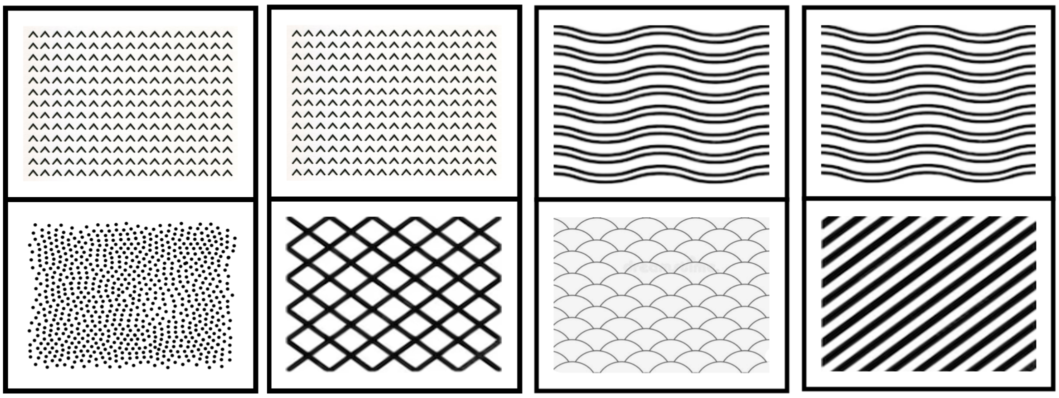

Figure 14: *Pattern comparison by pairs for question 3*

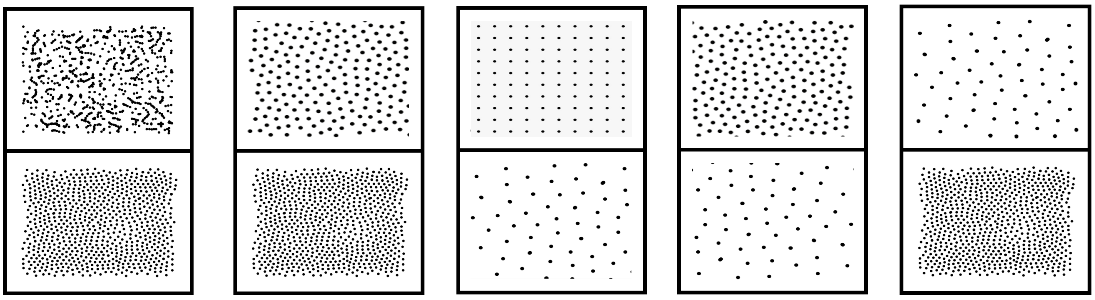

Figure 15: *Different correlations and densities of point patterns for questions 1 and 2*

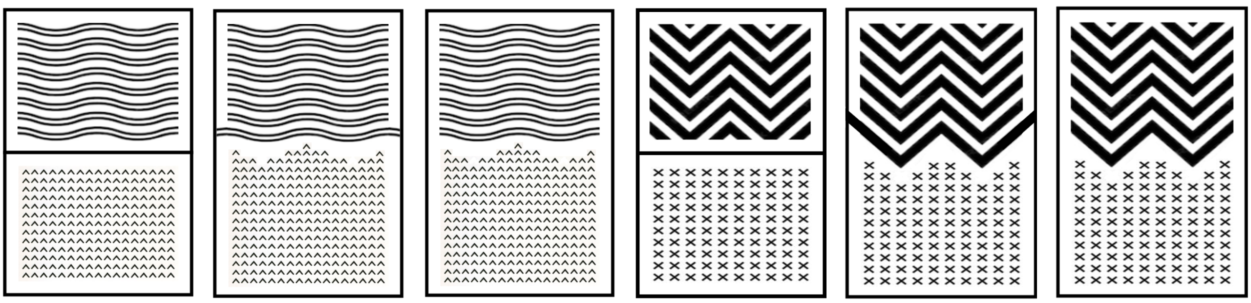

Figure 16: *Patterns with varying boundaries for question 5*

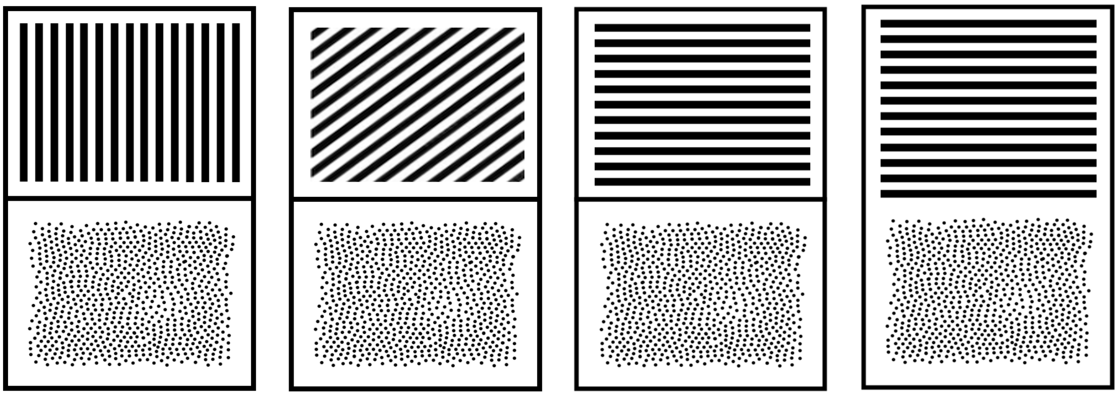

Figure 17: *Hashes with different angles and boundaries for question 6*

1. PHASE 1 on Figure 14. Patterns compared by pairs with one pattern in common. Hypothesis : two patterns within a same environment group should have a lower haptic distance than two patterns within different environment groups.

2. PHASE 1 on Figure 15. Hypothesis : For point patterns, density transition is better perceivable than correlation transition .

3. PHASE 1 on Figure 15. For point patterns, measuring the threshold change of density that is perceivable.

4. PHASE 1 on Figure 16. Investigating the impact of boundary choice and shape for curved patterns.

5. PHASE 1 on Figure 17. Investigating the impact of boundary shape for hashes and their optimal angle with respect to the boundary.

6. PHASE 2 on the groups of patterns of Figures 10, 11, 12, 13. Patterns compared one by one. Finding the most relevant pattern for each specification within environment groups.

Analysis and Discussions Due to time constraints, a meeting with INSHEA experts could not be facilitated prior to the report submission deadline. However, we have received confirmation from them that they will soon provide us with "technical and educational elements on the issue of tactile frames" based on their expertise, design practices, and experience with tactile readers. This valuable input will allow us to refine our initial set of patterns and materials prepared for the user study (for more details, refer to the Appendix A) in accordance with their recommendations. Subsequently, we will be able to conduct the user study with VI children from the French NGO Voir Ensemble and from the INJA Institute. We hope that the analysis of the user study results will yield significant insights into optimizing the selection of textures and boundaries for optimizing the transition perception.

3.4 Applications of the concept of haptic distance

A graph formulation Based on the results of the user study, we can adjust the initial sample of patterns per category by removing the pairs of patterns that are not discernable enough. Then, the haptic distance can be maximized over the whole sample to propose an optimized set of patterns. To better formalize the setting, let us represent the set of selected patterns as nodes of a graph, where each environment group corresponds to a cluster of nodes. We suppose that the weight associated to each edge of this graph corresponds to the haptic distance between the two corresponding patterns. Although absolute haptic distances are unknown, relative distance information obtained through pairwise comparisons between tactile textures in our experiments allows us to maximize over the distances within this framework.

Optimal pattern selection for a given map Let us adapt the proposed graph formulation of representing the set of patterns to a specific situation with a fixed map. The map provides details about the number n_e of distinct environments it contains as well as the way these environments border each other. This information allows us to construct a corresponding graph with n_e clusters representing the different environments. However, unlike a complete graph, edges will only connect clusters that represent neighboring environments on the actual map. Indeed, such a graph reflects the spatial layout of the map as environments that are not directly adjacent are not needed to be considered in our texture transition optimization. As a result, based on the graph connectivity, the haptic distances between textures for these non-neighboring environments will not be considered. By following adjacency paths within this graph, we can optimize for the most suitable combination of textures for the map, as shown in red in the example of Figure 18. As explained before, this optimization will consist in maximizing the edge weights representing the relative haptic distances.

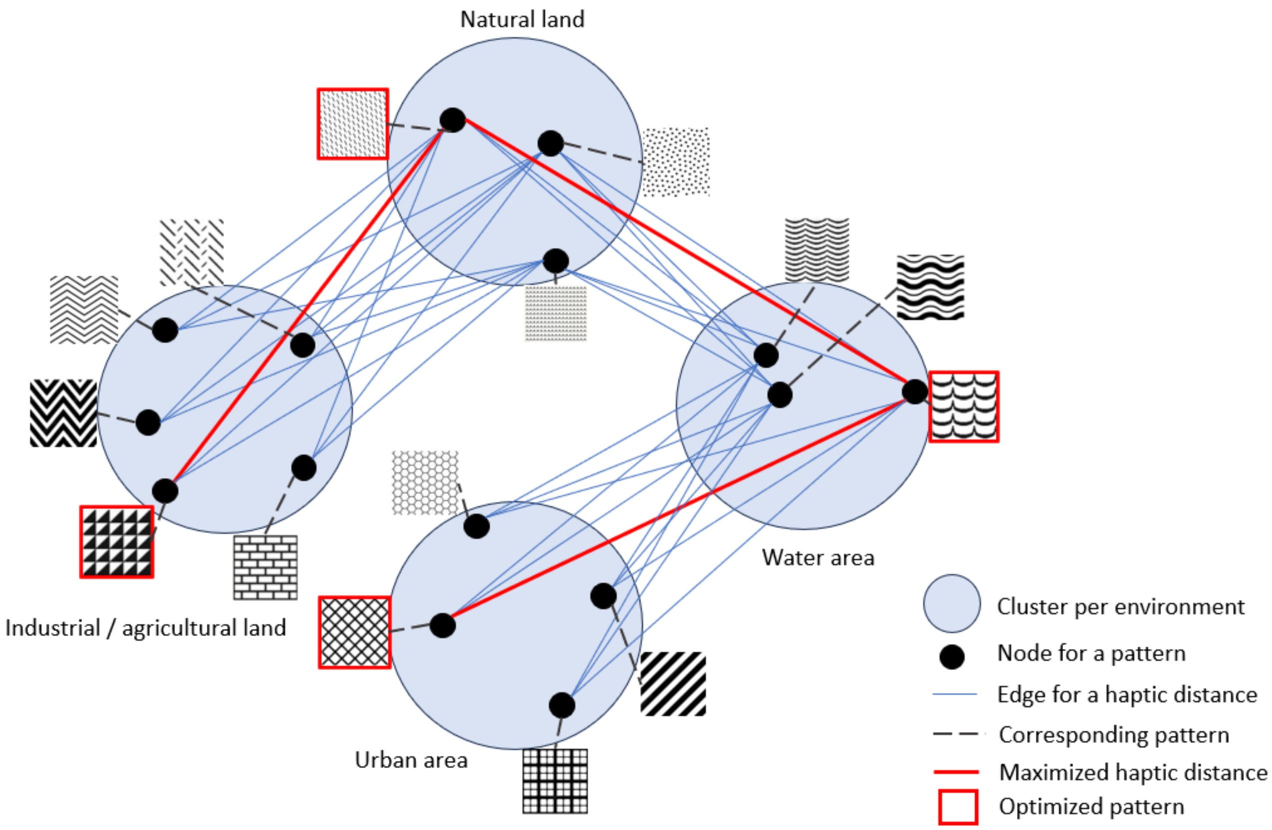

Figure 18: *An example of graph formulation for a fixed map*

Maximum number of textures on a map We have considered two scenarios for our validation regarding the maximum number of patterns to use within a single map. This first scenario leverages the existing environment categories used in our model. We propose testing user perception on maps with distinct textures corresponding to each environment type. We would begin with a single, representative pattern for each environment and iteratively increase the complexity by introducing additional textures based on environment specifications. As an illustration, in the first step the map's water areas would share a single texture. Gradually, we would introduce new textures to differentiate still water from flowing water or waving water. Our objective is to pinpoint the threshold at which VI users struggle to discriminate between textures within the same environment. This "confusion point" will indicate when the number of patterns becomes counterproductive and hinders clear recognition.

The second scenario departs from the environment-based approach. By using again the graph formulation for the set of patterns, instead of relying on the category clustering of our graph, we would generate maps with textures based on the k largest edges. Theses edges represent the most contrasting pairs of textures within our set of patterns. By varying the value of k, particularly around 5, we would create maps with different levels of haptic complexity. Similarly to the first scenario, we would conduct a new user study with VI users to evaluate the effectiveness of each map, allowing us to investigate the haptic contrast between textures independent of the environment categories.

4 Conclusion and Future work

In this study, we have laid the groundwork for identifying a set of representative patterns for tactile maps divided into four different categories of environment type commonly present in geographic maps, under expert quidance. We have introduced a new measure called the haptic distance, assessing the level of haptic distinguishability by comparing patterns by pairs. We have also investigated the impact of varying boundary shapes to better reflect the characteristics of tactile maps. We hope that this study helps to initiate a step toward an estimation of optimal pattern combination for a clear transition between textures.
An interesting future direction would be to develop an algorithmic approach for calculating the haptic distance between patterns. While there exist methods for quantifying visual geometric dissimilarity such as feature-based techniques (analyzing spatial relationship), image processing methods (e.g SSIM, PSNR [44]), or even graph-based approaches (suitable for representing patterns as graphs), these visually computed distances do not directly translate to haptic perceptions. Bridging this gap would enable efficient computation of haptic distance, paving the way for practical applications such as those described in Section 3.4.

Acknowledgements I would like to express my sincere gratitude to my supervisor Pooran Memari for her invaluable guidance throughout this research project. Through our daily meetings, her insights proved instrumental in every step of the process, from the initial review of research papers to brainstorming potential contributions and planning the user study. I am particularly grateful for her willingness to answer my questions and for her proactive approach, which included initiating a key meeting with an expert from INSHEA which was a turning point in my research and significantly shaped its direction.

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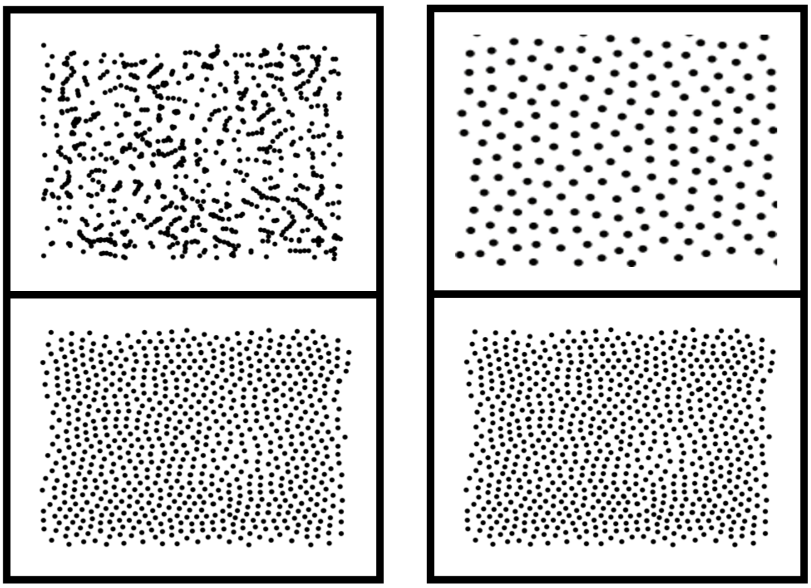
A Appendix

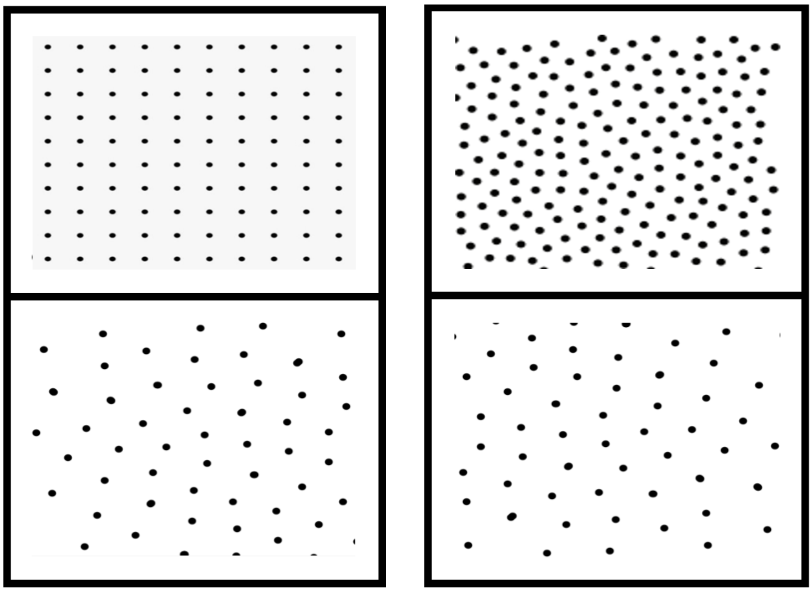
User Study Questions

Instructions for the teachers Cette étude a pour but d'explorer l'utilisation de textures (autrement appelées trames) sur les cartes géographiques tactiles pour les déficients visuels. Nous souhaitons nous focaliser sur différents axes d'étude : la sélection des motifs géométriques en rapport avec le type d'environnement représenté (zones d'eau, naturelle, urbaine, industrielle), la détermination de combinaisons de textures à fort contraste et d'autres facteurs favorisant la transition haptique entre les textures. Ces éléments permettront par la suite de déterminer le nombre maximal de textures différentes perceptibles sur une carte tactile. Dans le cadre de cette étude utilisateur, nous avons collecté un ensemble de textures validées par un expert des dessins tactiles à but pédagogique. Durant la première phase de l'expérience, à plusieurs reprises les élèves devront comparer deux paires de textures comportant une en commune. La question reste la même pour les différents couples de paires : Parmi les deux paires de textures, laquelle a le plus grand contraste ? Les élèves devront répondre par "droite" ou "gauche". Il est important de demander aux élèves d'utiliser leurs deux mains pour explorer afin d'avoir toujours un point de référence sur la texture "principale". Durant la deuxième phase, les élèves seront amenés à comparer une texture au sein d'un groupe de textures afin de les associer à une "spécification" d'environnement. Avant de commencer l'expérience, vous serez amenés à récolter des informations concernant les élèves afin que nous puissions déterminer leur profil.

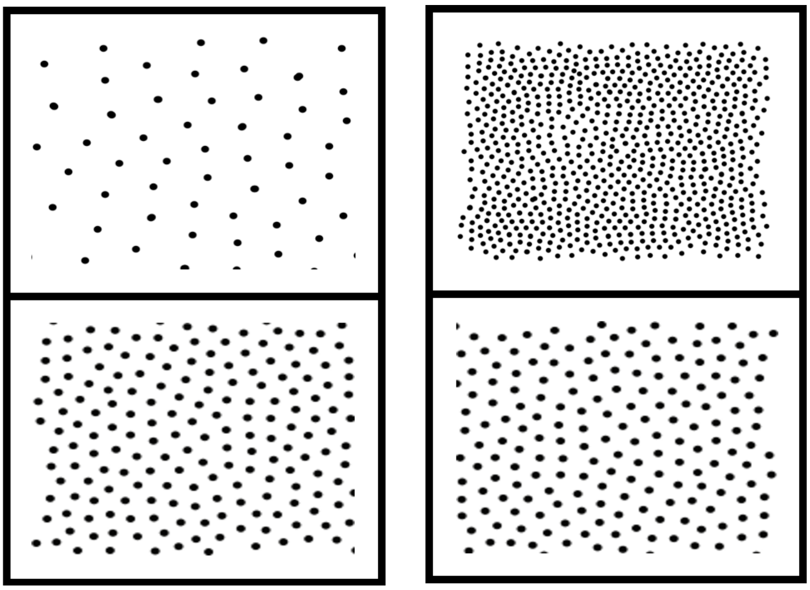
Phase 1 : Parmi les deux paires de textures, laquelle a le plus grand contraste ?



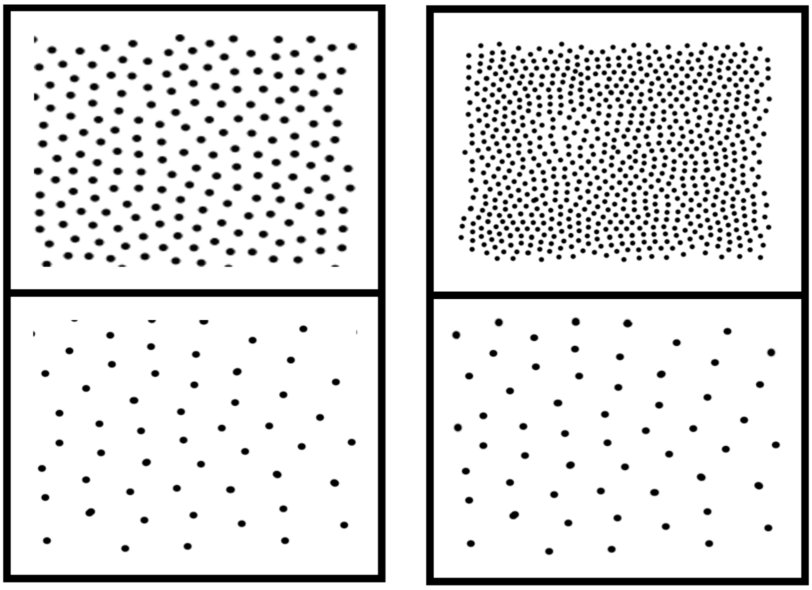
Point pattern : correlation VS density



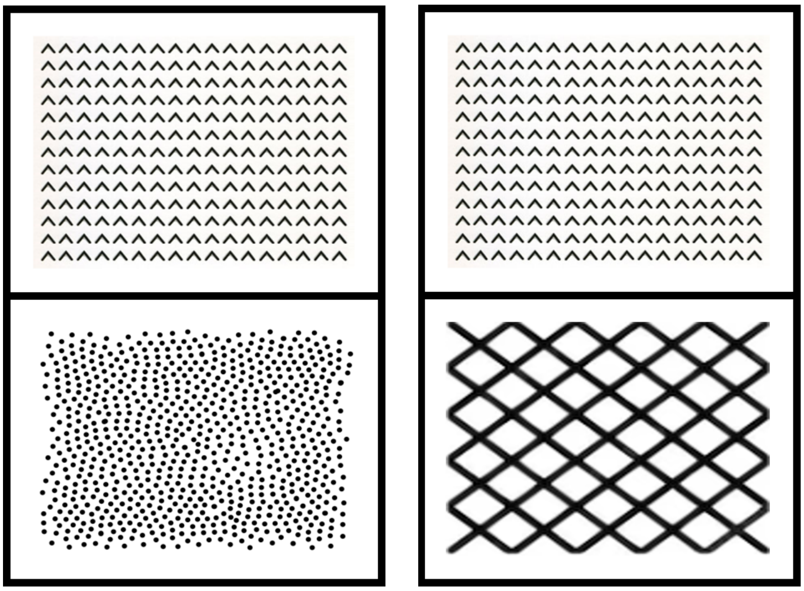
Point pattern : correlation VS density



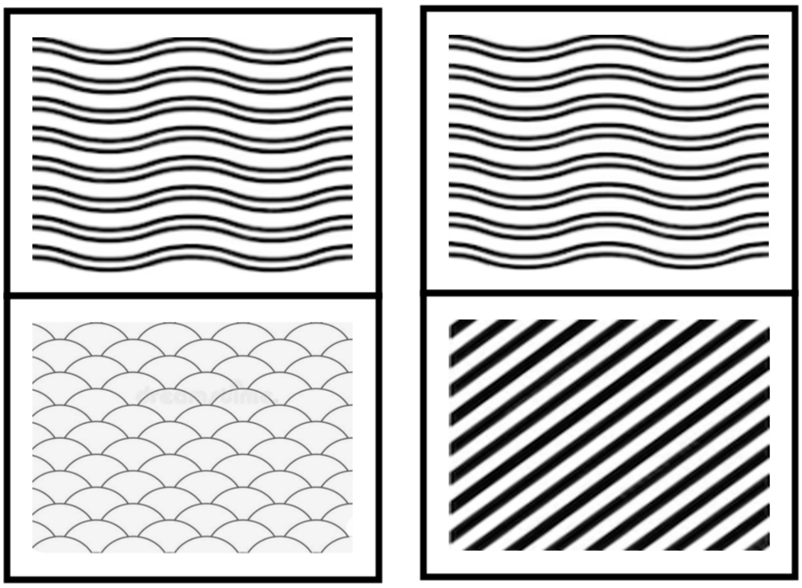
Point pattern : density threshold



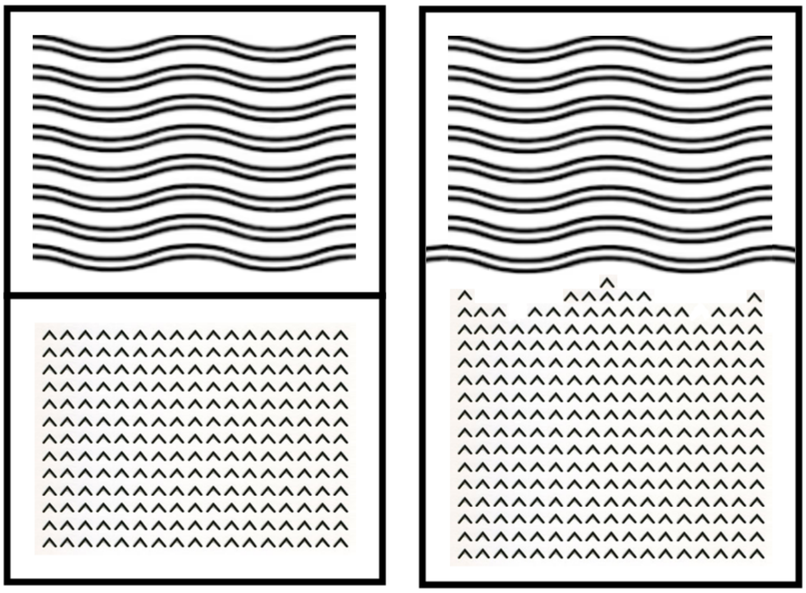
Point pattern : density threshold



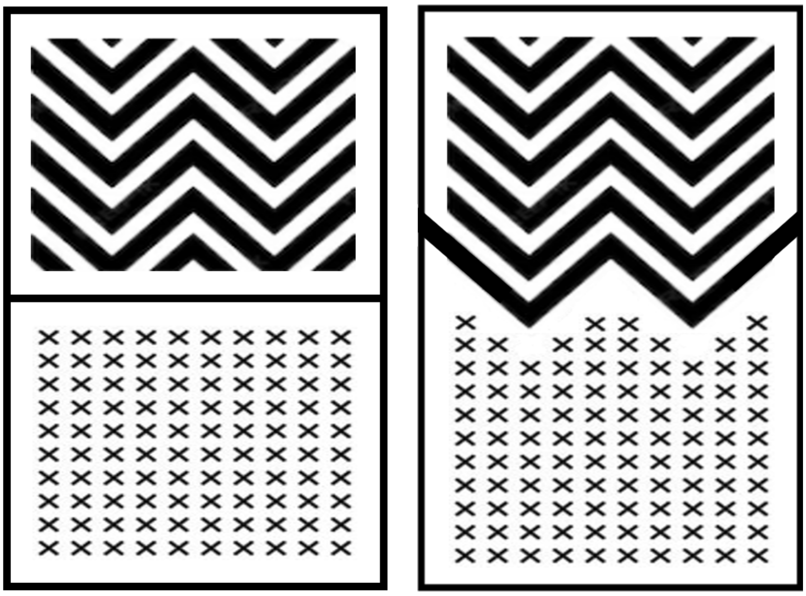
Haptic distance determination



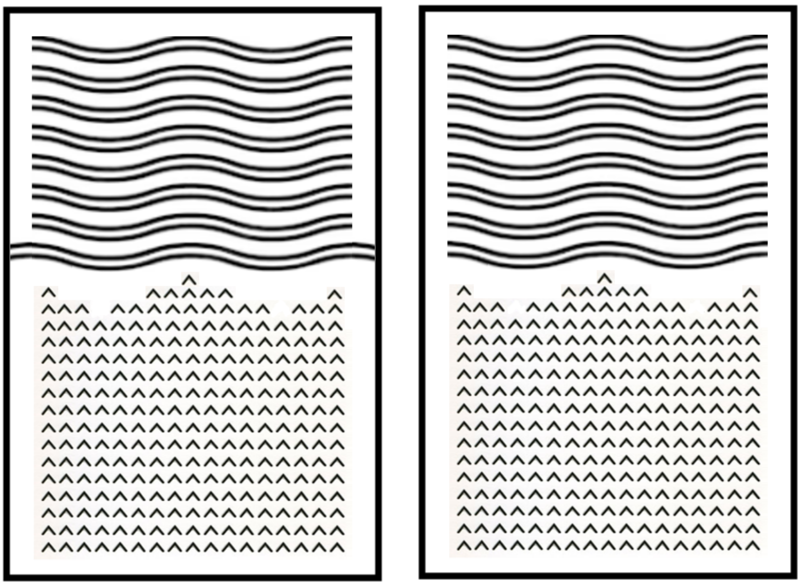
Haptic distance determination



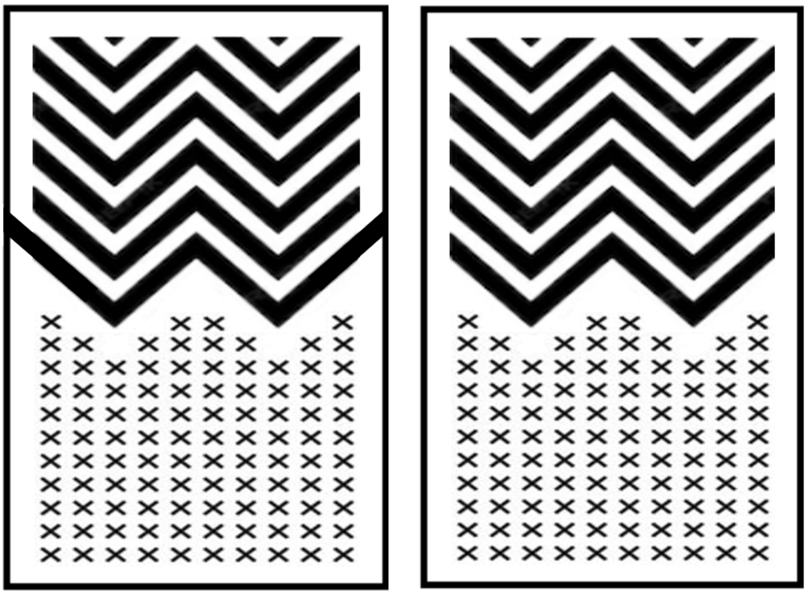
Straight boundary VS curved boundary



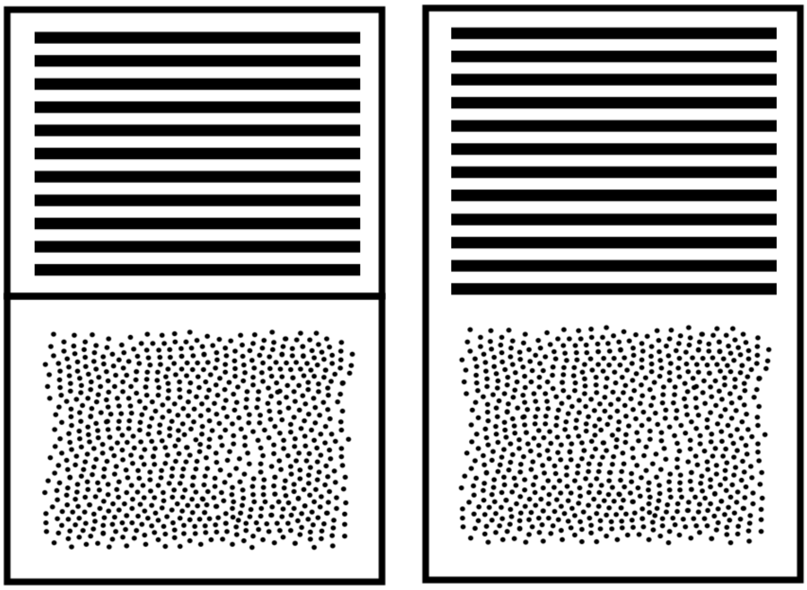
Straight boundary VS curved boundary



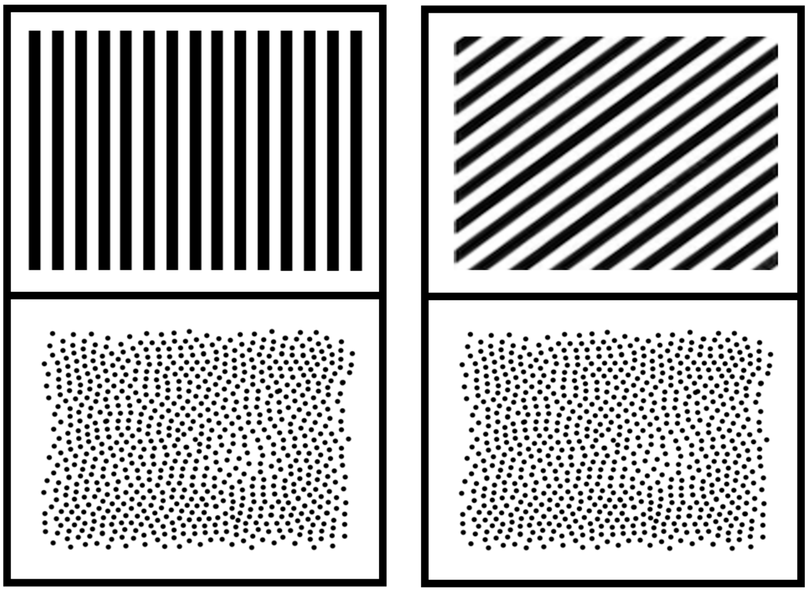
Curved boundary VS no boundary



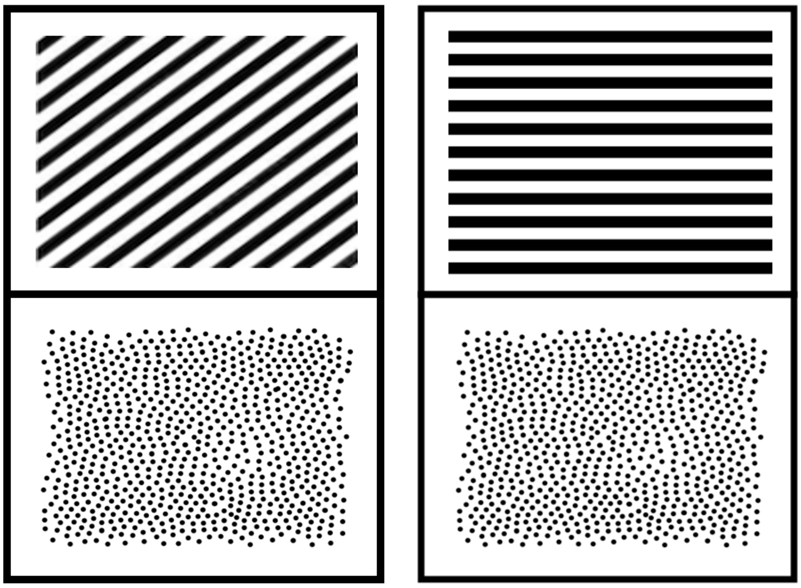
Curved boundary VS no boundary



Hashes : straight boundary VS no boundary



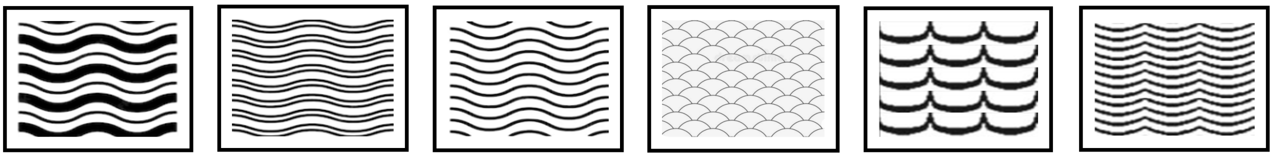
Hashes : vertical VS diagonal



Hashes : diagonal VS horizontal

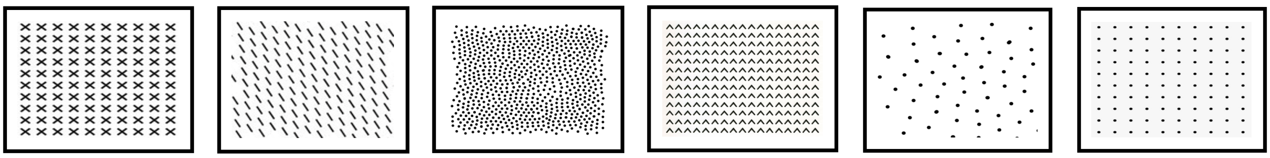
Phase 2 : Associer une spécification d'environnement à une ou plusieurs trames.

Caractéristiques d'une zone d'eau (3) : eau à vagues (ex : mer, océan), eau ruisselante (ex : rivière, ruisseau) , eau stagnante (ex : lac, marécage, étang) .



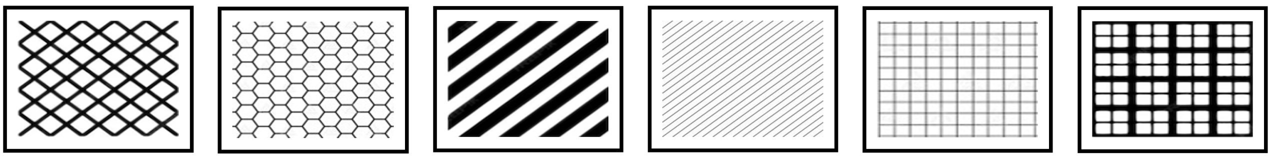
Water area specifications : waving watre, flowing water, still water

Caractéristiques d'un milieu naturel (4) : haute altitude (ex: colline, montagne), basse altitude (ex : plaine, vallée), terre végétalisée (ex : forêt, herbe, parc en zone urbaine), terre non végétalisée (ex : plaine sèche, désert, glace).



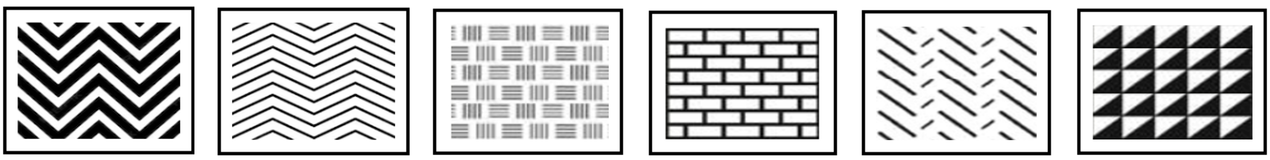
Natural land specifications : high elevation, low elevation, vegetated land, non-vegetated land

Caractéristiques d'un milieu urbain (3) : quartier résidentiel, zone commerciale / d'affaires / universitaire, zone historique.



Urban area specification : residential area, commercial / business / academic area, historical area

Caractéristiques d'une zone péri-urbaine (2) : industrielle, agricole.



Peri-urban area : industrial zone, agricultural area