A series of psychological studies on the design of tactile maps

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Abstract

Tactile maps are raised line images that convey spatial information to people with visual impairments. Tactile perception presents particular challenges, therefore tactile maps need to be carefully designed in order to be readable. This thesis describes a series of psychological studies on tactile map design. Thorough experimental methods and knowledge of tactile perception were used in order to provide results that are applicable in practise and theoretically robust.

Four experimental, quantitative studies were conducted on several aspects of tactile maps design, followed by a qualitative evaluation. In the first study, the relative suitability of several substrate materials for producing tactile maps was determined. Then, we investigated the optimal elevation (i.e. height) for tactile features. The third study investigated the minimum gap width between the two elements of double lines that is required to reliably discriminate between single and double lines. In the fourth study, a set of highly discriminable tactile symbols was determined and we investigated what makes symbols discriminable from each other. After exploring individual aspects of tactile maps, entire maps were evaluated in a qualitative study, in order to assess the findings of this thesis and to compare some of the leading methods of tactile map production.

This research was conducted as part of the Tactile Inkjet Mapping Project, which also included the development of a Tactile Inkjet Printer. This printer allowed us to produce experimental stimuli with great accuracy and with a high level of choice and control over map design features.
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1 Introduction and literature review

This chapter provides an overview of literature that is relevant to the thesis in general. Subsequent chapters contain more detailed reviews of literature that is related to the research topics described in those chapters. Below, we explain what tactile maps are, how they can be used and how they are generally produced. We also review existing research on tactile map design. Since tactile maps are explored by touch, we provide a basic overview of neurophysiological and psychophysical research on tactile perception. Finally, we discuss the current research project and provide a short outline of the thesis.

1.1 Tactile maps

1.1.1 What are tactile maps?
Maps represent spatial relationships of features within an area in an easily accessible format, usually as a visual, two dimensional image. Maps are small, symbolic depictions of a larger area, ranging from small scale maps of a building to large scale maps of the universe. Maps contain symbols (points, lines and areas) to represent objects and features of the mapped area. Only a limited number of the most relevant objects and features can be shown on a map. Maps provide us with spatial information that would otherwise be impossible or difficult to collect. This information can be used in many different ways. For example, it can allow us to navigate in unfamiliar environments, or it can help us form an understanding of the spatial layout of the world around us.

Visually impaired people cannot access visual maps and, therefore, may not benefit from this invaluable information, unless they are offered the information in an alternative format, such as tactile maps. Tactile maps are raised images that are used to convey spatial information to visually impaired people. Where visual maps use differences in colour to create an image, tactile maps use elevation. At the most basic
level, a tactile map is similar to a visual map where the symbols have been raised to create a tactile image. However, visual maps cannot be directly translated into effective tactile maps, as will be explained in Section 1.1.4. By definition, tactile maps are accessed by touch, although many can also be explored visually. Similar to visual maps, tactile maps can represent a wide variety of spaces, ranging from small environments, such as a floor plan of a building, to large environments, such as a political map of the world.

Tactile maps can be used for a number of purposes. Mobility maps may facilitate navigation of familiar and unfamiliar environments, and can potentially increase the user’s independence. These maps can, for example, represent the floor plan of a hospital or the layout of an urban neighbourhood. General reference maps and thematic maps are not generally used for navigation, but for developing a better understanding of aspects of the environment. General reference maps show the spatial relations between geographic features. These maps can represent, for example, the countries and major cities in Europe. Thematic maps show the spatial distribution of a specific attribute, for example the amount of corn produced by each European country. Both mobility maps and general/thematic maps are used by visually impaired people, as suggested by an international survey that showed that tactile map producers were equally likely to produce mobility maps as general reference or thematic maps (Rowell & Ungar, 2003b). However, users’ understanding of mobility maps has been studied more extensively (see below).

On both visual and tactile maps, spatial features are represented by point, line and area symbols, depending on the scale of the map and the size and extent of the feature. Point symbols represent single features, such as toilets on a small scale map, buildings on a medium scale map and cities on a large scale map. Line symbols are used for linear features, such as roads, rivers and borders. Area symbols represent larger areas, such as parks on a medium scale map and countries on a large scale map.
1.1.2 Use of tactile maps

Tactile map users

A large number of people is visually impaired. In England alone, approximately 152,000 individuals are on the register of blind people, and approximately 155,000 are registered as partially sighted (Government Statistical Service, 2006). However, the actual number of visually impaired people is substantially larger, because an estimated 51% of visually impaired people have not registered as such (Bunce et al., 1998). A large proportion of visually impaired people of working age is employed (44% in 2001, (Smith & Twomey, 2002)) or study (1440 visually impaired students enrolled in their first year of Higher Educatons in 2005, (Higher Education Statistics Agency, 2007)). These figures suggest that, in addition to the large number of visually impaired users who may benefit from good quality tactile maps for domestic, general reference and leisure use, many may need tactile maps for work and study.

Spatial cognition without vision

Vision can provide immediate and detailed spatial information. Visually impaired people do not have access to visual information and therefore rely on other senses, such as haptics, hearing and locomotion, to gain knowledge of spatial relations. This process requires more time and effort than it would for sighted individuals. The spatial abilities of people with visual impairments are relevant to this thesis for three reasons. Firstly, a certain level of spatial cognition on a smaller scale (i.e. haptics) is required to explore and interpret tactile maps. A map user needs to understand the spatial relations between features on a tactile map in order to be able to explore the map successfully. Secondly, the map user needs spatial cognition skills to transfer the information on a map to a spatial understanding of a larger environment. These two processes are similar to the requirements of perception and interpretation of visual maps, including a stage of perceptual organisation of map information and a stage of meaning extraction (Thorndyke & Stasz, 1980; Winn, 1991). Thirdly, tactile

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1 According to the National Assistance Act 1948, a person can be registered as blind if they are “so blind as to be unable to perform any work for which eye sight is essential”. A person can be registered as blind if visual acuity is 3/60 Snellen or less, or if the field of vision is severely restricted. A person can be registered as partially sighted if visual acuity is between 3/60 and 6/60 Snellen, or if the field of vision is moderately restricted (Department of Health, 2003). A visual acuity of 3/60 means that a person can see at 3 metres what a normally sighted person can see at 60 metres.
maps may contribute to spatial cognition by providing information that is otherwise not accessible through absence of vision.

Spatial cognition of visually impaired people has been investigated in many studies (see Golledge et al. (1996), Kennedy et al., (1992), Millar (1994), Thinus-Blanc & Gaunet (1997) for overviews). Kitchen et al. (1997) review the three groups of literature on the subject of spatial cognition without vision. Firstly, the deficiency theory suggests that vision is essential to spatial cognition and, therefore, people with visual impairments are unable to develop a functional level of spatial cognition. Secondly, the inefficiency theory states that spatial cognition of people with visual impairments is inferior to that of sighted people, due to inefficient perceptual processes, i.e. hearing and haptics. Thirdly, according to the difference theory, visually impaired people have the same potential for developing spatial cognition as sighted people and any qualitative or quantitative differences are due to “intervening variables such as access to information, experience or stress” (p. 229). The performance of visually impaired participants in studies of spatial cognition has varied. In some of these studies, performance was inferior to that of sighted participants (for example, in Bigelow (1996)), which contributed to the belief that visually impaired people lack certain aspects of spatial understanding. In other studies, there was no difference in performance between sighted and visually impaired participants (for example, in Loomis et al. (1993) and Passini et al. (1990)). Most researchers argue that the spatial cognition of visually impaired people has the potential to be functionally equivalent to that of sighted people, but that visually impaired people may develop spatial cognition in different ways and more slowly (Collis et al., 2002; Fletcher, 1980; Jurmaa, 1973; Millar, 1988, 2002; Passini et al., 1988; Passini & Proulx, 1988; Passini et al., 1990). Based on the research described above, we can assume that people with visual impairments potentially have a sufficient level of spatial cognition to be able to understand spatial relations between objects in the real world, to understand spatial relations between features on a map and to transfer spatial information on a map to an understanding of real world environments.
Use of tactile maps

There is a large difference in the way map users explore tactile and visual maps. When exploring a map visually, information about the general layout of a map and the relations between map features is instantly available. A tactile map user, however, needs to sequentially touch and remember individual map features, and needs to build up a coherent mental image from these details. People with visual impairment are generally less successful in understanding a map than sighted people, possibly due to ineffective strategies for map exploration (Hampson & Daly, 1989; Ungar et al., 1995b; Ungar et al., 1997).

A number of studies have investigated to what extent tactile maps can be useful to people with visual impairment. Tactile maps can be used to gain knowledge of an environment and can facilitate navigation. As part of a pioneering research project on ‘tactual mapping’, Wiedel and Groves (1969) investigated the performance of almost 400 visually impaired participants on thermoform maps of an urban neighbourhood and a shopping centre. Tasks were desk based and included symbol identification, route finding and orientation/direction of map features. Wiedel and Groves report the percentage of correct responses for different participant groups, based on age, onset of blindness, amount of map reading training and mobility instruction and mobility proficiency. The correct response rate ranged between 40% and 91%. In an early study (Leonard & Newman, 1967), six visually impaired children successfully used a map to navigate and find detour routes in an urban area. In another study (Bentzen, 1972), six visually impaired participants were trained to navigate a college campus using a tactile map. All participants were able to successfully plan routes on the map and walk to target locations, and thought a tactile map was preferable to a verbal route description for this task. Ungar, Blades and Spencer and Espinosa conducted a series of studies on the usefulness of tactile maps. In the first study (Ungar et al., 1993, 1995a) visually impaired children were presented with tactile maps and performed spatial tasks, including estimations of distance and direction, in a relatively small area set up in a large hall or playground. Generally, children were able to perform these tasks and in some conditions, performance was better after using a map than after using direct exploration of the area. In another study (Ungar et al., 1995b; Ungar et al., 1997), sighted and visually impaired children explored a
tactile map while “thinking aloud”, and then reproduced the map from memory. In general, sighted children reproduced more accurate maps than visually impaired children, possibly because they used more efficient strategies for map explorations. A small number of visually impaired children used more efficient exploration strategies and performed well on map reproduction. Therefore, the authors argued that visually impaired children are potentially able to successfully use tactile maps, if trained to use efficient map learning strategies. In another study (Blades et al., 1999; Espinosa et al., 1998), visually impaired participants learned a route in an urban environment in one of three ways; by direct experience alone (i.e. being walked the route), by a combination of direct experience and a tactile map or by a combination of direct experience and a verbal description along the route. Participants performed better on tasks involving wayfinding and spatial understanding when they had learned the route using a tactile map. As part of a series of studies on cognitive mapping without vision (Jacobson, 1992, 1998), three visually impaired students were asked to draw a sketch map of their campus, which was very familiar to them. They were then presented with a map of the campus and encouraged to use the map in practise. One week later, participants produced another sketch map of their campus. The sketch maps that were produced after experience of the tactile map contained more detail and fewer errors, suggesting that the cognitive maps of participants improved. The studies described above suggest that people with visual impairments are able to use tactile maps to gain spatial knowledge.

In addition to investigating the potential of tactile maps to increase and improve spatial knowledge, several studies looked at other aspects of tactile map use. For example, participants performed desk based map tasks in order to compare production methods (Canadian Braille Authority, 2003; Dacen Nagel & Coulson, 1990; Pike et al., 1992, 1993), to investigate the use of map templates (Blades et al., 1999) and the use of target route maps, in which the desired route was magnified (Harder & Michel, 2002). Other studies investigated map users' strategies for performing simple tasks, such as matching geographical shapes of US states (Berlá et al., 1976) and locating point symbols and tracing lines (Berlá & Murr, 1975a). A more detailed discussion of most of these studies can be found in Section 6.1.1. The fact that participants were able to perform the tasks in the above studies contributes
to the argument that people with visual impairments can use tactile maps successfully.

1.1.3 Production methods

Tactile maps can be produced by various methods. These methods employ a range of materials and processes to create a raised image. There is no standard recommended method. The choice of method depends on a number of factors such as availability of materials and technology, intended use (for example, wall mounted maps or single-use mobility maps) and budget. An international survey of tactile map producers (Rowell & Ungar, 2003b, 2003d) showed that microcapsule was the most commonly used production method, used by 63% of respondents. Thermoform was used by 55% of respondents, and 41% used tactile models. Braille embossing (25%) and tactile printing (19%) were less often used for the production of tactile maps. These most common methods of manufacture of tactile maps are described below. For more detailed discussions of the processes and (dis)advantages of production methods, see Bentzen (1997), Edman (1992), Gardiner (2001) and McCallum (2006).

Multi-textural process

The multi-textural process is the most basic method for producing tactile maps, because it does not require any special equipment or materials. A raised image is created by attaching a variety of materials, such as cloth, beads, string and cardboard, to a substrate (see Edman (1992) and Gardiner (2001) for a more detailed description of the multi-textural process). The materials for multi-textural maps are readily available and cheap and, depending on the choice of materials, the maps can provide a large range of elevations and textures. However, the manufacturing process for each map is time consuming and an accurate reproduction of multiple copies is difficult.

Microcapsule paper

Microcapsule, also called swell paper or Minolta paper, is most commonly used for the production of tactile maps and diagrams. This process involves paper that contains heat sensitive elements. Black and white images are printed, photocopied or
drawn onto the paper, which is then passed under a fuser (radiating lamp), heating up the dark elements. As the capsules in the dark elements expand, a raised image is created. If a fuser and microcapsule paper are available, the production of tactile graphics can be very quick and easy. However, this method presents several problems. Firstly, the output is rather soft and pliable. Raised images deteriorate with repeated use. The paper material is also not suitable for permanent outdoor or indoor displays. Secondly, the limited control over elevation may be a problem. The elements on microcapsule graphics are generally uniformly raised to about 0.5 mm, although very small differences in elevation may be achieved by using a greyscale for the original image (i.e. grey areas raise to a lower elevation than black areas). As a consequence, microcapsule maps cannot use differences in elevation to facilitate map reading. An example of a microcapsule map is shown in Figure 1.1.

Fig. 1.1 An example of part of a map produced on microcapsule paper.

Thermoform

Thermoform is another popular production method, often chosen for the durability of the finished product (Rowell & Ungar, 2003b). In the thermoforming process, a heated thermoplastic sheet is pulled over or into a master mould by reduced air pressure in a vacuum forming machine. Multiple copies of a graphic can easily be
produced off the same mould. The mould is generally created by manually arranging three dimensional objects, such as pieces of string and small blocks of wood, into the desired configuration. Prefabricated kits have been developed, containing various three dimensional symbols for thermoforming, such as the Nottingham map making kit (James & Armstrong, 1976). Moulds can also be produced by a milling machine, which shapes a solid material using a drill. The creation of the mould is a time consuming and possibly expensive process, and the biggest disadvantage of thermoform. In addition, the thermoforming process often produces rather undefined edges on the tactile elements, producing a ‘dull’ image (Dacen Nagel & Coulson, 1990), and it is difficult to produce small and precise features, due to the thickness and inflexibility of the PVC. The most important advantages of thermoform graphics are their robustness and elevation. There is no real upper limit to the elevation of the tactile features (Edman, 1992), and the elevation of features on a single map can easily be varied. Figure 1.2 shows an example of a thermoform image.

Fig. 1.2 A thermoform image of a fly (right) and the master that was used to produce it (left).

Braille embossing

The printing technology of Braille embossers is also used to produce tactile images (Fig. 1.3). These embossers use hammers to punch out the individual dots of Braille cells. After adaptations to the hardware and software, they can also be used to punch
the elements of more complicated graphics (Gardner, 1997). After the initial purchase of the embosser, production of graphics can be rather quick and straightforward. Multiple copies can easily be produced from one digital image. However, the limited elevation is a serious disadvantage of this method. Images are only as high as a Braille dot. In addition, the graphics may feel rough and undefined, because the elements are made of repeated small dots. Braille embossing also has similar vulnerability problems as microcapsule paper, because the dots can get compressed and the paper material is not durable enough for permanent displays or outdoor use.

![Image of a Braille embossed map](image)

*Fig. 1.3 An example of part of a map produced by Braille embossing.*

### 1.1.4 Design of tactile maps

*Visual versus tactile map reading*

It is more challenging to read a map by touch than by vision for two reasons. Firstly, there is an important difference in the way information is accessed. Vision uses parallel processing, whereas touch is limited to serial processing. Using vision, it is possible to get an overview of an entire map almost instantly, by quickly casting one’s eye over the map. The general layout, size and main features of the map are instantly accessible. After getting an overview, the map reader can investigate the
map in more detail. For tactile maps, this process is reversed. Since tactile readers use the restricted perceptual field of the fingertip, they are forced to study map details first, and to build up an overview image from these details. This process places large demands on working memory. It could be compared to looking at a visual map through a straw. Secondly, spatial acuity of the finger is much lower than that of the eye. Consequently, tactile map features need to be larger and/or less complex in order to be perceived correctly. Due to the sequential processing and low spatial acuity of touch, reading a tactile map can be challenging. Therefore, it is important to carefully design the map in order to facilitate reading. A direct translation of a visual map into a tactile one is not likely to be effective.

Tactile variables
Map symbols can be described and compared in terms of variations in graphic variables. For example, a red circle and a red square differ from each other in form, while a red circle and a green circle differ in hue. Bertin (1977) proposed 7 variables for the generation of visual point, line and area symbols. These included plane, size, value, grain/texture, form, orientation and hue. Vasconcellos (1993) translated these visual variables into tactile ones, replacing hue with elevation (Figure 1.4). Griffin (2002) produced a more extensive set of haptic variables, including kinaesthetic variables (resistance, friction and location) and tactile variables (vibration, flutter, pressure, temperature, size, shape, grain/texture, orientation and elevation). Considering variations in tactile variables, and their effect on perception and discrimination of symbols, can help build the foundations of a more scientific approach to symbol design.
Several authors of guidelines (see Section 1.1.6) for tactile maps have described ways in which tactile symbols can vary. Vasconcellos's and Griffin's sets of variables are clearly reflected in these guidelines. Point symbols can be varied by altering their shape, size, elevation and nature of outline (smooth or broken outline or filled symbol) (Bentzen, 1997). Varying width and profile of the individual lines of the point symbol can also generate different symbols (Gardiner & Perkins, 2002a). Line symbols can be varied by making them continuous or interrupted, thick or thin, smooth or rough edged, single or double and by varying elevation, profile and shape (Bentzen, 1997; Edman, 1992). Area symbols may differ from each other in density of elements, regularity of element spacing, size of elements, shape of elements, direction of elements and elevation (Bentzen, 1997; Edman, 1992).

The tactile variables describe the ways in which tactile symbols can differ from each other. In order to generate tactile symbols that are detectable, identifiable and discriminable from other symbols, the value of each variable needs to be within a certain range in order for a symbol to be successful. For example, point symbols need to be larger then a certain size to be readable, and if small and large symbols are used to signify different meanings, the difference in size needs to be large enough to be clearly perceived. Empirical research on tactile map symbols (see Section 1.1.5) and tactile guidelines (see Section 1.1.6) have made suggestions for the creation of successful tactile symbols.
1.1.5 Empirical research on tactile map design

Empirical research on tactile map design is rather sparse. The largest body of research involved studies on the discriminability of symbols (Gill & James, 1973; Heath, 1958; James & Gill, 1975; Jansson, 1972a, 1972b, 1973; Morris & Nolan, 1961; Nolan & Morris, 1971). These studies aimed to find discriminable sets of symbols for use on tactile maps. Generally, paired comparisons were made of combination of symbols in order to find the most discriminable symbols. Although valuable progress was made in research on tactile map design, several problems existed with the methods of these studies, such as the small number of symbols tested and the unrealistic nature of the experimental testing. A more detailed discussion of these studies and their limitations can be found in Chapter 5.

A smaller body of research on design related to the choice of production method for tactile maps (Blades et al., 1999; Canadian Braille Authority, 2003; Dacen Nagel & Coulson, 1990; Pike et al., 1992, 1993). In these studies, participants performed desk based tasks using entire maps, in order to compare performance across production methods. These studies are discussed in more detail in Section 6.1.1.

Berlá and Murr (1975a) studied the effects of area symbols on participants’ ability to locate point symbols and to track line symbols on a tactile pseudo map. This map contained a regular array of tactile features. Performance on maps with and without area symbols was measured in terms of accuracy and time. The authors found that the inclusion of area symbols made it more difficult for participants to perform the tasks, and they concluded that the use of area symbols on maps should be limited. The methods and analysis used in this study were rigorous and appropriate. However, the results are not surprising; providing redundant information generally makes a cognitive task more difficult. Berlá and Murr considered area symbols as “irrelevant noise”, whereas these symbols can provide valuable information on a map.

Berlá and Murr (1975b) also conducted a psychophysical study on the discrimination of line width. This study aimed to find the proportion of change in width that was necessary to discriminate line widths, indicated by Weber fractions. Rigorous
methods and analyses were used in this study. The authors discussed their results in terms of psychophysical theory and practical issues related to tactile map design.

In a study on the traceability of lines (Bentzen & Peck, 1979), participants traced single smooth, single rough, double smooth and double rough lines. Lines contained angles and curves. The stimuli included lines with and without intersections with other lines. Tracing time, errors and restarts were recorded. The results suggested that double lines are more suitable for tracing in displays where lines intersect, and single lines are more suitable for displays where lines do not intersect. In a related study, Easton and Bentzen (1980) examined participants' performance on route configurations consisting of single, narrow double or wide double lines. Route configurations consisted of triangular and rectangular routes, or linear routes with T-junctions and crossings. Participants explored a standard route configuration, and chose the matching configuration from a set of alternatives. Contrary to earlier findings (Bentzen & Peck, 1979), performance was better on single lines than on double lines. Appropriate methods and analyses were used in both studies, and results were considered in terms of map design.

In a series of three studies, Easton, Kenedy and Bentzen (1980) examined the discriminability of angles of intersecting lines. In their first study, participants compared pairs of angles between single lines, and identified which angle was larger. The angles were between 0 and 45 degrees and between 45 and 90 degrees. Pairs of angles between 0 and 45 degrees where more easily discriminated than angles between 45 and 90 degrees. A similar experimental method was used for the second study, but here double lines at angles between 70 and 90 degrees were used. The angles between double lines were more accurately discriminated than between single lines. In the third study, pairs of angles were presented consecutively, rather than simultaneously. Five configurations of both single and double lines were used. Easton, Kenedy and Bentzen concluded that angles between intersecting lines on a map should differ from another by at least 20 degrees.

Horsfall and Vanston (1981) studied the discriminability of three shapes, produced in four textures (i.e. four production methods with distinctively different textures) at
five sizes. Participants identified the shapes, using a three alternative forced-choice method. Shapes and textures were discriminable when symbols were 7.9 mm or larger. Horsfall and Vanston successfully studied a specific aspect of tactile map design. However, in their conclusions, they provided general suggestions for tactile map design that were not supported by their specific research.

The Canadian Braille Authority (Canadian Braille Authority, 2003; Holbrook et al., unpublished) directed a series of 12 studies on tactile graphics. These studies mostly examined aspects of symbol design, such as symbol size and the use of point symbols within an area symbol. Larger design issues, such as the use of gridlines in graphs, were also explored. All stimuli were produced in several production methods in order to compare between methods. The series of 12 small studies provided some useful suggestions for tactile graphics design. However, since the methods were rather basic and many research questions were asked of each study, the results were somewhat indefinite.

The overview above shows that research on tactile map design is rather sparse and dated. There appeared to be a wave of interest in the 1970s, and little research was done after that. As a consequence, tactile map research has not benefited from more recent developments in production technologies and research in fields such as cognitive psychology and tactile perception. In addition, many aspects of tactile map design have not yet been investigated.

1.1.6 Guidelines

Several guidelines have been published on the design of tactile maps. These are aimed at the producers of tactile maps and give suggestions on map design in varying levels of detail. The guidelines are generally printed in a handbook or are available online.

Edman’s book on tactile graphics (1992) contains an extensive collection of information on the design and production of tactile images. Production methods for tactile images are discussed in one of the chapters, and another chapter is dedicated
to a discussion of the design of tactile maps. Although Edman incorporated existing empirical research to support her claims where possible, the guidelines are mostly based on her practical experience of the production of tactile images. However, Edman does not explain how this experience led to the development of the guidelines. Presumably, this process involved feedback from map users.

Bentzen (1997) published a chapter on orientation aids, including guidelines on tactile map design and map training. The chapter includes specific recommendations for the design of tactile maps, and supports these with empirical research where possible. Bentzen covered a wide range of topics, such as scale, information density and the design of individual symbols.

The American Printing House for the Blind (1997) made a short, bullet pointed set of guidelines available online. These guidelines were developed from a workshop involving a group of producers of tactile maps. The guidelines include specific statements, for example, they suggest that “lines, points, and Braille must be physically separated by at least 1/8 inch”. The authors do not explain on what these statements were based.

Another online resource (Gardiner & Perkins, 2002a) presents a set of guidelines for the design of thermoform maps. The authors give suggestions for the entire process, from general considerations of the purpose of the requested map to suggestions about choice of symbols. Although the authors do not appear to have conducted empirical tests of their guidelines, they include references to previous research where possible. The authors also state that their guidelines were based on extensive practical experience of producing maps in close collaboration with visually impaired people. However, as was the case for Edman’s guidelines (1992), they do not explain how this experience led to the development of the guidelines.

Eriksson, Jansson and Strucel (2003) produced a handbook for the design of tactile maps. They provide examples of a range of maps, including geographical maps of countries and continents, maps of cities and floor plans of buildings. The guidelines
for map design are very general and there is no mention of research supporting their suggestions.

As useful as the above guidelines are for tactile map producers, they also have some limitations. The guidelines are generally based on the authors’ practical experience with the design of tactile maps, and on feedback and anecdotes from users, rather than on research. Some guidelines incorporate empirical research on tactile maps design. However, this research is sparse and it does not provide nearly enough information for a full set of guidelines. In addition, the guidelines sometimes contradict each other. Although the guidelines may not be highly relevant from an academic point of view, they are an important and easily accessible tool for producers of tactile maps.

1.2 Tactile perception

Since tactile maps are explored by touch, knowledge of tactile perception is vital for research on tactile map design. Limits of tactile perception dictate, for example, the minimum size and elevation of map symbols. Knowledge of tactile perception can also contribute to improvements in tactile map design, by enabling us to take full advantage of the characteristics of touch, such as a high sensitivity to sharp edges. Several authors have published comprehensive overviews of research on tactile perception (Cholewiak & Collins, 1991; Griffin, 1999; Hughes & Jansson, 1994; Lederman, 1982; Lederman & Browse, 1988; Loomis & Lederman, 1986; Pick, 1994). Therefore, only the basic mechanisms of tactile perception will be discussed below. Research related to specific aspects of our studies can be found in the relevant chapters.

Two areas of research on tactile perception are particularly interesting in the context of this thesis. Firstly, neurophysiological studies on mechanoreceptor responses in the fingertip can be used to understand how the perceptual system responds to tactile features on a map. Secondly, psychophysical studies on touch provide an insight into the very limits and capabilities of tactile perception.
1.2.1 Neurophysiology

The neural mechanisms of touch have been studied extensively. These mechanisms are based on mechanoreceptors located in the skin (see Johnson (2001) and Johnson et al. (2000) for an overview), which transfer signals to the somatosensory cortex. The fingertip, as well as the lip and tongue, contains a high density of receptors (Johansson & Vallbo, 1979; van Boven & Johnson, 1994), making it highly suitable for tactile perception. Neurophysiological studies generally use invasive techniques, measuring mechanoreceptors’ electrical responses to stimuli directly at the nerve fibres.

The skin contains four types of mechanoreceptors, which are specialised for distinct perceptual functions. Slowly adapting type 1 (SA1) receptors are highly sensitive to points, edges and curvature, and they have a high spatial resolution (LaMotte & Srinivasan, 1996; Phillips & Johnson, 1981). Slowly adapting type 2 (SA2) receptors mainly respond to skin stretch. Consequently, they can perceive the movement of objects across the skin (Olausson et al., 2000). Together with receptors in muscle spindles, SA2 receptors can also perceive the position of the hand and fingers, which affects the way the skin stretches over the hand (Collins et al., 2000). As the name suggests, rapidly adapting (RA) receptors do not respond to static tactile stimuli, but are highly sensitive to dynamic skin deformations. They have poor spatial resolution (Phillips & Johnson, 1981; Srinivasan & LaMotte, 1987). RA receptors are crucial for grip control (Macefield et al., 1996). The fourth type of mechanoreceptors are Pacinian corpuscles. These receptors are extremely sensitive to skin motion and have extremely low spatial resolution (Brisben et al., 1999). Pacinian receptors specialise in perceiving vibrations that are transmitted through objects that are held in the hand, such as a tool.

The perception of tactile features depends on the neural mechanisms of touch. An understanding of these mechanisms may contribute to the design of tactile maps, by enabling us to take advantage of the sensitivity of mechanoreceptors to specific tactile features, such as edges.
1.2.2 Psychophysics

In psychophysical studies on touch, researchers explore the limits of tactile perception by studying participants' ability to perform highly controlled and measurable perceptual tasks. These studies generally investigate the smallest perceivable differences between stimuli.

Weber is considered to be the founder of psychophysics. In his early publications, Weber (1834) suggested that the intensity of a stimulus had to increase or decrease by a certain amount in order for the change to be perceived. This Just Noticeable Difference was a ratio of the standard stimulus, and was used to calculate constant Weber fractions. Weber's Law is expressed as \( \frac{\Delta I}{I} = k \), in which \( \Delta I \) represents the difference threshold, \( I \) represents the stimulus intensity and \( k \) is a constant. Modern psychophysical research still uses the concepts and methods first introduced by Weber.

Since the 19th century, a large amount of psychophysical research has been conducted in all modalities (see Gescheider (1997) and Gordon (1997) for an overview). A large portion of the research on touch has focused on tactile spatial acuity, including the study of two point limen (Stevens et al., 1996), gap detection (Johnson & Phillips, 1981; Stevens et al., 1996) and the orientation of gratings (Craig, 1999; Craig & Lyle, 2001; Essock et al., 1997; Grant et al., 2000; Johnson & Phillips, 1981; J. W. Morley et al., 1983; Sathian et al., 1997; van Boven et al., 2000; van Boven & Johnson, 1994). Tactile spatial acuity ranged between 0.65 and 2.81 mm in these studies, depending on the experimental method. A more detailed discussion of research on tactile acuity can be found in Sections 3.1 and 4.1.1.

Since map features need to be easily perceived and recognized, understanding the limits of tactile perception is important for the design of tactile maps. For example, a map user needs to be able to feel the space between two lines on a map. The smallest distance between lines that allows reliable identification could be suggested by studies on tactile acuity. However, the results of psychophysical studies cannot be directly translated into design recommendation for tactile map, because of the differences in task. Psychophysical studies are conducted in a highly controlled
environment, where the participant is focussing solely on a perceptual task. The process of reading a map is much less controlled and the map reader needs to pay attention to a larger number of perceptual tasks at once.

Psychophysical studies employ highly controlled experimental methods. Experiments are performed in a controlled laboratory environment. For example, tactile stimuli are often mechanically pressed onto the fingerpad at a specific location and with a specific force (Craig & Lyle, 2001; Vega-Bermudez et al., 1991). Psychophysical studies generally involve a large number of trials using very accurately produced stimuli, and thorough statistical testing of the results. In addition, because of the long history of psychophysics, experimental methods have been tested thoroughly and have reached a high level of refinement. For these reasons, psychophysical methods can be used to inform experimental design in other areas of psychological research.

1.3 Current research

1.3.1 Tactile Inkjet Mapping Project

The research for this thesis was undertaken as part of the Tactile Inkjet Mapping Project (TIMP). A list of publications resulting from this project can be found in Appendix A. The objectives of this three year project were to develop a tactile inkjet printer for the production of tactile maps and to improve the design of tactile maps. There was a strong link between the two general objectives of the project. Improvements in printer output allowed for more accurate testing of different map design features, and requirements for map design brought about improvements in printer capabilities.

The Tactile Inkjet Mapping Project was an inter-disciplinary project, combining research from engineering, cartography and psychology. Three engineers developed the tactile inkjet printer. Don McCallum, a mechanics engineer, investigated manufacturing parameters such as the ink, substrate, print-head, ultra-violet curing of
ink and the electro-mechanical infrastructure of the printer. Snir Dinar, a systems engineer, focussed on creating a stable production process and devised print algorithms for the software controlling the printer. Kafeel Ahmed studied the behaviour of the printer’s ink using computational fluid dynamics. Jonathan Rowell studied the cartographic aspects of tactile maps, and considered the requirements of tactile map users and producers. Sandra Jehoel, the author of this thesis, studied the perception and use of tactile map features, using psychological theories and methods. The researchers were supervised by principal investigators Dr. Simon Ungar (psychology), Prof. Derek Sheldon (engineering) and Prof. Helen Petrie (human computer interaction). The researchers also received regular feedback and assistance from the TIMP collaborators: Ordnance Survey (OS, the UK’s national mapping agency), the Royal National Institute of Blind People (RNIB, the UK’s leading charity dedicated to people with visual impairments), Royal National College for the Blind (RNC, a college for people with visual impairments), the National Centre for Tactile Diagrams (NCTD, now part of the RNIB) and Patterning Technologies Limited (PTL, a research and development company specialising in inkjet technology).

1.3.2 Tactile Inkjet Printer

Inkjet printers create an image by ejecting drops of ink onto a surface. As part of the Tactile Inkjet Mapping Project, a Tactile Inkjet Printer was developed. This printer and its capabilities are described in several articles (McCallum et al., 2005; McCallum et al., 2003; McCallum & Ungar, 2003a, 2003b) and, in more detail, in McCallum’s PhD thesis (2006).

The Tactile Inkjet Printer (Fig. 1.5) produces raised images by depositing multiple layers of ink on a substrate material. Digital images are sent to the printer using a personal computer, which also controls the printing process. The main components of the printer itself are the printhead, the substrate, the ink, the UV curing system, and the motion control system for the substrate. The printhead ejects small drops of ink at a resolution of 180 dots per inch onto a substrate (background material). Almost any flat sheet of material can act as a substrate, such as paper, plastic and
aluminium. A curing ink is used, which solidifies upon exposure to UV light. The ink is dark blue, allowing printed images to be explored by both vision and touch. Trials were also successful with other colours and clear ink. To build up the raised image, the printhead deposits multiple layers of ink on top of each other until the desired elevation is achieved. After the deposition of each layer of ink, the substrate is passed under a UV light to solidify the ink. The substrate is attached to a movable tray. A motion control system moves the tray underneath the printhead and the UV light.

Fig. 1.5 The Tactile Inkjet Printer, including A) the printhead, B) the UV curing system, C) a map on the movable tray and D) the personal computer controlling the printer.

The output of the Tactile Inkjet Printer was studied extensively by McCallum (2006). An example of the printer output is shown in Figure 1.6. Depending on the substrate used, tactile inkjet maps are robust and hardwearing, and are therefore suitable for repeated and/or outdoor use. Raised features can be of any elevation, using increments of approximately 10 μm. Elevation can be varied within a single image.
In addition to full control over elevation, the Tactile Inkjet Printer also allows the producer to control texture (rough or smooth) and line profile (for example, rounded or triangular) (Dinar et al., 2005). Consequently, it is possible to produce a wide range of tactile features.

Fig. 1.6 An example of part of a map printed by the Tactile Inkjet Printer.

The Tactile Inkjet Printer has many advantages over other production methods (see Section 1.1.4 and Table 1.1). The process provides more choice and control over map design features than other production methods. Maps can be printed on a large variety of background materials, including paper, plastic and aluminium. As a result, maps can be geared to a specific use, such as a strong aluminium map on the wall of a railway station or a lightweight, foldable paper map for carrying around town. Since the printer uses small drops of ink at a high resolution, tactile features can be produced accurately and in great detail. The printer can produce tactile features at almost any width and elevation, and allows for variations in elevation within an image.
In addition to a high level of choice and control over the tactile output, the production process is quick and easy. A digital image is created using a regular drawing program on a computer, and is then printed by the Tactile Inkjet Printer. Multiple, identical copies of the tactile image can easily be produced. The production of each copy takes approximately 12 minutes.

The strength of the output is another advantage of tactile inkjet maps. Depending on the choice of background materials, these maps are sturdy, hard wearing and waterproof. This makes them suitable for repeated use, both indoors and outdoors.

Unfortunately, tactile inkjet printing has a number of disadvantages as well as advantages. Currently, the Tactile Inkjet Printer is a prototype machine used for research, and it is not yet commercially available. If the printer becomes available in the future, the purchase price is expected to be rather high. Therefore, the Tactile Inkjet Printer might not be cost effective for infrequent production of tactile images. However, since substrate materials and ink are cheap, and production time is short, tactile inkjet printing might be a good solution for production of large quantities of tactile images.

<table>
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<tr>
<th></th>
<th>Multi-textual</th>
<th>Microcapsule</th>
<th>Thermoform</th>
<th>Braille embossing</th>
<th>Tactile inkjet</th>
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<td>Quick production of multiple copies</td>
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<td>Easy access to materials and equipment</td>
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Table 1.1 Advantages and disadvantages of the most common production methods and tactile inkjet printing.

The stimuli used in the current research were produced by tactile inkjet printing for a number of reasons. Firstly, the high level of control and choice over tactile features
allowed us to produce highly accurate stimuli for experimental testing. It also allowed us to manipulate design variables, such as elevation, with great accuracy. Existing production methods for tactile images could not have produced samples of this quality and variation. Secondly, the stimuli used in the experiments had to be resilient enough to withstand repeated use and transportation between test locations. Tactile inkjet printing provided hard wearing stimuli. Finally, as part of the Tactile Inkjet Mapping Project, we needed to evaluate the output of the Tactile Inkjet Printer. The experimental testing described in this thesis provided a good opportunity for this evaluation.

1.3.3 Rationale for current research

As discussed in Section 1.1, tactile maps need to be designed very carefully in order to help the map user overcome the challenge of reading a map by touch rather than by vision. Unfortunately, research on the design of tactile maps is limited in quantity and quality. The current research project was intended to further the understanding of the design of tactile maps, by conducting empirical research that used appropriate methodological and analytical techniques.

In visual cartography, researchers have made a connection between scientific research and map design. Both Keates (1982) and MacEachren (1995) discussed how an understanding of perceptual and cognitive processes can contribute to the design of effective maps. For example, principles of perceptual grouping explain why a thematic map containing symbols of varying shades of grey is easier to understand than a map containing symbols of different shapes; in visual selective attention, colour value is selective while shape is not (MacEachren, 1995).

In tactile cartography, scientific research on perceptual and cognitive processes has not been exploited in the same way. In the current project, we took a scientific approach to improving the design of tactile maps. Existing research was used in three ways. Firstly, evaluations of the experimental methods and analyses used in previous studies allowed us to choose appropriate methods and analyses for our studies. Secondly, knowledge of the limits, strengths and weaknesses of touch allowed us to
There appears to be a gap between scientific research and the design of tactile maps. On the one hand, the results of psychophysical and neurophysiological studies (see Section 1.2) cannot be applied directly to the design of tactile maps, because the experimental setup of these studies is very controlled and does not resemble the process of exploring a map in everyday life. On the other hand, guidelines for tactile maps are generally based on experience and anecdotes, rather than on research. In the current research project, we attempted to bridge the gap between scientific research and more practical considerations of map design, by using an understanding of tactile perception and using thorough experimental methods to investigate several aspects of the design of tactile maps.

Both visually impaired and sighted people took part in our studies. Since visually impaired people were the intended users of tactile maps, it was crucial to include them in our studies. By recruiting sighted participants in addition to visually impaired ones, we increased the overall number of participants, which allowed us to conduct appropriate statistical analyses. In addition, we were interested in potential differences in performance between sighted and visually impaired participants, possibly caused by different levels of experience with tactile images. An appreciation of potential differences could be helpful in designing tactile maps for newly blind people, who do not yet have extensive experience with tactile images.

1.3.4 Research topics

We conducted a series of five experimental studies on the design of tactile maps. The research topics increased in complexity. We started at a fundamental level of tactile map design, investigating the basic physical properties of maps (Chapter 2 and 3). We then explored the design of symbols (Chapter 4 and 5) and finally, we evaluated entire maps (Chapter 6).
Since it was not possible to investigate all aspects of map design, a selection was made on the basis of gaps in previous research and new developments of the TIMP printer. The ability of this printer to produce maps on any substrate gave rise to a study on the choice of substrate material (Chapter 2). Next, we investigated the required elevation (i.e. height off the substrate) of map features (Chapter 3). In Chapter 4, we report a study on the perception of single lines and double lines at varying gap widths. In Chapters 3 and 4, we relate previous neurophysiological and psychophysical research to the workings of touch in a more practical setting. We developed a highly discriminable set of symbols and explored principles of symbol discriminability in Chapter 5. In the final study (Chapter 6), we performed a qualitative evaluation of entire maps produced by several production methods and designers, in order to evaluate the findings of this thesis and to compare production methods and design aspects. The TIMP printer allowed us to produce highly accurate stimuli for all studies.
2 An evaluation of substrates for tactile maps

At the most basic level, a tactile map is produced on a certain material. The TIMP printer can produce tactile graphics on sheets of almost any material. In this chapter, we investigate the use of seven substrate materials, including plastics, papers and aluminium.

2.1 Introduction

Tactile images are produced using a variety of substrates (background materials), depending on the production method used (Horsfall, 1997; Morley & Gunn, 2002). For example, the microcapsule process uses cloth embedded paper that contains heat activated microcapsules, embossed graphics are produced using paper, thermoform uses thermoplastic polymers, and screen printing involves wax based paper. Due to the nature of tactile map reading, users touch the substrate for relatively long periods of time. Therefore, it is important to find a suitable substrate for the production of tactile maps.

Previous studies have attempted to measure differences in map reading performance between various production methods. Dacen-Nagel and Coulson (1990) studied performance on maps of several complexities, which were produced by four different methods. They found that microcapsule maps were explored fastest and received the most favourable comments, followed by multi-textural and letter press plate maps. Thermoform maps yielded the slowest response times and unfavourable comments. Pike, Blades and Spencer (1992) investigated map reading performance of visually impaired children using microcapsule and thermoform maps. They found no significant differences in performance between map types. The Canadian Braille Authority (2003) conducted a series of 12 studies on several aspects of tactile diagrams. Each study included diagrams produced in thermoform and one of 5 other production methods (Flexi-paper, microcapsule paper, Graphtact ink, Tactile Vision ink and Braille embossed paper). Participants performed tactile tasks, such as
identifying shapes and counting the number of textures on a display. Performance was measured by accuracy and preference. Although these studies did not compare tactile maps, they allowed for a comparison of production methods across a range of tasks. In 9 out of 12 studies, performance and/or preference was higher on thermoform diagrams than on diagrams produced by other production methods. The other 3 studies did not show a difference in performance between production methods. These results suggest that controlled, simple tasks can be used to differentiate between tactile production methods.

As Perkins (2002) pointed out, difficulties may arise when trying to compare different production methods using tactile maps. Firstly, obtaining equal levels of complexity over pseudo maps is very problematic. Secondly, in most production methods the symbols consist of the same material as the substrate, so it is not possible to vary substrate while keeping the symbols constant across substrates. Although previous studies compared map production methods, substrate was dependent on the choice of production method and could not be investigated independently.

The study reported here evaluated the relative suitability of a range of substrates for producing tactile maps, using the Tactile Inkjet Printer. In this study, the two potential problems mentioned above were sidestepped. Firstly, abstract symbol matrices were used, ensuring equal levels of complexity across trials. Secondly, the displays were constructed using the TIMP tactile inkjet printer, which can print tactile images in polymer onto a large variety of substrates. This technology therefore allowed us to compare a range of substrates, while keeping other factors constant.

The aim of this study was to determine what substrates or types of substrate are most suitable for the production of tactile maps and diagrams. The suitability of a substrate can be defined in two ways. Firstly, substrates may vary in ease of extraction of information. This variation may be caused by differences in contrast between the substrate and the symbols that are printed on it. As Keates (1982) suggested, visual detection of a symbol will depend on symbol size and the contrast with the background on which it appears. Likewise, tactile detection might depend on a
similar relationship between symbol and substrate. Properties of the material, such as roughness and absorbency, may also affect the ease with which information can be extracted by influencing the speed at which the user can move the fingers. Numerous studies have explored the perception of roughness. For example, Lederman (1974, 1981, 1983) and Lederman and Taylor (1972) found that groove width and finger force were the most important factors in the perception of roughness of gratings. In another study on roughness perception, Heller (1989) did not find differences in smoothness judgements between sighted and blind participants nor between passive and active touch. These studies suggest that observers are able to differentiate between materials over a range of roughness levels.

The second aspect of substrate suitability is related to users’ preferences. Ekman, Hosman and Lindström (1965) reported that the participants in their study preferred smoother, rather than rougher, surfaces among seven surface textures, ranging from paper to coarse sand paper. However, in a recent survey of tactile map users (Rowell & Ungar, 2003a) in which participants were presented with identical maps (produced by inkjet printing as in the present study) on two different substrates, all participants who commented expressed a preference for the rough surface over the smooth one. The contradictory results of these two studies could be caused by a difference in the range of roughness levels. The smoothest paper in the first study may have been as rough as the roughest substrate in the second study.

In this study, we investigated which substrates allow for easy extraction of information in terms of the relative time taken to identify symbols. We also aimed to investigate further the relationship between preference and roughness in the hope of clarifying previous findings.

2.2 Methods

2.2.1 Participants
Twenty-nine sighted and visually impaired people took part in the study. Fifteen participants were visually impaired (10 males and 5 females). Fourteen visually impaired participants were recruited at the Royal National College in Hereford, and
one at Anglia Ruskin University in Chelmsford. Their ages ranged from 18 to 51, with a mean age of 29.8. Eight participants were totally blind and seven had some form of residual vision. Ten visually impaired participants were frequent Braille users. Fourteen sighted participants (4 males and 10 females) were recruited at the University of Surrey. They were aged between 17 and 49, with a mean age of 25.1 years. Table 2.1 shows more details of the visually impaired participants.

<table>
<thead>
<tr>
<th>Age</th>
<th>Gender</th>
<th>Age at onset of blindness</th>
<th>Residual vision</th>
<th>Cause of blindness</th>
<th>Braille reader</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>F</td>
<td>Birth</td>
<td>Yes</td>
<td>Nystagmus, myopia, stigmatisation, cataracts</td>
<td>Yes</td>
</tr>
<tr>
<td>18</td>
<td>M</td>
<td>9 years</td>
<td>No</td>
<td>Retinal detachment</td>
<td>Yes</td>
</tr>
<tr>
<td>18</td>
<td>M</td>
<td>5 years</td>
<td>Yes</td>
<td>Alstrom syndrome</td>
<td>Yes</td>
</tr>
<tr>
<td>18</td>
<td>M</td>
<td>Birth</td>
<td>No</td>
<td>Retinopathy of prematurity</td>
<td>Yes</td>
</tr>
<tr>
<td>18</td>
<td>M</td>
<td>Birth</td>
<td>Yes</td>
<td>Retrolental fibroplasia</td>
<td>Yes</td>
</tr>
<tr>
<td>20</td>
<td>M</td>
<td>Birth</td>
<td>Yes</td>
<td>Tumour</td>
<td>Yes</td>
</tr>
<tr>
<td>22</td>
<td>F</td>
<td>18 years</td>
<td>Yes</td>
<td>Diabetes related</td>
<td>No</td>
</tr>
<tr>
<td>28</td>
<td>F</td>
<td>3 months</td>
<td>No</td>
<td>Retinal blastoma</td>
<td>Yes</td>
</tr>
<tr>
<td>35</td>
<td>F</td>
<td>Birth</td>
<td>Yes</td>
<td>Optic nerve dystrophy, nystagmus, optic nerve glioma</td>
<td>No</td>
</tr>
<tr>
<td>38</td>
<td>F</td>
<td>Birth</td>
<td>Yes</td>
<td>Glaucoma</td>
<td>Yes</td>
</tr>
<tr>
<td>38</td>
<td>M</td>
<td>12 years</td>
<td>No</td>
<td>Glaucoma</td>
<td>Yes</td>
</tr>
<tr>
<td>39</td>
<td>M</td>
<td>25 years</td>
<td>No</td>
<td>Diabetes related</td>
<td>No</td>
</tr>
<tr>
<td>43</td>
<td>M</td>
<td>Birth</td>
<td>No</td>
<td>Undiagnosed</td>
<td>Yes</td>
</tr>
<tr>
<td>45</td>
<td>M</td>
<td>Birth</td>
<td>Yes</td>
<td>Corneal ulcers, cataracts, discoloration of the iris</td>
<td>Yes</td>
</tr>
<tr>
<td>51</td>
<td>M</td>
<td>22 years</td>
<td>No</td>
<td>Glaucoma</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Table 2.1 Characteristics of the visually impaired participants (all information obtained from participants' verbal reports).

2.2.2 Materials

On the basis of crossing seven types of substrate with seven different arrays of symbols, 49 experimental displays were constructed. As a result, seven sets of stimuli were available, each set containing a different combination of the seven substrates and seven symbol arrays. Figure 2.1 presents an example of the displays. The seven substrates used in this study were: rough plastic (high impact polystyrene with a rough finish), smooth plastic (high impact polystyrene with a smooth finish), textured PVC film (Brailon), standard grade aluminium, rough paper (the reverse side of Avery Dennison SU5134), smooth paper (Avery Dennison SU5142) and microcapsule paper (Zy-Tex2, produced by Zychem Limited). The microcapsule
paper was not heated. Displays were printed using the TIMP tactile printer. All substrates were backed by a rigid sheet of medium-density fibreboard and measured 29.7 x 21.2 cm (A4). Each array measured 25.8 x 19.2 cm and contained nine rows of eight symbols. Five shapes were used, which had been found to be highly discriminable (Rener, 1993): outline circle, ellipse, square, inverted T and inverted V. The T and V in Rener’s set were turned 180 degrees in order to prevent association with print letters. Four of the shapes were randomly distributed over nine rows of eight symbols. The fifth shape, an inverted V, was used as the target symbol. Eight targets were randomly distributed across the first eight rows. The ninth row contained zero, one or two target symbols in order to vary the overall number of target symbols across arrays. This prevented the participants from counting the target symbols. In order to keep constant the number of target symbols in the measured time, the ninth row was disregarded in data collection. Symbols were 8 x 8 mm (except for the ellipse which was 5.5 x 11 mm), which is a size at which symbols have been shown to be readily identifiable and discriminable (Horsfall & Vanston, 1981). Line width was 1.3 mm and line height was nominally 340 μm. This height is in the middle to lower ranges of common heights for tactile and Braille features produced by other methods and is well above the thresholds of size and elevation for identification of tactile symbols (see Chapter 3). On the left side of the page, horizontal lines were printed that enabled participants to keep track of their position on the display.
Fig. 2.1 An example of a stimulus display.

2.2.3 Procedure

The experiment was conducted at a desk in a quiet room at the participant’s college. The experiment consisted of a tactile scanning task and a preference ranking task. Sighted participants and those with residual vision were blindfolded during both tasks. The scanning task was performed first. Participants were asked to scan the arrays of symbols as fast and as accurately as possible, proceeding from the top left corner to the bottom right corner, and to give a verbal response when encountering a target symbol. Participants were asked to use their right hand to explore the rows of symbols. They used their left hand to keep track of their position by placing it on one
of the horizontal lines to the left of each row. Full details of the instructions to participants can be found in Appendix E.

As explained in Section 2.2.2, seven sets of displays were available, each containing a different combination of all seven substrates and all seven symbol arrays. After a practice trial, 14 displays were presented in two sets of seven, so each substrate material was presented twice. Each set contained all seven substrates materials and all seven symbol arrays. As a result, each substrate material was presented twice, and each symbol array was presented twice, but never in the same combination. Apart from the specific combination of array and substrate, the two sets were replications and did not differ in any meaningful way. The order of substrates and arrays was pseudo random, making sure that participants explored each substrate twice with a different array. The substrate materials and the array of symbols were guaranteed to vary between consecutive trials, so the participant was never presented with the same substrate or array twice in succession. A digital video camera with microphone was used to record the participants performing the task. These images were then used to determine the amount of time that was needed to complete the eight by eight arrays and to record errors in identifying target symbols (false negatives and false positives).

Upon completion of the scanning task, participants were asked to rank all substrates in order of preference. Participants received all seven substrates in a pile presented in random order and lined them up on a table in order of preference. The experimenters did not suggest any basis for ranking, but simply asked the participants to order the substrates on the basis of how much they liked each one. After the ranking task, participants were asked to explain the bases for their judgements.

2.2.4 Statistical methods
We investigated the suitability of substrates for tactile maps. Substrate material was the independent variable and seven substrates were used. Two dependent variables were measured and analysed. Firstly, we measured the time (in seconds) it took participants to complete a search task on each substrate. Since each substrate was presented twice, the mean of both presentations was used. The time score was
converted into z-scores, which will be explained in Section 2.3.3. Secondly, participants ranked all substrates in order of preference. Each substrate was assigned a preference score (1 to 7, where 1 was most preferred).

We hypothesised that certain substrates might be easier to use and more preferred than others. Although we did not have specific expectations about the suitability of any of the substrates, we expected that the roughness of the materials may play a role.

Data were analysed by a series of repeated measures ANOVAs. The effects of visual status and substrate on scanning time were investigated in a 2 (visually impaired or sighted) x 7 (substrates) ANOVA. A 2 (visually impaired or sighted) x 7 (substrates) ANOVA was used to investigate the effects on standardised scanning time. Wilcoxon signed rank tests were used to investigate differences in preference for all substrates. Since most participants expressed a preference for either smooth or rough substrates, we investigated the effects of preference group on standardised scanning time in a 2 (smooth preference or rough preference) x 7 (substrates) ANOVA.

2.3 Results

2.3.1 Errors

Overall, very few errors occurred in identification of the target symbol. A total of 464 target symbols (29 participants x 8 target symbols x 2 presentations of a substrate) was explored on each substrate. Table 2.2 shows the total number of errors. The number of errors was very small and there was no evidence of any relationship between substrate type and number of errors ($F(6, 301) = 0.46, p > 0.05$, $\eta^2 = 0.01$) for false negatives). Therefore, the errors were disregarded in further data analyses.
<table>
<thead>
<tr>
<th>Substrate</th>
<th>False negatives</th>
<th>False positives</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rough plastic</td>
<td>9</td>
<td>0</td>
</tr>
<tr>
<td>Smooth plastic</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>Rough paper</td>
<td>15</td>
<td>0</td>
</tr>
<tr>
<td>Smooth paper</td>
<td>11</td>
<td>0</td>
</tr>
<tr>
<td>Microcapsule paper</td>
<td>6</td>
<td>0</td>
</tr>
<tr>
<td>Braillon</td>
<td>8</td>
<td>2</td>
</tr>
<tr>
<td>Aluminium</td>
<td>15</td>
<td>0</td>
</tr>
</tbody>
</table>

*Table 2.2 Number of errors in identification of target symbol.*

### 2.3.2 Roughness

The data suggested that substrate roughness played an important role in both scanning speed and preference rankings. The average roughness of the substrates was measured with an interferometer\(^2\). Figure 2.2 shows the roughness values for each substrate and how these were related to scanning time, which will be discussed later.

![Fig. 2.2 Roughness and scanning time for all substrates. Error bars indicate standard errors of the mean.](image)

\(^2\) Measurements were taken using Wyko RS-2 Interferometric Surface Profilometer. An interferometer is able to generate detailed topographical information by scanning an optical beam over a material and analysing the interference of reflected fringes. The unit used in this experiment had a lateral resolution of 1 \(\mu\)m and depth resolution of 5 nm.
2.3.3 Time

Scanning time was measured from the moment participants touched the first symbol in the display until they left the last symbol in the eighth row \((M = 77.6 \text{ seconds}, SD = 33.5 \text{ seconds})\). A mixed-measures analysis of variance (ANOVA), using Greenhouse-Geisser corrections where necessary, with visual status (visually impaired versus sighted participants) as a between subjects factor and substrate as a within subjects factor, showed that the type of substrate had an overall effect on scanning time \((F(6, 162) = 5.22, p < 0.01, \eta^2 = 0.16, \text{power} = 0.94)\). Visual status also had a significant effect on scanning time \((F(1, 27) = 24.72, p < 0.01, \eta^2 = 0.48, \text{power} = 1.0)\). Visually impaired participants performed the task faster than sighted people did \((M_{VI} = 56.8 \text{ seconds}, SD = 23.2 \text{ seconds}, \text{and } M_{sighted} = 99.8 \text{ seconds}, SD = 28.0 \text{ seconds})\). There was no interaction effect between type of substrate and visual status \((F(6, 162) = 1.82, p > 0.05, \eta^2 = 0.06, \text{power} = 0.50)\). Since the statistical power of the interaction was relatively low, we cannot say with confidence that there was no significant effect of this interaction. Table 2.3 presents an overview of the statistical results of the ANOVA.

<table>
<thead>
<tr>
<th></th>
<th>(F)</th>
<th>(p)</th>
<th>(\eta^2)</th>
<th>power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substrate *</td>
<td>5.22</td>
<td>&lt; 0.01</td>
<td>0.16</td>
<td>0.94</td>
</tr>
<tr>
<td>Visual status *</td>
<td>24.72</td>
<td>&lt; 0.01</td>
<td>0.48</td>
<td>1.0</td>
</tr>
<tr>
<td>Substrate X visual status</td>
<td>1.82</td>
<td>&gt; 0.05</td>
<td>0.06</td>
<td>0.50</td>
</tr>
</tbody>
</table>

*Table 2.3 Effects of substrate and visual status on scanning time. Significant effects are indicated by *. 

The standard deviation in mean scanning time between participants was quite large \((SD = 33.5 \text{ second})\). However, the standard deviation within participants was considerably smaller \((mean SD = 10.2 \text{ seconds})\). This indicates that, although mean scores differed greatly between participants, all participants scored within certain limits from their own mean. In order to be able to compare the means of all participants, each participant’s scores were standardised by conversion to \(z\)-scores. Since the ANOVA analysis revealed no significant interaction between visual status and substrate, Figure 2.3 shows mean scanning time across all participants.

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\(^3\) \(z\)-scores indicate the number of standard deviations of each time measurement from the participant’s own mean time.
A mixed-measures analysis of variance (ANOVA with visual status (visually impaired versus sighted participants) as a between subjects factor and substrate as a within subjects factor, showed that the type of substrate had an overall effect on standardised scanning time \((F(6, 162) = 8.03, p < 0.01, \eta^2 = 0.23, \text{power} = 1.0)\).

Since the data of each participant was standardised to his or her own mean, there was by definition no main effect of visual status. There was no interaction effect between type of substrate and visual status \((F(6, 162) = 0.19, p > 0.05, \eta^2 = 0.01, \text{power} = 0.10)\). Since there were no time differences and no interaction effects between the two participant groups, the data for the two groups were collapsed for further analysis. Table 2.4 presents an overview of the statistical results of the ANOVA.

<table>
<thead>
<tr>
<th>Substrate *</th>
<th>(F)</th>
<th>(p)</th>
<th>(\eta^2)</th>
<th>power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substrate X visual status</td>
<td>8.03</td>
<td>&lt;0.01</td>
<td>0.23</td>
<td>1.0</td>
</tr>
<tr>
<td>Substrate X visual status</td>
<td>0.19</td>
<td>&gt;0.05</td>
<td>0.01</td>
<td>0.10</td>
</tr>
</tbody>
</table>

*Table 2.4 Effects of substrate and visual status on standardised scanning time. Significant effects are indicated by *.

Pair-wise comparisons indicated which substrates differed significantly in scanning time \((p < 0.05)\). Aluminium and smooth plastic were scanned more slowly than Braillon, smooth paper, rough paper and microcapsule. Participants required more
time scanning rough plastic than rough paper and microcapsule paper. Scanning time for Braille on was longer than that for rough paper and microcapsule.

2.3.4 Preferences

Participants' preferences for substrates, as indicated by their responses to a specific question about the basis of their preference rankings, showed two distinct patterns. The majority (9 visually impaired and 10 sighted participants) indicated that they preferred rougher substrates over smoother substrates (see Figure 2.2 for roughness values of the substrates). A minority (5 visually impaired and 4 sighted participants) preferred smooth substrates over rough ones. On this basis, it was therefore possible to assign participants to one of two preference groups: rough or smooth. One participant did not show a clear preference pattern and was disregarded in the analysis of preference data.

![Mean ranking scores for preference groups. Error bars indicate standard errors of the mean.](image)

Fig. 2.4 Mean ranking scores for preference groups. Error bars indicate standard errors of the mean.

The participants ranked all substrates on a 7-point scale, assigning more points to highly preferable substrates. Figure 2.4 shows the mean ranking scores of the two preference groups. The data suggest that there is an interaction between type of substrate and preference group. Multiple Wilcoxon signed rank tests (with a
significance level of \( p < 0.0024 \), according to a Bonferroni correction for multiple comparisons), were used to explore differences in preference between substrates. There were no significant differences in preference for substrate among the smooth preference group. However, participants in the rough preference group ranked aluminium and smooth plastic significantly lower than rough paper, microcapsule paper and Braillon, and ranked rough plastic lower than rough paper and microcapsule paper. In order to examine differences in preference between the preference groups, multiple Wilcoxon tests were performed (with a significance level of \( p < 0.007 \), according to a Bonferroni correction for multiple comparisons). The rough preference group gave a significantly higher ranking than the smooth preference group to microcapsule paper, rough paper and Braillon, and gave a significantly lower ranking to aluminium.

2.3.5 Time and preference

There was a significant correlation between the z-scores of scanning time and the preference ranking scores (\( r = -0.16, p < 0.05 \)). Table 2.2 shows the z-scores for the two preference groups. A mixed-measures ANOVA, using preference groups as a factor, was conducted to investigate differences in exploration time for the two preference groups. One participant who did not express a preference for rough or smooth substrates was not included in this analysis. There was a main effect of substrate type (\( F(6, 156) = 7.15, p < 0.01, \eta^2 = 0.22, \text{power} = 1.0 \)). Since the data was standardised, there was no main effect of preference group on exploration time. There was also no interaction between preference group and type of substrate (\( F(6, 156) = 0.69, p > 0.05, \eta^2 = 0.03, \text{power} = 0.27 \)), although the power of this test was low.

<table>
<thead>
<tr>
<th></th>
<th>( F )</th>
<th>( p )</th>
<th>( \eta^2 )</th>
<th>power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substrate *</td>
<td>7.15</td>
<td>&lt; 0.01</td>
<td>0.22</td>
<td>1.0</td>
</tr>
<tr>
<td>Substrate X preference group</td>
<td>0.69</td>
<td>&gt; 0.05</td>
<td>0.03</td>
<td>0.27</td>
</tr>
</tbody>
</table>

Table 2.5 Effects of substrate and preference group on standardised scanning time. Significant effects are indicated by *. 49
2.4 Discussion

2.4.1 Discussion of results

In this study, blind and sighted participants performed a scanning task on seven different substrates. Scanning time was measured and participants ranked the substrates on the basis of their individual preferences. In general, paper substrates were explored faster than plastic and aluminium substrates. This might be related to surface characteristics such as roughness and absorbency. The plastic and aluminium substrates were smoother and less absorbent, possibly causing the fingers to stick to the substrate and slowing down exploration. Most participants did not only explore paper substrates faster, they also preferred them over plastic and aluminium substrates. When asked about the reasons for their preferences, most participants (18 out of 29) reported that they either liked paper and rough substrates because it was easier to move their fingers across these rougher substrates, or disliked the plastic and aluminium substrates because of their stickiness, which irritated their fingertips and made it more difficult to move across the display. Although not mentioned by participants, familiarity with the materials may also play a role. It is likely that most people, and particularly visually impaired individuals who read Braille, touch paper more frequently than plastic and aluminium.

Interestingly, a small number of participants (8 out of 29) preferred the plastic and aluminium substrates because of their smoothness, which reportedly made it easier to move their fingers across. Observations suggested that these participants had dry skin and/or used light touch, which may have made it more pleasant to run their fingers across a smooth surface than a rough one. However, the data on exploration time suggest that, regardless of preference, participants explored plastic and aluminium substrates more slowly than paper ones.

Although the interaction effects of participant group (based on visual status or preference group) and type of substrate were not significant, these analyses had relatively low statistical power. This implies that we cannot confidently conclude that there were no interaction effects. Generally, statistical power can be increased by
increasing the number of participants. However, in order to achieve acceptable levels of power for the extremely small effect sizes found for interaction effects in the current study, a very large of participants would be required. This was neither realistic nor necessary. Since the effects of the interactions were so small, they are not likely to be of theoretical or practical interest.

The substrate study was designed and conducted before the other studies in this research project. It provided us with the opportunity to test our approach of using thorough empirical methods to investigate practical issues related to the design of tactile maps. This study confirmed that performance on practical tactile tasks could be measured and analysed successfully. The results of this study could be applied meaningfully to the design of tactile maps. The success of this study encouraged us to use a similar approach in subsequent studies.

2.4.2 Theoretical considerations

The data suggest a U-shaped relationship between surface roughness on the one hand and preferences and scanning time on the other. Very smooth substrates scored relatively low and scores improved with rougher substrates. However, very rough substrates appeared to obtain lower scores again. In this study, very smooth substrates such as shiny plastic and aluminium were explored more slowly and were less preferred than fairly smooth substrates such as rough plastic and smooth paper. Rough paper and microcapsule paper, which are rougher, were most preferred and fastest explored. Brailllon, which was the roughest substrate used in this experiment, had an intermediate score on exploration time and preference. The U shaped relationship may also explain the apparent inconsistency between the findings of Rowell and Ungar (2003a) and of Ekman and colleagues (1965). As the textures used in the latter study were considerably rougher than those used in our studies, they were possibly in the range of roughness where preference begins to decrease. Another explanation for the inconsistency relates to the purpose of the task. Both in the present study and in the study by Rowell and Ungar, the main task involved scanning an image on the substrate. In Ekman et al.'s study, however, the task focussed on the bare substrate itself.
Given the U shaped relationship between surface roughness and performance, it is unlikely that our data can be explained in terms of difference in roughness between the substrate material and the surface of the symbols (which was of a constant level of roughness and relatively smooth). Previous research (Lederman, 1974, 1981) suggests that discrimination of roughness increases as difference in roughness increases. If increasing difference in roughness between symbol and substrate were the main factor facilitating identification of the symbols, performance would be expected to improve as substrate roughness increased. The fact that it did not, implies that difference in roughness can at best be only one of a number of factors determining differences in performance across substrates.

The results of this study suggest that surface roughness has an effect on the exploration of and preference for substrates. However, other surface characteristics might also have an effect. Firstly, absorbency of the material will influence the amount of sweat that remains on the finger and thus the stickiness of the surface. A second characteristic is thermal conductivity, which influences the subjective feeling of temperature. In this study, for instance, many participants spontaneously remarked that the aluminium substrate, which has high thermal conductivity, felt cold. Third, surface softness is considered a robust perceptual dimension of texture (Hollins et al., 1993). Other characteristics that may influence exploration and preferences include elasticity or springiness (Srinivasan & LaMotte, 1995), friction, surface chemistry such as acidity and surface energy. More detailed research could indicate what surface characteristics influence the ease of extraction of information and the preferences for substrates.

2.4.3 Practical considerations

The results of this study suggest that paper substrates, in particular rough paper and microcapsule paper, would be most suitable for the production of tactile maps using an inkjet printing method. These results are based on exploration time and user preferences. However, other factors should be considered as well. First, the selection of a substrate depends on the functions of the map or diagram. For example, durable
substrates such as plastic and aluminium are more suitable for use in public places (for example a map on the wall of a railway station), whereas paper substrates, which are lightweight and can be folded up, can more easily be taken with the individual user. Production cost is another factor in the selection of substrates; paper substrates are usually cheaper than plastics and aluminium. Still another consideration is the use of maps and diagrams by visually impaired people with residual vision. The use of residual vision is often hindered by reflection and matt substrates, which have less reflection, may be more suitable in this respect.

It could be argued that the specific task used in the present study lacks ecological validity, and that the results may not generalise to the use of actual tactile maps and diagrams in complex, real-world tasks. However, it seems likely that the relative properties of substrates would have an even greater effect in the context of many map or diagram tasks, in that the reader is likely to spend a greater amount of time with their finger in contact with the background material while scanning the display for information. The relative advantages of moderately rough substrates are therefore likely to hold for most tactile display tasks, as well as for our scanning task.

It should be noted that the microcapsule paper in this study was not heated. In regular use of microcapsule paper, the paper is passed through a heater, which causes the black parts of an image to swell. This creates a raised image. However, as we found in the evaluation study (Chapter 6), the blank parts of the image also swell slightly during the heating process, creating an unpleasant, sticky surface. The high preference and good performance on unheated microcapsule paper in this study would probably not be sustained on a heated sheet of microcapsule paper.

The current study on substrate materials was conducted before subsequent studies were designed. Therefore, it was possible to incorporate the findings of this study into the design of stimuli. In the following chapters, we investigate the elevation of tactile features, the perception of single and double lines of varying gap width and the discriminability of symbols. All tactile features in these chapters were printed on rough plastic, as suggested by the current study. Due to the nature of subsequent studies, we required a sturdy, hard wearing material. Although rough plastic did not
receive the highest preference and performance scores overall, it scored highest of the sturdy materials (plastics and aluminium).
3 Tactile elevation perception and its implications for tactile map creation

In the previous chapter, we investigated the choice of substrate materials for tactile maps. Next, we explored what is shown on this substrate; the tactile features. The main characteristic of a tactile image is that it has elevation (vertical height). In this chapter, we studied how much elevation is needed to perform tactile tasks.

3.1 Introduction

Tactile features, such as the raised lines on tactile maps, need to be produced at a sufficient size and elevation (relief, vertical height) relative to a background surface in order to be readable. In this chapter, we discuss two studies on the minimum elevation of tactile symbols. We aimed to find the minimum elevation and size at which symbols could be identified accurately (Study A), and the minimum elevation at which tactile symbols could be identified quickly (Study B). We used experimental methods and results from psychophysical and neurophysiological research to inform the design of our studies, in order to find the minimum elevation of tactile symbols for identification in an applied context.

Currently, the elevation of tactile map features varies widely and largely depends on the production method used, rather than on knowledge of tactile perception. For example, thermoformed plastic does not impose an upper elevation limit and, as a consequence, images are often rather high; commonly well over 1 mm (Gardiner & Perkins, 2002a). Features on swell paper are generally raised by around 0.5 mm and Braille embossers produce dots at elevations of 0.25 to 1.0 mm (Gill & Silver, 2005). The elevation of tactile symbols is usually either dictated by the production method or cannot be controlled accurately. The printer developed in the Tactile Inkjet Mapping Project (McCallum, 2006; McCallum & Ungar, 2003a, 2003b), however, allows more accurate control over the elevation of the printed features by depositing multiple layers of polymer ink. This printer can produce tactile images at almost any
elevation, in increments of approximately 10 μm, depending on type of ink, substrate material and curing process. An important balance needs to be struck, with this new technology, between the need to minimise machine resources while maximising user performance. Therefore, it is important to find the minimum elevation (saving printing time and ink) at which tactile maps are easily read and understood. However, there is a lack of empirical research on symbol elevation. Guidelines for tactile map design (Edman, 1992; Gardiner & Perkins, 2002a) generally agree that features need to be of a sufficient elevation, but they do not specify a minimum or optimal elevation.

Psychophysical studies can give an indication of the sensitivity of the fingertip to raised features. Spatial acuity of the finger has been studied in detail, including the controversial two point limen tests, tests on gap detection and letter recognition (Johnson & Phillips, 1981; Stevens & Cruz, 1996) as well as studies on tactile gratings (Craig, 1999; Johnson & Phillips, 1981; Nefs et al., 2001; van Boven & Johnson, 1994). These experiments suggest that the tactile spatial resolution of the fingertip ranges between 0.87 and 2.36 mm. In other words, they indicate that the fingertip can be used to interpret tactile features (gaps between bars, the difference between two points and a single point, the difference between a horizontal and a vertical grating etc.) only when the elements of these features are separated by more than the minimum resolution distance. Spatial acuity of the fingertip provides information to map designers about the minimum size of tactile symbols. Few studies have investigated tactile sensitivity for the elevation (third dimension) aspect of tactile features, even though elevation is a crucial parameter for touch. A study on detection thresholds showed that a single edge can be detected at an elevation of 0.85 μm relative to a flat background (Johansson & LaMotte, 1983). In a study on the amplitude of gratings, participants discriminated amplitude (elevation) differences as small as 2 μm (Nefs et al., 2001). In addition to elevation, the shape of an edge is important in detecting the tactile feature. Physiological studies show that sharp edges

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4 Machine resources include ink and printing time. The polymer inks used by the TIMP printer cost £125 per litre. The production of an A3 print with 5% coverage, at an elevation of 500 μm, required approximately 3 ml of ink. The relationship between elevation and volume of liquid ink required for that elevation is approximately linear. A higher elevation also requires a longer printing time. The TIMP printer takes approximately 30 seconds to print and cure one layer of ink onto an A3 sheet, which adds approximately 10 μm of elevation to the image.
produce higher neural activity in the fingertip receptors than gradually sloping or curved edges (LaMotte & Srinivasan, 1987).

Unfortunately, the results of psychophysical studies cannot be translated directly into decisions on tactile map design. Features that can be detected and identified in isolation on a single intensive trial of a psychophysical study, may not be correctly identified or may even be missed altogether when presented in the context of a complex tactile map, and in the context of a task where information needs to be acquired quickly and efficiently. In short, tactile maps may not be readable at an elevation of 0.85 μm (0.00085 millimetres), even though this elevation is above the detection threshold. At the same time, the psychophysical studies show that the fingertip is very sensitive to elevation, which suggests that tactile maps may be produced at considerably lower elevations than generally assumed. Currently, there is no satisfactory link between psychophysical studies on elevation and the general recommendations of guidelines for the design of tactile maps. We attempted to bridge this gap in two studies on the perception of the elevation of tactile symbols, using more practical and realistic tasks. Optimum elevations and sizes for identification have not been studied in psychophysical and neurophysiological studies before. However, they are the key issue for tactile map design; detection of a feature is useless if you cannot identify it.

Mechanoreceptors in the fingertip form the basis of tactile perception (for an overview of the tactile functions of mechanoreceptors, see Johnson et al. (2000). Exploration of small tactile symbols mainly engages responses in SA1 (Slowly Adapting) and RA (Rapidly Adapting) receptors (Phillips et al., 1990). Accordingly, the design of our studies was determined by three strands of neurophysiological research on these receptors. Firstly, an increase in elevation was expected to improve performance, because of an increase in mechanoreceptor responses. For example, Blake, Johnson and Hsiao (1997b) found that the response of SA1 and RA mechanoreceptors increased with higher elevations. However, the effect of increasing elevation was expected to level off: at a certain elevation, any further increase in elevation was not expected to improve performance significantly. This point would determine the optimal elevation, at which resources (ink and printing
time) are minimised and performance is maximised. One of the aims of these studies was to identify the optimal elevation for tactile maps.

Secondly, we sought to determine the effect on performance of sharpness of edges. According to neurophysiological research, the mechanoreceptors in the fingertip are highly activated by sharp edges (LaMotte & Srinivasan, 1987; Srinivasan & LaMotte, 1987). When pressed onto or stroked across the fingertip, sharp edges triggered a larger neurophysiological response than smooth edges. Capitalising on this edge effect, we hypothesised that tactile features consisting of sharp edges would be more discernible than those with smooth edges and would hence be readable at lower elevations.

Thirdly, we presumed that readability could be improved further by taking into account the adaptation characteristics of mechanoreceptors. Whereas SA1 afferents continue to respond, RA afferents adapt to continual stimulation and cease to respond. This suggests that tracing a solid line may not activate the RA mechanoreceptors in an optimal way. However, an array of dots continued to activate both the SA1 and RA receptors when stroked across the fingertip (Blake et al., 1997a; Phillips et al., 1992). Therefore, we hypothesised that a dotted line would trigger responses in both receptor types and would, therefore, be easier to read at low elevations than a smooth, continuous line.

Based on these considerations, we conducted two experiments, with sighted and visually impaired participants, to systematically address the identification of tactile symbols at various elevations and sizes. The first study investigated the minimum size and elevation at which individual tactile symbols can be identified accurately. Participants identified shapes at several elevations and sizes. Performance was measured by percentage correct identification. In the second study, we aimed to determine the elevation at which tactile features can be identified quickly in the context of a task designed to be more analogous to map reading. Here, participants performed a timed scanning task on arrays of symbols at several elevations using three line types, in order to study the interaction between line type and elevation. We designed three lines (smooth, sharp and rough), intended to take advantage of our
knowledge of tactile perception of elevation, sharp edges and dot arrays. A rounded, smooth line was expected to trigger a relatively weak response of the mechanoreceptors and, therefore, require higher elevations. A line with a sharp edge was expected to trigger a stronger response and therefore require lower elevations. A rough line, consisting of dots, was expected to cause continual stimulation of both SA and RA receptors in the fingertip. Therefore, we expected the rough line to be readable at the lowest elevations.

Both visually impaired and sighted participants took part in these studies. Since tactile maps are used by visually impaired people, it was important to test elevation and size of tactile symbols with this user group. We were also interested in the performance of sighted participants, without extensive experience with tactile symbols. This could provide a baseline for the production of tactile maps for users with a recent visual impairment. Previous research suggests that visually impaired participants perform certain tactile tasks faster and more accurately than sighted participants (Heller, 1989a; van Boven et al., 2000). Therefore, we expected the visually impaired participants in our study to outperform sighted ones.

3.2 Study A: Accuracy of symbol identification

This study aimed to determine the lowest elevation at which individual symbols of different sizes could be accurately identified. We hypothesised that symbols would be more easily identified at higher elevations and at larger sizes.

A pilot study was conducted to identify an appropriate range of sizes and elevations. Seven visually impaired and five sighted participants (18 to 51 years, mean age 31.8) identified circles, squares and triangles, using a forced choice staircase method. Elevation ranged from 7 to 100 μm and size ranged from 2.1 to 11.4 mm. The pilot study showed that discrimination of symbols smaller than 3.9 mm was very difficult. Moreover, increasing the size of symbols over 7.1 mm did not improve performance. Therefore, the sizes used in the current study ranged between these two extremes. The pilot study also showed that tactile symbols are discriminable at surprisingly low
elevations. Larger symbols were identified at elevations of 7 μm. Therefore, the elevations used in the main study ranged between 7 and 47 μm.

This study was performed as a distraction task within a study on the discriminability of symbols (see Chapter 5). It could be argued that this method may have affected performance, because participants were required to retain unrelated information while performing the current task. This effect, however, was not considered to be a disadvantage to our method. In fact, by embedding it in another task, our task became more similar to map reading, which may also require a reader to retain information about several symbols. A more detailed discussion of the implications of this method can be found in Section 5.1.3 and Section 5.6.1.

3.2.1 Methods

Participants

Nineteen volunteers took part in this study. Ten participants were sighted (6 male and 4 female, 19 to 30 years, mean age 22.3) and nine were visually impaired (5 male and 4 female, 18 to 62 years, mean age 29.1). Details of the visually impaired participants' characteristics can be found in Table 3.1. Visually impaired participants were recruited through the Royal National College and the Surrey Association for Visual Impairment. Sighted participants were recruited at the University of Surrey and Anglia Ruskin University.

<table>
<thead>
<tr>
<th>Age</th>
<th>Gender</th>
<th>Age at onset of blindness</th>
<th>Residual vision</th>
<th>Cause of blindness</th>
<th>Braille reader</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
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<td>birth</td>
<td>No</td>
<td>Retinopathy of prematurity</td>
<td>Yes</td>
</tr>
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<td>F</td>
<td>birth</td>
<td>Yes</td>
<td>Retinopathy of prematurity</td>
<td>No</td>
</tr>
<tr>
<td>18</td>
<td>M</td>
<td>9 years</td>
<td>No</td>
<td>Detached retina</td>
<td>Yes</td>
</tr>
<tr>
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<td>M</td>
<td>5 years</td>
<td>Yes</td>
<td>Alstrom syndrome</td>
<td>Yes</td>
</tr>
<tr>
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</tr>
<tr>
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<td>Leber's amaurosis</td>
<td>Yes</td>
</tr>
<tr>
<td>33</td>
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<td>6 months</td>
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<td>Retinal blastoma</td>
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</tr>
<tr>
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<td>M</td>
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<td>Glaucoma</td>
<td>Yes</td>
</tr>
<tr>
<td>62</td>
<td>F</td>
<td>birth</td>
<td>Yes</td>
<td>Cataracts, scars, nystagmus</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Table 3.1 Characteristics of the visually impaired participants in Study 1 (all information obtained from participants' verbal reports).
Materials

Circles, squares and triangles were printed on blank business cards (54 x 85 mm), using the TIMP printer, in a range of sizes and elevations. The cards were made of rough plastic, as suggested by the substrate study (Chapter 2). Outline circles, squares and triangles were selected, because these are the most basic and most commonly used shapes for map symbols. One symbol was printed in the middle of each card. Based on the pilot study, symbols were printed at six elevations (7, 14, 22, 30, 38 and 47 μm) and 5 sizes. The diameters of the circles and the heights of the triangles were 3.9, 4.7, 5.5, 6.3 and 7.1 mm. In order to keep identification accuracy constant across shapes (as suggested by a pilot study), the heights of the squares were smaller; 3.6, 4.3, 5.0, 5.8, and 6.5 mm. In total, 90 cards were printed that accommodated all shapes, elevations and sizes.

The cards were presented in a wooden jig with slots for each card (see Figure 3.1). The slots were 14 mm apart on a horizontal line. Small indentations along the base of the jig indicated the position of the corresponding symbols. The jig contained three symbol cards at a time, and two cards that were part of a study on symbol discrimination (see Chapter 5). The jig was placed on a table in front of the participant. Participants were asked to adjust the position of the jig so they were comfortable, in order to create a realistic reading position.

![Fig. 3.1 Example of a wooden jig containing three symbol cards in the middle. The jig also contains two line symbols, which were part of the study on symbol discrimination (see Chapter 5).](image)

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5 Elevation is controlled within the TIMP process by the number of layers of polymer laid down sequentially, with each layer adding approximately 10 μm to the elevation of a structure. The elevations of symbols listed here were obtained by measuring the height of each symbol using a set of digital calipers.
Procedure

This study was conducted as a distraction task within a pair-comparison task (see Chapter 5). Participants were seated at a desk in a quiet room at their college or home. Participants explored the first symbol in the jig and memorised it, then performed the identification task of the current study, and finally explored the last symbol in the jig and compared it to the first symbol. Every combination of size and elevation was presented ten times to each participant. This resulted in 300 symbol presentations (6 elevations x 5 sizes x 10 presentations). Cards were presented in a random order.

A forced choice paradigm was used, in which participants were asked to identify each symbol as circle, square or triangle. The experimenter recorded these responses. Sighted participants and those with residual vision were blindfolded. Participants used one hand of their own choice, and were allowed to swap hands during the experiment. The choice of hand (left or right) was not recorded. Participants scanned each card in turn, from left to right, and were not allowed to return to a previously scanned card. Full details of the instructions to participants can be found in Appendix E.

In order to provide a fixed time delay for the pair-comparison task (see Chapter 5), scanning of each symbol was limited to five seconds. Imposing a time limit made sense in the context of map reading, because a map reader should not have to spend a large amount of time exploring a symbol. A laptop was used to indicate the time limit for each line symbol. The experimenter observed participants’ finger movements and started a timer as soon as the symbol was found. After five seconds, an auditory signal prompted participants to lift their finger off the symbols and to give a response. This procedure was repeated for each card.

Statistical methods

We manipulated elevation (6 elevations) and size (5 sizes), in order to investigate the minimum elevation and size for identification of symbols. Accuracy of identification was the dependent variable. Each participant made 10 judgements on each combination of elevation and size. For each participant, each combination was then
given a score reflecting the number of correct identifications. For example, if a participant correctly identified a symbol at a particular elevation and size 8 times out of 10, that combination was assigned a score of 8 for that participant. We expected accuracy to decrease as elevation and size decreased.

The effects of size and elevation on accuracy of symbol identification were investigated in a 2 (visually impaired or sighted) x 6 (elevations) x 5 (sizes) ANOVA. Post hoc pair-wise comparisons were used to identify what sizes and what elevations were significantly different from each other.

3.2.2 Results
The total percentage of correct responses for each size-elevation combination was calculated, as an indication of accuracy of identification. Figures 3.2 and 3.3 show the results for the visually impaired and the sighted participants respectively. The data show that an appropriate range of sizes and elevations was used; accuracy ranged from chance level to 100% correct. Both sighted and visually impaired participants performed at chance level on the smallest, lowest symbol (31.0% and 33.3% respectively). Visually impaired participants reached 100% correct identification on the large, high symbols.
Fig. 3.2 Accuracy of identification by symbol size and elevation (visually impaired participants). For legibility, errors bars indicating standard errors of the mean are only shown for the smallest and largest symbol size.
Fig. 3.3 Accuracy of identification by symbol size and elevation (sighted participants). For legibility, errors bars indicating standard errors of the mean are only shown for the smallest and largest symbol size.

A mixed-measures ANOVA was conducted to explore the effects of elevation and size on accuracy of symbol identification, using Greenhouse-Geisser corrections to the degrees of freedom where necessary. Visual status (sighted or visually impaired) was used as a between-subjects variable. An overview of the results is shown in Table 3.2. There was a significant difference in accuracy between visually impaired and sighted participants ($F(1, 17) = 27.09, p < 0.001, \eta^2 = 0.61, \text{power} = 1.0$); visually impaired participants (mean accuracy = 82.4\%, $SD = 8.6$) performed better than sighted participants (mean accuracy = 60.7\%, $SD = 9.5$). Identification accuracy improved with increasing elevation ($F(2.46, 41.78) = 50.65, p < 0.001, \eta^2 = 0.75, \text{power} = 1.0$). Identification performance also improved significantly with increasing symbol size ($F(1.94, 32.96) = 63.63, p < 0.01, \eta^2 = 0.79, \text{power} = 1.0$). There were no significant interactions between elevation and visual status ($F(2.46, 41.78) = 0.73$.
$p > 0.05$, $\eta^2 = 0.04$, power = 0.18), size and visual status ($F(1.94, 32.96) = 1.53, p > 0.05$, $\eta^2 = 0.08$, power = 0.30), elevation and size ($F(8.17, 138.90) = 0.73, p > 0.05$, $\eta^2 = 0.04$, power = 0.33) or between elevation, size and visual status ($F(8.17, 138.90) = 1.53, p > 0.05$, $\eta^2 = 0.08$, power = 0.67). Due to the small effect size, combined with a relatively small number of participants, the analysis of most interaction effects does not have sufficient power to find significant effects.

<table>
<thead>
<tr>
<th></th>
<th>$F$</th>
<th>$p$</th>
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<td>Elevation X size</td>
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<td>Elevation X visual status</td>
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<td>Size X visual status</td>
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<td>$&gt; 0.05$</td>
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<tr>
<td>Elevation X size X visual status</td>
<td>1.53</td>
<td>$&gt; 0.05$</td>
<td>0.08</td>
<td>0.67</td>
</tr>
</tbody>
</table>

*Table 3.2 Effects of elevation, size and visual status on accuracy of symbol identification. Significant effects are indicated by *.

Figures 3.2 and 3.3 illustrate the improvements in performance with both increasing size and elevation for each visual status group. Although the patterns of identification across size and elevation were similar for visually impaired and sighted participants, visually impaired participants had a higher level of accuracy. Although the interactions between visual status and elevation or size were not significant, the power to detect these effects was low. A significant effect may occur with a larger sample size. Therefore, the trends in the data are discussed separately for visually impaired and sighted participants. On average, visually impaired participants reached the 80% correct level at an elevation of 14 $\mu$m for symbols of 5.5 mm in size. Symbols of 4.7 mm in size could be reliably identified at 22 $\mu$m. Identification of symbols that were 3.9 mm did not reach 80% at any elevation. Sighted participants could reliably identify the largest symbols (7.1 mm) at elevations of 22 $\mu$m and higher. Smaller symbols could not reliably be identified at any elevation. For both visually impaired and sighted participants, performance appeared to level off around 22 $\mu$m, where an increase in elevation did not further improve the accuracy of identification.

Post hoc pair-wise comparisons on the effects of elevation on the accuracy of identification revealed that symbol identification was significantly poorer on
elevations of 7 and 14 μm, than on all other elevations \((p < 0.05)\). Identification at 7 μm was also poorer than at 14 μm \((p < 0.05)\). There were no significant differences in accuracy of identification between elevations of 22 μm and above \((p > 0.05)\). This suggests that the performance curve levels off above 22 μm.

Post hoc pair wise comparisons on the effects of symbol size showed that there were significant differences in accuracy of identification between all symbol sizes \((p < 0.05)\), except between 5.5 and 6.3 mm in size \((p > 0.05)\).

### 3.2.3 Discussion

In this experiment, we studied the effect of symbol size and elevation on the accuracy of identification of tactile symbols. Participants identified simple shapes of 3.6 to 7.1 mm in size, at elevations ranging from 7 to 47 μm. As expected, both an increase in elevation and an increase in symbol size resulted in a higher accuracy of symbol identification. Since the accuracy curves typically levelled off by 22 μm in elevation, this suggests that the minimum elevation for reliable identification of individual symbols is around 22 μm.

No minimum values of size or height separately were found for identification of symbols above chance levels. The smallest symbols were identified above chance level at higher elevations. Likewise, the lowest symbols could be identified at larger sizes. Only a combination of low elevation and small size decreased performance to chance levels. In general, participants were able to identify symbols at remarkably low elevations and small sizes. Larger symbols could be reliably identified (> 80% correct) at 14 μm by visually impaired participants and at 22 μm by sighted ones. The smallest symbols that could be reliably identified by visually impaired participants measured 4.7 mm.

Our data suggest that symbols are identifiable at elevations and sizes that are considerably lower than usually recommended for symbols in tactile graphics. Decreasing symbol dimensions could improve legibility and production of tactile graphics. First of all, larger symbols take up more space on a map, resulting in
excessively large or ‘crowded’ graphics. Smaller symbols would allow for smaller and/or less cluttered maps. Secondly, in a deposition process like the TIMP printer, lower elevations can reduce printing time and the amount of ink being used, consequently reducing production costs. However, although the results of this study suggest that tactile symbols are legible at elevations and sizes that are smaller than usually recommended, these results cannot be translated directly into tactile map design. It should be taken into consideration that this study involved identification of individual symbols in isolation, and that reading a tactile map is a more complex process. A second study investigated the elevation of tactile symbols in a more realistic task.

3.3 Study B: Speed of symbol identification

Study A yielded minimum elevations and sizes at which individual symbols can be identified accurately. This information provided a baseline for the second study, in which the elevation of tactile symbols was considered in a more realistic context, by investigating the minimum elevation at which a tactile task could be performed quickly. We examined the speed of identification of symbols that were large and high enough to be accurately identified. We also attempted to apply previous findings on the tactile perception of edges and dot patterns to create more effective stimuli. Participants performed a timed search task on an array of symbols at several elevations and line types.

3.3.1 Methods

Participants

Nineteen volunteers took part in this study. Eight participants were sighted (2 male and 6 female, 18 to 30 years, mean age 22.5) and 11 were visually impaired (7 male and 4 female, 18 to 37 years, mean age 22.9). Details of the visually impaired participants’ characteristics can be found in Table 3.2. Visually impaired participants were recruited through the Royal National College and the Royal London Society for the Blind. Sighted participants were recruited at the University of Surrey.
<table>
<thead>
<tr>
<th>Age</th>
<th>Gender</th>
<th>Age at onset of blindness</th>
<th>Residual vision</th>
<th>Cause of blindness</th>
<th>Braille reader?</th>
</tr>
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<tbody>
<tr>
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</tr>
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<td>37</td>
<td>M</td>
<td>birth</td>
<td>No</td>
<td>Cerebral aneurism</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Table 3.3 Characteristics of the blind and visually impaired participants in Study 2 (all information obtained from participants' verbal reports).

Materials

Stimuli were printed on rough plastic, as suggested by the substrate study (Chapter 2), using the TIMP tactile printer. On the basis of crossing six elevations, three line types and two symbol arrays, 36 tactile displays were created. Symbols were printed at elevations of 20, 40, 80, 160, 320 and 640 μm, using 'smooth', ‘sharp’ and ‘rough’ line types. The lowest elevation of 20 μm was informed by the results of Study A, as this was the lowest elevation at which symbols could be accurately identified. The smooth line was a solid line with a convex line profile, while the sharp line had a triangular profile. The rough lines consisted of two parallel rows of small dots. Figure 3.5 shows a cross section of the line types. Due to limitations of the printing technique, rough lines could not be printed adequately at an elevation of 640 μm. Therefore, these displays were discarded. Each tactile display consisted of a six by six array of outline circles and outline circles with gaps of 45°. Gaps were positioned at the top, bottom, left or right side of the circle. Seven full circles, acting as target symbols, were randomly located on each display. Displays could be rotated to produce four different versions of the symbol array. Circles were 2.5 cm in diameter and had a line width of 1.6 mm. The circle arrays measured 20 by 20 cm. To the left of each row, a horizontal line was printed that enabled participants to keep track of their position on the display. Figure 3.6 shows an example of the displays.
Fig. 3.4 A) Top view of outline circles. B) Corresponding cross sectional profiles of smooth, sharp and rough line types.

Fig. 3.5 Example of a stimulus array.
Procedure
Participants were seated at a desk in a quiet room at their college or home. The experiment consisted of a tactile scanning task. Sighted participants and those with residual vision were blindfolded during the task. Participants were asked to scan the arrays of symbols as fast and as accurately as possible, proceeding from the top left corner to the bottom right corner and to give a verbal response when encountering a target symbol. Participants were asked to use their right hand to explore the rows of symbols. They used their left hand to keep track of their position by placing it on one of the horizontal lines to the left of each row. Full details of the instructions to participants can be found in Appendix E. After a practice trial, 17 displays were presented in random order, representing all possible combinations of elevation and line type. A digital video camera was used to record the amount of time that was needed to complete the 6 by 6 arrays.

Statistical methods
We manipulated elevation and line type, in order to find the optimal elevation and line type for the production of tactile maps. The dependent variable was the time (in seconds) it took participants to complete each display.

We hypothesised that an increase in elevation would lead to faster performance, but that this improvement would level off at an optimal elevation. In addition, we expected that rough and sharp lines would be easier to read than smooth lines.

The effects of elevation and line type on scanning time were analysed with an ANOVA, using a 2 (visually impaired or sighted) x 5 (elevations) x 3 (line types) design. Since rough lines were not printed at the highest elevation, this elevation was not included in the ANOVA. Post hoc pair-wise comparisons were used to identify significant differences. Linear fits were made to the data in order to determine the optimal elevation at the point where an increase in elevation did not further increase performance.
3.3.2 Results

The aim of this study was to investigate the effects of line type and elevation on performance of an identification task. We recorded the time it took participants to scan arrays of symbols, from the moment participants touched the first symbol in the display until they left the last symbol ($M = 111.3$ s, $SD = 85.8$ s). Figures 3.7, 3.8 and 3.9 show mean scanning times for visually impaired and sighted participants.

**Fig. 3.6** Mean scanning time on arrays featuring several line types and elevations (visually impaired participants). Error bars indicate the standard errors of the mean.

**Fig. 3.7** Mean scanning time on arrays featuring several line types and elevations (sighted participants). Error bars indicate the standard errors of the mean.
The number of errors on each trial was very small ($M = .43$, $SD = 1.1$), including false positives and missed identifications of the target symbol. A Pearson correlation was used to determine the relationship between scanning time and number of errors. A negative correlation could indicate a trade off between speed and accuracy. However, the analysis showed that there was a positive correlation between scanning time and number of errors ($r = .34$, $p < .001$), and therefore there was evidence that there was no trade off between speed and accuracy. This correlation suggests that participants' performance was both slower and less accurate on more difficult arrays.

A mixed between-within subjects ANOVA was conducted, to investigate the relationship between elevation and line type with scanning time, using a Greenhouse-Geisser correction to the degrees of freedom (see Table 3.4 for an overview of results). We used elevation and line type as within-subjects variables and visual status (sighted or visually impaired) as a between-subjects variable. This analysis did not include the highest elevation of 640 μm, because no data was available for rough lines at that elevation. Visual status affected scanning time significantly ($F(1, 17) = 16.49$, $p < 0.001$, $η^2 = 0.49$, power = 0.97); visually impaired participants performed the task faster than sighted people ($M_{VI} = 81.3s$, $SD = 52.2s$ and $M_{sighted} = 155.3s$, $SD = 104.7s$). Scanning time decreased with increasing elevation ($F(1.2, 20.9) = 49.68$, $p < 0.001$, $η^2 = 0.75$, power = 1.0). Post hoc pair wise comparisons showed that there were significant differences in scanning time between all elevations ($p < 0.01$) that were included in the analysis. Line type also had a significant effect on performance ($F(2, 34) = 24.28$, $p < 0.001$, $η^2 = 0.59$, power = 1.0). Post hoc comparisons showed that rough lines were scanned faster than sharp and smooth lines ($p < 0.05$), and smooth lines were scanned faster than sharp ones ($p < 0.05$). The interaction between line type and elevation was significant ($F(1.9, 32.5) = 3.70$, $p < 0.05$, $η^2 = 0.18$, power = 0.63), as was the interaction between elevation and visual status ($F(1.2, 20.9) = 8.46$, $p < 0.05$, $η^2 = 0.33$, power = 0.84). However, the effect sizes of these interaction effects were quite small. There was no significant interaction between line type and visual status ($F(2, 34) = 0.72$, $p > 0.05$, $η^2 = 0.04$, power = 0.15) and no significant interaction between elevation, line type and visual status ($F(1.9, 32.5) = 2.05$, $p > 0.05$, $η^2 = 0.11$, power = 0.38).
Table 3.4  Effects of elevation, line type and visual status on scanning speed. Significant effects are indicated by *.

To explore the interaction between line type and elevation, we made linear fits to the scanning time data. This post-hoc analysis allowed us to verify the optimal elevation for performance of the scanning task. The data suggest that performance levels off at 160 µm, as the graph shows an ‘elbow’ at this point. In order to confirm that an increase in elevation over 160 µm did not lead to a further decrease in scanning time, we explored the slope of fitted lines at higher elevations. For each participant, we fitted three lines to the data on scanning time. One line was fitted to the data points of the smooth line types at 160, 320 and 640 µm (mean \( R = 0.76, SD = 0.25 \)). Similarly, a line was fitted to the data points of the sharp line type (mean \( R = 0.86, SD = 0.17 \)). Since the rough line type was not produced at 640 µm, the third fitted line simply connected the rough data points at 160 and 320 µm (\( R = 1 \)). One-sample t-tests were conducted to compare the slopes of the fitted lines to a slope of 0.

Since there was a significant difference between visual status groups and a significant interaction between elevation and visual status, linear fits of visually impaired and sighted participants were analysed separately. The slopes of the smooth line (mean_{VI} = -0.23, SD_{VI} = 0.66, mean_{S} = -0.48, SD_{S} = 1.19) and rough line (mean_{VI} = -0.02, SD_{VI} = 0.06, mean_{S} = -0.04, SD_{S} = 0.13) were not significantly different from 0 (Visually impaired: \( t(9) = -1.10, p > 0.05 \) and \( t(9) = -1.52, p > 0.05 \); Sighted: \( t(8) = -1.20, p > 0.05 \) and \( t(8) = 0.89, p > 0.05 \)). However, the slope of the sharp line (mean_{VI} = -0.03, SD_{VI} = 0.03, mean_{S} = -0.08, SD_{S} = 0.06) was significantly different from 0 (Visually impaired: \( t(9) = -3.34, p < 0.05 \); Sighted: \( t(8) = -4.41, p < 0.04 \)). This slope, however, is very shallow and is unlikely to have any practical consequences.
3.3.3 Discussion

In this study, participants performed a timed search task on an array of symbols at different elevations and line types. Our findings confirm the hypothesis that an increase in elevation would lead to better performance, up to a certain elevation. Performance levels rose steeply by increasing the elevation of symbols up to 160 μm, but a further increase in elevation did not affect performance.

Based on the findings of neurophysiological studies on mechanoreceptor responses to edges (LaMotte and Srinivasan, 1987; Srinivasan and LaMotte, 1987), we expected that sharp lines could be read at lower elevations than curved, smooth lines. This did not appear to be the case. On the contrary, we found that the sharp lines in our setting were more difficult to read at lower elevations. These results could be due to the shape of the line types. At similar elevations, triangular sharp lines contained a smaller amount of raised material than semi-circular smooth lines. Possibly, the mechanoreceptors in the fingertip responded to the volume of the material, as well as to the elevation and edges. This volume effect did not appear in previous studies, since they investigated the mechanoreceptor response to a single edge on a stair-like step, which did not involve the same variation in volume as profiled lines. However, Goodwin et al. (1991) touched on this issue in their paper on the discrimination of curved surfaces. Circumventing the issue of volume differences, it might be possible to take advantage of the edge effect by using a rectangular line profile with two sharp edges and a similar volume to smooth lines.

We further found that rough lines were read more quickly than smooth and sharp lines. This was expected, as previous work suggests sharp edges, such as those of the dots, cause a stronger mechanoreceptor response and that dot patterns provide repeated presentation of edges as the finger traces the line, which may have caused a continual response in both RA and SA receptors (Phillips et al., 1992). We also speculate that the orientation of ‘attack’ on the fingertip plays a role. Finger movement needs to be perpendicular to the orientation of a raised edge in order for the edge to be of maximum effect. When tracing a solid line, the edge of the line stays in more or less the same position on the fingertip and, therefore, may not cause maximum edge effect. The edge will be more perceptible if the finger scans at 90
degrees across the line, because the edge will move across a larger number of receptors. In the case of a dotted line, the finger will always move perpendicularly across edges of individual dots, regardless of the orientation of movement of the finger.

This study also attempted to find the optimal elevation for tactile images, represented by the lowest elevation at which tactile symbols could be identified quickly. At this elevation, resources (ink and printing time) are minimised and performance is maximised. In order to find the optimal elevation, we identified the ‘elbow’ in the graph. Although visually impaired participants performed the task faster and appeared to be less affected by a decrease in elevation, the pattern of results for visually impaired and sighted participants was comparable. The amount of time needed for scanning arrays decreased sharply as elevation was increased from 20 to 160 μm. Increasing elevation further did not decrease scanning time. This suggests that 160 μm is the optimal elevation for raised lines on tactile maps.

3.4 General discussion

The aim of the studies reported here was to identify the minimum elevation at which tactile symbols can be identified accurately and quickly. The studies extended previous psychophysical work on elevation, by comparing performance across two tasks of increasing ‘ecological validity’ (defined as the extent to which a task reflects demands of a real world task - in this case interrogating a tactile map or diagram for information). Study A compared with previous psychophysical studies, in which individual tactile stimuli are examined in isolation, but here we focused on symbol identification rather than simple detection or discrimination. Previous studies suggested that spatial tactile resolution may range between 0.87 and 2.36 mm (Craig, 1999; Johnson & Phillips, 1981; Nefs et al., 2001; Stevens & Cruz, 1996; van Boven & Johnson, 1994), and that tactile features could be detected at an elevation of 0.85 μm (Johansson & LaMotte, 1983). This study showed that active identification of symbols requires higher elevations (higher than 22 μm) and larger sizes (larger than 5.5 mm) than detection and discrimination.
After determining the minimum elevation for accurate identification of individual symbols in Study A, Study B showed that elevation needs to be increased significantly for performance to be maintained in the context of a more complex task. However, the optimum elevation indicated (0.16 mm) is considerably lower than would be predicted on the basis of existing tactile maps and existing design guidelines. These studies give a strong indication that tactile map features need not be as high as is typically recommended. The use of a low elevation on an actual map will be investigated in Chapter 6.

In addition to considering the results of these studies for the design of tactile maps, it is important to take into account user preference and experience. For example, although performance on the rough lines was better than on the two smooth line types, extended exposure to rough line types during map-reading might result in the fingertips becoming desensitised, or even painful. Secondly, regardless of the optimum elevation found in this study, users may happen to prefer higher lines. A previous study on the use of substrate materials (see Chapter 2 and Jehoel et al. (2005)) showed that some users reported a preference for smoother background substrates while performing better on rougher substrates, indicating that preference may not simply be determined by effectiveness of use.

We attempted to use previous research on the neurophysiology of touch to design more effective tactile features. This research suggested that sharp and dotted lines may be easier to read than smooth lines. Although performance on dotted lines improved according to expectations, sharp lines were more difficult to use than smooth lines. This discrepancy demonstrates the difficulty in generalising neurophysiological research to performance in practical tasks. Tactile perception is a complex process, which involves cognitive processing in the cerebral cortex based partly on physiological responses in a large number of receptors. Therefore, the response of a single cell, as measured in neurophysiological research, does not necessarily translate into the actual perception of a feature. However, the success of the dotted line and the possible explanation for the failure of the sharp line suggest
that considering the mechanisms of tactile perception can be valuable for the design of practical tactile tasks.
4 Identification of single and double lines: tactile acuity

After investigating basic map components (the substrate material and the elevation of tactile features), we progressed to examining tactile symbols. This study dealt with the perception of single lines and double lines of varying gap widths.

4.1 Introduction

Since the sense of touch has a lower spatial acuity than the sense of vision, tactile features need to be of a lower resolution than visual features in order to be perceived correctly. This difference between vision and touch has implications for tactile map design. It is not possible to produce a useful tactile map simply by creating a relief version of a visual map. Features on a tactile map need to be larger and more widely spaced. Guidelines for the design of tactile maps (American Printing House, 1997; Gardiner & Perkins, 2002a; Tactimages & Training, 2000) and map producers (Rowell & Ungar, 2003c, 2003d) emphasise the importance of size and spacing of tactile features. Guidelines recommend a widely varying range of separation distance of 2.3 to 8 mm between symbols (American Printing House, 1997; Canadian Braille Authority, 2003; Edman, 1992; Gardiner & Perkins, 2002a; Tactimages & Training, 2000), in order to ensure that the gap between map features can be perceived. However, there is no experimental research to suggest the minimum distance between features that can be used in practise. In this paper, we investigate the minimum gap distance between the two elements of double lines that is required to correctly discriminate between single and double lines.

4.1.1 Previous psychophysical studies

Psychophysical studies can shed some light on the tactile acuity of the fingertip. Attempts have been made to study this sensitivity in a variety of ways. One of the earliest measures of tactile acuity is the two point limen test. During a typical two point limen test, two points of contact are pressed onto the skin. The separation
between the points varies from zero to a given distance. After each presentation, the participant decides whether the stimulus felt like one or two points. The smallest distance at which two points can be discriminated, is considered to be the threshold of spatial acuity. Almost 200 years ago, Weber (1834) acted as his own participant, applying the two point limen test to various parts of his body. He found that two contact points could be clearly distinguished at the fingertip at a separation distance of 1.25 mm. In a more recent experiment, Stevens et al. (1996) studied the decline of tactile acuity as a function of age. They conducted a two point limen test, using a forced choice staircase methodology, and found an average two point threshold of 1.01 mm for blind and 1.21 mm for sighted participants between 18 and 81 years of age. Acuity deteriorated with age at a rate of 1% threshold rise per year.

A number of critics have suggested that the two point limen test is not a measure of spatial acuity. Johnson et al. (1994) and Craig and Johnson (2000) published an overview of these criticisms. The first problem relates to the way in which stimuli are judged. Participants are usually asked to respond “two” when they perceive two distinct points of contact. However, the change in perception between one and two points is gradual, ranging from the impression of a point, circle, line, ‘dumbbell’ to two distinct points (Boring, 1942). Therefore, the judgement “two” is subjective and varies between and within participants. It is possible to infer the presence of two points without perceiving two separate points of contact. Weber (1834) reported perceiving the orientation of two points without being able to perceive the two points separately. A second problem regarding the two point limen test, is the finding that participants can discriminate between a single point and two points with zero separation. Titchener (1916) suggested this discrimination is possible because one point feels sharper than two points in apposition. Johnson and Philips (1981) provided a similar explanation. Two apposed points differ from one point in contact area and overall dimensions, triggering a different afferent discharge from the nerve endings. A two point stimulus causes higher intensity of the afferent signal. Therefore, discrimination between one and two points might be based on intensive cues rather than on spatial information.
One of the problems regarding the two point limen task is the difference in overall dimensions and contact area between the stimuli. Gap detection tasks were developed to overcome this problem. Participants discriminate between stimuli with and without gaps. The overall dimensions of the stimuli are constant and gaps are small in relation to the contact area. In a study by Johnson and Philips (1981), participants discriminated between two circular disks; one containing a small gap in the outside edge of the cylinder, and the other containing no gap (Fig. 4.1A). Disks containing gaps of 0.87 mm were reliably identified as such. A similar study (Stevens et al., 1996), using a forced choice staircase methodology, showed a gap detection threshold at 2.0 mm. A second study by Stevens et al. used bars with a gap (two squares with a gap of varying size between them) and bars having the same total length but no gap (Fig. 4.1B). Participants were presented with pairs of stimuli, and decided which one contained a gap. In this case, thresholds ranged from 1.18 mm for young, blind participants to 2.81 mm for elderly, sighted participants. The differences in threshold levels between Johnson and Stevens could be explained by their different methodologies, or by the fact that Stevens' participants were considerably older.

![Fig. 4.1 Sketches (not to scale) of stimuli for gap detection studies using (A) disks, (B) bars and (C) stimuli for grating studies.](image)

Translating the results of gap detection studies into tactile acuity levels is still problematic. Although the overall dimensions of the stimuli are held constant, intensive cues might still play a large role (Johnson & Phillips, 1981). A higher neural sensitivity to edges than to flat surfaces (Philips & Johnson, 1981) is likely to cause a higher afferent discharge for stimuli with gaps. In addition, the contact area differs for stimuli with and without gaps, causing another difference in discharge.
Again, discrimination between stimuli in gap detection tasks is likely to be based on information other than spatial cues.

More recently, grating orientation studies have been developed, which involve asking participants to identify the orientation (horizontal or vertical) of a small array of parallel lines (Fig. 4.1C). In grating orientation studies, an attempt is made to vary spatial information only, while keeping non-spatial variables (such as contact area and presence of edges) constant, in order to give a better indication of tactile acuity. The stimuli consist of gratings of parallel lines with varying groove width (i.e. distance between the lines). The gratings are pressed onto the participant’s fingertip. Tactile acuity is determined by the smallest spatial frequency of lines at which participants are able to identify the orientation of the grating. Several studies have involved grating orientation (Craig, 1999; Craig & Lyle, 2001; Essock et al., 1997; Grant et al., 2000; Johnson & Phillips, 1981; J. W. Morley et al., 1983; Sathian et al., 1997; van Boven et al., 2000; van Boven & Johnson, 1994). In these studies, the threshold for correct identification of gratings ranged between a groove width of 0.65 and 1.19 mm.

4.1.2 Previous neurophysiological studies

In addition to the psychophysical studies described above, neurophysiological studies can also provide information on the spatial acuity of the fingertip. Perception of tactile features depends to a large extent on the response of mechanoreceptors in the fingertip, in addition to feedback from proprioception. In relation to identification of single and double lines, the mechanoreceptor responses to raised lines at varying widths and separation distances are crucial. A mechanoreceptor afferent only gives a maximum response to a raised bar if that bar is separated from other tactile features by a certain distance, as shown by a study on the neural representation of bars (Phillips & Johnson, 1981). In this study, gratings were pressed onto the finger pad of anesthetised monkeys and neural responses were measured directly at the mechanoreceptive fibres. Figure 4.2 shows the effect of separation distance on afferent discharge in the monkey finger pad. The firing rate for bars that are close together (peak 2 and 3) was very low. The firing rate increased with increased...
distances between the bars, until a plateau was reached (peak 8). By examining the responses to the bars indicated by arrows (\(^\circ\)) in Figure 4.3, it is clear that the fingertip is highly sensitive to edges. A narrow edge caused a single peak of mechanoreceptor responses. Wider bars caused a double peak, where receptors responded to both edges of a single bar. A study by Blake et al. (1997b) showed a similar edge effect. Raised squares of varying sizes were pressed onto the monkey finger pad. Small squares caused a single concentrated response pattern, whereas larger squares caused mechanoreceptor responses around the edges.

Fig. 4.2 Mechanoreceptor response profile to bars with varying separation distances pressed onto the monkey finger pad (Figure taken from (Phillips & Johnson, 1981))
Fig. 4.3 Mechanoreceptor responses to bars of varying width pressed onto the monkey finger pad (Figure taken from (Phillips & Johnson, 1981), arrows added).

The psychophysical and neurophysiological studies mentioned above shed some light on the tactile acuity of the fingertip in controlled, experimental settings. These experiments involved static, passive touch. This is very different from the way touch is used in realistic settings (e.g. exploring a tactile map), in which active touch and finger movements are used. Katz (in Krueger (1970)) was the first to argue that motion between skin and surface is important for tactile perception. He also argued
that there is a distinction between the quality of passive touch, where movement is not controlled by the observer, and active touch, where the observer controls movement (Gibson, 1962, 1966; Krueger, 1970). However, some studies suggest that, depending on the tactile task, there is no difference between active and passive touch (Lederman, 1981; Vega-Bermudez et al., 1991). In this study, we wanted to investigate tactile acuity in a realistic setting, involving active, moving touch, and compare our results to findings from previous studies on tactile acuity involving passive, stationary touch.

4.1.3 The current study

The aims of this study were twofold. Firstly, we aimed to identify the minimal separation distance of two elements of a double line for the use of double lines on tactile maps. Secondly, we wanted to investigate to what extent tactile sensitivity in a practical task corresponded to the findings of highly controlled psychophysical and neurophysiological studies. Our experimental task involved identifying single and double lines, at varying gap widths (double lines) and line widths (single lines). A realistic task was used, in which participants could explore the lines freely and were set a reasonable time limit for exploration.

Based on the results of previous studies, we expected accuracy of identification of double lines to decrease as gap width decreased. We also expected that single lines may be perceived as double lines.

In addition to varying the width of gaps between double lines and the width of single lines, orientation was used as a variable. Lines were presented horizontally and vertically. We expected performance to be better on vertical lines. Psychophysical and neurophysiological studies suggest that tactile sensitivity might be higher for stimuli that are parallel to the axis of the finger, and lower for stimuli that are orthogonal to the finger axis (Blake et al., 1997b; Essock et al., 1997; Phillips & Johnson, 1981; Wheat & Goodwin, 2000).
This study was performed as a distraction task within a study on the discriminability of symbols (see Chapter 5). A more detailed discussion of the implications of this method can be found in Section 5.1.3 and Section 5.6.1.

4.2 Methods

4.2.1 Participants

Ten sighted and ten visually impaired people participated in the study. The sighted participants (3 males and 7 females) were students at the University of Surrey. Their ages varied between 19 and 48, with a mean age of 24.8 years. The visually impaired participants (4 males and 6 females) studied at the Royal National College Hereford or were connected to the Surrey Association for the Visually Impaired. Their ages ranged between 17 and 52, with a mean age of 29.1 years. Seven visually impaired participants were totally blind and 3 had residual vision. Table 4.1 provides more information about the visually impaired participants.

<table>
<thead>
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<th>Gender</th>
<th>Age at onset of blindness</th>
<th>Residual vision</th>
<th>Cause of blindness</th>
<th>Braille reader</th>
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<tr>
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<td>F</td>
<td>Birth</td>
<td>Yes</td>
<td>Retinopathy of prematurity</td>
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<td>Birth</td>
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<td>Retinitis pigmentosa</td>
<td>Yes</td>
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Table 4.1 Characteristics of the visually impaired participants (all information obtained from participants’ verbal reports).

4.2.2 Materials

Presentation materials

The TIMP tactile inkjet printer produced single and double lines on rough plastic, blank business cards (54 x 85 mm), as suggested by the study on substrate materials
The cards were presented in an MDF jig with slots for the cards. The slots were 14 mm apart on a horizontal line. Small indentations along the base of the jig indicated the position of the corresponding symbols. The jig was placed on a table in front of the participant. Figure 4.4 illustrates the presentation of stimuli. The first and the last slot on the jig were used for a paired comparison study on the discriminability of symbols (Chapter 5), within which the current study was used as a distraction task. A laptop indicated the time limit for each line symbol by beeps.

Fig. 4.4 The presentation jig with 3 stimulus cards in the centre, bordered by two point symbols that were part of a study on symbol discrimination.

**Stimuli**

Lines were 50 mm long and 0.19 mm in elevation. Single and double lines were used. The double lines varied in the width of the gap between them. There were 8 gap widths. The smallest and largest gap widths were 0.2 and 2.1 mm respectively. Gap width varied with increments of approximately 0.27 mm. In addition to gap width, individual line width was a variable of the double lines. Over all gap widths, two line widths were used; 0.7 and 1.3 mm. These lines will be referred to as thin and thick lines, in order to avoid confusion with the variable of line width. The width of the thin and thick lines added to the overall width of the double line and did not influence gap width. For example, the widest double line consisting of thin individual lines had an overall width of 3.5 mm (0.7 mm line + 2.1 mm gap + 0.7 mm line). The widest double line consisting of thick individual lines had an overall width of 4.7 mm (1.3 mm line + 2.1 mm gap + 1.3 mm line). The width of the single lines corresponded to the overall widths of the double lines. In order to accommodate all widths of the double lines, 13 single lines were produced. The narrowest and widest single lines were 1.4 and 4.7 mm respectively. Again, width varied with increments of approximately 0.27 mm. Single and double lines were oriented both
horizontally and vertically. In total, 58 cards were used; 26 single lines (13 widths x 2 orientations) and 32 double lines (8 gap widths x 2 line widths x 2 orientations).

4.2.3 Procedure

A forced choice paradigm was used, in which participants were asked to identify each line as single or double. The participants were told that the width of a line was unrelated to it being single or double. Each participant completed 3 randomised sets of lines, resulting in 174 responses (3 x 58 lines). Each trial consisted of three lines. Participants were asked not to use their nails. Sighted participants and those with residual vision were blindfolded. Participants used one hand of their own choice to explore the lines, moving from left to right across the jig. They were allowed to swap hands during the experiment. Choice of hand (left or right) was not recorded. Participants were seated at a desk in a quiet room at their college or home. Full details of the instructions to participants can be found in Appendix E.

Similar to the study on accuracy of symbol elevation (see Chapter 3), the current task was used as a distraction task for a paired comparison study involving two point symbols at the far sides of the jig (see Chapter 5). The implications of embedding a task in another experiment were discussed in Section 3.2.1. The amount of time available to explore each line was controlled by beeps at intervals of 5 seconds. Each beep prompted participants to move their hand to the next line. All participants were able to locate and explore a line and to give a response within the 5 seconds time limit. The experimenter recorded the responses.

4.2.4 Statistical procedure

In this study, we investigated the identification of single and double lines. Data for single and double lines were analysed separately. For double lines, we manipulated three variables: gap width (8 gap widths), line width (think or thin) and orientation (vertical or horizontal). For single lines, we manipulated two variables: line width (13 line widths) and orientation (vertical or horizontal). Each stimulus line was presented three times. Accuracy of identification was the dependent variable, expressed as the number of errors (0 to 3) on each line.
Several hypotheses were formulated. We expected accuracy of identification of double lines to decrease as gap width decreased and line width increased. We also expected that single lines may be perceived as double lines. We expected that performance on vertical lines may be better than on horizontal lines.

Data were analysed by separate ANOVAs for single and double lines. For double lines, a 2 (visually impaired or sighted) x 8 (gap widths) x 2 (thick or thin) x 2 (vertical or horizontal) ANOVA was used. For single lines, we used a 2 (visually impaired or sighted) x 13 (line widths) x 2 (vertical or horizontal) ANOVA. Post hoc pair-wise comparisons were used to identify differences.

4.3 Results

Participants were asked to identify single and double lines. The number of errors in identification (0 to 3) of each participant on each of the 58 lines was recorded. Figures 4.5 and 4.6 show the percentage correct identification across participants for each line, respectively by gap width and by line width. These graphs do not contain error bars, since a standard variation based on the three trials per line per participant was not meaningful.
A mixed-measures ANOVA was conducted to explore the effects of line width (thick or thin), orientation (vertical or horizontal) and gap width (0.2 to 2.1 mm) on the identification of double lines, using Greenhouse-Geisser corrections to the degrees of freedom.
freedom where necessary. A full overview of all effects can be seen in Table 4.2. Visual status (sighted or visually impaired) was used as a between-subjects variable, but was not significant ($F(1, 18) = 2.52, p > 0.05, \eta^2 = 0.12, \text{power} = 0.32$). Identification performance was better on thin than on thick lines ($F(1, 18) = 21.53, p < 0.005, \eta^2 = 0.55, \text{power} = 1.0$). Performance was also better on vertical lines than on horizontal lines ($F(1, 18) = 89.14, p < 0.005, \eta^2 = 0.83, \text{power} = 1.0$). An increase in gap width significantly improved the accuracy of identification ($F(7, 126) = 68.95, p < 0.005, \eta^2 = 0.79, \text{power} = 1.0$). Post hoc pair-wise comparisons, using a Bonferroni correction for multiple comparisons, showed that the accuracy of performance on each of the double lines with smaller gap widths (0.2, 0.5 and 0.8 mm) was significantly different from the performance on all other lines ($p < 0.05$), except for the difference in performance between lines with a gap width of 0.8 and 1.0 mm ($p > 0.05$). There were no significant differences in performance between lines with a gap width of 1.0 mm and wider ($p > 0.05$), suggesting that an increase in gap width over 1.0 mm did not improve the accuracy of identification of double lines. After exploring the interaction effects between all variables, three significant interactions appeared. At smaller gaps widths, vertical lines were more often identified correctly than horizontal lines ($F(7, 126) = 37.02, p < 0.005, \eta^2 = 0.67, \text{power} = 1.0$). In addition, thin lines were more often identified correctly than thick lines at smaller gap widths ($F(7, 126) = 7.76, p < 0.005, \eta^2 = 0.30, \text{power} = 0.99$). Thirdly, there was an interaction between orientation, line width and gap width ($F(7, 126) = 5.90, p < 0.005, \eta^2 = 0.25, \text{power} = 0.96$)
A second ANOVA was conducted to explore the effects of line width (1.4 to 4.7 mm), orientation (horizontal or vertical) and visual status (sighted or visually impaired) on the identification of single lines (see Table 4.3). Visual status (sighted or visually impaired) was used as a between-subjects variable, but was not significant \((F(1, 18) = 0.78, p > 0.05, \eta^2 = 0.04, \text{power} = 0.13)\). There was no significant effect of line orientation on performance \((F(1, 18) = 0.64, p > 0.05, \eta^2 = 0.03, \text{power} = 0.12)\). Line width had a significant effect on the accuracy of identification of single lines \((F(12, 216) = 6.48, p < 0.005, \eta^2 = 0.27, \text{power} = 0.99)\). Post hoc pairwise comparisons, using Bonferroni corrections for multiple comparisons, showed that identification of lines at 1.4, 1.7 and 1.9 mm wide was better than identification of lines at 3.0 mm \((p < 0.005)\) and 3.5 mm wide \((p < 0.07)\). The ANOVA showed a significant interaction effect between orientation and width \((F(12, 216) = 3.50, p < 0.005, \eta^2 = 0.16, \text{power} = 0.89)\); identification of the vertical lines was better than the horizontal lines at 2.2 and 3.0 mm \((p < 0.05)\).
4.4 Discussion

4.4.1 Discussion of results

This study investigated the identification of double and single lines. The gap width between the two elements of double lines was varied, as was the line width of single lines. In general, double lines were reliably (> 80% correct) identified at gap widths of 1 mm and larger. A decrease in gap width resulted in a poorer performance. Single lines were reliably (> 80% correct) identified at most line widths. However, performance was optimal (close to 100% correct) at line widths up to 1.9 mm.

One of the aims of this study was to investigate how psychophysical studies on tactile acuity and neurophysiological studies on mechanoreceptor responses correspond to performance in a more practical task. Studies on touch generally involve passive, static touch, and are conducted in a very controlled manner. In our study, participants were able to actively explore stimuli freely. One could argue that imposing a time limit of five seconds per line identification was not entirely realistic. However, the allotted time appeared to be adequate; participants often identified lines before the time limit was reached. In addition, it would not be practical to spend more than five seconds on identifying a single symbol on a map. Interestingly, despite the methodological differences, the results of our study compare closely to and can be explained by psychophysical and neurophysiological findings.
In our study, we found that double lines could be identified correctly at gap widths of at least 1 mm. This corresponds to measures of tactile acuity identified in previous psychophysical studies (see Section 4.1.1). These studies found that tactile features needed to be separated by 0.65 to 2.81 mm, depending on the task and the sample of participants. Our results are within the low end of this range. In fact, the thin vertical double lines in our study were correctly identified 80% of the time at gap widths as small as 0.2 mm, which implies a much higher tactile sensitivity than previously found in psychophysical studies. This could be due to the beneficial effects of active touch with free movements. However, it could also reflect perceptual differences that are unrelated to the spatial resolution of touch. The arguments against many of the tests of tactile acuity described in the introduction could apply here as well. Firstly, double lines have a smaller contact area than single lines of the same overall width, possibly causing a difference in firing rate of the mechanoreceptors. Secondly, the presence of more edges could result in a higher afferent discharge for double lines, due to the edge effect. Thirdly, movement of the finger tip over the stimuli may play a role. A double line may feel rougher than a single line, due to the extra edges. This roughness may provide information about the type of line, even if the gap itself cannot be perceived.

The result of this study also fit in well with neurophysiological research on touch (see Section 4.1.2). The mechanoreceptors in the finger tip respond minimally to passively presented raised bars that are close together. However, bars that are separated by more than 0.75 to 1 mm trigger a considerably higher response peak (see Figure 4.2). This corresponds closely to the findings of our study, where double lines could be identified correctly at gap widths of 1 mm. Similarly, identification of single lines appears to be governed by the responses of receptors in the finger tip. As suggested by Philips and Johnson, single bars that are wider than approximately 2 mm cause a clear double peak in the mechanoreceptor response profile. Our data show that, even with active touch, single lines with a width of at least 2.2 mm were occasionally perceived as double lines. These findings suggest that there may be a direct relationship between the mechanoreceptor activity at cellular level, and the higher level functions of tactile perception and identification, even in a practical task involving active touch.
Our participants explored rows of stimuli that were positioned in front of them in a left-to-right orientation. Although participants were mostly unrestricted in their hand movements, the request to explore rows of stimuli from the left to the right meant that horizontal stimuli were mainly positioned across the finger axis, and that vertical stimuli were mainly positioned along the finger axis. Identification performance was better on vertical double lines than on horizontal ones. This conforms with psychophysical and neurophysiological studies, which suggest that tactile sensitivity is greater along than across the finger axis (Blake et al., 1997b; Essock et al., 1997; Phillips & Johnson, 1981; Wheat & Goodwin, 2000).

In addition to the effects of orientation on stationary touch, we speculate that the direction of movement across the stimuli plays a role in the difference in performance between vertical and horizontal stimuli. Since edges cause a high mechanoreceptor response, the orientation of ‘attack’ on the fingertip might be important. Finger movement needs to be perpendicular to the orientation of a raised edge in order for the edge to be of maximum effect. When finger movement and orientation of a line are in the same direction (e.g. tracing a horizontal line with a horizontal movement), the edge of the line stays in more or less the same position on the fingertip and, therefore, may not cause maximum edge effect. The edge is likely to be more perceptible if the finger scans at 90 degrees across the line. This way the edges move across the fingertip, stimulating a large number of mechanoreceptors along the way, and avoiding adaptation of the receptors. As explained above, participants were likely to move their fingers horizontally over all stimuli, due to the experimental set up. This could explain the higher score on vertical double lines.

In addition to gap width of double lines, line width of single lines and orientation, we varied the width of the two elements of the double lines. Performance was better on thin lines than on thick lines. These findings are supported by neurophysiological studies, in which narrow bars were related to clearer mechanoreceptor response peaks at smaller gap widths than wide bars (Phillips & Johnson, 1981).
There was no significant difference in performance between sighted and visually impaired participants in the current study. This may be due to the nature of the task. Generally, visually impaired participants may perform better than sighted in tasks that benefit from the use of experience (see Chapter 7 for a more detailed discussion of the differences between sighted and visually impaired participants). Since performing the current task involved basic skills and was limited by tactile sensitivity, performance was not expected to improve with practice. This finding corresponds with several studies that also found no differences in performance on tactile tasks between visually impaired and sighted participants (Grant et al., 2000; Heller, 1988, 1989b; Pascual-Leone & Torres, 1993). Alternatively, the lack of significant differences between sighted and visually impaired people on the identification of double lines could be due to low statistical power. Our results suggest that the possible effects of visual status might be small. If there were a small difference, we might have been able to detect it by using a larger number of participants, thereby increasing the statistical power.

4.4.2 Practical considerations

These findings have implications for tactile map design. They suggest that double lines on a map should have a gap width of at least 1 mm to be correctly perceived as a double line. However, if the gap width is too large, the double line on a map might be incorrectly perceived as two individual single lines. It is not clear how large the maximum gap width for a double line is, but common sense suggests that both elements of the double line should fit under the finger tip. According to our results, wider single lines are sometimes incorrectly perceived as double lines. In order to avoid confusion on a tactile map, the width of single lines should not exceed 1.9 mm.
5 Discriminability of point and line symbols

In previous chapters, we studied basic components of tactile maps (substrate material and elevation of features) and perception of small elements of individual symbols (single and double lines). In this chapter, we progressed to combinations of symbols. We studied the discriminability of point and line symbols, and explored the principles of symbol discriminability.

5.1 Introduction

Exploring a tactile map is a complex process, which involves scanning small areas of a map and committing them to memory. It is important to facilitate map reading as much as possible, by producing maps that are easy to understand. The discriminability of symbols is an important aspect of a map’s legibility. A highly discriminable set of symbols contains symbols that are not easily confused with each other. In this study, we identified a set of highly discriminable point and line symbols, and investigated general principles that govern symbol discriminability.

5.1.1 Previous studies on symbol discriminability

Since the 1950s, several studies have been conducted on tactile symbol discriminability. These studies aimed to find discriminable symbols for use on tactile maps, and used similar methods involving pair-wise comparisons of symbols. Below is a chronological overview of studies to date.

In 1958, Heath conducted a pioneer study on the discriminability of tactile symbols, as part of his doctoral research. This study examined the discriminability of area symbols that were produced by solid dot Braille printing, in which heat-sealing drops of plastic ink are deposited on a paper substrate. Heath’s symbol set contained 40 area symbols, selected to give a wide variety of structures. These symbols were randomly divided into 4 groups of 10 symbols, within which paired comparisons
were made during testing. Each group of symbols was presented to 50 or 60 participants. Participants compared two symbols simultaneously, with one hand on each symbol. Paired comparison matrices were produced, calculating the number of errors between each combination of symbols. Unfortunately, these matrices were not published. Instead, a general table was published, which showed the total number of errors (self confusions and confusions with any other symbol within the group) for each symbol. The table also showed the rank order of discriminability of each symbol across the entire set of 40 symbols. This presentation of results poses two problems. Firstly, it does not allow for a thorough examination of discriminability of the symbols, because the total number of confusions for a symbol depends to a large extent on the make-up of the other symbols in its group. A high confusion score could mean that the symbol was confused with many other symbols in its group, or it could mean that it was often confused with a single other symbol. Secondly, the rank order of discriminability is problematic. Since the symbols were tested within groups of 10, it is not possible to compare discriminability across these groups by extending the rank order across the entire set of symbols. Although Heath's methods did not allow him to suggest a discriminable set of area symbols, his thesis set the stage for further studies on tactile symbol discriminability.

As an extension of Heath's research, Morris and Nolan (1961) examined the discriminability of 12 area symbols. They aimed to increase the number of discriminable area symbols that Heath found, by using some of his discriminable symbols and adding symbols that they considered to be visually different. Ninety-six participants performed paired comparison tasks where each symbol was compared to all other symbols in the set, and to itself. The researchers found a discriminable set of 8 area symbols, where each symbol showed less than 10% confusions with itself and other symbols.

Nolan and Morris (1971) published a report on the improvement of tactile symbols for visually impaired children. A large part of this report described their attempts to create a large set of discriminable symbols. Selection of symbols to be tested was guided by dimensions along which Nolan and Morris believed that symbols varied, for example continuous versus interrupted and thick versus thin lines. The research
was conducted in four separate studies, using the same experimental methods. In each study, 60 or 58 participants performed paired comparison tasks on adjacent symbols that were presented simultaneously. Each symbol was compared to all other symbols in the set, and to itself. Nolan and Morris produced confusion matrices, showing the percentage correct recognition on each pair of symbols. Selection criteria for inclusion in the discriminable symbol set were “(1) that average confusion with other acceptable symbols should be 5% or less and (2) that confusion with itself or any other single symbol acceptable by criterion (1) should be 10% or less” (p. 19). In addition, there should be no significant difference in discriminability of acceptable symbols among the different school age groups. In the first study, 11 area symbols and 13 lines symbols, produced by thermoform, were examined, resulting in a discriminable set of 8 area symbols and 7 line symbols. The second study investigated the discriminability of a set of 12 symbols produced in two sizes, using thermoform. Eight of the larger symbols and five of the smaller symbols were found to be discriminable. All five smaller symbols were included in the set of eight larger symbols, which suggests that the paired comparison method produces reliable results. In their third and fourth study, Nolan and Morris examined 19 point symbols and 21 line symbols that were produced by a Braille embosser, and found a discriminable set of 11 point symbols and seven line symbols.

In addition to writing reviews of studies on the discriminability of tactile symbols (Jansson, 1972a, 1972b), Jansson conducted studies on symbol discriminability himself (1973). He recognised the problem of translating the results of adjacent pair comparison studies into the selection of symbols for use on an actual map. In an attempt to solve this problem, Jansson asked participants to find a target symbol in an array of symbols, hereby mimicking the use of a map with a key. Symbols to be tested were selected on the basis of discriminability in previous studies. The study included ten line symbols and eight area symbols that were tested in several combinations of five area symbols. By using the same inclusion criteria as Nolan and Morris (1971), and by producing a confusion matrix, Jansson found a set of five discriminable lines. The number of area symbols in the final set was predetermined, and the most discriminable set of five area symbols was established, using the smallest proportion of confusion between all symbols in the sets of five. Jansson also
suggested a number of possible reasons for confusions between symbols, based on an informal ‘visual inspection’ of the data of previous studies and his own studies.

Gill and James conducted a series of discriminability studies using point symbols in thermoform (Gill and James, 1973), and line and area symbols produced in Braillon (James & Gill, 1975). The set of test symbols was based on previous research on discriminability and also included symbols that were used in practise. The symbol set included 30 point symbols, eight area symbols and 17 line symbols. Point symbols were divided into three groups of ten for testing, by allocating symbols that were likely to be confused to the same group. Discriminable point symbols were established within each group, and were then compared to all potentially discriminable symbols across the groups. Forty-five and 62 participants made paired comparisons of adjacent symbols in the two studies respectively. Gill and James used Nolan and Morris’s selection criteria to establish discriminable sets of 13 points, ten lines and six area symbols. They also published confusion matrices.

Lederman and Kinch (1979) published an excellent review of studies on the discriminability of area symbols. They focussed mostly on methodological and theoretical issues. After identifying several weaknesses in the design of studies, Lederman and Kinch offered suggestions for further research, which included the use of more sophisticated experimental methods, such as multidimensional scaling, and evaluations of discriminability of symbols in the context of a map.

Lambert and Lederman (1989) evaluated the legibility and meaningfulness of 17 point symbols. Twelve participants performed a match-to-sample task, similar to Jansson’s task (1973). Unfortunately, Lambert and Lederman did not report an analysis of their results, but sufficed to say that the entire set of symbols was discriminable. Without a confusion matrix or other representation of error scores, it is not possible to evaluate their results.

Rener (1993) conducted a meta analysis, in which he identified tactile symbols that were found to be discriminable in several studies. He included 5 studies of point symbols, 7 studies of line symbols ands 7 studies of area symbols. Rener counted the
number of times each symbol was found to be discriminable. Although a meta
analysis of these studies was interesting, its validity might be problematic. First of
all, the number of discriminability studies, and the number of symbols tested in them,
was rather small. Some of the symbols were tested more frequently than others, and
therefore might have ended up with a higher discriminability score than expected.
Secondly, although it was possible to identify a set of symbols that were
discriminable in a large number of studies, these symbols were not always tested
against each other. Therefore, it is not possible to comment on the discriminability
within the resulting set of symbols.

5.1.2 Limitations of previous studies

Previous discriminability studies have provided us with some usable symbol sets for
tactile maps. However, their experimental methods had several weak points. The first
potential problem relates to the small number of symbols that are used in most of
these studies. The number of symbols was often limited by the experimental method
of paired comparison, where each symbol is tested against all other symbols. Adding
a symbol to the set increases the number of trials enormously. For example, there are
45 possible pairs of symbols in a set of ten symbols, whereas there are 55 possible
pairs in a set of 11 symbols. In order to keep the entire experiment within a
reasonable time limit, most researchers decided to limit the number of symbols to be
tested.

A second problem relates to the choice of symbols. In some studies, symbols seemed
to be selected rather haphazardly, without justifying why these particular symbols
were included. As a result, combinations of symbols that were found not to be
discriminable in an earlier study were occasionally used again by a different
researcher. In several studies, symbols sets were selected based on the results of a
single previous discriminability study, and were expanded by including symbols that
were thought to be different, based solely on the experimenters' speculation.

The third problem lies in the lack of correspondence between the experimental
methods and the application, i.e. the use of symbols on actual maps. In most studies.
participants compared pairs of adjacent symbols. As Jansson (1973) pointed out, this task cannot be compared to reading a tactile map. On a map, symbols are generally distributed over a larger area. A map reader will spend time travelling from one symbol to another and is likely to encounter several other symbols while doing so. This process poses a much higher load on memory than would a direct comparison of adjacent symbols. A study on differences in working memory capacity for visual and tactile letter recognition (Bliss & Hämäläinen, 2005) suggests that processing of tactile symbols is inferior to that of visual symbols when a memory component is added to the task. In the context of map reading, this would suggest that it is more difficult to discriminate between tactile symbols than visual ones, because a map reader needs to process symbols in working memory in order to compare them. In adjacent pair comparison tasks, tactile sensory memory (Mahrer & Miles, 2002) is available, which does not require symbols to be retained in working memory. In addition, Berlá and Murr (1975a) showed that area symbols on a pseudo map interfered with the coding of point and line symbols. This suggests that discrimination between symbols on a map, which contains area symbols and other distracting features, might be lower than discrimination of two individual symbols. The differences between comparing symbols in a map context and in a pair comparison task are likely to cause qualitative and quantitative differences in discriminability of symbols as measured by the two types of task. Unfortunately, it is not possible to conduct a discriminability study on an actual map, due to the lack of control over map reading tasks and due to the time required to perform a map task, which would limit the number of symbols that could be tested. For these reasons, discriminability studies have involved paired comparison tasks, which are more easily controlled and allow for comparison of many symbol pairs.

The final limitation of previous studies on symbol discriminability relates to the analysis of the results. Several studies reported a total correct response rate for each symbol, but did not provide a confusion matrix to show which symbols were confused with each other. As a result, it was not possible to accurately identify a set of discriminable symbols, as explained above. The production of confusion matrices allowed a more thorough examination of symbol discriminability, and provided the opportunity to study the general principles of discriminability (i.e. why symbols are
confused or discriminated easily) more closely. However, although several researchers suggested basic principles of discriminability by a visual inspection of the data, no formal analyses were conducted.

5.1.3 The current study

The aim of our study was to develop a set of highly discriminable point and line symbols that can be used on tactile maps. Similar to previous studies, we used a paired comparison methodology with same/different judgements. However, we attempted to address the problems mentioned above.

First of all, Jonathan Rowell (the cartographer in the TIMP team) selected symbols from a very large pool of potential map symbols. The selection process is described in Appendix B. Jonathan Rowell conducted a meta analysis of previous literature on tactile symbols, including general tactile cartography research, experimental studies on symbols (such as discriminability studies) and map producer surveys. He also collected tactile symbols that were used in practise from archives of tactile maps at the National Centre for Tactile Diagrams and the Royal National Institute for the Blind. He selected symbols that were found to be discriminable in previous research and symbols that were already in frequent use on tactile maps. This thorough selection process enabled us to include symbols that were highly likely to be discriminable.

The selected set of symbols (40 point symbols and 18 line symbols) was considerably larger than most previously tested sets. Due to the large number of symbols and, therefore, the large number of paired comparisons, this study was conducted in two phases. In Phase 1, symbols were tested within smaller sets of symbols of a similar shape, in order to find the most discriminable symbols within each set. In Phase 2, the most discriminable symbols from phase one were tested against each other, in order to define the final set of discriminable symbols. Gill and James (1973) divided their symbol sets in a similar way. By dividing symbols into smaller sets, it was not possible to compare all symbols against each other. Therefore, it was not possible to evaluate the discriminability of the entire initial set.
In addition, the final set of discriminable symbols may have contained different symbols if it had been possible to test all symbols against each other. However, the small disadvantage of dividing the set into smaller sets was thought to be justified by the considerable advantage of being able to test a large set of symbols.

As discussed above, a paired comparison of two adjacent symbols does not resemble the process of finding symbols on a map. There is a trade off to be made between a high level of control and being able to test many symbols in a paired comparison task on one hand, and evaluating a smaller number of symbols in a less controllable but more realistic task on a map on the other hand. In this study, the problem of task validity was addressed by creating a more ecologically valid task, in which the control of the paired comparison task was maintained. In order to make our task more relevant to map reading, we added a distraction task between exploration of the two symbols of each paired comparison. The distraction task involved the identification of several symbols between the target symbol and the comparison symbol. The task was designed to provide spatial distance, a time delay and the exploration of unrelated distraction symbols between the paired symbols. The distraction task ensured that paired symbols could not be compared by relying on sensory memory. Although it was not possible to conduct a discriminability study on an actual map, we felt that the task involved sufficient elements of tactile map use to generate valid results. Figure 5.1 clarifies which distraction tasks were used in the four stages of this study. In order to avoid direct confusion between paired comparison and distraction task, different types of symbols were used. Distraction tasks using line symbols were used for paired comparisons between point symbols. Paired comparison between line symbols involved distraction tasks with points or areas.

<table>
<thead>
<tr>
<th>Discriminability study</th>
<th>Distraction task</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase 1 Points</td>
<td>Identifying single and double lines (Chapter 4)</td>
</tr>
<tr>
<td>Phase 1 Lines</td>
<td>Identifying point symbols, elevation study A (Chapter 3)</td>
</tr>
<tr>
<td>Phase 2 Points</td>
<td>Identifying the directions of arrows (not reported)</td>
</tr>
<tr>
<td>Phase 2 Lines</td>
<td>Judging the roughness of area symbols (not reported)</td>
</tr>
</tbody>
</table>

*Table 5.1 Overview of distraction tasks used in the discriminability study.*
As discussed above, we incorporated a distraction task in order to increase the ecological validity of the current study. Since we collected data from the distraction tasks (see Chapters 3 and 4), this method also allowed us to maximise the amount of data we could collect from each participant. This was especially important in relation to the visually impaired participants, who were often difficult to gain access to and who generally had a limited amount of time available to spend with us. In addition to the possible advantages of increasing the ecological validity and therefore the error score, and making data collection more efficient, there is a possible disadvantage to this approach. Participants may focus on one of the tasks and, as a result, neglect the other task. This could endanger the validity of results of the neglected task. However, we believed the advantages of including an embedded task outweighed the possible disadvantages.

The number of participants taking part in Phase 1 of the study on point symbols is larger than the number of participants in study on the identification of single and double lines. All participants performed the same tasks. However, for some participants we did not record responses on the identification of single and double lines. This enabled us to conduct the discriminability study with one experimenter rather than two for a number of participants.

In addition to developing a highly discriminable set of point and line symbols, we aimed to identify general principles that underlie symbol discriminability, using Multi Dimensional Scaling techniques. If we can determine what makes symbols discriminable from each other, it would be possible to design new discriminable symbol sets. This has not been addressed in previous discriminability studies.

5.2 Phase 1: Methods

5.2.1 Participants

Fifty-nine volunteers took part in Phase 1 of the study. Forty participants completed the point symbols study; 20 were visually impaired (8 males and 12 females, 16 to 52
years, mean age 25.2) and 20 were sighted (5 males and 15 females, 19 to 48 years, mean age 23.5). Nineteen participants completed the line symbol study; 10 were sighted (6 males and 4 females, 19 to 30 years, mean age 22.3) and 9 were visually impaired (5 males and 4 females, 18-62 years, mean age 29.1). Tables 5.2 and 5.3 provide more information about the visually impaired participants. Visually impaired participants were recruited at the Royal National College for the Blind and the Royal London Society for the Blind. Sighted participants were recruited at the University of Surrey.

<table>
<thead>
<tr>
<th>Age</th>
<th>Gender</th>
<th>Age at onset of blindness</th>
<th>Residual vision</th>
<th>Cause of blindness</th>
<th>Braille reader</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>M</td>
<td>Birth</td>
<td>Yes</td>
<td>Micro cornea</td>
<td>Yes</td>
</tr>
<tr>
<td>17</td>
<td>F</td>
<td>Birth</td>
<td>No</td>
<td>Underdeveloped optic nerve</td>
<td>Yes</td>
</tr>
<tr>
<td>17</td>
<td>M</td>
<td>Birth</td>
<td>Yes</td>
<td>Retinal detachment</td>
<td>Yes</td>
</tr>
<tr>
<td>18</td>
<td>M</td>
<td>9 years</td>
<td>No</td>
<td>Retinal detachment</td>
<td>Yes</td>
</tr>
<tr>
<td>18</td>
<td>M</td>
<td>5 years</td>
<td>Yes</td>
<td>Alstrom syndrome</td>
<td>Yes</td>
</tr>
<tr>
<td>18</td>
<td>F</td>
<td>Birth</td>
<td>No</td>
<td>Retinopathy of prematurity</td>
<td>Yes</td>
</tr>
<tr>
<td>18</td>
<td>F</td>
<td>Birth</td>
<td>Yes</td>
<td>Retinopathy of prematurity</td>
<td>No</td>
</tr>
<tr>
<td>18</td>
<td>M</td>
<td>Birth</td>
<td>Yes</td>
<td>Retrolental fibroplasia, Nystagmus, myopia, optic nerve dystrophy, dysfunctional retina</td>
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<td>Birth</td>
<td>Yes</td>
<td>Disease of the optic nerve</td>
<td>Yes</td>
</tr>
<tr>
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<td>F</td>
<td>Child</td>
<td>Yes</td>
<td>Retinopathy of prematurity</td>
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</tr>
<tr>
<td>19</td>
<td>F</td>
<td>Birth</td>
<td>Yes</td>
<td>Glaucoma</td>
<td>Yes</td>
</tr>
<tr>
<td>19</td>
<td>F</td>
<td>Birth</td>
<td>Yes</td>
<td>Rod/cone dystrophy</td>
<td>No</td>
</tr>
<tr>
<td>20</td>
<td>M</td>
<td>Birth</td>
<td>No</td>
<td>Unknown</td>
<td>Yes</td>
</tr>
<tr>
<td>20</td>
<td>F</td>
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<td>No</td>
<td>Unknown</td>
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<td>F</td>
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<td>Retinal blastoma</td>
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</tr>
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<td>F</td>
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<td>Gradually</td>
<td>Yes</td>
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<td>51</td>
<td>M</td>
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<td>No</td>
<td>Glaucoma</td>
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</tr>
<tr>
<td>52</td>
<td>F</td>
<td>Birth</td>
<td>No</td>
<td>Retinitis pigmentosa</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Table 5.2 Characteristics of the visually impaired participants in the point symbols study, Phase 1 (all information obtained from participants' verbal reports).
<table>
<thead>
<tr>
<th>Age</th>
<th>Gender</th>
<th>Age at onset of blindness</th>
<th>Residual vision</th>
<th>Cause of blindness</th>
<th>Braille reader</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>M</td>
<td>9 years</td>
<td>No</td>
<td>Retinal detachment</td>
<td>Yes</td>
</tr>
<tr>
<td>18</td>
<td>M</td>
<td>5 years</td>
<td>Yes</td>
<td>Alstrom syndrome</td>
<td>Yes</td>
</tr>
<tr>
<td>18</td>
<td>F</td>
<td>Birth</td>
<td>No</td>
<td>Retinopathy of prematurity</td>
<td>Yes</td>
</tr>
<tr>
<td>18</td>
<td>M</td>
<td>Birth</td>
<td>Yes</td>
<td>Retinopathy of prematurity</td>
<td>No</td>
</tr>
<tr>
<td>20</td>
<td>M</td>
<td>Birth</td>
<td>No</td>
<td>Micro anophthalma</td>
<td>Yes</td>
</tr>
<tr>
<td>23</td>
<td>M</td>
<td>3 years</td>
<td>No</td>
<td>amaurosis</td>
<td>Yes</td>
</tr>
<tr>
<td>33</td>
<td>F</td>
<td>6 months</td>
<td>No</td>
<td>Retinal blastoma</td>
<td>Yes</td>
</tr>
<tr>
<td>51</td>
<td>M</td>
<td>22 years</td>
<td>No</td>
<td>Glaucoma</td>
<td>Yes</td>
</tr>
<tr>
<td>62</td>
<td>F</td>
<td>Birth</td>
<td>Yes</td>
<td>Cataracts, scars, nystagmus</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Table 5.3 Characteristics of the visually impaired participants in the line symbols study, Phase 1 (all information obtained from participants' verbal reports).

5.2.2 Materials

Presentation materials

Tactile symbols were printed on blank business cards (54 x 85 mm) using the TIMP tactile inkjet printer. The cards were made of rough plastic, as suggested by the study on substrate materials (Chapter 2). The cards were presented in an MDF jig with slots for 5 cards. The three inner slots were used for a distraction task. Symbol cards were presented in the two outer slots, resulting in a distance of 40 cm between symbols. Small indentations along the base of the jig indicated the position of the corresponding symbols. The jig was placed on a table in front of the participant. Figure 5.1 illustrates the presentation of stimuli.

Stimuli

Point and line symbols were selected from a larger pool, which included symbols that had been identified as discriminable in previous studies and symbols that are frequently used on tactile maps (based on map producer surveys and archives of tactile maps). Forty point symbols were selected from this pool, and divided into 4 sets of equal size, containing circles, squares, triangles and cruciforms (Fig. 5.2). Circles and squares were 8.9 mm in height. Triangles were 10 mm in height. The height of the cruciforms ranged between 5.5 mm and 9.9 mm. Eighteen line symbols were selected and divided into two groups of nine (Fig. 5.3). Lines were 6 cm long.
For both point and line symbols, line width was 1.0 mm and line elevation was 0.4 mm.

Several symbols required a guaranteed inclusion into Phase 2 of the experiment, as suggested by Jonathan Rowell, the cartographer in TIMP. Guaranteed inclusion occurred on the basis of cartographic principles. The outline circle, square and triangle (A1, B1 and C1) were considered to be the most basic shapes, lending themselves to most functions on a map. Therefore, they were predetermined to be tested in both the first and the second phase of the study.

Fig. 5.1 The presentation jig with a pair of point symbols and 3 distraction cards.
Fig. 5.2 Forty point symbols, divided into 4 sets of 10. Symbols are referred to by the code in the adjacent column.
5.2.3 Procedure

The point symbols and the line symbols were tested in two separate experiments, using different participants. Due to the large number of trials in the point symbols study, the paired comparisons were spread over two participants. Pairs of participants were randomly selected and shared a complete set of comparisons between them. Our 20 participants completed, in effect, 10 runs of the experiment.

The study consisted of a tactile comparison task and a short interview at the end of the experiment. A paired comparison methodology was used in which participants...
made same/different judgements. Each symbol was compared once to all other symbols in its set and twice to itself. Symbol pairs were presented in a random order, with pairs from different sets interleaved randomly. Each symbol was presented an equal number of times on the left side and on the right side of the jig.

Participants were seated at a desk in a quiet room at their college or home. Sighted participants and those with residual vision were blindfolded during the task. Participants used one hand to explore the symbols and always moved from left to right across the jig. They were allowed to swap hands during the experiment. The choice of hand (left or right) was not recorded. Each trial consisted of three stages. First, participants explored the point symbol on the left side of the jig and committed it to memory. Then, they performed a distraction task for 15 seconds. Finally, participants explored the point symbol on the right and decided whether it was the same as or different from the point symbol on the left. Exploration time for the point symbols was unlimited, but participants were instructed not to return to the first point symbol at any stage. After completion of the tactile comparison task, participants answered a number of questions relating to their subjective experience of the point symbols. First, they reported verbally which symbols they remembered. Then, they described what characteristics made symbols easy and difficult to discriminate. Full details of the instructions to participants can be found in Appendix E.

The purpose of the tactile distraction task was to make the discriminability task more realistic and applicable to map design. By introducing effects of a time delay, movement in space and exploration of other symbols, the discriminability task more closely resembled tactile map reading. The distraction task consisted of three judgements in every trial. The amount of time available to explore each distraction card was controlled by beeps at intervals of five seconds, resulting in a 15 second distraction task. For the point symbol study, the distraction task involved identifying single and double lines amongst a range of lines of different widths, gap sizes and orientations (see Chapter 4). The distraction task in the line symbol study involved identifying small circles, triangles and squares (see Chapter 3).
5.2.4 Statistical methods
We investigated the discriminability of a set of symbols in order to determine a discriminable set and to explore principles of discriminability. We measured the number of errors when participants compared pairs of symbols. Errors included a ‘same’ response on a ‘different’ pair of symbols, and a ‘different’ response on a ‘same’ pair of symbols.

For each participant, the total number of errors was calculated in order to perform independent samples t-tests to explore the effects of visual status and to correlate performance with performance on the distraction task.

Discriminability of symbols was explored by the number of confusions (i.e. errors) across participants on each pair of symbols. Custom-made software\(^6\) was used to determine the number of confusions within each possible set of four symbols in each symbol group. Multi-dimensional scaling was used to explore symbols of discriminability.

5.3 Phase 1: Results

Participants made same/different judgements on 130 point symbol pairs or 108 line symbol pairs. Errors included ‘different’ judgements on ‘same’ pairs and ‘same’ judgements on ‘different’ pairs. Independent samples t-tests showed that there was no significant difference in the number of errors between sighted (\(M = 13.4\) and \(SD = 7.2\) for point symbols, \(M = 20.8\) and \(SD = 7.8\) for line symbols) and visually impaired participants (\(M = 10.0\) and \(SD = 6.2\) for point symbols, \(M = 15.1\) and \(SD = 3.0\) for line symbols); \(t(38) = 1.62, p > 0.05\) for point symbols, \(t(17) = 2.05, p > 0.05\) for line symbols). Confusion matrices were produced for the subsets of point and line symbols, showing the number of errors on each combination of symbols (see Appendix C). Further analysis only included scores on the pairs of different symbols.

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\(^6\) Custom-made software was used analyse the data. This software calculated the number of confusions within each possible set of four symbols in each symbol group, regardless of confusions with other symbols in the group. It then listed all combinations of four symbols in order of error score. This allowed us to find the best combinations of symbols.
Highly discriminable subsets

The aim of Phase 1 of this study was to find the most discriminable subset of symbols from each set. After preliminary inspection of the data and participants' comments, it turned out to be necessary to exclude some symbols from further analysis. Participants' responses in the short interview served to exclude a number of point symbols from further consideration. First of all, participants often described certain symbols as letters, when reporting which symbols they remembered. Symbols A5, B5 and C5 were often referred to as 'Braille-like' symbols by participants. In order to avoid confusion with Braille letters on a map, these symbols were excluded from further analysis. Similarly, symbols D2, D6, D7 and D9 were excluded in order to avoid confusion with print letters. Second, when asked what characteristics made symbols difficult or easy, complexity was mentioned most often. The majority of participants (22 out of 40) mentioned that complex symbols were more difficult than simple symbols. The half textured symbols and symbols with crosses in it (A8, A9, B8, B9 and B10) were found to be especially difficult and where, therefore, excluded from further analysis. It was not necessary to exclude symbols because of high confusability with themselves; the error score was less than 5% on all same pairs. None of the line symbols were excluded from the final set to be tested.

The most discriminable combination of three or four symbols from each set was selected to go through to Phase 2. This resulted in a set of 15 symbols to be tested in Phase 2, which was the largest number of symbols that could be tested within a reasonable time frame per participant. For all sets, we calculated the number of confusions ('same' responses for 'different' pairs) that occurred within each possible combination of 4 symbols. Thus, the number of confusions only reflects the errors within a subset of 4 symbols, regardless of confusions with other symbols in the original set. This minimises contaminating effects of specific symbols. For example, symbol C8 and C9 had a large total number of confusions in the whole set, which mainly consisted of confusions with each other. However, these symbols are discriminable from most other symbols in the set. The subset with the smallest number of confusions contains the most discriminable combination of symbols from a set (Fig. 5.4 and 5.5).
Although there was no significant difference in the number of errors between sighted and visually impaired participants, the difference in mean error score suggests that there may have been a small difference that we were not able to detect, due to a relatively small sample size. In order to investigate this possible difference further, we compared the discriminability of subsets for visually impaired and sighted participants separately. There were some small differences in the patterns of discriminability, which was expected because of the relatively small sample size. However, the most discriminable subsets of point and line symbols (Fig. 5.4 and 5.5) were always ranked within the top three of most discriminable combinations of symbols in both participant groups. This confirmed that the results were applicable to both sighted and visually impaired people.
5.4 Phase 2: Methods

In Phase 1, we examined the discriminability of 18 line symbols, divided into two sets of nine, and 40 point symbols, divided into four sets of ten. The large number of possible combinations of symbols in the original symbol pool necessitated the division into smaller sets. In Phase 2, we tested the most discriminable combination of symbols from each set against each other, in order to determine a final set of discriminable symbols.

5.4.1 Participants

Thirty-six volunteers took part in Phase 2 of the discriminability study. Nine sighted (3 males and 6 females, 21 to 34 years, mean age 27.5) and nine visually impaired participants (4 males and 5 females, 18 to 45 years, mean age 26.8) completed the second phase of the point symbol study. Nine sighted (2 males and 7 females, 25 to 56 years, mean age 30.4) and ten visually impaired volunteers (6 males and 4 females, 16 to 19, mean age 17.9) took part in the second phase of the line symbol study. Tables 5.4 and 5.5 provide more information about the visually impaired participants. Visually impaired participants were recruited at the Royal National College for the Blind and the Royal London Society for the Blind. Sighted participants were recruited at the University of Surrey.

<table>
<thead>
<tr>
<th>Age</th>
<th>Gender</th>
<th>Age at onset of blindness</th>
<th>Residual vision</th>
<th>Cause of blindness</th>
<th>Braille reader</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>M</td>
<td>9 years</td>
<td>No</td>
<td>Retinal detachment</td>
<td>Yes</td>
</tr>
<tr>
<td>18</td>
<td>F</td>
<td>Birth</td>
<td>No</td>
<td>Retinopathy of prematurity</td>
<td>Yes</td>
</tr>
<tr>
<td>18</td>
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<td>Birth</td>
<td>No</td>
<td>Leber's amaurosis</td>
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</tr>
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<td>Retinoblastoma</td>
<td>Learning</td>
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<tr>
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<td>M</td>
<td>Birth</td>
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<td>Norrie's disease</td>
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<td>Retinal blastoma</td>
<td>Yes</td>
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<tr>
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<td>15 years</td>
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<td>Glaucoma</td>
<td>Yes</td>
</tr>
<tr>
<td>37</td>
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<td>No</td>
<td>Cerebral aneurism</td>
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<tr>
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<td>35 years</td>
<td>Yes</td>
<td>Tumor causing optic atrophy</td>
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</table>

Table 5.4 Characteristics of the visually impaired participants in the point symbols study, Phase 2 (all information obtained from participants' verbal reports).
<table>
<thead>
<tr>
<th>Age</th>
<th>Gender</th>
<th>Age at onset of blindness</th>
<th>Residual vision</th>
<th>Cause of blindness</th>
<th>Braille reader</th>
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<tr>
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<td>Birth</td>
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<td>Missing data</td>
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<tr>
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<td>Birth</td>
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<tr>
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</tr>
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<td>Missing data</td>
<td>Learning</td>
</tr>
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<td>Missing data</td>
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<tr>
<td>19</td>
<td>F</td>
<td>Birth</td>
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<td>Missing data</td>
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</tr>
<tr>
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<td>F</td>
<td>Birth</td>
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<td>Missing data</td>
<td>No</td>
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</tbody>
</table>

Table 5.5 Characteristics of the visually impaired participants in the line symbols study, Phase 2 (all information obtained from participants’ verbal reports).

5.4.2 Materials

The presentation materials used in Phase 2 of this study were identical to the materials used in Phase 1. In the second phase of this study, we used the symbols that were found to be most discriminable in each set tested in Phase 1 (Fig. 5.4 and 5.5).

5.4.3 Procedure

The procedure followed in phase two was similar to the one followed in Phase 1 of this study. One group of participants made same/different judgements on all combinations of point symbols. Another group of participants performed this task on all combinations of line symbols. The distraction tasks, however, were different. In the line symbol study, participants estimated the roughness of textured areas. The distraction task in the point symbol study involved identifying the direction of arrows (McCallum et al., 2006).

5.4.4 Statistical methods

The statistical methods used in Phase 2 were similar to the methods in Phase 1.

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7 We conducted a study on perceived roughness of textured area symbols consisting of dot patterns. However, for reasons described in Chapter 6, we decided not to include the study on roughness in this thesis.
5.5 Phase 2: Results

5.5.1 Set of discriminable symbols

Participants made same/different judgements on 119 pairs of point symbols and 44 pairs of line symbols. Again, there was no significant difference between the error scores of visually impaired and sighted participants (Points: $M_{sighted} = 5.9$, $SD_{sighted} = 4.7$, $M_{vi} = 4.6$, $SD_{vi} = 4.3$) $t(16) = .63, p = .54$, lines $M_{sighted} = 5.3$, $SD_{sighted} = 3.5$, $M_{vi} = 4.9$, $S_{vi} = 3.0$) $t(17) = 0.29, p > 0.05$) and therefore their data were combined.

The aim of the second phase of this study was to find the largest possible set of highly discriminable symbols. Discriminability was based on the number of confusions between symbols (‘same’ judgements for ‘different’ pairs). We amended the two criteria first used by Nolan and Morris (1971) in order to establish discriminable symbol sets. First of all, the overall confusion between all symbols in a set should be less than 5%. Secondly, according to Nolan and Morris, the confusion between any pair of symbols within a set should be less than 10%. We raised the tolerance level to 15%, because our task was more ecologically valid and, therefore, the error score was higher. When the confusion between a pair of symbols was more than 15%, one of the symbols was discarded. The aim was to discard as few symbols as possible while minimising the number of confusions in the resulting set.

The largest acceptable set of discriminable point symbols, according to our two criteria, consisted of 11 symbols (Fig. 5.6). The overall confusion in this set was 3.2%. The highest confusion between any pair of symbols within this set was 11.1%. The final set of discriminable line symbols contained 4 symbols (Fig. 5.7). The overall confusion was 1.75% and the highest confusion between any two symbols was 10.5%.
5.5.2 Principles of discriminability

In addition to finding a set of highly discriminable symbols, we attempted to explore underlying principles of symbols discriminability. We wanted to determine what makes symbols discriminable from each other. This knowledge could enable tactile map designers to create new sets of highly discriminable symbols, without the need for extensive testing on discriminability.

We used Multi Dimensional Scaling (MDS) in order to explore underlying principles of discriminability, as previously suggested by Lederman and Kinch (1979). This technique is based on the similarity between items, based on the number of confusions between pairs of symbols. In this case, MDS produced a two-dimensional graphic, in which the distance between symbols was an indication of discriminability. Symbols that were far apart were less often confused with each other (i.e. more discriminable) than symbols that were close together.
Figure 5.8 to 5.13 show the MDS diagrams that were produced using the data from phase 1 of this study. These two-dimensional models have a good fit (Circles: stress = 0.13, $R^2 = 0.90$. Squares: stress = 0.04, $R^2 = 0.99$. Triangles: stress = 0.06, $R^2 = 0.98$. Cruciforms: stress = 0.08, $R^2 = 0.96$. Continuous lines: stress = 0.18, $R^2 = 0.83$. Broken lines: stress = 0.13, $R^2 = 0.91$). Producing a one-dimensional model did not produce a good fit, and adding a third dimension did not considerably improve their fit. The MDS diagrams show that symbols that are similar in some way tend to cluster together. For example, all squares with a linear feature inside (B7, B8, B9 and B10) are located in close proximity to each other. This implies that they are not discriminable from each other. On the other hand, highly discriminable symbols are located at a large distance from other symbols. For example, the filled (A2, B2 and C2) and the dotted symbols (A5, B5 and C5) were highly discriminable from all other symbols in their set and are, therefore, positioned further away from other symbols in the MDS diagrams. As expected, the sets of most discriminable symbols from each shape set (Fig. 5.4 and 5.5) are consistent with the MDS diagrams. The discriminable sets contain symbols that are positioned far away from each other in the MDS diagrams.
Fig. 5.8 MDS diagram showing the degree of similarity between circles.

Fig. 5.9 MDS diagram showing the degree of similarity between squares.
Fig. 5.10 MDS diagram showing the degree of similarity between triangles.

Fig. 5.11 MDS diagram showing the degree of similarity between cruciforms.

Fig. 5.12 MDS diagram showing the degree of similarity between continuous lines.
Fig. 5.13 MDS diagram showing the degree of similarity between broken lines.

The distribution of symbols in Figures 5.8, 5.9 and 5.10 show a similar pattern. This implies that the discriminability of tactile symbols of different shapes is governed by a common set of principles.

All discriminability data in Phase 1 fitted two-dimensional models. This indicates that the discriminability of symbols within each group was dictated by symbol characteristics along 2 dimensions (i.e. axes). The direction of axes in the figures is not relevant. In general, point symbols appear to be organised by complexity (number of elements) and density (amount of raised material). In these figures, complexity decreases along the horizontal axis for squares and triangles, and along the vertical axis for circles. Density decreases along the vertical axis for squares and triangles, and along the horizontal axis for circles. Both density and complexity increase along a diagonal axis (bottom left to top right) for cruciforms, but it is not apparent what the second dimension represents here.

Discriminability within the groups of line symbols is also dictated by symbol characteristics along 2 dimensions. For continuous lines (Fig. 5.12), these dimensions appear to be waviness (vertical axis) and overall width (horizontal axis). The broken lines (Fig. 5.13) are clearly separated into lines consisting of dots and lines consisting of other elements (horizontal axis). The size of internal elements increases along the vertical axis.
Several principles of discriminability within symbol shapes are apparent. The following symbol characteristics appear to make a symbol discriminable from other circles, squares, triangles and cruciforms within the group:

- **Dotted symbols**: These symbols (A5, B5, C5) are highly discriminable from other symbols.
- **Solid symbols**: These symbols (A2, B2, C2) are highly discriminable from other symbols.
- **Internal elements**: Symbols with any internal elements, such as lines (A7, A9, B7, B9, B10, C7), textures (A3, A8, B3, B8, C3) and dots (A4, B4, C4) are often confused with each other. However, they are discriminable from other symbols in their groups.
- **Outline symbols**: Outline symbols of a similar basic shape (A1, A6, A10 and C1, C6) are often confused with each other, but are discriminable from other symbols in their groups.
- **Open shapes**: These symbols (B6, C8, C9, C10, D9, D10) are discriminable from other symbols in their groups. However, they are often confused with each other.
- **Crosses**: Variations of crosses (D1, D2, D4, D5) are often confused with each other. However, they are discriminable from other cruciforms.

The MDS diagrams also suggest principles of discriminability for line symbols.

- **Wavy lines**: These lines (E5, E8, E9), although confused with each other, are highly discriminable from non-wavy lines.
- **Double lines**: These lines (E2, F6) are discriminable from single lines.
- **Dots/dashes**: Most lines consisting of dots and/or dashes (F1, F2, F3, F4, F5) are confused with each other, but all are discriminable from discontinuous lines consisting of other elements.

We also applied Multi Dimensional Scaling to the discriminability data of Phase 2, in which the most discriminable point and line symbols from Phase 1 were tested together (Fig. 5.14). These data on point symbols did not fit well in a two-dimensional model (Points: stress = 0.30, $R^2 = 0.41$), and the fit did not markedly increase for a 3 dimensional model. This may suggest that there are no clean patterns
of discriminability and that all remaining point symbols are quite discriminable from each other. This is not surprising, because all symbols in this set were expected to be highly discriminable, based on selection in Phase 1 or by belonging to different shape groups.

Considering the bad fit of the two-dimensional model, it is difficult to draw conclusions from Figure 5.14. However, symbols of the same basic shape seem to appear in clusters, which was not an artefact of the order in which the data were entered. This suggests that symbols of the same shape but with different internal elements (e.g. A1 and A4), are more often confused with each other than symbols of different shapes (e.g. A1 and B1).

![MDS diagram showing the degree of similarity between all point symbols in phase 2.](image)

The data on the discriminability of line symbols in phase 2 did not fit well in a two-dimensional model (stress = 0.20, $R^2 = 0.76$). However, a three-dimensional model provided a good fit (stress = 0.08, $R^2 = 0.92$). Figure 5.15 and 5.16 in combination show the position of the lines in a 3 dimensional model. The figures show what symbol characteristics govern discriminability of these line symbols. Line symbols appear to be organised by longitudinal complexity along dimension x. Symbols on the left contain more internal elements than symbols on the right. Dimension y appears to represent changes in amplitude. Towards the bottom of figure 15, the
amplitude of line symbols increases. Dimension $z$ (Fig. 5.16) separates the double line (E2) from all other lines.

Fig. 5.15 MDS diagram showing the degree of similarity between all line symbols in phase 2, using a 3 dimensional model (x-y dimensions).
5.6 Discussion

Tactile maps can be difficult to read, because they require the user to interpret, remember and use a large amount of information. Map reading can be facilitated by designing maps with symbols that are easy to discriminate from each other. In this study, we aimed to establish a set of highly discriminable point and line symbols for use on tactile maps. The large, initial set of symbols was based on previous research on discriminability and on symbols already in regular use. We narrowed down the initial set to a smaller, highly discriminable set of symbols. Discriminability of symbols was defined as the number of confusions between symbols in our paired comparison task. The experimental methods also included a distraction task, which attempted to increase the validity of the task by simulating a more realistic map reading task. Since we tested a large set of symbols, which was based on previous research and common practise, and since the experimental task involved several
elements of map reading, the results of this study should be applicable to tactile maps design in practise.

5.6.1 Theoretical considerations

Principles of discriminability

Multi Dimensional Scaling was used to identify general principles of symbol discriminability. We identified the dimensions of symbol characteristics that govern discriminability, such as complexity, density and the size of internal elements. We also identified clusters of symbols. The symbols within these clusters were often confused with each other, but were discriminable from symbols outside the cluster. These principles can be used for the generation of new sets of discriminable symbols. For example, since symbols of the same basic shape with different internal elements (lines, dots or textures) are often confused with each other, only one such symbol can be present in a discriminable set of symbols.

The MDS analysis provided us with a basic understanding of principles of discriminability, but the findings are limited by the fact that the symbol sets were intended to be as discriminable as possible from the start. Future studies could refine the current findings and focus on some of the dimensions identified here, by producing sets of symbols that are more similar.

Verbal descriptions

In the experiment, participants were asked to compare two tactile symbols, separated by a distraction task. The strategies participants used for completing the paired comparison task can partly explain the discriminability data. Observations and direct questions revealed that many participants used verbal repetitions (spoken or in silence) throughout the distraction task. For example, after exploring an outline circle, a participant repeatedly muttered "empty circle" until he reached the comparison symbol. Inevitably, the verbal labels attached to the symbols were an abstraction of the original tactile symbol, and this might be the reason for some of the confusion between symbols. Participants sometimes matched the simplified verbal description of the first symbol to the comparison symbol, resulting in false
judgements of sameness. For example, the symbol set included several lines consisting of dots. If a participant attached the simplified label “dotted line” to this symbol, it was likely to be confused with other dotted lines.

Comparison to previous studies on discriminability
The results of this study can be compared to previous studies on symbol discriminability, which were reviewed in Section 5.1.1. In general, the percentage of confusions between symbol pairs was higher in the current study than in previous experiments. This difference was expected, due to the use of different experimental methods. Previous studies involved direct paired comparisons between symbols, whereas a distraction task was included in our experiment. The distraction task made the paired comparison task more realistic and more complicated, resulting in a higher percentage of errors.

Comparing the discriminability of symbols across studies is difficult. Each study uses a different set of symbols, and the discriminability of a symbol depends on the other symbols in the set. However, it is useful to determine if symbols included in our discriminable symbol set were also found to be discriminable in other studies. This allowed us to determine if our discriminable symbols were also discriminable from each other in previous studies, regardless of other symbols that were included in the testing. In addition, it is useful to compare the patterns of discriminability, based on confusion matrices.

The set of four discriminable lines identified in the current study closely compared to results from previous studies. In agreement with our results, Jansson’s set of discriminable lines also included a single line, a double line and a double dotted line (Jansson, 1973). The wavy line was not included in Jansson’s pool of symbols. Nolan and Morris’s discriminable set of lines (1971) also included the four lines we suggested. Similar to the principle of line discriminability identified in the current study, lines consisting of dots or dashes were often confused with each other. The discriminable set found by James and Gill (1975), in which the wavy lines was not assessed, included a single line, double lines and double dotted line. Contrary to our results, James and Gill suggest that lines consisting of dots at varying intervals can
be discriminable from each other. However, this finding could be due to the design of lines. One of the dotted lines contained a very small inter-dot spacing, which may result in the perception of a rough line, which might be classed as an entirely different type of line. Corresponding to our results, James and Gill results suggested that double lines are highly discriminable from single lines.

The discriminable set of point symbols cannot be compared to earlier results as easily, because a larger variety of point symbols was used across studies. However, some comparisons can be made. In agreement with our results, Nolan and Morris's discriminable set included an outline circle, square without base and a 'v' shape (Nolan and Morris, 1971). However, it also included an outline ellipse, which was often confused with the outline circle in our study. Nolan and Morris also identified the dotted square and the letter T as highly discriminable. Although we disregarded these symbols because of their resemblance to Braille or print letters, they were found to be highly discriminable in our studies as well. Surprisingly, the outline circle and filled circle were often confused in Nolan and Morris's study. This could be due to the relatively small symbol size of 5 mm, which could have affected the perception of the empty space inside the outline circle. The discriminable set of a subsequent study by Nolan and Morris included the outline square, outline circle, '+' shape, and horse shoe shape, all of which were also included in our final set. In addition to agreement on several of the symbols in the final set, the principles of discriminability appear to be reflected in Nolan and Morris's study. Open shapes, such as the horse shoe, are often confused with each other, but are not generally confused with closed shapes. Various crosses also have a high level of confusion between themselves.

In conclusion, the discriminable sets of line and point symbols identified in the current study compared closely to the results of previous studies. Moreover, the principles of discriminability could be used to explain the results of earlier studies.

Implications of combining experiments

In order to create more ecologically valid tasks, a distraction task was included within the discriminability study. Participants performed three judgements on stimuli.
from other experiments between comparing the pair of symbols from the
discriminability study. The purpose of combining experiments was to increase the
ecologically validity and therefore the difficulty level of both experiments. It also
allowed us to collect data on several experiments at the same time. We expect
performance on both tasks to be lower than it would have been if the experiments
had been conducted separately.

It is important to consider the strategies participants employed for completing both
tasks. Ideally, participants attempted to perform well on both tasks. However,
participants may have focussed on one task while neglecting the other. This scenario
would cause problems for the interpretation of results from the neglected task. In
order to investigate this potential problem, we examined the correlation between
performance on the distraction task and the paired-comparison task.

In Phase 1 of the discriminability of point symbols, participants also identified single
and double lines (see Chapter 4). When discriminating lines, they also identified
point symbols at a range of sizes and elevations (see Chapter 3). The correlations
between the total number of errors on the discrimination task and the distraction task
were positive (Points/distraction: \( r = 0.67, p < 0.05 \); Lines/distraction: \( r = 0.66, p <
0.05 \)); participants who performed well on the discrimination task also performed
well on the distraction task and vice versa. This suggests that participants did not
prioritise one task over the other.

The correlations between discrimination tasks and distraction tasks in Phase 2 of the
study were not considered. The distraction tasks in this Phase, which are not reported
in this thesis, investigated participants’ subjective judgements to stimuli and did not
have right or wrong responses. Therefore, these tasks could not be analysed in terms
of performance levels and could not be correlate with performance on the
discrimination task. However, since participants did not appear to prioritise either
discrimination tasks or distraction tasks in Phase 1, we did not expect a priority effect
in Phase 2 either.
5.6.2 Practical considerations

The final set of highly discriminable symbols consisted of 11 point symbols and 4 line symbols (Fig. 5.6 and 5.7). Since the initial symbol set was both carefully chosen and larger than any set of symbols tested in previous studies, and since our experimental methods were thorough and realistic, our set of discriminable symbols is particularly valid and functional. We expect that these symbols will not cause any problems when used on a tactile map. A selection of symbols from the set was used on a map in an evaluation setting (Chapter 6). This evaluation study suggested that this selection of symbols was highly successful.

Fig. 5.17 Final set of highly discriminable point symbols.

Fig. 5.18 Final set of highly discriminable line symbols.
6 An evaluation of maps produced in several production methods and designs

In previous chapters, we described quantitative studies on aspects of tactile map design. In this final chapter, we conducted a qualitative evaluation of entire maps. We evaluated several production methods and map designs. We designed a map according to the findings of this thesis. By comparing this map to other maps, this chapter brings together the findings of all previous chapters.

6.1 Introduction

After studying individual aspects of tactile maps (Chapters 2 to 5), we evaluated entire maps in a qualitative study, using realistic map based tasks. The aims of this final study were twofold. Firstly, we wanted to evaluate the findings of this thesis (relating to substrate material, elevation of features, spacing of double lines and discriminable symbols) on a real map, by incorporating these findings into the design and production of a test map. Do the recommendations for individual aspects of map production and design, as studied in this thesis, continue to work when combined on an entire map? Secondly, we wanted to compare several of the leading production methods and several map designs. We were interested in comparisons between all production methods and designs, and in the evaluation of our tactile inkjet products and the design based on this thesis in particular.

We created seven tactile maps using several production methods (tactile inkjet, thermoform, microcapsule and Braille embossing) and map designers. Participants performed a number of tasks on each map in order to familiarise themselves with the production method and design, and were subsequently interviewed about their opinions on various aspects of the maps. A qualitative analysis of these interviews allowed us to evaluate the implementation of findings of this thesis, and to compare our map design and tactile inkjet process to other designs and production methods.
6.1.1 Evaluation of experimental methods of previous research

This section describes previous studies that involved the use of tactile maps. Although there are few studies on direct comparisons of tactile maps, a number of studies investigate the use of tactile maps or use tactile maps as a tool to measure internal cognitive maps. We examined the experimental methods used in previous research, in order to select an appropriate method for the evaluation study.

Comparisons of tactile maps

Although a considerable number of studies have investigated particular aspects of tactile maps, such as discriminability of symbols (see Chapter 5), studies evaluating entire maps are quite rare. The lack of evaluation studies might be partly due to methodological problems. It is difficult to design a study that can accurately measure the quality of a tactile map. Quantitative measures of performance are likely to be contaminated considerably by other factors, such as the participants’ experience with tactile maps or level of spatial cognition. Although these factors might have had an effect on participants’ performance in our previous studies (Chapter 2 to 5), such effects are hugely increased on a complex task like map reading. In addition, time based measurements, as used in Chapter 2 and 3, are unlikely to work well on tactile maps, due to the sequential nature of exploration. For example, the time taken to find a certain symbol on a tactile map depends to a large extent on when the fingers happen to come across this symbol by coincidence, and to a relatively small extent on map design factors. As a consequence, it is nearly impossible to use time measurements as a method to evaluate the quality of a map. These problems are illustrated by the studies described below.

A small number of studies have compared the use of several production methods for tactile maps. Dacen Nagel and Coulson (1990) compared performance on thermoform, letterpress plates, microcapsule and multi-textural maps at four levels of complexity, ranging from simple to complex. These maps represented a campus environment. Twenty participants performed desk based tasks, including locational and route-finding questions, simulating events related to spending a day at school. The experimenters measured the time that was required to answer each question. In addition, interviews were conducted to explore participants’ subjective impressions.
of the maps. Due to the small number of participants and the variations in experience within the participant group, Dacen Nagel and Coulson did not perform statistical tests on the data. However, they averaged time scores for each production method across participants and drew some conclusions from those. Since no statistical tests were performed on the data, we have to be careful when interpreting the results. Performance was fastest on microcapsule maps, followed by multi-textural and letterpress maps. Performance was slowest on thermoform maps. Locational and route-finding tasks took approximately twice as long on thermoform as on microcapsule maps. Qualitative data showed that, in addition to having the best performance, the microcapsule map was also the most preferred map for 70% of participants. Generally, participants felt that microcapsule maps were ‘nice, clean, clear and workable’. However, features felt low in elevation and ‘squashed’ to some. Multi-textural and letterpress plates were each preferred by 15% of participants. The relatively low score of the multi-textural maps could be due to a problematic decision in the production process. The size of the beads that were used for its production was larger than recommended, possibly resulting in a map of inferior quality (Gardiner, 2001). None of the participants preferred the thermoform maps. Most felt the multi-level surfaces of the thermoform had ‘too many bumps and ups and downs’. In addition, the image was not sharp enough. However, Perkins suggests that the thermoform maps in Dacen Nagel and Coulson’s study may have been poorly designed and that “their results are almost certainly a function of their experimental design” (p. 15, (Perkins, 2002)).

Pike, Blades and Spencer (1992, 1993) investigated the performance of children on microcapsule and thermoform maps. Children performed desk based tasks on pseudo maps, consisting of large shapes within a boundary. Participants were asked to find items on the maps, and to find routes between several items. The experimenters measured the time it took children to complete these tasks. Statistical tests revealed no differences in performance on microcapsule and thermoform maps. However, participants preferred thermoform maps over microcapsule ones, because of the higher elevation of thermoform. These results differ from Dacen Nagel and Coulson’s (1990) study, where thermoform maps were less preferred and slower to use than microcapsule maps. This discrepancy could be caused by differences in map production processes.
design or participant groups. Children might prefer bolder, more obvious maps than adults. Pike, Blades and Spencer suggest that the children’s familiarity with thermoform could also have played a role.

The two studies outlined above illustrate the difficulties in comparing tactile maps. Although both studies measured performance in terms of the time that was required to complete certain tasks, they do not show statistically significant differences in performance on different production methods. We expect that the standard deviation in time score varies widely between participants, due to the nature of tactile exploration, as explained above. Especially with a small number of participants, as is common in studies of this type, a lack of significant differences in performance is not unexpected. Unfortunately, neither study reports standard deviations in time scores. The value of these studies lies mostly in their qualitative reports of participants’ experiences.

Other studies using tactile maps
Several studies have involved the use of tactile maps. Some investigated the map performance of different user groups, whereas others studies used tactile maps as a tool to evaluate cognitive maps (internal representations of space), or as a means to increase spatial knowledge in visually impaired people. Although the maps were mainly used as tools in these studies, rather than the object of evaluation, an exploration of their experimental methods was useful for the design of our evaluation study.

As part of a pioneering research project on ‘tactual mapping’, Wiedel and Groves (1969) investigated the performance of almost 400 visually impaired participants on thermoform maps of an urban neighbourhood and a shopping centre. Tasks were desk based and included symbol identification, route finding and orientation/direction of map features. Wiedel and Groves report the percentage of correct responses for different participant groups. The correct response rate ranged between 40% and 91%, but standard deviations were not reported and no statistical testing was conducted. The results appear to be plausible, for example adults performed better on most tasks than children, which suggests that this type of desk
based map task may be suitable for an evaluation of performance on tactile maps. However, Wiedel and Groves' meaningful results might be due to the very large number of participants, which might not be attainable for most research studies.

Several studies used wayfinding tasks, instead of desk based tasks, to examine performance on tactile maps. In her attempts to demonstrate that a tactile map can facilitate independent travel, Bentzen (1972) tested a thermoform map of a campus. Six participants were asked to plan and walk routes using a map. Accuracy of performance and completion time were recorded. All participants successfully planned the route on the map. Two participants successfully walked the route without help from the investigator, whereas four participants needed help after becoming disoriented at least once. From these results, Bentzen concluded that tactile maps facilitate or enable independent travel. For the purpose of this evaluation chapter, it is interesting to look at the time and accuracy scores. Bentzen did not quantitatively analyse these results, due to the small sample size. Both time and accuracy scores vary widely between and within participants, on similar tasks. It is not possible to identify high and low scorers; participants' performance on the three routes seems fairly arbitrary. This suggests that other factors, external to the study, may have played a large role, and that this type of wayfinding task may not be suitable for the evaluation of tactile maps.

In a series of experiments, a group of researchers in the UK and Spain (Blades et al., 1999; Espinosa et al., 1998) investigated how tactile maps contribute to the cognitive maps of visually impaired people. In their first study, participants learned a route either by direct experience, through guiding or by studying a tactile map. They were then asked to perform way finding tasks. There were no differences in performance between participants who learned the route through direct experience and those who learned the route by exploring a map. However, in a similar study, participants performed better on way finding tasks after exploring a tactile map, as opposed to learning a route through direct experience or verbal descriptions, as evidenced by a statistically significant difference on the measures between conditions. These varying results for similar studies suggest that way finding tasks may not be a reliable method for assessing cognitive maps created by different map learning processes,
because of the large effects of potential confounding factors on performance. Similarly, way finding tasks are not expected to be a reliable method for comparing and evaluating different types of tactile map.

Cognitive maps (i.e. internal representations of space) have been studied both in the sighted and visually impaired population. Kitchin and Jacobson (1997) published an extensive assessment of a variety of techniques used to study cognitive maps in visually impaired people, including route-based techniques (for example, Klatzky et al. (1990)), sketch mapping and reconstruction tasks (for example, Passini & Proulx (1988)). The authors questioned the suitability of most tests to measure cognitive maps in visually impaired people, because the tests measured accuracy rather than utility, had low reliability, generally used small sample sizes and were performed in small, simple environments. The same criticisms could be made of most quantitative evaluations of tactile maps.

Perkins (2001, 2002) published recommendations for the evaluation of tactile map performance, including a short literature review. He suggested to use real world and laboratory based assessments, multi-method evaluation techniques and to incorporate both quantitative and qualitative evaluation criteria. However, Perkins did not demonstrate how these recommendations could be applied in practise. He introduced an interesting campus mapping project, in which sighted students created maps for visually impaired students. Unfortunately, Perkins did not discuss his own methods of evaluation of these maps, and sufficed to say that ‘results showed’ that the designs were effective. Interestingly, this thesis follows Perkins suggestions, as we used real world, qualitative studies (the current evaluation study) and laboratory based, quantitative assessments (previous chapters), using a wide rage of experimental methods.

Selecting a suitable method
It could be argued that the quality of a tactile map should be investigated by using realistic way finding tasks. However, after an investigation of experimental methods of previous research, it was decided that tasks involving a way finding component were inappropriate for this study for a number of reasons. Firstly, the previous
sections show that way finding tasks did not differentiate between large differences in conditions in earlier studies on tactile maps, such as the use of tactile maps versus direct experience of the environment, or the absence or presence of a map template. Therefore, we did not expect such tasks to identify more subtle differences such as map design or production method. Secondly, performance on way finding tasks was expected to vary widely within and between participants, based on ‘environmental’ factors unrelated to the maps themselves. For example, the time required to complete a route in a building might vary depending on how quickly the participant happened to locate a doorway. Thirdly, the performance on a way finding task would depend to a large extent on the mobility and spatial abilities of the map user. Since these abilities vary widely between individuals, and may not be related to the ability to understand tactile maps, they were expected to contribute too much random interference to the data. Fourthly, it is not possible to determine to what extent participants use map knowledge and cues in the environment when performing a way finding task. Finally, tactile maps are not only used for mobility purposes, but also for general reference. For these reasons, our study involved desk based tasks. These tasks minimised the number of confounding factors, and enabled us to evaluate tactile maps in a realistic, but more controlled manner.

As discussed above, the evaluation of performance on tactile maps using quantitative measures is problematic, even when using a desk based task. Due to the sequential nature and small ‘field of touch’ of tactile exploration, map symbols are often found rather haphazardly. Whereas a prominent feature on a visual map will immediately be perceived, a prominent feature on a tactile map may repeatedly be missed by ‘unfortunate’ movements of the hands. As a consequence, timed map tasks, especially with a relatively small number of participants, often produce results with very large standard deviations, and can be hard to interpret.

Although most previous studies focussed on quantitative measures of performance, some studies also included qualitative elements. The qualitative findings, although generally presented as afterthoughts, were often more interesting than the reports of problematic quantitative tasks. Informed by the pattern of findings of previous studies, the current study focussed on qualitative measures, rather than quantitative
ones. It is important to consider the subjective experiences of tactile map users, and these have been overlooked in previous research. Qualitative measures were highly suitable for an evaluation study, because they enabled us to collect very rich data, which could explain and elaborate on performance in our earlier studies. Interviews also gave participants the freedom to discuss issues that were important to them, without being limited by predetermined ideas of the researchers.

Although the study was based on qualitative data collection, it involved regulated desk based tasks as well. In order to form an opinion of each map, participants performed desk based map tasks only for the purpose of map familiarisation. No quantitative data was collected on these tasks. After performing the familiarisation tasks, participants evaluated the maps by ratings and in a structured interview.

6.1.2 The current evaluation study

In order to test the results of our studies on individual aspects of tactile maps (Chapter 2 to 5), and in order to test the output of the TIMP printer, we conducted an evaluation study on a set of realistic topographical maps.

We conducted an evaluation study on a set of maps, in order to investigate the following:

1) In chapters 2 to 5, we examined individual aspects of tactile maps design, including substrate material, elevation of tactile features, spacing and width of single and double lines and discriminability of symbols. The current study assessed if the results on the individual aspects continued to work well when incorporated together on an entire map.

2) The current study also included a comparison of maps produced by several production methods, using several map designs. Of particular interest was the performance of the tactile inkjet map and the design based on this thesis in relation to the other maps.
6.2 Methods

6.2.1 Participants

In order to produce generalisable results with this qualitative evaluation study, it was important to have a sample of participants that was representative of the visually impaired population. We obtained a sample of participants across a wide age range, with varying degrees of vision and a broad range of experience of tactile maps and Braille. We recruited participants from the Surrey Association for Visual Impairment, the Royal National Institute of the Blind and Anglia Polytechnic University.

Nine visually impaired participants took part (4 females and 5 males, 20 to 69 years, mean age 50.6 years). Six were visually impaired from birth, whereas three participants became visually impaired later in life. Five participants were totally blind and four had varying degrees of residual vision. Seven participants were experienced Braille readers, one participant used Braille infrequently and one participant was learning Braille at the time of the study. Four participants had used tactile maps before. Table 6.1 gives an overview of the participants.

<table>
<thead>
<tr>
<th>Name</th>
<th>Age</th>
<th>Gender</th>
<th>Age at onset of blindness</th>
<th>Residual vision</th>
<th>Cause of blindness</th>
<th>Braille reader</th>
<th>Tactile map experience</th>
</tr>
</thead>
<tbody>
<tr>
<td>AW</td>
<td>20</td>
<td>M</td>
<td>Birth</td>
<td>No</td>
<td>Retinopathy of prematurity</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>JW</td>
<td>42</td>
<td>M</td>
<td>12 yrs</td>
<td>No</td>
<td>Glaucoma</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>AC</td>
<td>46</td>
<td>F</td>
<td>Early childhood</td>
<td>Yes</td>
<td>Optic nerve dystrophy</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>GG</td>
<td>54</td>
<td>F</td>
<td>Birth</td>
<td>No</td>
<td>Retinitus pigmentosa</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>KC</td>
<td>54</td>
<td>M</td>
<td>Birth</td>
<td>No</td>
<td>Retinopathy of prematurity</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>JH</td>
<td>54</td>
<td>M</td>
<td>Birth</td>
<td>Yes</td>
<td>Cataracts, nystagmas, retinal detachment, macular underdevelopment</td>
<td>Yes infrequently</td>
<td>No</td>
</tr>
<tr>
<td>JF</td>
<td>57</td>
<td>M</td>
<td>Birth</td>
<td>Yes</td>
<td>Macular degeneration, retinal detachment</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>MC</td>
<td>59</td>
<td>F</td>
<td>Birth</td>
<td>No</td>
<td>Congenital cataracts</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>AG</td>
<td>69</td>
<td>F</td>
<td>55 yrs</td>
<td>Yes</td>
<td>Macular dystrophy</td>
<td>Yes learning</td>
<td>No</td>
</tr>
</tbody>
</table>

Table 6.1 Participant details
6.2.2 Stimuli

This study incorporated maps produced using several production methods: tactile inkjet printing (TIMP printer) and the other three main production methods (thermoform, microcapsule and Braille embossing). A description of these production methods can be found in Section 1.1.3. The maps represented the same area, but used different designs to exploit the positive characteristics of each production method. In order to test a realistic tactile map, we selected a map that was produced by the National Centre for Tactile Diagrams (NCTD). This map was used as the original, on which all other maps were based. All maps were produced by recognised designers for each production method, or by us.

In order to maximise the validity of the evaluation study, it was important to choose a suitable map carefully. After an examination of the archive of tactile maps at the NCTD, to which the TIMP project was given access, we chose part of a map of Chesham town centre as the basis for a map for our study. The original map was produced on microcapsule paper. This map segment was designed by the NCTD, but was modified slightly from its original design and presentation for the purposes of this study. The modification involved the selection of a suitable square area of the map, and the deletion of a small number of line symbols that were located near the edge of the resulting square map. Figure 6.1 shows the NCTD map design, on which all other maps in this study were based.

This map fulfilled our requirements in a number of respects. Firstly, this was an actual map that had been produced for use in practice, and the NCTD believed that this map was representative of the types of maps they produce. Secondly, it contained an appropriate level of complexity, with a sufficient number and diversity of point, line and area symbols to allow us to re-design the map in different ways. The map also provided sufficient complexity for the performance of map related tasks by participants.
We produced seven maps based on the original NCTD design. All maps measured 20 by 20 cm. In order to conceal the fact that the same map was used, maps were produced in four orientations by rotating the symbols and Braille labels. Abbreviated Braille labels were used to indicate street names, such as HS for High Street.

Maps were produced by microcapsule, thermoforming, tactile inkjet printing and Braille embossing. Table 6.2 shows the combinations of production method and design that were used. The design of the original NCTD map (Map D and E) was adjusted to take advantage of the capabilities of each production method. Map A incorporated the psychological findings as reported in this thesis. The TIMP design incorporated the findings of the entire project, including psychology, engineering and cartography findings. This design was produced in full three-dimensional TIMP inkjet printing (Map B), and in a two-dimensional microcapsule version (Map C). Ann Gardiner, a designer and producer of tactile maps and honorary research fellow at the University of Manchester, created a thermoformed (Map F) and Braille
embossed map (Map G), changing the design of the NCTD map to maximise performance on these production methods. Ann Gardiner was asked to produce these maps, because of her extensive scientific and practical experience with the design and production of tactile maps (Gardiner & Perkins, 2002b).

Microcapsule and Braille embossing production methods use paper as substrate material. The paper was glued onto sheets of cardboard, in order to make these maps more rigid. The tactile inkjet and thermoform methods produced rigid maps which did not need strengthening. Since microcapsule and Braille embossed paper may wear with use, each participant received a new copy of these maps. Tactile inkjet and thermoform maps were durable enough to be used repeatedly by several participants.

The TIMP printer produced all tactile inkjet maps in this study (Map A, B and D). Maps were printed on high impact polystyrene (plastic) with a rough finish, as suggested by our study on substrates (see Chapter 2 and Jehoel et al., 2004, 2005).

<table>
<thead>
<tr>
<th>Map</th>
<th>Design</th>
<th>Production method</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Thesis</td>
<td>Tactile inkjet printing</td>
</tr>
<tr>
<td>B</td>
<td>TIMP</td>
<td>Tactile inkjet printing</td>
</tr>
<tr>
<td>C</td>
<td>TIMP</td>
<td>Microcapsule</td>
</tr>
<tr>
<td>D</td>
<td>NCTD</td>
<td>Tactile inkjet printing</td>
</tr>
<tr>
<td>E</td>
<td>NCTD</td>
<td>Microcapsule</td>
</tr>
<tr>
<td>F</td>
<td>Ann Gardiner 1</td>
<td>Thermoform</td>
</tr>
<tr>
<td>G</td>
<td>Ann Gardiner 2</td>
<td>Braille embosser</td>
</tr>
</tbody>
</table>

*Table 6.2 Production methods and designs of the seven evaluation maps.*

The maps contained various line, point and area symbols. Tactile keys were provided, containing all symbols with Braille labels. Each map was accompanied by a key, which corresponded to the design and production method. For example, the key for Map B contained the TIMP symbols and was produced by tactile inkjet printing. Table 6.3 shows the key for the NCTD map. Keys for other maps are not shown here. However, although individual symbols and their exact positions may vary, all maps have the same general lay out. It is, therefore, possible to identify symbols on all maps by comparing them to Table 6.3 and Figure 6.1.
Table 6.3 Symbol key for NCTD map.
Map A: Thesis design – Tactile inkjet

Figure 6.2 shows a digital image of the Thesis map design. For this map, the NCTD design was modified in agreement with the studies described in this thesis. It resembles the TIMP design (Map B and C), but it does not include input from the engineering and cartography research that was conducted in the Tactile Inkjet Mapping Project. This map aimed to evaluate the findings of this thesis. The following changes were made to the NCTD design:

1. In Chapter 2, we evaluated the use of several types of substrate for tactile maps. Although the substrate study suggests that paper substrates are most preferred and allow for the highest performance, paper may not necessarily be the most suitable substrate in all circumstances due to its lack of durability. The maps in the evaluation study had to withstand transportation to and use by multiple participants. Since rough plastic (high impact polystyrene with a rough finish) combines durability with high preference and performance scores, it was selected as the substrate material for the evaluation study.

2. Footpaths were similar to minor roads, but printed at a lower elevation, in order to evaluate the results of the study on elevation (Chapter 3). In accordance with the results of this study, footpaths were produced at an elevation of 160µm. At this elevation, we expected performance to be maintained while resources where minimised. All other point and line symbols were produced at an elevation of 400 µm. Footpaths were not expected to be highly discriminable from the minor roads. Although this would present a problem on a real map, in this case we were only interested in the participants’ ability to use symbols at this low elevation.
3. The two elements of double lines, representing a railway line, were separated by 1 mm. This is in accordance with the study on single and double lines (Chapter 4), which suggested that double lines require a gap width of 1 mm or larger in order to be identified correctly. The study also suggested that single lines should be narrower than 1.9 mm in order to avoid misperception as double lines. Therefore, single lines on map A were 1.4 mm wide.

4. The original NCTD point and line symbols were replaced by symbols from the highly discriminable symbol set (Chapter 5). The NCTD map contained five point symbols, which were replaced by symbols from our set. The car park, which was symbolised by an area symbol on the NCTD map, was replaced by a point symbol on map A, because we wanted to maximise the number of discriminable symbols on this map, and car parks are commonly symbolised by a point symbol on visual maps. In addition, research suggests that area symbols contribute to clutter and create distractions (Berlá & Murr, 1975a), which provided an additional reason for replacing an area symbol with a point symbol. The original NCTD map included six line symbols, excluding the image border. Since our set of discriminable symbols only contained four line symbols, the pedestrian footway was replaced by a minor road. For footpaths, we used the symbol for minor roads at a lower elevation (see below). These replacements changed the meaning and complexity of the map slightly. However, this sacrifice allowed us to evaluate the discriminable symbol set at its full strength.

Where possible, symbols were chosen that may aid in conveying meaning to the map user, either based on similarities in shape (for example, a double line might invoke images of the double track of a railway line) or common practice (for example, a church is often represented by a cross).

5. The three remaining NCTD area symbols (representing park & woodland, lake and shopping centre) were replaced by dot patterns. The dots varied in
elevation (100 &m for park & woodland, 200 &m for shopping centre and 400 &m for lake), in order to trigger varying degrees of perceived roughness.

Map B: TIMP design – Tactile inkjet

Figure 6.3 shows a digital image of the map designed by TIMP. In designing this map, the original NCTD map was modified in agreement with the findings of the psychology, engineering and cartography research of TIMP. In order to create Map B, the following changes were made to the original NCTD design:

1. Based on the results of Chapter 2, this map was printed on rough plastic (see the section above on the design of map A for further explanation).

2. Double lines were separated by 1 mm and single lines were 1.4 mm wide, in accordance with the results of Chapter 4 (see the section above on the design of map A for further explanation).

3. Where possible, NCTD point and line symbols were replaced by symbols from the highly discriminable symbol set (Chapter 5). Point symbols were replaced as described above in the section on the design of Map A. Line symbols were also replaced as for Map A, with the addition of a dashed line that was retained to represent footpaths. The pedestrian footway was represented by a line with a triangular line profile. Although this line was not part of the set of discriminable symbols, it was added to evaluate findings of the engineering research within TIMP (Dinar et al., 2005).

4. The NCTD area symbols were replaced by dot patterns, as described in the section above.

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8 We conducted a study on perceived roughness of textured area symbols consisting of dot patterns. Elevation had a very large effect on perceived roughness, while dot size and spacing had a small effect. The results of this study suggested that differences in elevation might be used to create discriminable area symbols on a map. After the evaluation study was designed, we decided not to include the study on roughness in this thesis. Firstly, a study on area symbols did not fit in the general line of the thesis, which focused on point and line symbols. Secondly, the use of area symbols to a tactile map is thought to decrease legibility (Berla and Murr, 1975a) and should be limited. For these reasons, we decided not to deal with area symbols in this thesis.
5. In order to evaluate engineering findings on directional symbols (McCallum et al., 2006), a one-way street was added to the map. This line contained a succession of elongated triangles.

Tactile inkjet printing produced a true 3 dimensional version of Map B. First of all, the pedestrian footway had a triangular cross-sectional profile, and the one-way street had a longitudinal saw tooth profile (as suggested by McCallum et al. (2006)). Secondly, the dotted area symbols were printed at elevations of 100, 200 and 400 μm. All other line and point symbols were 400 μm high.

Map C: TIMP design - Microcapsule
In addition to a tactile inkjet version, the TIMP map was produced on microcapsule paper. This process used the same 2 dimensional image (Fig. 6.3), but did not include 3 dimensional features. Since lines on this map were generally the same width, the microcapsule produced a map with a rather uniform elevation of 550 μm. Due to the lack of a third dimension, the pedestrian footway, which was printed in a triangular profile on the inkjet map, could not be distinguished from minor roads. All microcapsule maps in this study were printed on Zy-Tex2 microcapsule paper, produced by Zychem Limited. A Zy-Fuse Heater was used to create the raised image.

Map D: NCTD design – Tactile inkjet
Figure 6.1 shows a digital image of the base map, designed by the NCTD. All maps in this study were based on this design. The NCTD map was produced by tactile inkjet printing (Map D) and on microcapsule paper (Map E). Map D and E were intended to investigate differences between microcapsule and tactile inkjet maps, without contamination by design issues. Features on this map were uniformly printed at an elevation of 400 μm.

Map E: NCTD design - Microcapsule
Figure 6.1 shows the design of this map, which is identical to the design of map D. Due to the nature of the production method, the elevation of raised features on this map varied between 550 μm for narrow lines and 750 μm for wide lines.
Map F: Thermoform
Figure 6.4 shows a picture of the thermoform map, designed and produced by Ann Gardiner. Thermoform maps were produced on the Clarke 750 FLB thermoforming machine, using clear plastic sheets (APET film, 250 μm thick). In order to create a realistic thermoform map, Ann Gardiner was given the freedom to redesign the NCTD map according to her own experience and preferences. The only requirement was that the general lay-out, number and meaning of symbols should remain similar to the original NCTD design.

Anne Gardiner produced a double layered map, consisting of two separate sheets of thermoform. The bottom layer contained all point, line and area symbols. The top layer contained all line symbols and Braille labels for street names. Point and area symbols were omitted from the top layer. The two layers were placed on top of each other, and connected at the top of the map. Participants were encouraged to combine the information, by exploring both sheets simultaneously with two hands.

The features on the thermoform map were larger and higher in elevation than the features on other maps in the evaluation study. Point symbols were the highest elements on this map, with an elevation up to approximately 5.8 mm (5800 μm). The lowest line symbol measured approximately 1.5 mm (1500 μm) in elevation. The map also contained an indented line symbol, representing water. Area symbols ranged in elevation from approximately 2 mm to a finely textured area at very low elevation.

Map G: Braille embosser
Ann Gardiner also produced a Braille embossed map (Fig. 6.5). In order to create a realistic Braille embossed map, she was given the freedom to redesign the NCTD map according to her own experience and preferences. The only requirement was that the general lay-out, number and meaning of symbols should remain similar to the original NCTD design.

The Braille embossed map was produced on a Tiger Club Junior Braille embosser, which has a resolution of 20 dpi (more information can be found at
www.viewplus.com). Standard Braille paper was used, as supplied by Force Ten (www.forcetenco.co.uk). The elevation of point and line symbols was approximately 400 μm. The area symbol for park and woodlands consisted of a texture at very low elevation. Many of the Braille dots at higher elevations were ruptured, creating a sharp feel.

Fig. 6.2 Digital image of thesis map design (Map A).
Fig. 6.3 Digital image of the TIMP map design (Map B and C).

Fig. 6.4 Picture of bottom layer of thermoform map (Map F). This layer contained all point, line and area symbols. A top layer (not pictured) was added as a separate sheet of thermoform, containing all line symbols and Braille labels for street names.
Fig. 6.5 Scanned image of Braille embossed map (Map G). This map was produced on white paper. For the purpose of illustration only, the raised image was made visible by blackening the white Braille dots with a pencil.

6.2.3 Procedure
The main aim of this study was to conduct a qualitative evaluation of tactile maps of several designs and production methods. In order to ensure that the participants gained sufficient experience of each map on which to base their subsequent evaluations, they were asked to perform several map-related tasks during a familiarisation phase. After familiarisation with each map, participants were asked general questions about their likes and dislikes for that map. Once all maps had been explored, participants expressed their opinions about the maps in a more extensive interview. They also rated specific aspects of the maps.

Experimental setup
Participants were seated at a table, on which the experimenter positioned the maps in the most comfortable location, according to the participants’ preference. Maps were
then fastened to the table with adhesive putty, in order to maintain the correct orientation. Map keys were placed to the right or the left of the map, according to the participant’s personal preference. Interviews were recorded with a tape recorder.

Seven maps were presented individually in semi-random order of design, production method and map orientation. For each participant, the random order of maps (A, B, C etc) was combined with semi-random order of orientation. Since maps were produced in four orientations, maps were presented twice in three randomly selected orientations and once in the remaining orientation. Maps of the same orientation were not presented in successive trials.

Map familiarisation
Participants performed several structured tasks during the familiarisation phase. No data was collected on these tasks. Firstly, participants were allowed briefly to explore each map and accompanying key, in order to get a rough idea of the layout and types of symbols used on the map. Then, participants performed several map related tasks. A variety of tasks was chosen to replicate realistic map use, including symbol finding, route finding and line tracing. In the first task, participants were asked to find point symbols (two churches and a public toilet), line symbols (a footpath and a minor road) and area symbols (two areas of parks & woodland). They were also asked to find the church on Stoke Road (indicated by SR in Braille), which required a combination of Braille, line and point symbols. In addition, participants were asked to find the pedestrian footway on Map B (TIMP design, inkjet). The second task related to finding a route on a map. Participants were asked to find a route between a car park and a church, located at opposite ends of the map. Participants were allowed to use any combination of roads and footpaths to connect the two points. Finally, participants were asked to follow the main road across the entire map.

Interviews and ratings
The interviews were designed to elicit participants’ comments on a wide range of issues related to the production method and design of the evaluation maps. Especially in the initial stages of the interview, participants were encouraged to freely discuss
issues that were important to them, without the experimenter controlling the topic of conversation. This freedom enabled participants to bring up unpredicted issues, which may have been neglected if the interview schedule only included predetermined topics. After the general questions, the interview questions gradually became more focussed. By using focussed questions, we encouraged participants to comment on aspects of the maps that we were particularly interested in. The full interview schedule can be found in Appendix E.

After familiarisation with each map, participants were encouraged to freely discuss their likes and dislikes for that map. The participants were also given the opportunity to give further comments about the map. These questions were asked immediately after exploration of each map to elicit spontaneous comments and opinions from the participant.

After all maps had been explored, the experimenter asked more focussed questions, involving a comparison of certain map aspects across all map design and production methods. These questions gradually become more specific. First, participants were asked to discuss any differences they had noticed between the maps. Participants were also invited to express particular likes or dislikes for any of the maps, and to indicate any features that were difficult to understand or uncomfortable to use. Then, the interviewer asked more specific question about several aspects of the maps. First, participants were asked how pleasant to touch each map was. Then, participants were asked to comment on the use of material of the raised features, and the substrate material. They were also asked to comment on the symbols and the lay-out used.

Where possible, a selection of the relevant maps was used for each question. For example, when asked about the materials of raised features, participants were shown one example of each production method.

In addition to expressing their opinions in a qualitative interview, participants verbally rated aspects of maps on a five-point scale, in which ‘1’ signified the lowest score and ‘5’ signified the highest score. Participants rated general liking,
pleasantness to touch, ease of use of materials of raised features, ease of use of substrate materials, ease of symbol use and ease of use of map layout.

The topics for the focussed questions and the ratings were established by taking into account the differences between production methods and map designs of the evaluation maps, and the topics of our earlier studies. Questions about ‘general liking’ were expected to encompass issues raised in all other questions, and were also intended to give participants the opportunity to raise issues that were not discussed elsewhere. Questions about ‘pleasantness to touch’ related mostly to the feel of materials that were used by different production methods, which was associated with the results of the substrate study (Chapter 2). This issue was explored further by questions about ‘ease of use of substrate material’ and ‘ease of use of material of raised features’, which were also intended to elicited comments about elevation (Chapter 3). Questions about ‘symbols’ encouraged participants to compare the design of symbols on different map designs. We also expected participants to comment on symbol discriminability (Chapter 5). Although earlier studies in this thesis did not deal with map layout, participants were asked to comment on it, because of its links with symbol design (for example, larger symbols may cause a more cluttered layout) and because the layout of the two-layered thermoform map was considerably different from other layouts.

6.3 Results

6.3.1 Map ratings

During the interview, participants rated aspects of tactile maps on a five-point scale (Fig. 6.6 to 6.11). The ratings included general liking and pleasantness to touch of each map. Participants also rated the ease of use of materials (raised features and substrate), symbols and layout. Statistical tests were not conducted on these ratings, due to the small number of participants. However, bar graphs suggest that there might be significant differences between maps on some aspects.

Figure 6.6 shows that, generally, participants liked the TIMP inkjet map (Map B) most, closely followed by the Thesis and NCTD inkjet maps (Map A and D), and the
thermoform map (Map F). The microcapsule and Braille embossed maps (Map C, E and G) were least preferred. Although the range of average rating scores is quite small, and some error bars overlap, it is clear that all inkjet and thermoform maps were highly liked.

![General liking graph](image)

Fig. 6.6 Average rating scores for general liking. Error bars indicate standard errors of the mean.

Figure 6.7 shows how participants rated the pleasantness to touch of each map. Microcapsule maps (Map C and E) were considerably less pleasant to touch than maps produced by other production methods. Braille embossed maps (Map G) also scored low on pleasantness, but the standard deviation was large. Inkjet and thermoform maps (Maps A, B, D and F) were rated as most pleasant to touch. The design of inkjet maps did not affect the pleasantness to touch. However, the TIMP microcapsule map (Map C) received a lower rating than the NCTD microcapsule map (Map E). This may be caused by the wider lines on the NCTD map, which create a smoother feel when produced on microcapsule paper.
Fig. 6.7 Average rating scores for pleasantness to touch. Error bars indicate standard errors of the mean.

Participants' ratings of the material of the raised features are shown in Figure 6.8. The raised features on thermoform were rated as easiest to use, while the raised feature on Braille embossed and microcapsule paper were rated as most difficult to use.

Fig. 6.8 Average rating scores for ease of use of material of the raised features. Error bars indicate standard errors of the mean.
Rating scores for the ease of use of the substrate material are shown in Figure 6.9. In this case, the rough plastic that was used as the substrate material for inkjet maps was rated as easiest to use. Microcapsule paper and thermoformed plastic were rated as most difficult to use.

![Substrate material](image)

**Fig. 6.9** Average rating scores for ease of use of the substrate material. Error bars indicate standard errors of the mean.

As shown in Figure 6.10, the symbols on the thermoform, TIMP and Thesis maps were rated as easiest to use. The NCTD symbols received a somewhat lower score. The symbols on the Braille embossed map were considered more difficult to use.
Fig. 6.10 Average rating scores for ease of use of the symbols. Error bars indicate standard errors of the mean.

Although the rating scores for the layout of the maps were rather close together (Fig. 6.11), the data suggest that the TIMP layout was easiest to use and that the Braille embosser layout was most difficult to use.

Fig. 6.11 Average rating scores for ease of use of the map layout. Error bars indicate standard errors of the mean.
6.3.2 Interviews

The interviews were recorded on tape and transcribed. Content analysis (Wilkinson, 2004) was used to explore the data. This analysis summarises and systematises interview data into categories. A thorough initial reading of the transcripts allowed us to establish a set of relevant categories. During further readings, participants’ statements were extracted and grouped into categories according to the aspect of map design or production method they related to. This resulted in a list of 619 individual statements. Common views were then determined, reflecting the general opinion about aspects of map design and production method. All comments reported below are drawn from the participants’ perceptions of the maps.

To establish the coding categories, we used both top-down methods and bottom-up methods. Top-down categories were determined by the researchers and were incorporated into the design of the interview schedule, where participants responded to a pre-determined question about a specific aspect of a map, such as layout or feel of map material. Bottom-up categories were established when participants made spontaneous comments about a map, on topics that were not prompted by the interviewer. Participants often discussed Braille and the intuitiveness of symbol meaning, which were not mentioned by the experimenter and were therefore formed into bottom-up categories. Of course, many spontaneous comments fell into already established top-down categories. Several other categories (clarity, elevation and symbol discriminability) were not directly asked about by the experimenter, but might have been implied by more general question about materials or symbols. Since participants often commented on these issues, they were formed into categories in their own right based on the large number of comments.

Because participants were encouraged to freely discuss any aspect of the maps in an unstructured manner, the final set of categories that emerged from the qualitative analysis of the interviews did not precisely match the rating topics (i.e. top-down categories) exactly. However, they were loosely linked to the quantitative ratings of map aspects and they served as an explanation and elaboration of the ratings. Figure 6.12 shows how the quantitative and qualitative data might be linked. We expected that participants’ rating of general liking would encompass an assessment of all
aspects of a map. More specific rating topics, such as pleasantness to touch and layout, were thought to only relate to those specific categories. Ratings of the maps materials were thought to be linked to the feel of material, clarity and quality of Braille. Ratings of symbols were thought to relate to symbol design, discriminability and intuitiveness.

![Diagram showing the relationship between rating topics and categories used in qualitative analysis of interviews.](image)

*Fig. 6.12 The relationship between rating topics and categories used in qualitative analysis of interviews.*

**Feel of material**

The majority of statements, both spontaneous and prompted, related to the feel of the map material. This was often the first aspect of a map that participants noticed and commented on upon exploring a new map.
Participants were generally positive about the feel of inkjet maps. These maps were described as smooth and pleasant to feel, and it was easy to move one’s fingers across these maps. (“This has got by far the best background. That’s smooth as anything, so firm and easy to move across. (KC)” “It’s nice and smooth. (AC)” “Your hands go easily over it. (GG)”)

Most participants described the microcapsule maps as rubbery, which was often found to be off putting. These maps gave a sticky feel and were resistant to move one’s hands across. (“The surface is slightly holding, [...] you can’t read it fast. (KC)” “My hands were sticking on that a bit. (GG)” “The rubberised thing can be a bit off putting. (JW)”) However, two participants liked the feel of microcapsule maps. (“It’s quite pleasant to feel [...] nice soft rubber. (JF)”)

Opinions on the feel of thermoform maps varied. Most participants commented that the material felt sticky. (“It’s a bit sticky. (MC)” “It isn’t particularly pleasant to touch. It does feel quite slimy and sticky. [...] I should imagine that if it was quite hot your hands would stick to the plastic, which wouldn’t be good because it would just make it uncomfortable to read them. (AW)”)

However, two participants thought the thermoform material “had a pleasant feel about it” and was quick to read. (“Why is it pleasant? Because it is quick. You don’t have to do any work and it’s very smooth and your hands going across it. (KC)”)

The Braille embossed map felt like ordinary paper, which was not sticky and easy to run one’s hands across. (“I find it easy to run my hands over it. (GG)” “That just feels like ordinary paper which, it’s okay, it’s smooth. (AW)”)

However, the raised features felt rough and sometimes uncomfortable. (“I just don’t like it. It just feels completely like Braille to me. (AG)” “A bit uncomfortable because of the slightly rougher feel. (GG)”)

**Clarity**

In addition to comments about the feel of the map material, participants often commented on the clarity of symbols. The clarity was related to production method,
as some methods produced symbols with sharper edges and others produced less defined features.

Most participants commented that the symbols on inkjet maps were clear, because of the fine detail of the raised features. ("There's more clarity in the line. So there's all sharper lines. [...] It's very definite under your hands. (KC)" "The lines and the things are quite precise. (AC)") However, one participant said that "it's slightly less focussed. I imagine a cross section, it's a softer edge, which subjectively gives me a feeling of less definition. (JH)" Several participants mentioned that the clarity was sometimes compromised by the low elevation of tactile features, which will be discussed below.

The symbols on microcapsule maps were less clear, due to the softness of the material and the rounder edge of tactile features. Participants described symbols as "fuzzy (KC)", "squidgy (JW)", "less clear (JH)" and "not distinctive enough (JW)".

Symbols on thermoform maps were considered to be clear, because of their boldness and chunkiness. ("Things have a lot more clarity to them. (JW)" "[The symbols] are sort of sharper. You can actually feel the shape of them. (MC)" "Much bigger, bolder detail. (JF)"). However, according to one participant, the chunkiness of thermoform maps might have a negative effect on the clarity of symbols. ("It's a bit too chunky for my taste. [...] The chunkiness loses quite a bit of detail. (JF)"

Opinions on the clarity of Braille embossed maps varied. Some participants felt that these maps provided fine detail and high levels of clarity. ("I quite like the better detail of it. (JF)" "It's sharp, it's focussed, it's clear. This was the easiest, maybe because it reminded me of Braille. There's a kind of clarity about it. Clearness on the edge, [...] it's almost sharp. I don't literally mean that. It feels very strong definition. (JH)") However, other participants thought these maps were less clear than maps produced by other production methods ("It's very fuzzy, undifferentiated and the images are all rather fluffy. (KC)" "It doesn't feel quite as clear as some of the others. (MC)"

Elevation

The elevation of tactile features is another aspect of production method. Elevation could be considered as part of the clarity of symbols (see above), because higher elevations will generally produce clearer symbols. However, it is discussed separately because it was mentioned specifically by many participants. The large number of comments on this topic warranted the creation of a separate category.

Most participants commented that features on the inkjet maps were too low in elevation, reducing the clarity of these maps. Features were often described as “flat (JW, KC)”, “shallow (JW)”, “faint (AW, MC)” and “low (KC)”.

Only one participant commented on the elevation of features on microcapsule maps, saying “it was very faint again, very 2D, quite hard to distinguish what was what (AW)”. Elevation on these maps did not appear to be an issue for other participants.

Thermoform maps were produced at higher elevations than other maps. Most participants liked the high elevation, because it increased clarity. (“Symbols are very, very clear. Very obvious because they stick up a lot. (GG)” “I like the really 3D nature of the symbols. (AW)””) However, some participants expressed irritation at the high elevations. (“A bit too up and downy for my liking. It could be a bit sharp, because you’ve got things like the churches stick out and you could hurt your fingers doing that. (JW)” “You don't have to be quite so blunt about it. (JF)”)

Braille embossed maps were considered to be low in elevation, which reduced the legibility of these maps. (“The symbols are flattened and difficult to do. (KC)” “That isn’t quite as good, they’re not quite so raised. (GG)”)  

Braille

We have not considered the use of Braille on maps in this thesis, and we did not ask participants about it in the interview. However, since 8 out of 9 participants spontaneously commented on the quality of Braille on the evaluation maps, we created a separate category.
All comments on Braille on inkjet maps were favourable. Braille was considered to be clear and sharp. ("Nice sharp Braille. (KC)" “The Braille was easy to read. (AC)")

Opinions about Braille on microcapsule maps varied. Some participants found the Braille easy to read (“I think the Braille was easier on these. (AC)”). Others commented that the Braille was difficult to read because it felt “squashy (JW)” and “flattened (KC)”. This is an interesting finding, considering that microcapsule paper is often used for the production of Braille text.

All comments on Braille on thermoform maps were negative. The Braille was too low in elevation and, therefore, difficult to read. (“The Braille was extremely faint and hard to read. (AW)” “I found the embossing [i.e. elevation] of the Braille not enough. (JH)"

Symbol design
In addition to comments related to production methods, participants expressed their views on the design of the maps. Most design related comments, both prompted and spontaneous, related to the design of symbols. This category included general statements about sets of symbols and evaluations of individual symbols. Participants also commented on the discriminability and intuitiveness of symbols, which will be discussed later. Participants did not often mention specific aspects of symbol design, but several general views on symbols are discussed below.

Participants regularly commented on the size of symbols. Although symbols on most maps were a good size, some symbols were too small for comfort, such as the church and the toilet symbol on the NCTD map (“If I was desperate to go to the loo, I’d be losing the will to live by now because it’s just really hard to feel. It’s a tiny little blob and that’s just not very easy at all. […] I think the church things are miles too small (JW).”) Generally, larger symbols were easier to use (“[Symbols on the Thesis map] are bigger and easier to feel. (JW)”) However, several participants mentioned that some symbols were too large. (“I thought some of the symbols [on the Braille embossed map] were too big. (JH)”) One participant noted that “one thing that’s
important is you can feel the [...] whole of the symbol under your finger (AC)"], which was the case on the Thesis map.

In general, area symbols were found to be more difficult to use than point and line symbols, due to their lower discriminability (see below). Therefore, maps that replaced the area symbol for car park by a point symbol (Thesis and TIMP map), were sometimes considered to be easier to use ("The ones with the square car park are, on the whole, a lot easier than where they used an area one. (AC)").

The church symbol was the most frequently discussed individual symbol. Most participants expressed a preference for the church symbols that was shaped like a ‘+’ (Thesis, TIMP and thermoform design), over the symbol shaped like an ‘x’ (NCTD design). ("The church symbols [on the NCTD map] are not very clear because of the angle that they’re at. (JW)" "I liked the plain cross with the church [on the Thesis map]. (JF)" "The church [on the Thesis map] was lovely. (GG)""). In addition to being more intuitive (see below), the ‘+’ symbol appeared to be easier to feel. Especially on microcapsule maps, the ‘x’ "felt like Braille (AC)" and "looked like a lump (AW)".

Symbol discriminability
As part of symbol design, symbol discriminability was discussed frequently by participants. This related to the ease of discrimination between symbols on a map. High discriminability contributed to the ease of use of a map ("I think the ones that have got the simpler symbology, simpler ways of distinguishing between these things are obviously better and easier to learn. (AC)"). Participants commented on problems with discrimination between specific symbols, and on discriminability of entire sets of symbols.

In general, area symbols on all maps were more difficult to discriminate than point and line symbols, except on the thermoform map. ("The area symbols are difficult to tell apart. (AC)" "You’ve still got this problem with lakes, parks and shopping centres. (KC)") Neither the two-dimensional variation in pattern of the area symbols on the NCTD design, nor the three-dimensional variation in elevation of area
symbols on the TIMP and Thesis design provided a discriminable set of area symbols. The discriminability of area symbols on the Braille embossed map was not considered, because this map contains only one area symbol. Participants’ inability to discriminate between area symbols may be surprising, considering accurate performance in pair-comparison studies on the discriminability of area symbols (see Chapter 5). However, this evaluation study supports our claim that symbol discriminability needs to be studied in the context of a realistic task, rather than in artificial conditions of adjacent pair comparisons.

Participants commented favourably on the discriminability of symbols on the Thesis map. (“It has quite distinctive differences between the symbols. (JW)” “[The symbols] contrasted better with each other. (AW)””) However, as expected, the line symbols (footpath and minor road) and area symbols that differed from each other only in their level of elevation were not thought to be highly discriminable. (“The level on the lake in the park [...] is very difficult to tell unless it’s in context with each other. And the same with the footpath and the minor road. (AC)”)

The symbol set of the TIMP map was largely similar to the symbol set of the Thesis map and, therefore, comments were similar. Participants generally thought the TIMP symbols were highly discriminable. (“There are no complex differences, there are no fiddly little differences between them. (AC)” “It’s easy to differentiate between the different roads. (JF)””) However, several participants had problems discriminating between the footpath, one-way street and image border. (“The footpath was similar to the border. (AW)” “The footway and the one-way were a bit the same. (KC)”)

Discrimination between line symbols on the NCTD map was problematic. This is in agreement with our discriminability study (Chapter 5), which suggests that discriminability is low between broken line symbols that vary in the length and gap distance of their elements. In general “the differentiation between roads is less clear (JF)”. Participants often specifically mentioned confusions between the footpath and the image border. (“Another problem was with the footpath. It was too similar to the map’s border. (AW)””)
Discriminability of most symbols on the thermoform map was high. ("It's very easy to discriminate between the different symbols. (AW)" "Very distinctive, very easy to feel the differences. (JW)") However, several participants found it difficult to discriminate between major and minor roads, indicated by a difference in line width. ("The difference [...] between major and minor roads, I don't think is really very good. (JF)"

Discriminability of line symbols on the Braille embossed map was problematic. This problem might be a combination of map design and production method. ("With a Braille or a dot matrix orientated Braille embossing system, the range of different textures is not so distinctive, so they do feel similar. That makes it difficult to differentiate between one and the other. (JW)"

Intuitiveness of symbol meaning

Although participants were not prompted to comment on intuitiveness of symbol meaning, they often spontaneously mentioned it. Intuitiveness of symbol meaning refers to the degree of immediate symbol identification, without the need to refer to a key. Participants preferred highly intuitive symbols, because they facilitated map reading.

The church symbol was most frequently mentioned in relation to intuitiveness. The cross symbol ("+"), which was used on the Thesis, TIMP and thermoform map, intuitively symbolised 'church' for many participants. However, the ‘x’ symbol, which was used on the NCTD design, and the triangle, which was used on the Braille embossed map, did not spontaneously invoke their assigned meaning. ("I actually like the symbol of the church [on the thermoform map] because it's more logically like a church. (GG)" "I preferred this cross [on the Thesis and TIMP map] linked in with the church so you associate it. [...] I wouldn't associate a triangle with a church. (AW)"
The line symbol for A roads was also discussed frequently. Participants mentioned that the wide and smooth line for A roads on the NCTD map had an intuitive meaning. ("I like the lines on the main road; that's quite clear that it's a main road. (MC)") However, the dotted lines for A road on the Thesis, TIMP and Braille embossed map did not generally conjure up the correct meaning. ("I don't like the bumpy texture to the road [on the Thesis and TIMP map]. It doesn't say 'road' to me. It feels more like gravel footpath or river or something else like that, but not road. (JW)")

Some participants commented on the symbol for railway line. The double line, used on the Thesis and TIMP map, intuitively represented the two lines of a railway track, as did the double line with ‘sleepers’ on the thermoform map. ("The railway line [on the thermoform map] couldn't be anything else, could it? I haven't got the legend in front of me, but I know that's a railway line. (KC)" "I like the dual line [on the Thesis and TIMP map], the two lines running in parallel with each other. (JW)"") However, the dotted line on the NCTD map was "not very railway-ish (KC)".

Map layout
Participants were asked to comment on the layout of each map during the interview. Most participants found it difficult to answer this question. This could be due to the fact that all maps were rather similar in layout, or to difficulties in evaluating the map as a whole, rather than evaluating single symbols or pairs of symbols. ("I'm not sure I've really picked up a distinctive difference [in layout] between all of them. [...] I'm trying to interpret your definition of layout. I find it very hard to answer your question. (JW)"")

Although all maps contained the same number of symbols, some maps felt more cluttered than others. This could be related to the size of symbols. Cluttered maps were more difficult to use than less cluttered ones. ("The symbols [on the thermoform map] feel like they're all joined together a bit more. It's harder to feel in that sense. They're a lot closer together, maybe they're bigger. So therefore it's going to be a little more cluttered. (JW)"") Less cluttered maps provided more empty space around symbols, which facilitated map use. ("I found the layout [of the Thesis..."
map] good because there is space in between [the symbols], so that you've got a chance to really feel each individual one. (GG)"

"I think it's better if there's a bit of distance between a church and a .... so you can get your fingers around it, [like on the TIMP map]. (AG)"

Although participants preferred a reasonably amount of space around symbols, Braille labels needed to be close to the symbol they referred to. "[The Braille and point symbols on the TIMP map] are very close to the roads and the streets that they are referring to. It makes it easier and you don't feel lost if you go more than a little while, if you go and move your finger off. (AC)"

Most participants commented on the use of two map layers on the thermoform map. Although participants realised the advantages of reducing clutter this way, most participants found it difficult to use the two layers. Handling the map was awkward, and mentally combining the two images was thought to cause confusion. ("I think there is some good in the overlay, but it makes it difficult to swap from one to the other. Trying to locate where you are from the top level to the bottom level, I think, will be a bit of a nightmare. (AC)"

"It's quite hard working with two sheets. (AW")"

6.4 Discussion

In this study, we evaluated tactile maps of a town centre. In addition to evaluating the findings described in this thesis and the output of the TIMP printer, we were interested in the assessment of other production methods and map designs. First, participants completed several map related tasks, in order to familiarise themselves with the map designs and production methods. Then, participants assessed and compared maps in interviews and ratings.

The familiarisation tasks were intended to encourage the participants to use the maps and to form opinions on different map aspects. These tasks were devised to replicate tasks that a user might perform on an actual map. Informal observations suggest that we succeeded in creating realistic map tasks. Rather than using low level, abstract
search strategies (for example, searching for a shape in a meaningless collection of
distraction shapes), participants performed the tasks by interpreting the maps in a
meaningful way. This was demonstrated by comments such as “If I walk down this
road and turn left here [...]” and “This must be the railway station, because it is at
the end of the railway line”.

Participants were able to complete the familiarisation tasks on all maps. This
suggests that, even though participants expressed clear preferences for certain maps,
all maps were useable. However, informal observations suggest that performance
was somewhat affected by the use of non-discriminable symbols on the Braille
embossed map and, to a lesser extent, on the NCTD designed maps. Participants who
had no previous experience with using tactile maps did not appear to find the task
more difficult than more experienced map users. This is an encouraging result for the
production and design of tactile maps in general.

The qualitative nature of this evaluation study, although fully intended and justified
by the literature, may cause concerns about the generalisability and reliability of the
results. As suggested by our previous studies on map substrates (Chapter 2),
qualitative preference is not always directly related to quantitative performance.
However, since we did not expect to be able to find quantitative difference in
performance in a map evaluation study, we used qualitative measures. Fortunately,
participants generally expressed the same opinion about most aspects of the maps,
and the opinions expressed in the qualitative interviews correspond to and can
explain the quantitative results of the map ratings. This suggests that our results are
reliable. In addition, the qualitative nature of this study provided us with very rich
data and with some unpredicted insights into map production and design, neither of
which we would have been able to attain with a quantitative study.

Another cause for concern is related to the design of the study. Although all
participants found it easy to express their opinions about production methods, most
participants found it more difficult to comment on design factors. The production
method was immediately noticeable and seemed to have a larger impact on the
general opinion of a map than the map design, which was only noticeable after more
detailed exploration of the map. On occasion, some participants were not able to consider design issues, such as the design of symbols, separately from the production method. In future research, production methods and map designs should be considered in separate studies, in order to avoid the overshadowing effects of production method.

6.4.1 Comparing production methods and designs

Regarding production methods, participants preferred materials that were easy to slide their fingers across and not sticky. They preferred sharp, precise symbols at high elevations. Thermoform and tactile inkjet maps fulfilled most of these criteria. Although the material was considered to be somewhat sticky, thermoform maps were appealing because they presented symbols at very high elevations. Participants reported that inkjet maps were made of smooth materials and produced well defined symbols. The elevation of inkjet features was considered to be a little low, but this problem could easily be addressed by printing features at higher elevations. Microcapsule maps were generally disliked because of their sticky feel, and the symbols were often found to be fuzzy and undefined. The symbols on Braille embossed maps were undefined and the maps had an unappealing feel, making this production method clearly unpopular.

Discriminability of symbols, intuitiveness of symbol meaning and clutter were the most important aspects of map design. Participants reported that the thermoform, TIMP and Thesis maps contained the most discriminable symbols, followed by the NCTD map. The symbols on the Braille embossed map were not considered to be highly discriminable. However, it is not clear whether the lower perceived discriminability on the Braille embossed map is due to the overshadowing effect of the inferior production method or the design of the symbols.

Most map designs contained both symbols with intuitive meaning and symbols with no intuitive meaning. Since participants commented on a limited number of individual symbols, it was not possible to deduce the level of intuitiveness of entire
sets of symbols. However, the fact that most participants spontaneously mentioned intuitiveness, suggests that it is important to assign meaning to symbols carefully.

In general, the results of the evaluation study suggest that tactile maps should be produced on smooth material that is easy to move one's fingers across. Symbols should be clearly defined and produced at relatively high elevations. Most production methods can only partly fulfil these requirements. Thermoform can produce clear symbols at high elevations, and Braille embossed maps are produced on a highly suitable substrate. The tactile inkjet printer is able to fulfil all these requirements. Tactile features produced by this printer are clearly defined and can have any required elevation. Inkjet maps can be produced on a range of substrates, including highly suitable papers and rough plastics. Regarding design, symbols should be discriminable and intuitive, and maps should not be cluttered.

6.4.2 Evaluating findings of thesis

In addition to comparing maps created in several designs and production methods, we evaluated the research findings described in this thesis. The Thesis map was designed according to the results of our earlier studies and could therefore be used to evaluate the application of the findings on a real map, in comparison to maps that were not designed according to the findings.

Substrate

The Thesis map was printed on rough plastic, in accordance with the findings of our studies on substrate material (Chapter 2). This substrate received high scores in the preference ratings and was commented on favourably in the interviews. The rough plastic substrate was described as smooth and easy to use. Although participants liked the rough paper of the Braille embossed map, the raised features on this map were problematic. The sticky paper of microcapsule and smooth plastic of thermoformed maps were not highly liked.

The preference for rough plastic (tactile inkjet) and rough paper (Braille embossing) correspond to the results of the substrate study. In addition, the negative comments
about the smooth plastic (thermoform) reflect the findings of our earlier study. Surprisingly, microcapsule paper elicited negative comments in the evaluation study, whereas it was one of the favourite materials in the substrate study. This discrepancy might be due to the fusing process of microcapsule paper. Whereas in the substrate study, inkjet symbols were printed on unheated microcapsule paper, the evaluation maps were heated to create a raised image. The fusing process often alters the surface properties of the entire map, including the white background, creating a sticky feel. The unfavourable reactions to the processed microcapsule map, as opposed to untreated microcapsule paper, have implications for the interpretation of the results of the substrate study. Contrary to our initial findings, the material of microcapsule maps does not appear to be conducive to map reading.

**Elevation**

The symbols for footpaths on the Thesis evaluation map were printed at an elevation of 160 µm. According to the results of the elevation study (Chapter 3), this elevation was expected to be easily readable. Participants were able to use these lines at low elevations, as shown by their ability to find and trace the footpaths in the familiarisation tasks. However, participants criticised these lines for being too faint.

Many participants mentioned that the overall elevation of inkjet maps (400 µm) was low, and that they preferred the high elevations of the thermoform map (up to 5800 µm). This does not correspond to the results of the elevation study, in which participants' performance did not increase at elevations over 400 µm. However, the dislike of lower, but readable elevations supports the claim that preference and performance are not always linked, as we also found in the results of the substrate study. In retrospect, it might have been beneficial to include a qualitative assessment of participants' subjective experience in the elevation study, in the form of preference ratings, confidence ratings or interview questions. This qualitative information might have alerted us to the finding that, although participants were able to use tactile features at a low elevation, they did not feel comfortable with such low elevations.
The comments on elevation of the Thesis map related to the specific map design rather than production method per se, as the inkjet printer has the potential to produce tactile features at any elevation. It might be possible to improve the evaluation of the Thesis map by simply producing the map at a higher elevation. However, the findings of this thesis do not identify an ideal elevation for tactile maps. On the one hand, an elevation of 160 μm, as suggested by the evaluation study, appears to be too low. On the other hand, some participants disliked elevations of 5800 μm, as used on the thermoform map.

**Single and double lines**

The double line on the Thesis map, representing a railway line, had a gap distance of 1 mm, as suggested by the study on single and double lines (Chapter 4). Although this symbol was not included in the familiarisation task, many participants commented on it. All comments reflected a successful identification as a double line. This indicates that the results of our study on the gap distance of double lines are applicable to the design of tactile maps.

The A road on the NCTD map was indicated by a single line of 3.7 mm wide, when produced by the inkjet printer. Although the results of our earlier study suggests that wide, single lines are sometimes perceived as double lines, none of the participants in the evaluation study described this symbol as a double line. This could be explained by a combination of the small proportion of incorrect identifications in the earlier study (approximately 20%) and the small number of verbal identification of the symbol in the evaluation study. Incorrect identifications of the wide, single line might have occurred with a larger number of participants and/or a larger number of verbal identifications of this symbol. The wide, single lines on the microcapsule and thermoform maps had a rounded profile, and were therefore not expected to be perceived as a double line.

**Discriminability of symbols**

In general, the evaluation study confirmed the results of the study on symbol discriminability. The Thesis map contained the highly discriminable symbols that were identified in Chapter 5, with the addition of a line that was printed at a lower
elevation. In general, this set of symbols maintained its discriminability when used on the evaluation map. However, the two line symbols that differed by elevation only were not discriminable from each other. This was an expected result and it does not invalidate the results of the study on discriminability, since the low line was not part of the discriminable symbol set.

The findings of the discriminability study also explained the problems with discriminability on the NCTD map. Participants often commented that the broken lines on this map were not discriminable, which accords our earlier finding that broken lines containing dots and dashes were often confused with each other.

Point symbols on the Thermoform map were found to be highly discriminable. Ann Gardiner selected an outline symbol (roundabout), a solid symbol (toilets), a cross (church) and two symbols with internal elements (station and post office). Except for the two symbols with internal elements, this is in accordance with the suggestions for creating a discriminable set of symbols by the principles of discriminability (see Section 5.5.2).

6.4.3 Use of evaluation study

The previous chapters in this thesis described quantitative studies on tactile map design and production. These studies mainly investigated performance on individual aspects of tactile maps, although we attempted to create tasks that resembled map reading as closely as possible. In the final study, we used qualitative measures to evaluate the application of our findings from our earlier studies on an actual tactile map.

Participants provided a mostly positive evaluation of most map designs used in this study. Although some aspects of design, such as the non-discriminable line symbols on the NCTD map and the low elevation of the inkjet maps received unfavourable comments, all maps were usable. It may appear that the application of the results of the current research to the design of the experimental Thesis map did not greatly improve the design of the original map. This may cause concern about the
contribution of the current research to the improvement of design of tactile maps in general. However, all maps in this study were designed by experienced map producers. As a result, all maps were well designed and did not cause considerable problems for the participants. In retrospect, the evaluation study might have benefited from the inclusion of a badly designed map. This would have allowed a comparison of participants' reactions to well designed and badly designed maps.

Generally, the qualitative data from the evaluation study was in line with the results from the quantitative studies. Participants' comments on the evaluation maps reflected performance on map aspects in earlier studies. In addition, the evaluation map that was designed according to the findings of this thesis mostly received favourable comments. This indicates the value of the experimental studies, and it suggests that the results of studies on individual aspects of tactile map design can be successfully applied to the design of entire maps.

The quantitative studies described earlier in this thesis provided us with definite, measurable data. The evaluation study provided us with qualitative data, based on participants' perceptions rather than on performance. This study gave us the opportunity to collect very rich data. In addition, since participants were asked to freely discuss any aspect of the maps, several issues and opinions came up that were not anticipated by the researchers beforehand. The resulting data sheds light not only on the application of the findings of this thesis, but also on issues related to other map designs and production methods.
7 Conclusions

7.1 Summary of thesis

Tactile maps are raised images that can be used by blind and visually impaired people. These maps are explored by touch, which has considerably lower spatial acuity than vision and requires sequential exploration strategies. As a consequence, tactile maps can be more difficult to read than visual maps. Therefore, tactile maps need to be designed carefully in order to be easily readable by blind and visually impaired users, taking into account the characteristics of tactile perception.

Although several guidelines on tactile map design, which made recommendations based on the authors’ experience, have been published, little empirical research has been conducted on design issues. In order to address this problem, we conducted a series of studies on aspects of tactile map design. The methods used in these studies were thorough and, when appropriate, took advantage of knowledge of tactile perception. This way, we attempted to bridge the gap between experience based guidelines and pure psychophysical and neurophysiological studies on tactile perception, and to find experimentally valid results that could be applied to map design in practise.

The current research project was conducted as part of the Tactile Inkjet Mapping Project. Other researchers in this project developed a Tactile Inkjet Printer. This printer was used to produce stimuli for experimental testing. The tactile printer enabled us to produce stimuli with great accuracy and allowed us to manipulate several aspects of tactile features, such as elevation and roughness.

7.1.1 Substrates

The first study in this thesis explored the use of different substrates (i.e. background materials) for tactile displays. The reasons for this study were mostly practical. The TIMP printer was able to produce map on a wide range of substrate materials, which
was a new development in tactile map production. Therefore, we investigated the suitability of several substrates.

A range of substrates was explored, including substrates were rough plastic, smooth plastic, Braille, aluminium, rough paper, smooth paper and microcapsule paper. Substrates were assessed in terms of ease of extraction of information, measured by completion time for a search task, and subjective preference rankings. Participants scanned arrays of symbols and were instructed to verbally identify target symbols. After completion of the task, participants were asked to rank the seven substrates in order of preference. In general, paper substrates were explored faster than plastic and aluminium ones, and were preferred by most participants. These results appeared to be related to the roughness of materials. Smoother materials may have caused the fingers to stick more, slowing down exploration.

The value of the substrate study lies mostly in its practical implications. The results of this study provided clear information about the suitability of a range of substrate materials for tactile maps. In addition, the outcome of this study demonstrated that experimental, quantitative studies could be used to investigate practical issues related to tactile map design. This finding justified the methodological approach we used for subsequent studies, and it suggested that similar approaches could be beneficial to research on tactile maps in general. Further research could investigate the effect of roughness on readability further, by including a wider range of roughness levels.

7.1.2 Elevation of tactile features

Sufficient elevation of tactile features is an important requirement for a readable tactile map. The optimal elevation of maps has not been studied in previous research. However, psychophysical and neurophysiological research provided us with an understanding of the perception of elevation. Research on the perception of edges directly influenced the design of stimuli in this study. We attempted to find minimal and optimal elevations of tactile features. We also attempted to design effective tactile features that would take full advantage of the mechanisms of tactile perception.
Elevation was investigated in two studies. In the first study, we aimed to determine the lowest elevation at which individual symbols of different sizes could be accurately identified. Participants identified circles, squares and triangles at several sizes and elevations in a forced choice paradigm. Performance levelled off around 22 μm, where an increase in elevation did not further improve the accuracy of identification. In a second study, we investigated the effect of elevation on identification speed using arrays of symbols. We also attempted to create more effective tactile features (rough lines and sharp lines, in addition to smooth lines) that could be read at lower elevations, by using knowledge of tactile perception of edges. Performance levels rose steeply by increasing the elevation of symbols up to 160 μm, but a further increase in elevation did not affect performance. As expected, rough lines were read more quickly than smooth and sharp lines. However, contrary to our expectations, sharp lines were more difficult to read than smooth lines at low elevations. The results of these studies suggest that symbols could be identifiable at elevations that are considerably lower than usually recommended for symbols in tactile graphics.

The implications of these studies for the design of tactile maps are limited by the later finding that, although participants could perform tasks on tactile features at low elevations, they preferred maps to be printed at higher elevations. This discrepancy between quantitative performance on the experimental task and qualitative experiences in the subsequent evaluation study emphasises the importance of using a combination of quantitative and qualitative measures in this type of research.

The results of these studies are valuable in comparison to previous studies on psychophysics and neurophysiology. The results show that knowledge of perceptual processes can be used to predict performance in a practical setting and to inform practical design considerations. However, the discrepancy between theory and practice, relating to the unexpected inferior performance on sharp lines, also illustrates that results from neurophysiological research do not necessarily translate directly into perception in practice.
7.1.3 Single and double lines

Although most guidelines for tactile map design emphasise the importance of spacing between tactile features, empirical research to suggest a specific gap distance does not exist. The ability to identify a gap between features is related to tactile spatial acuity, which has been studied extensively in a large number of psychophysical studies (see Section 4.1.1). Neurophysiological studies (see Section 4.1.2) have also investigated mechanoreceptor responses to tactile stimuli at varying gap width. In the current study, we investigated the minimum gap distance between the two elements of double lines that is required to correctly discriminate between single and double lines. We related our findings to the results of studies on tactile perception, in order to explore how these studies could be extended to more practical settings.

Stimuli consisted of single lines of varying widths, and double lines (thick or thin lines) with varying gap distance. Lines were presented horizontally and vertically. Participants identified lines as single or double. Double lines were reliably identified at gap distances of 1 mm and larger. An increase in gap width over 1.0 mm did not improve the accuracy of identification of double lines. Vertical double lines were easier to identify than horizontal ones, and performance on thin double lines was better than on thick ones. Singles lines were reliably identified at all widths, but lines wider than 1.9 mm were occasionally incorrectly perceived as double lines.

The value of this study to tactile map design is relatively small, because it can only make recommendations for the design of a specific symbol type. Similar to the implications of the studies on elevation, the results of the study on single and double lines are important in comparison to previous studies on psychophysics and neurophysiology. The pattern of identification of single and double lines corresponded to results of previous psychophysical and neurophysiological studies, which suggests that knowledge of perceptual processes can be used to predict performance in a practical setting and to inform practical design considerations.
7.1.4 Discriminability of symbols

Good symbol discriminability (recognising that 2 symbols are the same or different) is vital for tactile map reading. Several studies on discriminability have been conducted previously. However, the validity of these studies was limited by their experimental design. In the current study, we improved the experimental design by carefully selecting symbols from a large pool and by designing a more ecologically valid experimental task. We also explored principles of symbol discrimination, which was not been studied previously.

The study was designed to produce a set of highly discriminable tactile symbols (points and lines) and to investigate what makes symbols discriminable from each other. A large number of point and line symbols was selected for this study, based on previous research and existing use. Participants were asked to test these symbols in a paired-comparison, same-different judgement task. Discriminability was measured by the number of confusions; the smaller the number of confusions between a given pair of symbols, the more discriminable they were. This methodology allowed us to produce a highly discriminable set of tactile symbols, consisting of 11 point symbols and 4 line symbols.

In addition to producing a set of discriminable symbols, we explored the factors that underlie symbol discriminability. Using multi-dimensional scaling, the discriminability of symbols was represented in a two dimensional graphic, where larger distances between symbols indicated higher discriminability and symbols with similar features clustered together. These plots allowed us to categorise symbols and speculate on the bases for tactile symbol discriminability. Using these generalisations, it might be possible to generate further symbol sets that are highly discriminable.

This study is of great importance to the design of tactile maps, because it provides a set of discriminable symbols that can be used on any map. Although similar studies have been conducted previously, the improvements to the design of this study allowed us to obtain results that were more valid and more interesting. In addition to
the high practical value of this study, the examination of principles of symbol
discriminability is also of theoretical interest.

7.1.5 Evaluation of maps

After studying individual aspects of tactile maps, we evaluated entire maps in a qualitative study. In this study, we firstly wanted to evaluate the findings of this thesis. Secondly, we wanted to compare several of the leading production methods (tactile inkjet, thermoform, microcapsule and Braille embossing) and several map designs.

An existing tactile map of a town centre was manipulated to create test maps, one of which was designed according to the findings of this thesis. Participants performed realistic map based tasks to become familiar with each map, and were subsequently interviewed about their opinions on various aspects of the maps. Participants also rated aspects of maps. This study generated rich data and covered many aspects of tactile map design, although participants found it easier to comment on production materials than on design issues. Participants preferred materials that were easy to slide their fingers across and that were not sticky. They preferred sharp, precise symbols at high elevations. Discriminability of symbols, intuitiveness of symbol meaning and clutter were the most important aspects of map design.

We also evaluated the findings of the thesis in the evaluation study. In general, the results of our studies were translated into the design of a successful map. Our earlier results could also explain some of the qualitative findings of the evaluation study. Participants’ preferences for substrate materials of the map were consistent with the results of the study on substrates. However, the relatively low elevations of tactile symbols that were suggested by the elevation study were not entirely successful. Although participants were able to read symbols at low elevations, they preferred reading maps at higher elevations. The double line that was designed according to the results of the study on single and double lines was successful. Participants’ comments on the discriminability of symbols on the map were in accordance with the results of the study on discriminability, and our recommended set was successful.
The evaluation study is very important to the TIMP research project. It allowed us to evaluate and confirm the findings of studies on single aspects of tactile map design in a realistic setting. Since the results of the evaluation were in agreement with our earlier findings, this study validates the entire project. However, since both our map and most other maps were evaluated positively by participants, questions were raised about the contribution of our research to the design of maps. Since all maps were designed by experienced map designers, they were all well designed. This issue could have been addressed by the inclusion of a badly designed map.

This study is also important for tactile mapping in general. First of all, it provided valuable information about several production methods and map design issues. Secondly, it provided an example of an effective methodology for evaluating tactile maps.

**7.2 Evaluation of our approach**

Guidelines for the design of tactile maps are generally based on personal experience of the authors rather than on research, although references are regularly made to the limits of tactile perception. However, the results of psychophysical and neurophysiological studies cannot be translated directly into the design of tactile maps, because the experimental methods of these studies are very controlled and focussed. In the current research project, we attempted to bridge the gap between scientific research and more practical considerations of map design, by using an understanding of tactile perception and using thorough experimental methods to investigate several aspects of the design of tactile maps.

**7.2.1 Experimental methods**

Thorough experimental methods were used in our studies, in order to obtain valid and reliable results. First of all, the number of participants in all our studies, except for the qualitative evaluation study, enabled us to conduct appropriate statistical
analyses. Studies on tactile map design have not always involved enough participants. For example, Harder and Michel (2002) and Bentzen (1972) used very small numbers of participants, which severely limited the analysis of their data.

Secondly, we designed appropriate tasks for our studies. Care was taken to find a balance between internal validity and ecological validity. The issue of validity is discussed in more detail in Section 7.2.4. Highly controlled and focussed tasks, as are often used in psychophysical studies (for example, adjacent pair comparison tasks), can be very measurable and reliable. These tasks have high internal validity. However, having low ecological validity, these tasks do not resemble map reading and might therefore not produce results that can be translated into map design. At the other end of the scale, performance on tasks with high ecological validity, such as Berla and Murr’s search task using a pseudo map (1975a), can be difficult to measure. Our tasks involved scanning of arrays of symbols, identifying individual symbols in a limited time span and comparing pairs of symbols separated by a distraction task. These tasks were easily measurable and offered us a high level of control. At the same time, these tasks were designed to resemble processes involved in map reading.

Thirdly, our experimental design was rigorous and controlled. Robust stimuli were produced by the TIMP printer with great accuracy, ensuring that we had full control over the measurements of stimuli, which did not deteriorate during the course of the studies. Tasks were explained and stimuli were presented to each participant in the same manner, and presentations were randomised or semi-randomised. The performance and responses of participants were recorded unambiguously.

As a result of using thorough experimental methods, our studies were successful. All quantitative studies generated significant and meaningful results. The results of these studies were applied to the design of successful maps in the evaluation study, suggesting that the approach produced meaningful and generalisable results.
7.2.2 Knowledge of tactile perception

An understanding of psychophysics and neurophysiology was used for the design of several of our studies, particularly the studies on substrate material, elevation of tactile features and single and double lines. Knowledge of the principles of tactile perception enabled us to create highly effective stimuli. For example, based on research on increased mechanoreceptor responses to tactile edges, we included rough lines in our study on elevation, correctly hypothesising that rough lines are easier to read at low elevations.

Knowledge of tactile perception also helped us understand and interpret the results of our studies. For example, the perception of wide single lines as double lines could be explained by mechanoreceptor responses to both edges of this line. In general, our results were in line with results of previous research on tactile perception. This suggests that it is possible to use more practical studies to expand on psychophysical and neurophysiological research, in order to investigate practical limits of touch.

Finally, in relation to the methods used, we believe that studies like the present ones can help to explore the relationship between more abstract psychophysical and neurophysiological tasks and more concrete, ecologically valid tasks. While in the past it has been generally recognised that most psychophysical and neurophysiological findings cannot be directly applied to design (e.g. the two-point touch threshold is clearly smaller than the desirable separation of lines on a tactile map), few studies have attempted to link the principles of tactile perception to practical considerations of tactile map design. The current studies demonstrate the value of using knowledge of psychophysical and neurophysiological research in an applied context.

7.2.3 Participant sample

Sample size

The statistical power of an experimental test depends partly on the number of participants. As sample size decreases, the risk of committing a Type II error increases. This error occurs when the null hypothesis that there is no difference
between groups or conditions is accepted, when in fact there is a difference between groups or conditions.

In our quantitative experiments, the sample size ranged between 18 and 29 participants (Table 7.1), with approximately equal numbers of sighted and visually impaired participants in each study. The number of participants was determined by practical limitations. Within these limitations, we attempted to achieve a sample size that allowed relevant statistical analyses.

<table>
<thead>
<tr>
<th>Study</th>
<th>Sample size</th>
<th>Number of presentations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substrates</td>
<td>29</td>
<td>2</td>
</tr>
<tr>
<td>Elevation A</td>
<td>19</td>
<td>10</td>
</tr>
<tr>
<td>Elevation B</td>
<td>19</td>
<td>1</td>
</tr>
<tr>
<td>Single/double lines</td>
<td>20</td>
<td>3</td>
</tr>
<tr>
<td>Discriminability Phase 1 (point symbols)</td>
<td>20 x 2 (each of 40 participants completed half of the experiment)</td>
<td>1</td>
</tr>
<tr>
<td>Discriminability Phase 1 (line symbols)</td>
<td>19</td>
<td>1</td>
</tr>
<tr>
<td>Discriminability Phase 2 (point symbols)</td>
<td>18</td>
<td>1</td>
</tr>
<tr>
<td>Discriminability Phase 2 (line symbols)</td>
<td>19</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 7.1 Overview of sample sizes and the number of times each stimulus was presented.

Psychophysical studies on tactile perception (Craig, 1999; Essock et al., 1997; Johnson and Phillips, 1981; van Boven et al., 1994, 2000) commonly involve a small number of participants, generally between two and 15 individuals, who make judgements on a large number of repeated trials. We used a similar method in studies on elevation (Section 3.2) and identification of single and double lines (Chapter 4). Participants were presented ten times with each elevation and three times with each single or double line. This resulted in 190 and 60 observations respectively for each stimulus. Although the number of observations was small compared to the numbers used in psychophysical studies, this number of observations allowed us to find statistically significant effects from our main variables of interest. However, the

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9 The number of participants was limited by practical considerations. Visually impaired participants were visited in their home or college. Experiments were conducted with each participant individually and one or two experimenters were present at all times. As a result, the experimenters had to travel quite extensively and, due to the length of some of the experiments, only a very small number of participants could be visited in a day. This became a particular issue for time and budget limitations on the project.
small sample size did not provide enough statistical power to detect small interaction effects that may have existed.

The number of participants in the studies on symbol discriminability (Chapter 5) was small compared to earlier studies on discriminability (Gill and James, 1973; Heath, 1958; James and Gill, 1975; Morris and Nolan, 1961; Nolan and Morris, 1971), which contained sample sizes between 45 and 96 participants. Although the analysis of discriminability through confusion matrices and multi-dimensional scaling is sound, the small sample size may have caused a Type II error when comparing the sighted and visually impaired participant groups. The sighted participants appeared to have higher error scores than visually impaired participants in all four parts of this study. However, this difference was not statistically significant. A larger sample size would possibly have allowed us to find a significant difference between participant groups.

The statistical results reported in this thesis included values of observed power. Power is related to effect size, sample size, probability level and standard deviation. Power analysis allows us to determine how confident we can be that we were able to detect an effect of a certain size. Generally, a power level of 0.8 or more is considered to be sufficient. The smaller the effect of a variable, the more participants are needed to detect it. When the effects of our manipulations were moderate to large, we had sufficient power to detect them. As a result, these effects were found to be significant. However, we did not have sufficient power to detect small effect sizes. As a result, small effects were not found to be significant. This was a particular issue for the effects of visual status and interactions of visual status with other variables. Visual status was used as a between-groups variable, while other variables were repeated measures within groups. As a result, the sample size of visual status groups became an issue.

Statistical power can be increased by increasing the sample size. Statistically significant effects of visual status and its interaction may have been found in more
studies if we had used a larger sample size. We used GPower\textsuperscript{10} software to determine what sample sizes would have been necessary to detect the effects of visual status. The required sample sizes for detection of very small effects were larger than was realistically feasible. For example, in order to find the small interaction effect ($\eta^2 = 0.04$) of line type and visual status on scanning speed in elevation study B, GPower predicted that 220 participants were required. For some of the larger effects sizes, a more achievable number of participants was required in order to find the effect. For example, in order to find the effects of visual status ($\eta^2 = 0.12$), 64 participants were required.

In our non-significant statistical tests, the power was not sufficient to detect small effects sizes. However, small effect sizes were not particularly important. We wanted to know whether we had sufficient power to detect moderate effects sizes (0.5), if they had occurred. GPower was used to determine the effects sizes that we would have been able to find with the current sample size, with a minimum power of 0.8 and an alpha level of 0.05. Table 7.2 provides and overview of the effect sizes we would have been able to detect, if they had occurred. The statistical power was sufficient to find moderate effects of the interactions with visual status in approximately half of the statistical tests. In the other studies, we only had sufficient power to find very large effects. Statistical power can be increased by increasing the sample size. Statistically significant effects of visual status and its interaction may have been found in more studies if we had used a larger sample size.

<table>
<thead>
<tr>
<th>Study</th>
<th>Effect</th>
<th>Possible $\eta^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substrates</td>
<td>Visual status x substrate</td>
<td>0.49</td>
</tr>
<tr>
<td>Elevation A</td>
<td>Visual status x elevation</td>
<td>0.72</td>
</tr>
<tr>
<td>Elevation A</td>
<td>Visual status x size</td>
<td>0.68</td>
</tr>
<tr>
<td>Elevation B</td>
<td>Visual status x line type</td>
<td>0.55</td>
</tr>
<tr>
<td>Single/double lines</td>
<td>Visual status</td>
<td>0.44</td>
</tr>
<tr>
<td>Single/double lines</td>
<td>Visual status x gap width (double lines)</td>
<td>0.76</td>
</tr>
<tr>
<td>Single/double lines</td>
<td>Visual status x line width (double lines)</td>
<td>0.44</td>
</tr>
<tr>
<td>Single/double lines</td>
<td>Visual status x line width (single lines)</td>
<td>0.91</td>
</tr>
<tr>
<td>Single/double lines</td>
<td>Visual status x line orientation</td>
<td>0.44</td>
</tr>
</tbody>
</table>

Table 7.2 The size of effects we would have been able to detect with the current sample size.

\textsuperscript{10} GPower is a program for statistical power analysis. It can be downloaded from the internet.
In general, the sample size in our studies, which was limited by practical considerations, appeared to be sufficiently large for our purposes. It enabled us to identify significant differences between conditions and groups that were in line with results from other studies. However, a larger sample size may have allowed us to find further differences between sighted and visually impaired participants.

**Participant sampling**

Participants were found by volunteer sampling. Sighted participants were mostly university students and staff, who responded to e-mails and posters. Visually impaired participants at colleges were approached by a contact person within the college, who e-mailed information about the studies to suitable students. Other possible visually impaired participants were identified through lists from the Royal National Institute of Blind People and the Surrey Association for Visual Impairment. These individuals were contacted directly by e-mail or letter.

No quota or criteria were applied in our sampling procedure, other than the requirement that participants should be physically and mentally capable of performing the experimental tasks. The sample of visually impaired participants appeared to be representative of the population. The sample contained participants over a range of age, gender, level of visual impairment, onset of visual impairment and tactile experience. Since sighted participants were recruited at the university, volunteers tended to be students. Preference was given to mature sighted participants in order to match the age range of visually impaired participants.

Since participants were recruited by volunteer sampling, the visually impaired sample could be biased towards participants with experience and/or an interest in tactile maps. It is plausible that these individuals were more likely to volunteer to take part in our studies. Experience and interest in the use of tactile maps, or other tactile graphics, may have caused better performance on some tasks. It is important to consider this possible bias when using the results for the design of maps for inexperienced users. The performance of sighted participants, who did not have experienced of tactile graphics, was used to balance the performance of more experienced visually impaired participants. The performance of sighted participants
could be used to guide the design of tactile maps for people who have recently become visually impaired, or visually impaired people with little experience of tactile graphics.

Volunteer sampling may also have caused differences in extrinsic and intrinsic motivation between sighted and visually impaired participants. Extrinsic motivation is when individuals perform a behaviour because they are externally rewarded or coerced to do so, whereas intrinsic motivation is when individuals perform a behaviour without external incentives. According to the cognitive evaluation theory (Deci & Ryan, 1985), intrinsically motivated individuals are more actively engaged in tasks and perform better than extrinsically motivated people. Although both sighted and visually impaired participants were paid for participation, it is possible that visually impaired participants were more intrinsically motivated due to a personal interest in tactile maps. Several participants mentioned that they enjoyed taking part in our studies because they felt they could contribute to an interesting and important project. Sighted participants, however, may have been more extrinsically motivated by the rewards of money or course credits in return for participation. In addition to difference in tactile experience, this difference in motivation could be partly responsible for the inferior performance of sighted participants in some tasks.

7.2.4 Validity

In our studies, we attempted to make a link between thorough empirical research and design of tactile maps. This approach posed a challenge in terms of validity. Internal validity refers to the relationship between cause and effect in a study; changes in the independent variables result in changes in the dependent variable. External validity refers to the extent to which the results of a study can be generalised to other settings. Ecological validity refers to the extent to which experimental tasks resemble real-life situations.

High internal validity is usually achieved by thorough experimental testing in highly controlled laboratory settings, which generally leads to low ecological and external validity. This was the case in many of the psychophysical and neurophysiological
studies on tactile perception that were reviewed throughout this thesis. High ecological and external validity can be achieved by designing real-life experimental tasks, producing results that can be generalised outside the experimental setting. The internal validity of these types of studies is generally low. This was the case in many previous studies on tactile map design. When designing our studies, we were aware of the balance between internal validity on one hand and ecological and external validity on the other hand. In creating a link between empirical research and map design, compromises on validity were necessary.

The results of our studies were used to inform the design of tactile maps in practice and to shed light on the practical use of tactile perception. Therefore, a high level of external validity was required. This was achieved by finding a representative sample of participants, which allowed for a generalisation of results to the target population. In addition, we aimed to design experimental tasks that could be generalised to tactile performance outside the specific experimental setting. The complex behaviour of tactile map reading was segregated into smaller elements, i.e. substrate material, elevation, gap distance and symbol discriminability. The qualitative evaluation study confirmed that the external validity of these studies was high, by demonstrating that the results of the studies could be generalised to the practical design of tactile maps.

Ecological validity, which refers to the extent to which experimental tasks resemble real-life situations, can also contribute to external validity. The results of experimental tasks that resemble the process of map reading may be more suitable for generalisation to tactile map design. However, there is a trade-off between ecological and internal validity. Ecological validity in a tactile mapping study could be maximised by asking participants to perform real-life tasks on entire maps. Unfortunately, the internal validity of such a study would be extremely low and it would not be possible to draw valid conclusions from the results. In order to maintain internal validity, compromises on ecological validity had to be made. We attempted to preserve ecological validity by creating tasks that resembled elements of the process of map use, while maintaining an adequate degree of internal validity. The studies on substrate material and elevation of tactile features (Study B), which involved a timed scanning task, had possibly the lowest degree of ecological
relevance. However, although the experimental task did not resemble map use, the ability to scan a tactile map quickly is important, and map users may perform a quick scan of a map while searching for specific symbols. The studies on single and double lines and elevation of features (Study A) involved symbol identification tasks. Identifying single symbols is an important element of map reading and, therefore, these studies were ecologically relevant. The ecological validity of the study on symbol discriminability was high. Care was taken to create an experimental task that resembled map reading. This task included a comparison between two symbols that were separated by a distraction task, time delay and spatial distance.

In addition to designing studies that were ecologically and externally valid, we attempted to achieve a high level of internal validity by using thorough experimental methods. These methods included randomisation of stimuli presentation, acceptable numbers of participants and/or trials (sample size was debatable and discussed in Section 7.2.3) and accurate measurement of participants’ performance. In addition, we used experimental designs that were known to be effective, such as the paired-comparison methods in the study on symbol discriminability and the two or three alternative forced choice identification tasks on elevation (Study A) and on identification of single and double lines. The timed scanning tasks in the studies on elevation (Study B) and substrate materials also allowed a direct and straightforward assessment of participants’ performance.

Effects of demand characteristics, in which participants deduct the purpose of an experiment and attempt to respond accordingly, can pose a threat to internal validity. We attempted to avoid these effects by withholding an explanation of the purpose of experiments until participants had completed the tasks. However, in most of our studies, the purpose was fairly obvious. Demand characteristics were not expected to have a large effect on our quantitative studies, because performance was measured rather than more subjective opinions. Participants’ performance was not likely to be affected by their understanding of the purpose of the study. For example, although participants may have been aware of our interest in the suitability of different substrates, they were unlikely to adjust their performance based on this understanding. Demand characteristics may have played a role in the qualitative
evaluation study, in which participants discussed their subjective experiences of a range of maps. Effects of social desirability may also have played a role. In order to please the experimenter, participants may have been reluctant to express negative opinions about the maps. We attempted to avoid these effects of demand characteristics and social desirability in the evaluation study by emphasising that we were merely interested in their opinion on a range of maps and that there were no right or wrong answers.

Internal validity can also be affected by the experimenter expectancy effect, which suggests that the experimenter could influence the participants’ responses by unintentionally communicating the hypotheses of the study. The experimenters were aware of this threat and attempted to avoid any effects by minimising communication during the quantitative experiments. Stimuli were presented with a minimum of vocal communication by the experimenter and care was taken to speak with a neutral tone of voice at all times. In most studies (i.e. elevation (Study A), single and double lines and symbol discriminability), multiple stimuli were presented simultaneously in a jig by a silent experimenter, while the communicating experimenter recorded participant responses relatively blindly (i.e. without knowing what stimuli were presented). This process reduced experimenter expectancy. Since participants were either visually impaired or blindfolded, no visual cues of experimenter expectancy were available to the participants. Avoiding experimenter effects was more challenging during the qualitative evaluation study. In order to encourage participants to talk and to keep the conversation flowing, it was necessary to vocally interact with the participants to a larger extent. A careful balance was required between sustaining natural conversation and minimising experimenter effects. Care was taken to use a neutral tone of voice and to avoid qualifying statements of agreement or disagreement with the participant.

7.3 Sighted and visually impaired participants

Both sighted and visually impaired people took part in the studies. Sighted participants were included to achieve sufficient numbers for statistical analysis, and
to compare possible differences in performance between sighted and visually impaired groups. In the study on substrate materials, visually impaired participants completed the search tasks more quickly than sighted ones. This was also the case in the second elevation study, using a timed search task. In the first elevation study, in which the allotted time to complete an identification task was limited, visually impaired participants were more accurate than sighted ones. There was no significant difference in performance between sighted and visually impaired participants in the studies on single and double lines and symbol discriminability. However, a significant difference may have been found if a larger number of participants had been used. This was discussed in Section 7.2.3.

The above differences in performance were quantitative, rather than qualitative. The difference appeared to be related to speed; visually impaired participants performed significantly better than sighted participants in tasks where completion time was the dependent variable, or where the time to complete a task was limited. It is likely that visually impaired participants were able to complete the tasks more quickly due to a higher level of experience with tactile tasks. In addition, visually impaired participants were more likely to be genuinely interested in our research and may therefore have been more motivated to perform well than sighted participants.

The present findings that, in some of our studies, visually impaired participants performed better than sighted participants reinforces previous research (Craig, 1988; Easton & Bentzen, 1980; Grant et al., 2000; van Boven et al., 2000). However, this is not true for all tasks (Grant et al., 2000; Heller, 1988, 1989b; Pascual-Leone & Torres, 1993) and the differences are often explained by the relative contributions of tactile experience and the use of visual imagery in more complex tasks. The present studies are not set-up to distinguish these possibilities. Nevertheless, finding that visually impaired participants perform better on some tasks suggests that, although sighted participants can provide a useful reference point, it is important to test tactile perception with the, target, visually impaired group.
7.4 Contributions of research

7.4.1 Contribution to design of tactile maps

The results of this research project can be applied to the design of tactile maps in practice. Each chapter provides recommendations for the application of results. Due to time constraints, a limited number of design aspects could be studied during the course of this research project. The recommendations can therefore be applied to specific key issues in tactile map design. It is unfortunately not possible to develop comprehensive guidelines on the design of maps purely based on the present findings. We hope that the results of the current project will be incorporated into comprehensive guidelines that can be used by tactile map producers.

As discussed on Section 1.1.6, existing guidelines for the design of tactile maps (American Printing House for the Blind, 1997; Bentzen, 1997; Edman 1992; Eriksson, Jansson & Strucel, 2003; Gardiner & Perkins, 2002a) are generally based on practical experience and anecdotal evidence rather than on research. This appears to be due to a lack of research on tactile map design, rather than to a reluctance to incorporate research. Many authors of guidelines (Bentzen, 1997; Edman, 1992; Gardiner & Perkins, 2002a) have included recommendations based on the small body of tactile mapping research where this was available. They sometimes even attempted to draw relevant conclusions directly from empirical research on tactile perception. Considering this apparent desire to include research in guidelines, we hope that the results of the current research will be incorporated in future evidence-based guidelines on tactile map design.

Since the current research can be of considerable value to map designers, it is important to make the results available to them. However, bringing results of academic research into the non-academic world can be challenging. Publications in academic journals and conferences do not necessarily reach the majority of map designers. Map designers at larger institutions who specialise in the design of tactile maps may be aware of research in their field. However, occasional map designers, for example teachers at colleges for visually impaired students, are not likely to have access to this information. Unfortunately, these less experienced map designers are
also the ones who could benefit most from our research, because they are often not fully aware of the issues relating to tactile map design. Since publications of guidelines on tactile maps design are more easily accessible than academic publications, incorporation of our recommendations into guidelines is important. Promisingly, the Braille Authority of North America, in collaboration with the Canadian Braille Authority, requested permission to include the set of discriminable symbols in their publication on guidelines and standards for production of tactile graphics. We also attempted to make our research available to practitioners through our collaboration with the NCTD and RNIB, on the project’s website and through presenting at the Tactile Graphics Conference (Jehoel, Ungar & Rowell, 2005; Rowell & Ungar, 2005; Ungar 2005), which was attended by both academics and practitioners.

Tactile features used in this research were produced by the Tactile Inkjet Printer. Alternative production methods generate tactile features that may differ in several ways, such as roundness of edges, accuracy, line width, line height and hardness. Therefore, our results may not be directly applicable to maps produced by other production methods. More research is required to investigate to what extent our findings can be applied to other production methods. However, as the evaluation study shows, most of our findings appear to be valid across production methods.

In the current research, we investigated several basic aspects of tactile map design, involving the choice of map material and the design of symbols. This research only covered a fraction of the entire field of tactile map design. First of all, many issues related to the design of symbols have not yet been investigated. Future studies may, for example, investigate the use of point and line symbols on area symbols, design of line intersections or minimum distances between symbols. Secondly, although this research was limited to choice of materials and design of symbols, the field of tactile map design extends well beyond this. Other important issues include, for example, the selection of features to be included on a map, strategies for map reading, automatic generation of maps, design for other production methods, and use of map descriptions, labelling and keys.
7.4.2 Contribution to research on tactile map design

Empirical research on the design of tactile maps, which is reviewed in Section 1.1.5, is rather sparse. Studies of the scale and rigour of the current project have not been conducted before. Therefore, the current study is a substantial addition to existing research.

In addition to considerably increasing the volume of research on tactile maps, the current research suggests suitable approaches and methods that can be used in future studies. These related to the use of knowledge of tactile perception, rigorous experimental methods and the examination of single design aspects in isolation. These three issues will be discussed below. In future studies, researchers could investigate other aspects of map design in a similar manner, in order to develop more empirical evidence for guidelines on map design.

The use of knowledge of tactile perception in research on tactile map design is best illustrated in the studies on substrate material, elevation of tactile features and identification of single and double lines. In these studies, knowledge of tactile perception was used in three ways. Firstly, information from psychophysical and neurophysiological studies was used to form hypotheses. We expected that performance in studies on tactile perception could be used to predict performance on more practical tasks in our research. For example, we hypothesised that the minimum gap width at which participants could identify double lines would be related to measures of tactile acuity found in psychophysical studies. Secondly, we used knowledge of tactile perception to create effective stimuli that would take full advantage of the mechanisms of perception. For example, since neurophysiological studies suggested that receptors in the fingertip respond highly to sharp edges, we created stimuli with sharp lines. We also used knowledge of tactile perception to explain our results. This approach proved to be mostly successful and could therefore be replicated in other studies on map design. However, it is important to consider that results from psychophysical and neurophysiological studies cannot be translated directly into performance on more practical tasks.
We attempted to use rigorous experimental methods. This involved a careful consideration of the trade off between internal and ecological/external validity (see Section 7.2.4). We attempted to maintain internal validity, while maximising ecological validity by creating realistic tasks. We used a combination of qualitative and quantitative methods. The qualitative and quantitative results of our studies occasionally conflicted. Therefore, a combination of both quantitative and qualitative measures in future studies is crucial, in order to make design recommendations for maps that are both easy to use and liked by map users. We also used a variety of experimental tasks, such as scanning of symbol arrays, forced choice symbol identification and paired comparisons of symbols. Since the approach was successful across a variety of experimental tasks, it is likely that a similar approach could be used for other types of experimental tasks as well. A similar approach was suggested by Perkins (2001, 2002) but had not been assessed fully so far. The success of this approach suggests that future studies would benefit from using a similar approach.

In order to collect meaningful data, it was necessary to make a compromise on ecological validity by studying aspects in isolation rather than on an actual map. We studied several aspects of map design in isolation in quantitative, performance based studies. In order to explore how the results from these studies could be translated into tactile map design, the results were evaluated in a qualitative study involving entire maps. The successful application of the results of the quantitative studies in the qualitative evaluation study suggests that it is possible to study single aspects of map design in isolation and in relatively controlled experiments. The results of these studies can then be generalised successfully to the design of entire maps. Future studies could also examine aspects of map design in simple experiments. It is, however, important to verify the results of these studies in genuine map tasks.

7.5 Further research on tactile map design

Due to time constraints, we investigated a limited number of aspects related to the design of tactile maps. Many aspects of map design are yet to be investigated fully. Density of information on a map is a particularly interesting design aspect. It is one
of the largest challenges in tactile maps design, and one which can be difficult to investigate. It raises questions about the size of a map, the total number of symbols on it and the relative numbers of different point, line and area symbols. Other interesting topics of research are, for example, the minimum distance between separate symbols, the design of line intersections, the use of points and lines on area symbols, and the use and placement of Braille labels.

Recent developments in computer software and availability of spatial information have stimulated research on automatic generation of tactile maps based on spatial databases (Michel, 1996; Miele & Marsten, 2005; Theissen, 2000). Spatial information is readily available online, which enables individuals to produce visual maps on demand. Research is required on what types of spatial information should be included on automatically generated tactile maps, and how this information should be presented. Results from studies like the current one could go directly into the algorithms to design those maps automatically.

7.6 The future of tactile maps

Technological developments make it easier for visually impaired people to access spatial information. For example, several projects have investigated the use of Global Positioning Systems (GPS) for navigation assistance for visually impaired people. Since Collins (1985) and Loomis (1985) independently proposed these systems, technological progress on GPS has instigated ongoing research projects, including research by Loomis et al. (2001), Garaj et al. (2000), Ran et al. (2004) and Strothotte et al. (1995). GPS can provide a solution for navigational problems by providing instant information about location and direction. Unlike a tactile map, these systems generally cannot offer a two dimensional overview of spatial information. However, the use of auditory virtual reality in GPS navigation systems could be used to convey spatial information (Loomis et al., 2005). In addition, most GPS systems for visually impaired users are more expensive than tactile maps, and often require a user to carry around an unwieldy number of devices. Although GPS technologies may facilitate
navigation, they cannot be used for non-navigational, desk based access to spatial information.

The development of computer driven technology may facilitate the design and production of tactile maps. As discussed above, the availability of extensive databases of spatial information may allow for automatic generation of tactile maps. A recently developed system (Miele & Marsten, 2005) is already capable of automatically designing a tactile map using a web interface, and printing it using a Braille embosser. However, this system can only successfully design maps of North American cities with grid street patterns. The findings of this thesis could be used to inform the automatic design of these maps.

Developments are also being made in multi-sensory maps, usually combining auditory and tactile information. The Talking Tactile Tablet (Landau & Wells, 2003) combines a tactile map (or any other image) with auditory information when specific parts of the tactile image are pressed. This system has been used with considerable success and is currently commercially available. Talking Tactile Tablets are currently used with microcapsule images, but images produced by the Tactile Inkjet Printer would be highly effective and more durable.

Another multi-sensory system is being explored by Jansson et al. (2006). It allows visually impaired people to explore virtual maps on a computer by providing tactile information through pin matrices on a mouse in addition to auditory information. This system has proven difficult to use, although it might be improved with further research.

A large number of haptic feedback devices exists, mainly for use by sighted people in, for example, medicine, robotics and gaming. These devices use haptic force, vibrations and motions to create virtual objects. Some of these devices (see Raisamo (2005) for an overview), such as the SensAble PHANTOM device, can provide spatial information to visually impaired users. Although haptic feedback devices are not yet capable of successfully conveying virtual tactile maps, future developments might make this possible.
In conclusion, technological developments may facilitate both the design and the production of tactile maps. In comparison to more recent technologies, such as GPS navigation systems and haptic feedback devices, tactile maps are cheap, easy to use and widely available. Although new technologies are on the rise, there will always be a place for well designed tactile maps.
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Appendix A: TIMP publications

Journal Articles


**Conference Papers**


PhD theses


Appendix B: Selection of symbols for discriminability study

Jonathan Rowell, the cartographer of the TIMP team, selected the point and line symbols that were used in the discriminability study. Below is his account of the selection process, written by Jonathan Rowell and edited by Sandra Jehoel.

The symbols included in the discriminability study were not simply dreamt up, but resulted from a series of analyses. To avoid reinventing the wheel, attention was paid to previous tactile work on symbols. A systematic appraisal of symbols either in current use or that had already been tested was made. Symbols for this were derived by drawing on as large a number of sources as possible.

Sources

1. General tactile cartography literature: Useful tactile graphic design primers (Edman, 1992; Bentzen, 1997; Armstrong, 1973; James, 1976)
2. Previous research on tactile symbols, particularly studies involving tactile symbol discrimination (Bentzen, 1996; Gill & James, 1973; McCubbin, 1988; Thompson, 1983; Horsfall, 1981).
3. An international survey of tactile maps: production; design and research (Rowell & Ungar, 2003a, 2003b). Respondents to this survey were asked to provide samples of their typical tactile output.
4. Visits to institutions holding archives of tactile material to collect examples of tactile symbols from their records: National Centre for Tactile Diagrams (when it was separate from RNIB and based at Hatfield University, Hertfordshire, UK. Importantly, they held Ron Hinton’s archive of tactile material gathered over several decades producing diagrams for educational purposes. This was a collection of over 100 graphics.), and RNIB Maps and Diagrams based in Peterborough, UK.
5. Comparisons with conventional symbols used in visual cartographic design (Robinson et al., 1995)
Method

There were several stages in the process of deriving a pool of symbols to be tested. These included:

1. The production of two semi structured informal sourcebooks of tactile symbols. The first consisted of examples of symbols drawn from tactile cartography literature. The other contained examples of symbols used in practice, drawn from the archive search. These catalogues of symbols involved making copies of all the tactile symbols from the sources investigated, and then cutting & pasting them into different sections based on their inherent structure. At the roughest level it was divided by symbol type; point, line, and area. Then within these sections further divisions were made either by shape (point symbols); structural complexity (line symbols), or by both (area symbol textures). All the symbols were also annotated to identify their source, whether they had been tested in a discriminability experiment and if so were they recommended or not, and, if they had been used in practice, the feature they had been used to represent.

2. A quantitative evaluation of the sourcebooks was undertaken, to learn something about the types and numbers of symbols that had been (i) tested and (ii) used in practice, based on their structure. Levels of use were ascertained from the 30 sources consulted, 15 research publications and 15 examples of legends/keys from the archive search. A quick quantitative analysis established figures for both the number of (a) studies in which the most common shaped symbols appeared and (b) times they appeared in the 30 sources, the latter taking account of the various sizes at which similar forms appear.

3. A brief analysis based on tactile symbol function to discover what point symbols had been used for was also carried out. This largely consisted of compiling lists of the range of uses.
Symbol set construction

The symbol sets were then constructed on the basis of several criteria:

1. Previous psychophysical studies that made explicit recommendations about certain symbols being more discriminable than others, based on empirical tests, were acted upon (Nolan, 1963; Nolan & Morris, 1971; Wiedel & Groves, 1969; Rener, 1993) Also, early work of Gunnar Jansson was taken into consideration (Jansson, 1972a, 1972b)

2. Evidence of the extensive use of tactile symbols in practice was another factor that helped us pick symbols for our set: This was determined by a count of the number of times producers who provided examples of their work had used different symbols on actual tactile maps. However, as one of the conditions of them providing information was a guarantee of anonymity their names cannot be printed.

It is not the case that only symbols that had proved both effective in discrimination tests and appear to prevail in map use were included in the set of symbols to be tested. It was also important to identify symbols that have for whatever reason faired poorly in psychophysical experiments, but whose use has persisted regardless. And symbols that, despite performing well in discrimination studies, do not appear to have filtered through to being incorporated regularly on tactile maps.

One criticism that could be levelled at previous discrimination studies is that their group of symbols intended for testing was very limited from the start. Admittedly, the recommended numbers of any one type of symbol that should be used on a tactile map is small, but as our intention was to create a pool of symbols from which people could choose, we needed to find as large a group of potentially discriminable tactile symbols as possible. As we actively sought to avoid repeating the same mistake of some symbol studies, we were looking for large numbers of symbols.

Due to the fact that few individual symbols have been found to be discriminable, and figures from the survey of symbols in use indicate the numbers of common symbols
in regular use on tactile maps are small, this doesn’t provide nearly enough symbols to test. Additionally, just as evidence of symbols that are liked by users and work well in practice is scanty, so too are explanations for why some symbols are more or less discriminable than others. For both these reasons it is important to include some symbols we might otherwise have avoided using. In the absence of evidence about many symbols’ potential tactile qualities, some critical judgements have been made. These might constitute conceptual leaps, but it is possible to describe reasons for taking them.

Pictorial point symbols were immediately ruled out by virtue of the fact that they are often intricate and hence too difficult to decipher by touch.

Playing to the strengths of our new technology and the ability to print detail at high resolutions, that we know can be detected tactually, I wanted to introduce two new types of point symbol. One was the textured symbol that could be considered as falling somewhere between outlines and filled shapes. The other was a symbol of greater complexity in which another form was imposed within the general outline of the shape. A trawl through the literature on design in visual cartography provided conventional point symbols of this kind that usually appear on thematic maps (symbols other than those of a standard shape are rarely used except on thematic maps) and are known to be perceptually different in vision.

At this stage, the choice of what symbols to add was also partly determined by devising a methodology that would allow us to test certain hypotheses. The decision in the first instance to compare symbols for confusability in groups of like shapes/forms (i.e. comparing groups of circular, square shapes etc.), followed by testing the most discriminable shapes from each group against each other would allow us to identify some bases upon which discrimination between symbols is made. Is discrimination more likely to be based on differences in overall gross configuration; between shapes, or is it more likely to occur within shapes; on the basis of internal factors such as fill, texture, complexity etc.? For this reason there is often repetition between the internal configurations of the three major point shape groups.
General comments

It is of course possible that a set similar to the one derived could have been generated without any evaluations, but it is important to be able to justify why each symbol merited inclusion in our set. This method is not common in practice. Since generally held opinion indicates that design is intuitive, many people will chose symbols because they feel they are best, or inherently know they will work. Exactly how is difficult to say, and even harder to qualify or quantify. This whole situation is compounded by the fact that map users are rarely consulted, either before, during or after the design process, at least in any systematic way. Though many people use the phrase “the users said they liked it”, no evidence that records of these comments are made or kept exists. We have to take it on trust that the symbols and the way they are used, which is also important, are effective.

Reference list for Appendix B


Wiedel, J. W. & Groves, P. A. (1969). *Tactual mapping: design, reproduction, reading and interpretation.* University of Maryland, Maryland, USA.
Appendix C: Confusion matrices for symbol discriminability

The tables below are confusion matrices for the study on symbol discriminability. For ‘different’ pairs, the numbers indicate the total number of times the symbols were incorrectly identified as ‘same’ symbols. For ‘same’ pairs, the numbers indicate the total number of times the symbols were incorrectly identified as ‘different’. The images of line symbols are cropped for the purpose of these tables.

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Appendix D: Instructions for participants

Instructions for substrate study

We are doing research on how to design tactile maps for visually impaired people. We do lots of studies and in this particular one, we want to find out what kind of materials we should use.

We would like to videotape your hands, so we can see how you do the tasks. The tapes are confidential, and only your hands will be recorded, not your face. Nobody will be able to recognise you. Do you give us permission to videotape your hands?

[For sighted participants and visually impaired participants with residual vision] We are interested in how you do these tasks just by using touch, so we would like to blindfold you. Is that ok?

We will have regular breaks, but please let us know whenever you need a break.

We will show you several arrays of symbols, printed in raised lines. Your task will be to find a certain symbol amongst the others. This is called the target symbol. [Show all symbols and target symbol] There are several target symbols in each array. The symbols you are looking for can be anywhere in the array, you can’t predict where they are going to be. There are different numbers of target symbols, so there is no point in counting them.

When I give you a page of symbols, you can start searching for the target symbols. I want you to start at the top left corner, and end at the bottom right corner, going through each row from left to right. It’s just like reading a page of text. Please say ‘yes’ when you find a target symbol and continue searching for the next one immediately.
You can use your right hand to search for symbols. You can use your left hand to keep track of where you are, by putting it on the markers on the left side of the array. Please try to be both as fast and as accurate as possible.

[Show target symbol and other symbols again] So, basically, we want you to search for these symbols, say ‘yes’ when you find one and move on. Try to be as fast and as accurate as possible.

[Practise the task giving feedback: tell them to go back when they have missed a target, to move on if they stop after a target etc. Tell participants there will be no feedback during the rest of the experiment.]

**Instructions for elevation study A and discriminability study**

We are doing research on how to design tactile maps for visually impaired people. We do lots of studies and in this particular one, we want to find out what kind of symbols people can recognise easily, and how small and low symbols can be.

This study is going to take quite a long time. We will have regular breaks, but please tell us whenever you would like a break.

[For sighted participants and visually impaired participants with residual vision] We are interested in what symbols are easy to recognise just by touch, so we would like to blindfold you. Is that ok?

We are combining two separate tasks in this study. In one of the tasks, we would like you to feel a symbol, then compare it to another symbol and tell us if these are the same or different. You can take as much time as you like exploring the first symbol, but once you have moved on to the comparison symbol, you can’t go back to the first one. You can only use one hand, and you can chose which hand you want to use. If you like, you can swap hands during the study.
The symbols are put in front of you in this jig [show jig]. This is where the first symbol will be. Then next to that, there will be some other symbols, which will be explained later. At the end of the row is the comparison symbol, and we would like you to tell us whether it is the same or a different symbol than the first one.

[Practise comparing two symbols]

Now, we are going to make it a little bit more difficult. Between comparing the symbols on the left and the right, we are going to add some more symbols. We have made some holes in the jig to help you find the symbols. There is a hole for each symbol, and you can use your thumb to slide along the side of the jig to find them. [Show holes]

The other task we would like you to do, is to identify circles, squares and triangles. There will be three of these symbols in each jig. We would like you to feel each of them, and tell us if you think it is a circle, square or triangle. Some of them may be quite difficult, but don’t worry about that. If you don’t know, you can just guess.

You can only feel the symbol for a limited amount of time. When you hear a beep, you have to move your finger away from the symbol and tell me what you think it was. You can then immediately go on to the next symbol. There will be a beep for each symbol.

[Practise identification of circles, squares and triangles]

I know these instructions sound complicated, but it will be quite easy once you get into it. Basically, we will give a row of symbols. You can feel the first symbol for as long as you like. Then, you move on the symbol right next to it. This will be a circle, square or triangle. When you hear a beep, you move on to the next symbol. At the end of the line, you will feel the comparison symbol and you tell me if it is the same or a different symbol than the first one.
We will give you lots of rows of symbols, and the study will take quite a long time. Just let us know whenever you want a break.

[Practise entire row of five symbols]

Instructions for elevation study B

We are doing research on how to design tactile maps for visually impaired people. We do lots of studies and in this particular one, we want to find out what kind of raised lines we should use.

We would like to videotape your hands, so we can see how you do the tasks. The tapes are confidential, and only your hands will be recorded, not your face. Nobody will be able to recognise you. Do you give us permission to videotape your hands?

[For sighted participants and visually impaired participants with residual vision] We are interested in how you do these tasks just by using touch, so we would like to blindfold you. Is that ok?

We will have regular breaks, but please let us know whenever you need a break.

We will show you several arrays of circles, printed in raised lines. There will be full circles and circles with a gap at the top, bottom, left or right side. Your task will be to find the full circles. [Show example of circles] There are several full circles in each array. They can be anywhere in the array, you can’t predict where they are going to be.

When I give you a page, you can start searching for the full circles. I want you to start at the top left corner, and end at the bottom right corner, going through each row from left to right. It’s just like reading a page of text. Please say ‘yes’ when you find a full circle and continue searching for the next one immediately.
You can use your right hand to search for symbols. You can use your left hand to keep track of where you are, by putting it on the markers on the left side of the array. Please try to be both as fast and as accurate as possible.

[Show example of display] So, basically, we want you to search for the full circles, say ‘yes’ when you find one and move on. Try to be as fast and as accurate as possible.

[Practise the task giving feedback: tell them to go back when they have missed a full circle, to move on if they stop after a full circle etc. Tell participants there will be no feedback during the rest of the experiment.]

**Instructions for single/double line study and discriminability study**

We are doing research on how to design tactile maps for visually impaired people. We do lots of studies and in this particular one, we want to find out what kind of symbols people can recognise easily, and how well they can identify single and double lines.

This study is going to take quite a long time. We will have regular breaks, but please tell us whenever you would like a break.

[For sighted participants and visually impaired participants with residual vision] We are interested in what symbols are easy to recognise just by touch, so we would like to blindfold you. Is that ok?

We are combining two separate tasks in this study. In one of the tasks, we would like you to feel a symbol, then compare it to another symbol and tell us if these are the same or different. You can take as much time as you like exploring the first symbol, but once you have moved on to the comparison symbol, you can’t go back to the first one. You can only use one hand, and you can chose which hand you want to use. If you like, you can swap hands during the study.
The symbols are put in front of you in this jig [show jig]. This is where the first symbol will be. Then next to that, there will be some other symbols, which will be explained later. At the end of the row is the comparison symbol, and we would like you to tell us whether it is the same or a different symbol than the first one.

[Practise comparing two symbols]

Now, we are going to make it a little bit more difficult. Between comparing the symbols on the left and the right, we are going to add some more symbols. We have made some holes in the jig to help you find the symbols. There is a hole for each symbol, and you can use your thumb to slide along the side of the jig to find them.

[Show holes]

The other task we would like you to do, is to identify single and double lines. There will be three single or double lines in each jig. We would like you to feel each of them, without using your nails, and tell us if you think it is a single or a double line. They are all different widths, so you can’t tell whether it is a single or a double line just by the width. Some of them may be quite difficult, but don’t worry about that. If you don’t know, you can just guess.

You can only feel the symbol for a limited amount of time. When you hear a beep, you have to move your finger away from the symbol and tell me what you think it was. You can then immediately go on to the next symbol. There will be a beep for each symbol.

[Practise identification of single and double lines]

I know these instructions sound complicated, but it will be quite easy once you get into it. Basically, we will give a row of symbols. You can feel the first symbol for as long as you like. Then, you move on the symbol right next to it. This will be either a single or a double line and you say ‘single’ or ‘double’. When you hear a beep, you
move on to the next symbol. At the end of the line, you will feel the comparison symbol and you tell me if it is the same or a different symbol than the first one.

We will give you lots of rows of symbols, and the study will take quite a long time. Just let us know whenever you want a break.

[Practise entire row of five symbols]
Appendix E: Evaluation study interview schedule

Map familiarisation

I am going to show you seven different maps, one at a time, and I will ask you to do some tasks on these maps. You don’t have to memorise the maps, all I want you to do is make yourself familiar with them and do some tasks. We’re not testing YOU here, we’re testing the maps. After each map, I will ask you some quick questions about what you thought of the maps. Then, after you have seen all the maps, we will talk about the maps some more. I am just interested in what you think about these maps. You can say anything you like; there are no right or wrong answers. We are not testing you, we are only interested in comparisons between the maps.

I would like to record the interviews that we’ll do on tape. Is this ok with you?

So, I will show you seven maps. They all represent a different town centre. There will be lines on the maps, that represent things like roads and foot paths. There are also some small symbols (we call them point symbols), that represent buildings, such as churches and a post office. The maps will also have some larger, textured area symbols, that represent larger areas such as parks.

So, I will give you the first map now. You can spend some time getting familiar with the layout of the map, and then I will ask you to do some tasks. Once you’ve completed the tasks, I will ask some questions. And then we will move on to the next map. At the end, we will compare all the maps. We will only be able to spend a little bit of time on each map. It’s not important that you understand and memorise every little detail, all I want you to do is familiarise yourself with the map and use it. The maps are quite complex, but don’t worry too much about that. All I want you to do is use the maps and compare them.
Task 1: Have a look at this key. The key shows you what the symbols on the map mean. Any symbol you can find on the map is explained in the key. Now, I want you to find the following symbols on the map:
- 2 churches
- Public toilets
- 2 areas of parks and woodlands
- Footpath
- Minor road
Find the church on Stoke Road (labelled SR)

TIMP inkjet map only: Find the pedestrianised footway.

Task 2: In this task, I want you to find a route between two points on the map. There is a car park here [show location], and a church here [show location]. Now, try to find the shortest route between them, using any streets or paths you want.

Task 3: This line here [show on key] represents the main road. Try to follow the main road from start to end on the map.

Interview and ratings

Questions after each map
- Is there anything you particularly liked about this map?
- Is there anything you particularly disliked about this map?
- Is there anything else you want to say about this map?
Questions at the end

Now, let's talk about all the maps and compare them. Here they all are [spread all maps out on table], do have a feel of them all if you want to remind yourself.

- Show all maps
- Is there anything you want to say about the maps?

- Did you notice any differences between the maps? If so, can you describe the differences?

- Did you particularly like any of the maps? Which ones? Why?
- Did you particularly dislike any of the maps? Which ones? Why?
- I am going to ask you to rate all the maps on a scale of 1 to 5, where 1 is the worst score and 5 is the best score. So, if you really dislike a map, you can give it a score of 1. If you really like it, you can give it a 5. Or you can give it any number in between.
- RATING: How much did you liked each map, and why?

- Show all maps
- Were any of these maps particularly pleasant to touch? Which ones? Why?
- Were any of these maps particularly unpleasant to touch? Which ones? Why?
- RATING: How pleasant was each map was to touch, and why?

- Show an inkjet map, a microcapsule map and a thermoform map.
- The raised features on these maps are made of different materials. Just have a feel of the raised features and ignore the background material for now. Can you feel any differences? Can you describe the differences between the materials of the raised features?
- RATING: How easy was it to use the materials of the raised features, and why?
Now we are going to do the same for the background material. Just feel the different background materials we used. Can you feel any differences? Can you describe them?

- RATING: How easy was it to use the background materials, and why?

- Show the Thesis, TIMP and NCTD design in inkjet, and the thermoform and Braille embossed map.

- These maps use different symbols. They have different little symbols, lines and textures. For now, ignore all other differences and just concentrate on the symbols themselves. So ignore differences in material, just look at the shape of the symbols.

- Do you notice any general differences between the symbols that are used on these maps? Can you describe any differences?

- Prompt if needed: different symbols used for map features, how easy to differentiate between symbols on each map.

- RATING: How easy was it to use the symbols, and why?

- Show the Thesis, TIMP and NCTD design in inkjet, and the thermoform and Braille embossed map.

- These maps were designed in different ways. They may have a different layout, which means the symbols might be positioned in different ways. I am now going to ask you some questions about the layout of the maps. Just ignore all other things, such as material and the choice of symbols.

- Feel these maps. Do you notice any differences in lay out? Can you describe them?

- RATING: How easy was it to use the lay out, and why?

- Show all maps.

- Now, we go back to all of the maps.

- Are any of the features on any of the map uncomfortable to touch?

- Are any of the features on any of the map difficult to understand?