An empirical approach on the design of tactile maps and diagrams: the cognitive tactualisation approach

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Abstract

Tactile maps and diagrams need to be carefully designed in order to be readable by the visually impaired user. In the Tactile Inkjet Mapping Project, we attempt to provide a new orientation for tactile map design through a rigorous programme of experimental research on design issues (cognitive tactualisation approach). In this paper, we discuss three of our studies. The first study evaluates the use of different background materials for tactile graphics. The second study looks at the minimal perceptible distance between two lines. The third study investigates the optimal elevation (height off the paper) at which graphics are produced. We argue that experimental studies like these represent a necessary basis for the design of tactile maps.

Introduction

Tactile maps and diagrams have been available in some form for centuries, and now have increasing significance in the lives of blind and visually impaired people for education, work and leisure, as graphical information becomes ever more prevalent and central in our daily experience. Methods for the production of tactile materials continue to be devised, and a range of materials and processes is currently available, the most recent of which (e.g. microcapsule paper, Tiger printer) allow computer derived images to be printed more or less directly in tactile form. Nevertheless, however accurate and nuanced the printing of the relief image may be, a map or diagram is only as good as its original design. A poorly designed map is an illegible map, no matter how well it is printed.

A direct translation of a visual image into a tactile image generally produces inadequate results. This is because the tactile modality imposes very different requirements with regard to spatial layout and information content of a map or diagram. In recognition of this fact, a number of guidelines on tactile map design have been published (Edman, 1992; Amick and Corcoran, 1997; Bentzen, 1997; Eriksson, Jansson and Strucel, 2003; Gardiner and Perkins, 2003). However, these largely reflect experience-based assumptions and aesthetic judgements rather than empirical research. Although these may well result in good ideas and practical solutions (especially when a feedback loop involving users of the materials is included), this trial-and-error approach is generally also quite hit-and-miss. This state of affairs is not unique to tactile images: cartographic design and the design of diagrams have generally been based on aesthetic decisions of cartographers and designers, some unique design insights (e.g. Harry Becks' London Underground diagram) and, occasionally, on feedback from users of the materials.

The last twenty years have seen a shift within visual cartography from a practice-led approach, based on aesthetic judgements and experience-based assumptions, to a more scientific approach, which has attempted to reassess the design of maps by drawing on findings, and employing research methodologies, from cognitive psychology (Keates, 1982; MacEachren, 1995). For example, MacEachren discuss, in the context of cartographic legibility, research on how components of a visual scene are detected, discriminated and identified. This research, which can be termed ‘cognitive visualisation’, recognises that reading a map or diagram involves a set of perceptual and cognitive process. Knowledge of the nature and limitations of these processes can help to improve the legibility of maps by improving the fit between the map and the perceiver. Similarly, the design of tactile images can be improved by referring to research on the perception and cognition of tactile information. We refer to this as a cognitive tactualisation approach. However, such an approach has not yet been applied to tactile cartography in a systematic way.

Although much less is known about tactile perception and cognition than about vision, there is literature in this area on which a scientific approach to tactile cartography might be based. Neurophysiological and psychophysical studies on tactile perception can shed light on the mechanisms of tactile perception and its limits (for an overview see Loomis (1981) and Hughes and Jansson (1994). Neurophysiological studies on touch generally examine the responses of receptors in the fingertip to simple tactile stimuli. For example,
LaMotte and Srinivasan (LaMotte and Srinivasan, 1987; Srinivasan and LaMotte, 1987) found that the receptors in the fingertip respond more strongly to sharp edges than gradual edges. Psychophysical studies on touch generally explore the limits of tactile perception by assessing participants’ responses to tactile stimuli. For example, the ability to perceive the orientation of gratings has been used as an indicator of tactile spatial acuity (Morley, Goodwin et al., 1983; van Boven and Johnson, 1994; Craig, 1999). Although literature on neurophysiology and psychophysics could provide a basis for a cognitive tactualisation approach, translating the findings directly into tactile map design would be problematic, as psychophysical and neurophysiological studies are too controlled in their method and too sensitive in their measures to provide results that could be applied directly to the design of tactile maps.

A small number of studies has specifically investigated tactile map design in an empirical way (see Berla, 1982 for an overview). Berla investigated the effects of tactile noise on a tactile map (Berla and Murr, 1975). Nolan and Morris (Nolan and Morris, 1971) studied minimum sizes for point and area symbols. Bentzen and Peck (Bentzen and Peck, 1979) investigated the traceability of different types of lines in a graphic display. Taking a more general approach, Vasconcellos (1993) studied the tactile graphic language and proposed 7 tactile graphic variables for the generation of map symbols. These empirical studies provide excellent information that can be incorporated in the design of tactile maps. However, experimental studies specifically on aspects of tactile map design are relatively rare.

In order to fill the gap between psychophysical studies and experience-based guidelines for tactile maps, we are seeking to develop a cognitive tactualisation approach based on empirical studies that involve more practical, realistic tasks. Such studies are currently being conducted as part of the Tactile Inkjet Mapping Project, which incorporates 3 areas of research. One area involves the development of a tactile inkjet printer. This printer is capable of producing robust tactile images with great accuracy (McCallum and Ungar, 2003; McCallum, Ahmed et al., 2005), allowing us to print high-quality stimuli for experimental studies. A second area involves cartographic design of tactile maps, based on surveys of current tactile map producers’, of existing published design guidelines, and on surveys of tactile map user needs and preferences (Rowell and Ungar, 2003a; Rowell and Ungar, 2003b). The third research area, which is the focus of this paper, deals with cognitive and perceptual factors related to tactile map reading.

In this paper, we outline three of our studies that explore specific aspects of tactile map design in an empirical, yet realistic way. In the first study, which investigated what types of substrate (i.e. base or backing materials) are most suitable for the production of tactile graphics, participants performed a search task on different substrates. Search time was measured and participants were asked about their preferences for substrates. In second study, participants were asked to identify single and double lines, in order to find a minimum gap size between two lines at which these lines were identified as double. The third study aimed to find the optimal elevation (vertical height off the paper) for tactile features, at which resources are minimised and performance is maximised. In this study, participants performed a search task on tactile displays that were printed at several elevations.

Experiments

**Experiment 1: Substrate study**

Tactile maps and diagrams can be printed on a variety of substrates (background materials). The substrate might influence the quality of a tactile map or diagram (Dacen Nagel and Coulson, 1990; Pike, Blades and Spencer, 1992). For example, certain substrates might allow faster extraction of information or they might be more pleasant to touch. In the substrate study, we tried to determine what types of substrate are most suitable in terms of scanning speed and user preferences (see Jehoel, Ungar et al.,2005a, for a more detailed description of this study). Fifteen visually impaired and 14 sighted participants scanned symbols arrays by touch on 7 different substrates, searching for target symbols. The substrates were rough paper, smooth paper, microcapsule paper, Braille, rough plastic, smooth plastic and aluminium. A tactile inkjet printer printed 9 rows of 8 raised symbols on each substrate. Five different shapes were used, including an inverted V which was the target symbol. In the first part of the experiment, participants scanned symbol arrays on all substrates, searching for target symbols, and scanning time was measured. In the second part of the experiment, participants performed a preference ranking task in which they lined up all substrates in order of preference. Participants were then asked about the basis for their preference judgements. Sighted participants and those with residual vision were blindfolded during both tasks.

![Figure 1: The relationships between scanning speed on all substrates. Connecting lines indicate significant differences.](image-url)
Although visually impaired participants performed the search task faster than sighted participants, the pattern across substrates was similar for both groups. The task was performed fastest on rough paper and microcapsule paper, rather fast on smooth paper, intermediate on Braillon, rather slowly on rough plastic and slowest on aluminium and smooth plastic (figure 1). A similar pattern emerged from the preference ranking task (figure 2). Participants were divided into two preference groups, based on their comments about
preferences. The majority of participants (19 out of 29) indicated they preferred rougher substrates over smoother ones. A minority (9 out of 29) indicated a preference for smoother substrates. Most participants reported that they preferred certain substrates, because they felt it was easier to move their fingers across them. Interestingly, both preference groups performed the search task faster on rougher substrates. Since the rough preference group was more than twice the size of the smooth preference group and since their preferences were stronger, it is possible to conclude that the rougher substrates, especially rough paper and microcapsule paper, are most preferred as well as easiest to scan.

The results of this study can be used when deciding what substrate to use for the production of a tactile map or diagram. In general, microcapsule paper and rough paper appear to be the most suitable, both in terms of scanning speed and preference. However, the choice of substrate also depends on the functions of the map or diagram. Durable substrates, such as plastic and aluminium may still be more suitable for use in public places. According to this study, rough plastic would be most appropriate in those circumstances.

**Experiment 2: Single and double line study**

Single and double lines are often used on the same tactile map or diagram, for example to signify different types of roads, and it is important that users are able to identify these lines correctly. If the separation between the two elements of a double line is too small, it will be perceived as a single line, possibly causing confusion for the map or diagram reader. Although it is commonly recognised that tactile features require larger separation distances than visual features, it is not known how large the separation distance should be between the two elements of a double line. Psychophysical studies have found the smallest gap that is detectable by touch to be somewhere in the range from 0.87 mm (Johnson and Phillips, 1981) to 2.81 mm (Stevens, Foulke and Patterson, 1996). These gap detection studies give some indication of the minimum separation distance required for the perception of a double line. However, the results cannot be translated directly into the spacing between lines, because of the highly controlled methods used in such studies. Stimuli were mechanically applied to the fingertip and movement between finger and stimulus was not allowed, even though movement is considered to play an important role in tactile perception (Krueger, 1970).

In map reading, users continuously move their fingers across the display. The current study aims to find the minimum separation distance between the two lines of a double line by analysing the performance of participants when identifying single and double lines of different widths and separation distances using active touch.

Ten sighted and 10 visually impaired participants took part in the study. They were presented with straight single and double lines of 5 cm in length and 0.19 mm in height. Lines were printed onto plastic cards using a tactile inkjet printer. The separation distance of the double lines ranged from 0.2 to 2.1 mm. Over all separation distances, two line widths were used for the individual lines of the double line; 0.7 and 1.3 mm. These added to the overall width of the double line and did not influence separation distance. The width of the single lines corresponded to the overall width of the double lines (1.4 to 4.7 mm). Single and double lines were oriented both horizontally and vertically on separate cards. 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). A forced choice paradigm was used, in which participants were asked to identify each line as single or double, without using their nails. Sighted participants and those with residual vision were blindfolded during the task. There was a time limit of 5 seconds for each line.

Since no significant differences in performance were found between sighted and visually impaired participants, their data were combined. The percentage correct was calculated for each line, across all participants. Figures 3 and 4 show the percentage correct for double and single lines respectively. From figure 3 it can be concluded that vertical double lines are more easily perceived as double than their horizontal counterparts. This can be explained by differences in stimulation of the fingertip. Participants were most likely to explore lines in a left-to-right motion, regardless of the orientation of the line. Consequently, features of a horizontal double line (both lines and the gap between them) often remained in the same location on the fingertip, while the features of vertical double lines would move across the fingertip. This resulted in a changing pattern of stimulation for vertical lines, which ensured a higher level of neural excitation (see Lederman and Browse, 1988, for an overview of the physiology of touch). Figure 3 also shows that performance is better on thin double lines than on thick ones. This may be caused by the fact that the thin lines felt ‘sharper’ and produced a finer pattern of neural stimulation. Figure 4 shows an interesting result regarding single lines. Wide single lines are sometimes incorrectly identified as double lines. Previous research suggests that edges generate a high level of neural activity (Phillips and Johnson, 1981). Possibly, the two edges of wide single lines caused a sensation of two separate lines.
In order to produce double lines that can be correctly identified as such on a tactile map or diagram, our data suggest the use of a separation distance of at least 1.3 mm. At this separation distance, thin, thick, horizontal and vertical double lines were correctly identified more than 91% of the time in this study. Single lines that are wider than 2.2 mm might be perceived as double lines.
Study 3: Elevation study

Tactile maps need to be produced at a sufficient elevation (vertical height off the substrate) in order to be readable. Currently, the elevation of tactile features on maps varies widely, depending on the production method used. However, tactile maps may be readable at considerably lower elevations than generally assumed. Psychophysical studies show that the fingertip is highly sensitive to elevation; a single edge can be detected at an elevation of 0.85 microns (0.00085 mm) (Johansson and LaMotte, 1983). Study 3 aimed to determine the minimum elevation at which tactile graphics are readable. Participants searched for target symbols on arrays of raised symbols. Performance was measured in terms of scanning time. An increase in elevation was expected to improve performance. However, this effect was expected to level off. At a certain elevation, further increases in elevation were not expected to improve performance significantly. This point can be taken to be the optimal elevation, at which resources (ink and printing time) are minimised and performance is maximised.

Nineteen participants (8 sighted and 11 visually impaired participants) performed a tactile search task on arrays with symbols printed at 20, 40, 80, 160, 320 and 640 microns elevation. Each tactile display consisted of a 6 by 6 array of full outline circles and outline circles with gaps of 45°. Seven full circles, acting as target symbols, were randomly located on each display. Circles were 2.5 cm in diameter and had a line width of 1.6 mm. 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. Scanning time was recorded.

Figure 5: Mean scanning time on arrays at several elevations.

The results of this study are shown in figure 5. Elevation had a clear effect on performance: tactile features at higher elevation were scanned more quickly than features at low elevations. In order to find the optimal elevation, represented by the lowest elevation at which performance is good, we identified the ‘elbow’ in the graph. The amount of time needed for scanning arrays decreased sharply as elevation was increased from 20 to about 200 microns. Increasing elevation further did not significantly decrease scanning time. This suggests that tactile features can reliably be identified on a tactile map at elevations of as little as 200 microns (0.2 mm).

Conclusion

Three examples of studies within the cognitive tactualisation approach have been discussed. The substrate study aimed at finding the most suitable background material for tactile maps and diagrams. The results suggest that rough paper and microcapsule paper are most suitable. However, when a more durable substrate is required, rough plastic could be used. The second study explored the minimum separation distance between the two elements of a double line. According to the results of this study, two lines
separated by at least 1.3 mm are perceived as a double line. In the third study, we aimed to find the optimal elevation for tactile graphics, at which resources are minimised and performance is maximised, which appears to be around 200 microns.

We used the TIMP printer for the production of all experimental stimuli. It is important to bear in mind that this might limit the generalisability of our findings. The output of the TIMP printer is among the more rigid of production methods; polymer backing sheets are particularly tough and the ink sets hard. Therefore, the shape of symbols is reliably preserved in use, and symbols feel very clear and 'sharp'. Thermoformed maps are often made of thin sheets, and swell paper and embossers are paper-based and thus pliable, meaning that low symbols might become deformed. Symbols that are produced by these methodologies may also feel 'fuzzier' and less clear. Therefore, although small line distances and low elevation features may be effective when using an inkjet process on a rigid substrate, reliability may be reduced in other production methods.

In relation to the general methodology employed across the three studies, we believe that a series of studies like the present one can be used to explore the relationship between abstract psychophysics and real-world tactile map use, as a result of employing more concrete, ecologically valid tasks. While in the past it has been generally recognised that some psychophysical 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 - Johnson and Phillips, 1981), there are other findings that have been accepted more or less at face-value (e.g. evaluation of discrimination of tactile symbols, where testing took place in isolation) (Heath, 1958; Morris and Nolan, 1961; Nolan and Morris, 1971; Jansson, 1972; Gill and James, 1973; Jansson, 1973; James and Gill, 1975). The present studies demonstrate the value of taking studies of symbol usability further than the level of the individual symbol, and looking at their use in context and in a realistic setting. Further studies remain to be carried out to determine the validity of the findings in actual map contexts.

The studies reported here are part of a series of experiments on issues related to tactile map design. Other studies conducted by the Tactile Inkjet Mapping Project deal with, for example, line profile, roughness of textured areas and traceability of different line types. The development of a highly discriminable set of symbols (Jehoel, Ungar et al., 2005b) is another major aim of the project. These studies attempt to bridge the gap between psychophysical studies on tactile perception and guidelines on tactile map design, and should help to provide a more scientific basis for the design of tactile maps and diagrams.

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