Usability Evaluation of Tactile Map Symbols Across Three Production Technologies

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Structured abstract: *Introduction:* Technological advances have introduced three-dimensional (3-D) printing as an option for creating tactile maps for people with visual impairments (that is, those who are blind or have low vision), diversifying the types of map products that are available. At the same time, it presents a challenge to map makers to implement designs across multiple production methods. We evaluated map symbols to determine their discriminability across three different materials: microcapsule paper, 3-D printer plastic, and embossed paper. *Methods:* In a single session lasting less than 90 minutes, participants completed a matching task and provided informal feedback regarding their preferences. We measured speed and accuracy to establish discriminability of map symbols on each of the materials. Eighteen participants were recruited from a referred sample among attendees at the American Council of the Blind annual convention in 2013. *Results:* Response times were significantly different across the three materials ($p < 0.001$). Without sacrificing accuracy, response times were faster for the 3-D printed graphics than for either the microcapsule paper ($p < 0.001$) or the embossed paper ($p < 0.001$). User preference was divided across the three materials. Some people disliked the "sharp" corners of the 3-D printed symbols, while others preferred their "crisp" edges. *Discussion:* Our results demonstrate faster discriminability of a set of tactile symbols produced on a 3-D printer compared to those same symbols printed on microcapsule paper, the material for which the symbols were originally designed. Participant feedback reflected preferences both in favor of and against reading symbols produced on the 3-D printer. *Implications for practitioners:* This article discusses the functional equivalence of tactile symbols produced across multiple production technologies. It addresses two considerations when using 3-D printing to make tactile maps: preparing digital files for printing and the printing work flow. Digital files ready for printing on each of the three materials are available for download (Brittell, Lobben, & Lawrence 2016).

Tactile maps are a common approach to providing visually impaired people (that is, those who are blind or have low vision) with access to geospatial data. Map readers perceive information from tactile maps through raised symbols and distinct textures. Multiple production technologies produce raised symbols and textures. Vacuum form and microcapsule (swell) processes have been popular for many years (Perkins, 2001); physical models and embossed paper are common (Rowell & Ungar, 2003b); and, most recently, three-dimensional (3-D) printing has emerged. Likely owing to both the high cost and the high expertise required, 3-D printing has not yet been widely adopted into mainstream production (Ducasse, Macé, & Jouffrais, 2015; Hasiuk, Harding, Renner, & Winer, 2017; Poon, 2016). With the price of 3-D printing continuing to drop, though, and the predicted surge in the 3-D printing industry over the next several years (Columbus, 2015), this production method may become a viable alternative to the other processes currently used for tactile maps and graphics.

Perhaps due to the distinct characteristics of the graphics that each production method produces, and respective advantages and disadvantages (for example, levels of durability and convenience), a majority of map makers use more than one production method to meet the individual needs of visually impaired people (Rowell & Ungar, 2003b). Evaluation of production technologies in the published literature has included usability of specific symbols in isolation (Lawrence & Lobben, 2011), usability of specific symbols within the context of a map (Gual-Ortí, Puyuelo-Cazorla, & Lloveras-Macia, 2013), and comparison of production methods (Perkins, 2001). Our work contributes to the latter; in an experimental setting, we evaluated a single set of symbols across three production technologies: microcapsule paper, 3-D printing, and embossing. In this paper, we discuss the preparation of digital files for printing and our experience with the 3-D printing process. Our findings support the viability of using the same symbol set across multiple production methods.

Review of the literature

Acknowledging the potential connections with many bodies of literature, we focus on two areas to ground our work: tactile symbol design and map production using 3-D printing technology.

TACTILE SYMBOL DESIGN

Exploration of the vast design space for tactile symbols has provided guidelines for design that are related to either perception or recognition and interpretation within a specific context. Based on measurements of tactile acuity, for example, Jehoel, McCallum, Rowell, and Ungar (2006) identified a minimum symbol height and optimal separation between parallel lines that form a single symbol. Research has also found a relationship between readability and shape (see Rener, 1993, for a review). In addition to physical properties related to perception, specifying a context in which a collection of symbols must work together to convey

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meaning also influences the readability of tactile symbols. Research in tactile perception and design of tactile symbols, in concert with national organizations such as the Braille Authority of North America (2010) in the United States, inform and shape established guidelines.

Several projects have evaluated sets of symbols for use specifically in tactile map design, usually attached to a specific production technology (Perkins, 2002). For example, the Nottingham Map Making Kit and later the Euro-Town-Kit (Laufenberg, 1988) presented a set of 28 tactile symbols for urban mapping that could be produced using the thermoform production method. The standard symbols set was proffered for use in a specific application, town maps for European towns; it was neither intended for nor claimed to be exhaustive or to apply to all maps. Incorporating basic principles from the Euro-Town-Kit and newly collected empirical data, a navigational tactile map symbol set was developed by researchers at the University of Oregon specifically for large-scale reference maps made using microcapsule paper and a tactile image enhancer (Lobben & Lawrence, 2012). Field testing with visually impaired map users demonstrated the successful discrimination and use of the symbol set.

Creation of a standardized tactile symbol set, however, is challenging (Tatham, 2001). Challenges include the sheer number of unique environmental features that need to be represented, the limited range of possible symbol designs (the number of tactile symbols that are distinctly discriminable from one another), and the potential interaction between symbol design and the production method. Rowell and Ungar (2003a) suggested a structured collection of tactile symbol designs combined with metadata that details the symbol structure, describes any empirical evaluation, and makes suggestions for use. However, to our knowledge such a database of tactile map symbols is not publicly available and is not part of this study. More generally, online libraries of 3-D models have emerged over the last decade, and several tools have been developed to automate tactile map generation (see examples in Table 1). Table 1 summarizes some of the efforts to create publicly available symbols and maps.

Cartographers have long known that symbology behaves differently on different media; for example, designing for a printed map versus designing for a digital map. Further, symbol design for tactile maps should consider the intended production method (Perkins, 2001, 2002). There is a need to better understand the interaction between symbol design and production material across multiple production methods.

MAP PRODUCTION USING 3-D PRINTING TECHNOLOGY

Advances in technology have expanded the options for tactile map production. And, although there is a dearth of mainstream tactile map production, researchers have recently begun exploring ways to reduce the production burden (Ducasse et al. 2015; Poon, 2016; Voženílek & Vondráková, 2015). Among the new options are 3-D printers, and the distinction between 3-D printing technologies is worth noting. The sintering technology (fusing a powered material) provides flexibility and control over the finish (for instance, texture, as noted by Voženílek & Vondráková, 2015) of the printed artifact. Printers

Table 1
Examples of sources for rendered tactile maps, semiautomated tactile maps, and tactile map symbols.

Feature	Source
Existing rendered maps	Thingiverse (https://www.thingiverse.com)
(Semi-)automated tactile map generation	TMAP (Miele, Landau, & Gilden, 2006)
	HaptoRender (Lulu-Ann, 2009)
	TMACS (Watanabe, Yamaguchi, Koda, & Minatani, 2014)
	HaptoOSM (Haňβgen, 2014)
	TactileMpas.net (Taylor et al., 2015)
	BlindWeb (Götzelmann & Eichler, 2016)
	Haptické mapy (Èervenka, Bøinda, Hanouskovaì, Hofman, & Seifert, 2016)
	TouchMapper (Kärkkäinen, 2017; https://touch-mapper.org/en/)
Symbol wet	Euro-Town-Kit (Laufenberg, 1988; Deutsches Blindenstudienanstalt)
	Tactile symbol directory (Hagood, 1992; http://www.tsbvi.edu/tactile-symbols)
	Point, line, and texture symbols (Frascara & Takach, 1993)
	TacMap (Chamberlain & Dieng, 2011; http://tacmap.co.uk/, commercial)
	Street Symbol Set (Lobben & Lawrence, 2012)

that build up the printed artifact using an extrusion technology give control over the resolution (the thickness of each layer) and tend to be available at a lower cost, but have more limited control over the finish.

The introduction of 3-D printing has increased production options that take advantage of the *z*-axis (height) of symbols. In contrast, tactile symbols produced on microcapsule paper or using an embosser have limited resolution on the *z*-axis. Rather than providing only raised relief, 3-D printing can produce "volumetric" symbols such as spheres. In an empirical evaluation, Gual-Ortí et al. (2013) found that volumetric symbols were located faster and with lower error rates than were low-relief symbols. But general guidelines for the design of volumetric map symbols have yet to be established. Even though the technology would allow the production of volumetric symbols, in this study we concentrated on the feasibility of using the same symbol design across production methods.

Many map makers use multiple technologies (Rowell & Ungar, 2003b). The various production methods use different materials to fabricate the graphics. The characteristics of the base material may influence readability and usability for some (Jehoel, Ungar, McCallum, & Rowell, 2005), but not all (Rener, 1993), symbols. Further, user testing to determine preferences have produced inconclusive results (Perkins, 2002). To support the inclusion of 3-D printing in the map maker's toolbox, we are interested in questions of standard design and generalization across production technologies: How rigid is the connection between symbol design and production method? and Can a single symbol set be used across multiple production methods?

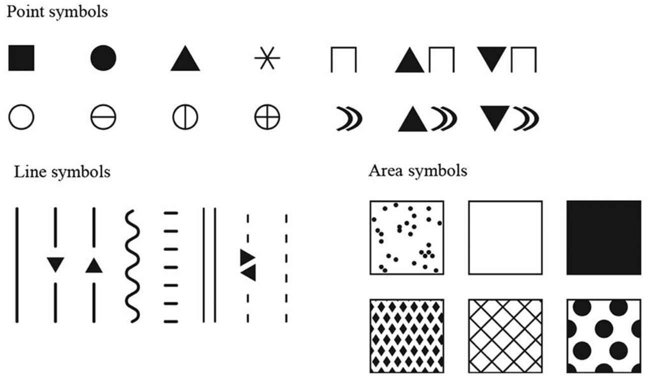

Figure 1. Symbols set.

Methods

To address our questions, we designed and conducted an experiment that measured and analyzed the discriminability of a set of tactile reference map symbols across three different production methods: printing on microcapsule paper, 3-D printing, and embossing. Tactile symbols were fabricated using each of the selected production methods. A group of potential users then participated in test sessions in which they completed a matching task. Specifically, this research tested the extent to which it was possible for the participants to discriminate the symbols across multiple production methods. The section below documents the symbol set selection, the production processes, the test instrument, and the evaluation by participants.

Symbol set selection

For this research, we used an existing symbol set that had been previously vetted for reliability and validity through field testing and analysis (see Lobben and Lawrence, 2012, for a full discussion of the development and subsequent testing of this symbol set). The symbol set, shown in Figure 1, was developed and designed for production using the microcapsule paper and tactile image enhancer process. The set includes point, line, and area symbols that were applied to large-scale navigation maps and were shown to be discriminable, meaningful, and usable in real-world tactile map use (Lobben & Lawrence, 2012).

Production processes

The original symbol set was designed for a single production method: microcapsule paper with a tactile image enhancer. For the comparison, we reproduced the original symbol set using microcapsule paper and two additional production methods: 3-D printing and embossing. All three methods followed a similar protocol of sending a digital file to a printing device, which required minimal manual intervention in the printing process. The experiment stimuli for the test instrument were produced using all three methods.

Microcapsule paper

The microcapsule paper production requires a traditional inkjet printer and a tactile image enhancer. This process works by first printing the symbols onto microcapsule paper, which contains tiny chemical-filled capsules sandwiched between two sheets of special paper. The microcapsule paper is then fed through a tactile image enhancer, which heats the surface of the paper, agitating the chemicals. The chemicals underneath the black ink are heated to a point that causes the capsules to expand, which results in raised relief—that is, the tactile map symbols. This production process results in a uniform *z*-height for the raised relief.

To create the experiment stimuli, the symbols were printed on microcapsule paper using an off-the-shelf inkjet printer. After ink was deposited on the microcapsule paper, the paper was fed through a tactile image enhancer.

The digital files that were sent to the printer were derived from the 3-D models, given solid black color in Adobe Illustrator, and exported in portable document format (PDF).

Embossed graphics

The same digital PDF files used for printing on the microcapsule paper were also used for the embossed graphics, and these files were sent directly to the embosser. The graphics were produced with an EmFuse Color Braille Station by ViewPlus (www.viewplus.com). To produce tactile graphics, the embosser punched raised dots on a page. Although the EmFuse provided up to eight different dot heights, the dot height for the stimuli in this experiment was uniform and used a greatest-height setting. The stimuli were printed on standard braille paper and included the tactile graphic (at 20 dpi) with a corresponding visual representation of the symbols beneath (at 600 dpi). The printed visual graphic aided the sighted researchers, but it was not available to participants for symbol discrimination.

3-D printed graphics

As the most recently developed technology, the description of the 3-D printing process is more extensive than that provided for the microcapsule paper and embossing processes. It includes both a description of the printer and additional details about the work flow that we followed to create the 3-D printed graphics.

For the 3-D printing, graphics were fabricated on a Replicator Dual by MakerBot (www.makerbot.com) using acrylonitrile butadiene styrene (ABS) plastic. Each symbol was modeled in three dimensions using an open-source, computer-aided drafting program by OpenSCAD (www.openscad.org) to mimic the size, shape, and approximate feel of that symbol when produced on microcapsule paper. The symbols were modeled as low-relief shapes (height = 1 millimeter). The software provided an option to export the graphics as a two-dimensional version of the raised height forms, which was used to create PDF files for printing on microcapsule paper and on the embosser.

Designing the computer models of the 3-D shapes involved specifying the symbols as combinations of simple shapes using the language of the computer-aided drafting (CAD) program. CAD was selected because of the precise control it provided over symbol size and shape. The symbols were specified using lines of code that could replicate identical copies of the symbols for each of the graphics. This approach was well-suited to meet our need for experimental control, and it could be automated with a computer script to fit into a geographic information system (GIS) work flow. But any 3-D design program could have been used to create the stereolithography (STL) files (Taylor, Dey, Siewiorek, & Smailagic, 2015).

The STL files are a portable format for 3-D models; to send these models to the printer, they must be converted into a format that is specific to the printer itself. Conveniently, this process is automated by software that comes with the printer. In the case of the MakerBot printer, the conversion involves slicing the shape into layers and creating an "x3g" file, a proprietary binary file format. Artifacts of the automated slicing meant that the design of the 3-D models was an iterative process. When lines were too thin, they were at risk of being lost in the automated slicing and were missing from the printed product. Or medium-weight lines risked being rendered as outlines without the intended fill. For convenience, we have published the 3-D models used in our study that produced readable symbols, and they can be downloaded and adapted for general use (Brittell et al., 2016).

The models represented low-relief shapes with flat tops, which were produced by raising the symbol shape as an orthogonal prism. Symbol height was set to one millimeter, which created symbols that were qualitatively similar to those printed on microcapsule paper (as subjectively judged by the researchers). To maintain some level of an average hypothetical work flow from digital file to final product, the 3-D figures were not optimized. Graphics were produced with "medium" resolution (slice thickness = 0.20 millimeters) using ABS plastic. Surface texture, which was an artifact of the production process, was not smoothed.

Major blemishes in the printed graphics were corrected, but minor blemishes were not. On the MakerBot, which uses filament extrusion technology, we found that larger print sizes tended to be sensitive to malformation of the base tile. Specifically, the corners tended to curl on larger pieces. When curls occurred, the piece was discarded, and the graphic was reprinted. Minor blemishes, such as inconsistencies in the finish of the top layer that did not change the outline shape of the symbols, were retained in the set of stimuli.

TEST INSTRUMENT

The symbol set from Lobben and Lawrence (2012) included three symbol types: points, lines, and areas. Cartographically, *point* symbols are used to represent objects with a limited x-y location (for example, a building entrance or bus stop). *Line* symbols represent objects that have considerable length relative to width (for example, streets, rivers, or boundaries). Finally, *area* symbols represent environmental objects that have continuous surfaces (such as a park, lake, or building footprint). To evaluate the symbols across the different production methods, we designed a 3 (symbol type) × 3 (production method) experimental matrix. We fabricated multiples of each symbol type using each production method.

We designed a matching task in which participants were asked to match the target symbol on the left with its matching symbol in a line of three response symbols on the right (see Figure 2). Every symbol in the symbol set from Lobben and Lawrence (2012) was presented as

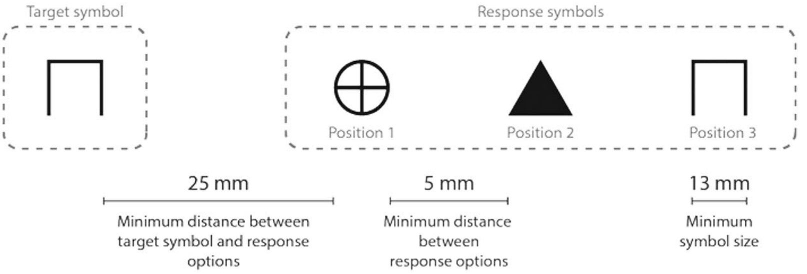

Figure 2. Example of matching task layout.

the target symbol three times to produce a robust measure of performance. The position of the correct matching response was balanced across the three positions in the response options. This task included 252 trials (28 unique symbols × 3 production methods × 3 response positions).

Each experimental graphic was presented to participants on letter-size paper or a hardboard base in landscape orientation (8.5 inches tall by 11 inches wide). The center of the target symbol was 66 millimeters from the center of the nearest response symbol; the distance from the center of one response symbol to the center of its neighbor was 42 millimeters. The width of the empty space between symbols varied due to the varying shapes of the symbols. The minimum separation between the target symbol and the response symbols was 25 millimeters; the minimum separation between response symbols was five millimeters. The presentation order was randomized, but each participant received the same randomized presentation order. The position of the correct (matching) response option was balanced across the three response positions.

Differences in response time between participants were mitigated by standardizing the response times. Observations for each participant were transformed into a measure of deviation from that participant's average response time. The amount of within-participant variability in response time that could be attributed to the experimental conditions was measured using a two-way ANOVA with repeated measures.

After completing the matching task, participants were asked to share their thoughts about the relative advantages and disadvantages of the three production methods and their related materials.

EVALUATION BY PARTICIPANTS

Our experimental design was administered as a timed matching task to evaluate the relative discriminability of a single symbol set across three materials. Eighteen people (average age 52 years old, 9 females and 9 males) participated in the testing. Participants were recruited from a referred sample among attendees at the American Council of the Blind annual convention in 2013. Eight participants were blind from birth, 2 participants became blind before the age of 3 years, and all other participants became blind after the age of 3 years. All participants reported that they read braille: 1 participant read uncontracted braille (also known as grade 1 braille); 15 read contracted braille (also known as grade 2 braille); and 2 read a densely contracted form of braille known as "grade 3." All participants either had no usable vision or wore a blindfold to block any visual or light perception cues that would impact the tactile symbol discrimination task. Sixteen participants reported having previously used tactile maps or graphics (two reported no previous experience), and eight of those participants reported that they received formal or informal training with tactile maps or graphics. The testing protocol was reviewed and approved by the Institutional Review Board at the University of Oregon. All participants gave informed consent to participate, and they were free to discontinue participation at any time. All participants chose to complete the full session.

All testing sessions were run consistently. Activity in each session was conducted in the following order: project description and informed consent; collection of demographic data; and introduction to the test materials and symbol set, followed by the matching task. In the matching task, participants were asked to respond as quickly and accurately as possible. Testing sessions were scheduled in two-hour blocks.

Results

Testing sessions lasted between 35 and 83 minutes (average: 57 minutes). Each trial took between 0.901 and 55.367 seconds (average: 5.368 seconds, median: 3.962 seconds).

In terms of accuracy, overall, participants selected the correct match in 95.5% of trials (embossed: 94.2%; microcapsule: 95.5%; 3-D: 96.7%). There was a difference in accuracy across the three conditions (repeated measures ANOVA, $p = 0.018$), which was attributable to better performance on the 3-D printed graphics compared to the embossed graphics (post hoc Tukey test, $p = 0.007$). Despite the statistically significant result, the lower accuracy for matching based on the embossed graphics could be explained by a design disadvantage discussed further in the next section. There was no significant difference in accuracy between the 3-D printed graphics and the microcapsule paper ($p = 0.321$), or between microcapsule paper and embossed paper ($p = 0.254$).

Response times were slightly faster on average for correct answers (5.315 seconds) than for incorrect answers (6.495 seconds). The faster response time for correct answers suggests that participants were not sacrificing performance accuracy in favor of faster response times. Strong variability in response time was observed between participants. As an example, the difference between the observed response times for two participants, participant #865 and participant #85, are statistically significant (paired Wilcoxon signed rank: $V = 382$, $p < 0.001$; mean response times were 29 seconds and 71 seconds, respectively). After standardization of the response time, the difference between the distributions of these same two participants' response times was not statistically significantly different ($V = 15545$, $p = 0.751$).

The standardized measures of response time (see Figure 3) revealed statistically significant differences across the three production methods (two-way ANOVA with repeated measures: $F = 25.93$, $p < 0.001$). A pairwise comparison based on the Tukey test revealed significant differences between all three pairs ($p < 0.001$ for each pair). A post hoc test for interaction

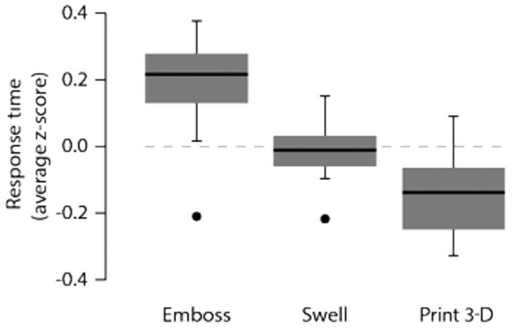

Figure 3. The standardized measures of response time.

between production method and symbol type indicated a significant interaction ($F = 3.028$, $p = 0.023$).

Discussion

Empirically observed performance on a matching task revealed faster responses for 3-D printed graphics than for embossed paper or microcapsule graphics. And that difference can be attributed to the production method and an interaction between the production method and the symbol type. This result is consistent with published findings related to volumetric symbols (Gual-Ortí et al., 2013) and roughness of the base material (Jehoel et al., 2005).

The distribution of response times had a positive skew. The maximum trial duration (response time) was over 55 seconds, but only a small proportion of the total trials were greater than 30 seconds (10 out of 4,518). We interpret these excessive durations on a handful of trials as outliers, possibly attributable to distraction. But we did not record that level of detail during testing.

The three selected production methods provided two distinct levels of resolution. The embosser was high resolution for its respective production method; however, the conversion of the graphics into a grid of embossed dots (20 dpi) could not represent curves or diagonal lines with the same precision as either the microcapsule paper and tactile image enhancer or the 3-D printer. This difference in resolution made the embossed graphics more difficult to read, and unsurprisingly resulted in slower response times and lower accuracy. In contrast, the 3-D printer was able to precisely create the shapes of the symbols, which had been designed for production on microcapsule paper. The degree of similarity in resolution between the microcapsule paper and 3-D printing was likely a factor in the successful generalization of the original symbol set to a new production method.

Physically well-defined corners were characteristic of the symbols in the 3-D printed graphics. These well-defined edges were met with mixed reviews. Some participants disliked the 3-D printed graphics, despite their perceived and actual faster performance in the matching task. They described the edges as “sharp” and unpleasant to the touch. Others preferred the “crisp” edges because they increased the contrast between the symbol and the base material and made the shape of the symbol easier to perceive.

Future work could pursue a balance between the unpleasant sharpness and the crisp readability. The versions of the symbols drafted for the 3-D printing used in this study were constructed as simple prisms. The models could be adjusted to round the corners and optimized to capture subtle profile changes. As an example, Schwarzbach, Sarjakoski, Oksanen, Sarjakoski, and Weckman (2012) use a smoothing approach to “make the touch of the trees more comfortable" (p. 175) in terrain modeling for reproduction on a 3-D printer.

The steps involved in preparing the files intentionally avoided extensive refinement (for instance, the 3-D printing resolution was set to medium and the 3-D printed pieces were used as they were printed without post-production smoothing), but the process was still outside that of a typical GIS work flow. It involved the introduction of additional software (CAD for 3-D modeling) and manual adjustment of the files produced through the automated process for printing 2-D shapes (such as the addition of black fill). While possible in a research setting, this approach could be a barrier to adoption of the technology by practitioners. As an alternative, symbols could be designed in a GIS program (Voženílek & Vondráková, 2014), which would more closely reflect a typical cartographic work flow, or could be automated using web-based tools (Taylor et al., 2015).

Our matching task evaluated symbols in isolation. This approach focused on the discriminability and functional equivalence of individual symbols, and further testing may be necessary to determine readability when generalized for use in a complete map. The original symbol set (Lobben & Lawrence, 2012) was validated for use in a map when produced on microcapsule paper, but 3-D printed maps may introduce confounds that hinder usability. For example, we did not investigate the influence of including both point symbols and line symbols in a single map. There may also be complications when using the 3-D printing technology to produce larger graphics.

IMPLICATIONS FOR PRACTICE

As with any new technology, adoption of 3-D printing will mean changes to a practitioner's existing work flow. Our finding that symbols that are familiar and usable on microcapsule paper could be directly applied to 3-D printing eliminates the need to completely redesign existing maps. The files that we have published (Brittell et al., 2016) can serve as a starting point for practitioners to develop their own maps. The scripts contain a full specification of the symbol shapes, and they can be positioned within the map by specifying numeric coordinates. The CAD program in which the symbols were implemented is open-source software and is freely available.

Conclusion

As 3-D printing technology continues to advance, its use in the production of tactile graphics is likely to increase. For map makers who are considering 3-D printing, a direct translation of an existing tactile symbol set into raised-height shapes constitutes a first step that offers a straightforward translation of existing symbols and may also improve the usability of tactile map graphics (as measured by speed in reading the individual symbols).

Cartographic convention and map symbol standardization are commonplace in maps used by people who are sighted, and tactile map users would benefit from similar consideration (Lobben, 2015). As two examples, consider the United States Geological Survey steadfast use of standardized symbols for topographic maps as well as unofficial cartographic conventions (for example, water is blue and land is tan) routinely employed by mapmakers, both professional and novice. The results of the consistent use of like symbols are that the map users become accustomed to the symbol meaning and then spend their time understanding the meaning in the map, rather than learning the symbols (Lobben, 2015). This research has demonstrated that the three types of production technology do not substantially alter the discriminability of the symbols, thus supporting the consistent use of commonplace tactile map symbology.

With the increasing diversity of tactile symbol production methods, evaluating the relative discriminability of graphics produced across the various methods is a valuable endeavor. But our results reveal much more significant implications for tactile map design and use, and they can even be extended to other types of tactile graphics. Our findings do not indicate generalized superiority of any particular printing method, but they do provide evidence to support the feasibility of symbol design that is portable across more than one production method. The fact that the same tactile symbols could be usable on multiple production technologies means that someone could use a single map design and fabricate that map across different technologies to meet the needs or preferences of a diverse population of map readers.

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