Display of Virtual Braille Dots by Lateral Skin Deformation: Feasibility Study

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When a progressive wave of localized deformations occurs tangentially on the fingerpad skin, one typically experiences the illusion of a small object sliding on it. This effect was investigated because of its potential application to the display of Braille. A device was constructed that could produce such deformation patterns along a line. Blind subjects' ability to read truncated Braille characters ('○○', '○●', '●○', and '●●') using the device was experimentally tested and compared to their performance with a conventional Braille medium. While subjects could identify two-character strings with a high rate of success, several factors need to be addressed before a display based on this principle can become practical.

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General Terms: Design, Experimentation, Human factors

Additional Key Words and Phrases: Braille display, tactile perception, lateral skin deformation

1. INTRODUCTION

1.1 Braille Displays

Louis Braille's reading and writing system has given the blind access to the written word since the early 19$^{\text{th}}$ century. Braille characters replace the sighted's written letters with tactile equivalents. In the Braille alphabet, each character consists of an array of two columns and three rows of raised, or absent dots. Traditionally embossed on paper, Braille has more recently also been provided by refreshable Braille displays that generally add a fourth row of dots. Refreshable Braille displays were initially the only type of computer interface available for the blind. Despite

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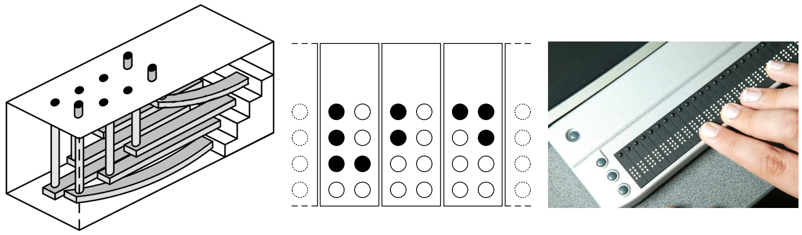


(a) (b) (c)

Fig. 1. Conventional Braille display: (a) cell actuation mechanism, (b) array of cells, and (c) picture of a commercially available Braille display (used with permission from Pulse Data International Ltd).

the growing popularity of more affordable speech synthesis hardware and software, refreshable Braille remains a primary or secondary access medium for many blind computer users.

Commercially available refreshable Braille displays have changed little in the past 25 years. Today's displays do not differ substantially from what is described by Tretiakoff [1977]. Typical systems use cantilevered bimorph piezo-actuators (reeds) supporting vertical pins at their free end. Upon activation, a reed bends, lifting the pin upward. Braille characters are displayed by assembling six or eight of these mechanisms inside a package called a cell (see Figure 1(a)). A basic system includes 40 or 80 cells to display a line of text (Figure 1(b)), plus switches to navigate in a page (Figure 1(c))[Stöger and Miesenberger 1994].

While the elements of these cells are simple and inexpensive, the cost is driven by the necessity to replicate the cell 40 or 80 times, or more if one contemplates the display of a full page. Typical Braille displays cost much more than a personal computer.

1.2 Alternative Technologies

In recent years many alternate designs have been proposed, all sharing the principle of raising individual pins, or dome shapes, out of a surface [Blazie 1998; Roberts et al. 2000; Yobas et al. 2003]. In 2004 alone, no less than six U.S. patents related to Braille cells have been granted, and many others are pending [e.g., Petersen 2004; Yang 2004; Biegelsen et al. 2004]. While most of the research focuses on reducing the cost of actuation, very little work is concerned with new approaches to the display of Braille.

Of note is a system proposed by Tang and Beebe [1998] who sandwiched discrete electrodes in a dielectric. The application of high voltage to these electrodes causes the skin to adhere locally to a glassy surface, thereby creating small tactile objects. Patterns resembling Braille characters could presumably be displayed with this method, however it appears to suffer from sensitivity to environmental factors such as humidity or skin condition.

Several investigators proposed the idea of a single display moving with the scanning finger rather than the finger scanning over an array of cells. Fricke [1997] mounted a single Braille cell on a rail and activated its pins with waveforms resembling "pink noise" in an attempt to imitate the effect of friction of the skin with a pin. Ramstein [1996] designed an experiment with a Braille cell used in conjunction with a planar "Pantograph" haptic device in an attempt to dissociate character localization from character recognition. The haptic device was programmed to indicate the location of the characters in a page, while the cell was used to read individual characters. Comparative tests were performed in different conditions with one or two hands. Again, the goal was to create an "array of Braille characters" with a single cell and reasonable reading performance could be achieved.

1.3 Overview

This paper reports on a feasibility study conducted to evaluate the potential of a new approach to the refreshable display of Braille. When the skin of the fingertip is locally deformed in the manner of a progressive wave, one typically experiences the illusion of objects sliding on the skin, even if the deformation contains no normal deflection [Hayward and Cruz-Hernandez 2000]. An electromechanical transducer was designed to create such skin deformation patterns with a view to investigate the feasibility of displaying Braille dots. The novelty of this approach lies in that it creates a progressive wave of lateral skin deformation, instead of a wave of normal indentation [e.g., Van Doren et al. 1987] or localized vibration [e.g., Bliss et al. 1970]. Our approach also relies on scanning motion, which is often mentioned as necessary to "refresh" the skin receptors and combat adaptation [Fricke 1997].

The transducer that we constructed was similar in principle to the 'STRESS' display [Pasquero and Hayward 2003], but had only one line of actuated contactors. This configuration allowed us to significantly increase the forces and displacements produced by the contactors. The Braille dots created by this device were "virtual" in that we attempted to recreate only the essential aspects of the skin deformation occurring when brushing against raised dots without actual physical dots.

The resulting system and the particular strain pattern — collectively termed "VBD" for Virtual Braille Display — were empirically designed with the assistance of the fourth author, a blind accessibility specialist, who also participated in the study in the capacity of "reference subject".

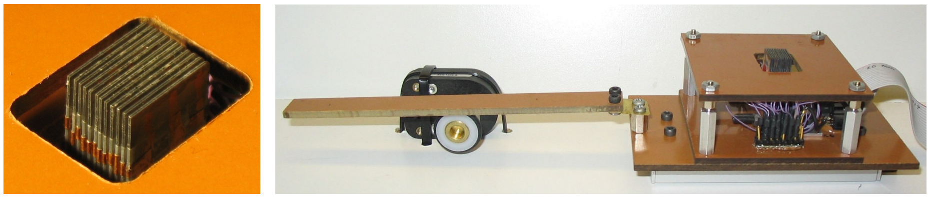
An experiment was conducted to tune the pattern's parameters to create a sensation as similar as possible to that experienced when brushing against physical Braille dots. The legibility of strings of truncated Braille characters — those comprising a single row of dots — was evaluated with five Braille readers on the VBD, and on a conventional Braille medium (embossed vinyl). The subjects' success rate and reading patterns were recorded and analyzed.

The study shows that reading with the VBD is possible with a high legibility rate given some personalization of the strain pattern. Reading is, however, more demanding and error-prone than on conventional media. More importantly, the study helped identify the strengths and weaknesses of the current prototype, and indicates how the device could be improved to yield a workable system.

2. VIRTUAL BRAILLE DISPLAY

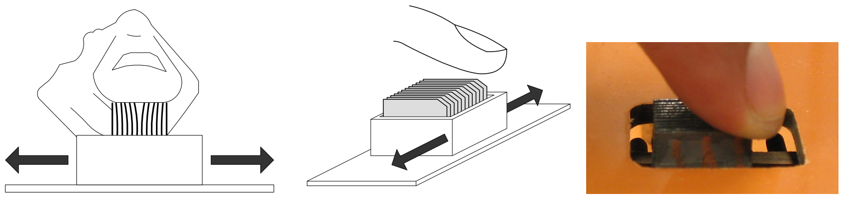
2.1 Device

The VBD device consisted of a tactile display mounted on a laterally-moving frictionless slider (see Figure 2) and interfacing control electronics.



(a) (b)

Fig. 2. VBD device: (a) STRESS-type tactile display, and (b) display mounted on a slider with rotary encoder.



(a) (b) (c)

Fig. 3. Interaction with the VBD: (a) strain applied during exploration, (b) illustration and (c) picture of finger contact with the VBD.

Reading virtual Braille was done by applying the tip of the index finger against the tactile display and sliding it laterally, as shown in Figure 3. When activated, the tactile display caused lateral deformation to the fingertip skin, that could be varied in response to slider movement. The finger remained in contact with the display and dragged it along the reading surface. Although this principle could allow reading with multiple fingers, the width of the display limited the reader to the use of a single finger.

2.1.1 *Tactile Display.* The tactile display was made of a stack of twelve 0.38-mm-thick piezoelectric bender plates[1], sandwiched at their base between neoprene spacers and clamped between two rigid end-plates using four locating pins and four screws (see Figures 4(a) and 4(b)). The spacers were cut in a 12-mm-high T-shape so that they rested on the locating pins and allowed room for electrical connections (see Figure 4(b)). Once tightly secured, the spatial period ϵ, or contactor pitch, was approximately 0.7 mm. This assembly method was selected for the convenience of allowing the design parameters such as thickness, length, shape and material of the actuators and spacers to be changed. In the present study, however, only one configuration was used.

The actuators were driven by a bipolar voltage applied between their central electrode and their two electrically-connected external electrodes. Because of the small space between adjacent plates, the electrodes could not be connected using the methods recommended by the motor supplier. Therefore, the actuators were prepared as shown in Figure 4(c). The external electrodes were joined with adhe-

[1] Y-poled, 31.8 mm x 12.7 mm, High Performance Bending Motors from Piezo Systems Inc., part number T215-H4CL-303Y.

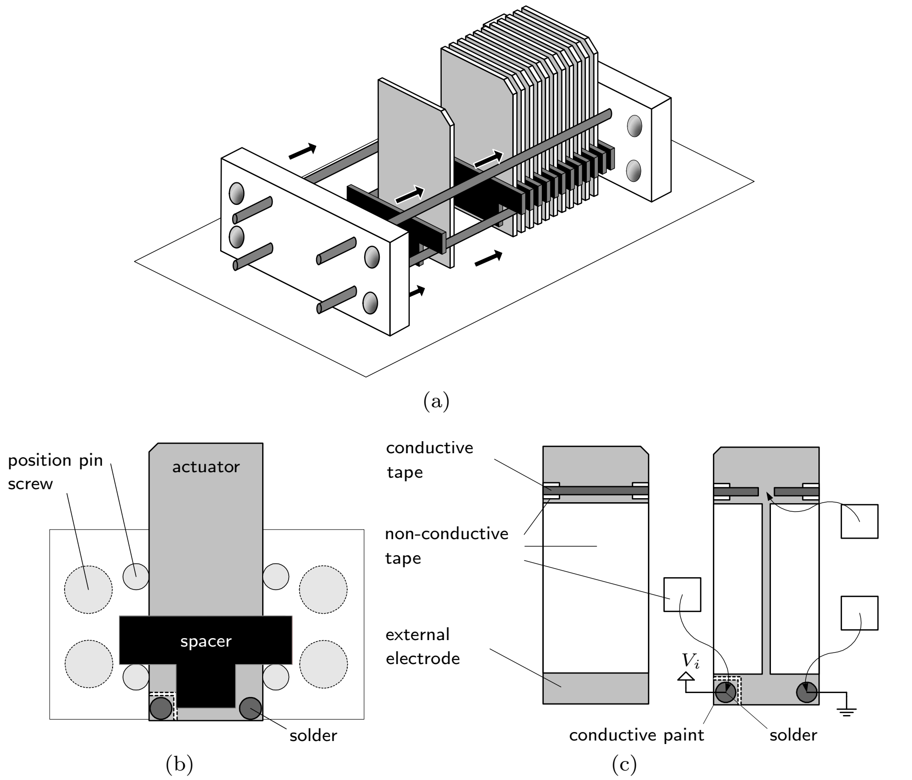


Fig. 4. Assembly of the VBD's tactile display: (a) perspective and (b) frontal views of stacked assembly, and (c) actuator fabrication process.

sive electrically conductive tape[2] running over non-conductive tape on the sides to prevent shorting with the central electrode. One corner of an external electrode was soldered to a ground wire. The other corner was turned into a small electrode pad (isolated from the rest by grinding off the conductive layer) and connected to the central electrode with conductive paint. A wire used for the control voltage was then soldered to this pad. To prevent contact with the adjacent actuator, the solders were kept significantly thinner than the spacers (0.5 mm) and were protected with non-conductive tape. Traces of conductive paint were applied along the length of the electrodes to improve their reliability (not shown). The actuators were then isolated from the metallic locating pins using non-conductive tape. As illustrated in Figure 3(b), the top corners on one side of the blades were beveled to create a narrow linear array of skin contactors (around 0.2 mm^2 in area each). Finally, the tips of the actuators were coated with varnish to isolate them from the skin.

The display could be used by applying the finger either on the large horizontal contact surface or against the surface formed of the beveled corners of the contactors. The latter surface, as shown in Figure 3, provided a narrower contact area

[2]3M Corporation, EMI Copper Foil Shielding Tape 1181.

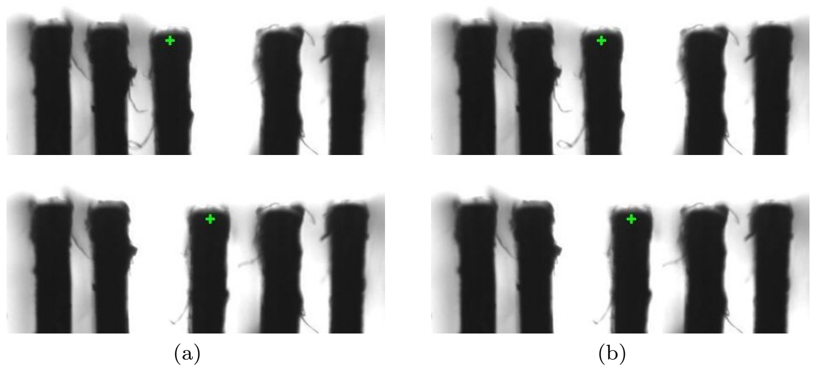


Fig. 5. Visual estimation of unloaded actuator deflection for (a) full range and (b) restricted range. Adjacent actuators were held deflected away from the actuator under study.

more appropriate for the display of dots and was the only one used in this study.

The deflection of the actuator tips was estimated with the help of a camera. Two sample measurements are shown in Figure 5. However, when not loaded by the finger, the deflection range was estimated to be 0.4 mm. As explained in the next section, the motion was limited in practice to a restricted range of approximately 0.3 mm. The deflection when loaded with the fingerpad could not be quantified but appears to be significantly lower than when unloaded.

2.1.2 *Control System.* The position of the linear slider on which the tactile display was mounted was measured by an optical encoder with a nominal resolution of 17 μm. Interfacing electronics were constructed to permit the refresh of the actuators at 500 Hz according to patterns programmed on a personal computer. This enabled us to program the deflection of each actuator with arbitrary functions of space (see Section 2.2).

The interfacing electronics, adapted from a previous project, made use of a Field-Programmable Gate Array (FPGA) development board[3] with a Universal Serial Bus (USB) 1.1 interface. It was programmed to convert control frames coming from the computer, or "tactile images", into twelve bender voltages by means of 156-kHz pulse-width modulation (PWM). The same, however, could be accomplished by adopting a variety of other approaches, including the use of micro-controllers or dedicated logic, interfaced to the computer via parallel I/O or high-speed serial I/O.

The computer generated a set of 8-bit actuator control values based on the encoder readout every 2 ms on average. These tactile images were sent to the FPGA by packets of 5 through the USB channel where a FIFO buffer regulated the flow of tactile images to ensure a constant output rate. The logic-level signals were then amplified to a $\pm$40 V range and low-passed by the circuit shown in Figure 6. In order to avoid non-linearities in the signal amplification at extreme PWM duty cycles, the control values were restricted to the range 10 (0x0A) to 250 (0xFA).

[3]Constellation-10KE^{TM} from Nova Engineering Inc. operating an Altera FLEX 10KE^{TM} chip.

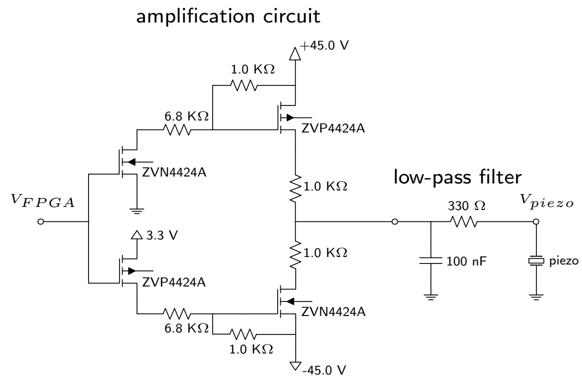


Fig. 6. Electronic circuits: amplification circuit (left) and low-pass filter (right).

2.2 Skin Deformation Patterns

Trial and error led us to select a pattern solely on the basis of the resemblance of the sensation it provided compared to that of actual Braille, as felt by the reference subject. We are however unable to offer a principled explanation as to why this particular pattern creates sensations that resemble Braille dots more than others. The determination of the actual parameters is described in Section 3.

The deflection δ_i of each actuator i was a function of the slider position x_s obtained from the encoder. The actuators followed the same deflection function $\delta(x)$, where x was the actuator position along the reading surface, as illustrated in Figure 7. The physical configuration of actuators introduced a spatial phase difference of ϵ. The first actuator was given a position corresponding to the slider position.

$$\delta_i(x_s) = \delta(x_s + i\epsilon), i = 0, \ldots, 11 \tag{1}$$

What we selected was a pattern[4] such that the deflection of each actuator swept the first half-cycle of a sinusoid, starting from the left position, as it scanned a virtual dot, as shown in Figure 7. A small-amplitude, high-frequency sinusoid could also be added to the nominal waveform to enhance contrast. These representations were termed nominal and textured.

These patterns were found to better approximate the sensation of scanning over Braille dots than others that were experimented with, such as triangular or square waves, full-cycle sinusoids, or textured blanks.

The spatial phase difference between actuators resulted in the representation of dots as a traveling wave. Figure 8 and 9 illustrate the movement of actuators as a virtual dot traverses the length of the display. Moving the slider in one direction across a region containing a dot resulted in a wave of actuator deflections traveling at the same speed in the opposite direction on the tactile display, causing the illusion that the reading finger was scanning over stationary Braille dots. Since the deflection function was independent of direction, it caused actuator deflections

[4]Movies of the VBD in action can be found online on the Haptic Laboratory's VBD web page, http://www.cim.mcgill.ca/∼haptic/vbd.html.

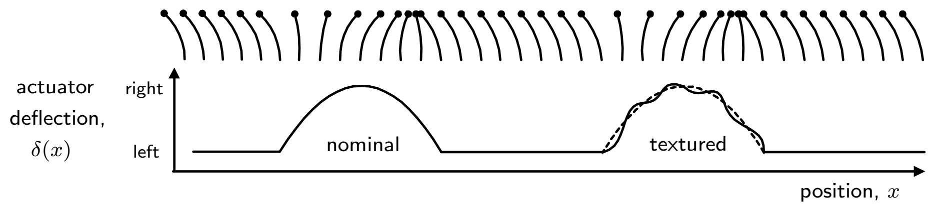


Fig. 7. Actuator deflection as a function of position. The curve shows the actuator deflection function with respect to actuator position for a nominal dot (left) and a textured dot (right). The deflection of actuators is illustrated at discrete points along the virtual reading surface. Texture was always applied either to all dots or none.

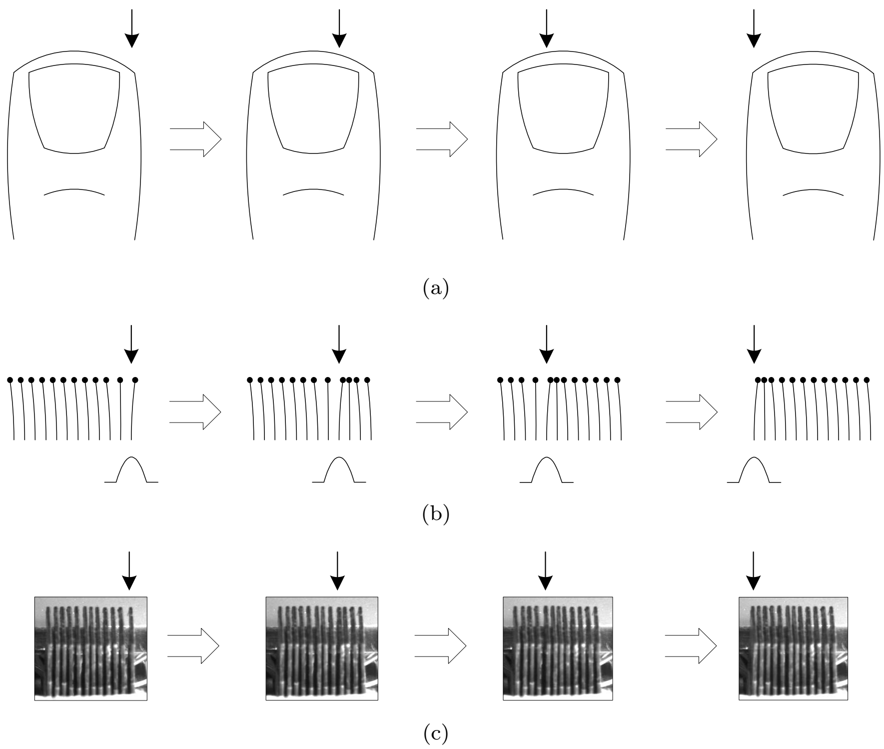


Fig. 8. Traveling wave representation of a Braille dot at four points in time: (a) finger-dot interaction, (b) depiction of the actuator deflection and corresponding deflection function, and (c) picture of the actuator deflection. The dot center is indicated by arrows.

in the direction of finger movement when reading from left to right, but opposing movement when reading from right to left. The resulting sensations, however, seemed to be similar.

This pattern had two distinct effects on the skin deformation. The first was to cause a net displacement of a skin region around each contactor. The second was a pattern of compression and expansion of each small region of skin located between two contactors. Patterns of expansion and compression can actually be

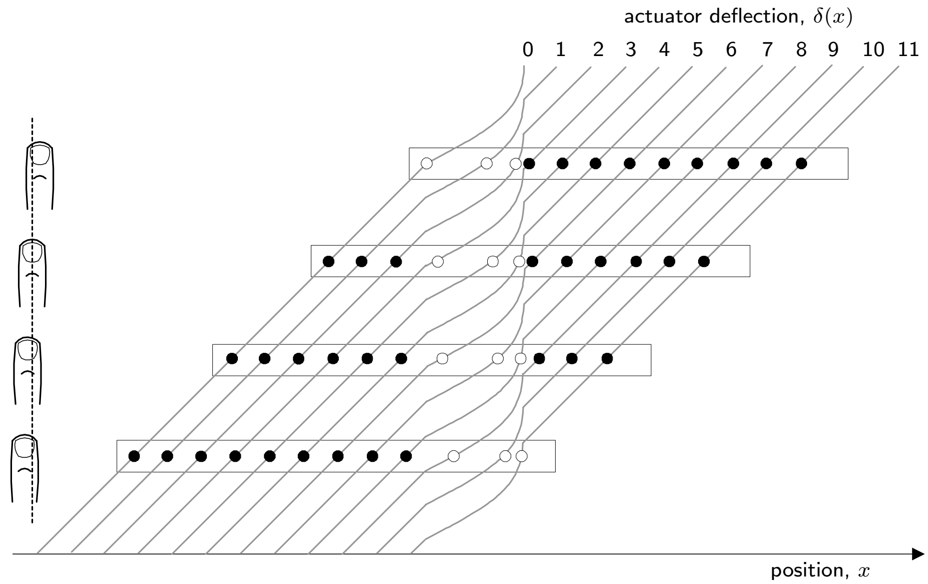


Fig. 9. Traveling wave corresponding to a single dot as the slider passes over it. Top-view of actuator deflections and corresponding finger-dot interactions are shown at four locations. Each of the twelve curves indicates the deflection pattern followed by an actuator as the slider moves from left to right.

observed when a finger scans over small shapes [Levesque and Hayward 2003]. The strain variations Δ_i caused by a pair of actuators is represented in Figure 10. The width ω of a virtual dot is shown relative to the spatial period ϵ. If $\omega < \epsilon$, then there was no overlap between the deflections of adjacent actuators. If $\omega > \epsilon$, then an overlap existed and there was a continuous transition from expansion to compression. If $\omega > 2\epsilon$ expansion and compression never reached their maximum values. It is not known whether local displacement or local variations in strain, or both forms of stimulation, caused the illusion of the dot moving under the finger.

The tactile display could only display a single row of Braille dots. From the Braille character set, the three characters that have dots in row 1 only, or a total absence of dots, could be displayed: '`a`', '`c`', and ' ', see Figure 11. The fourth possible combination, unused in Braille, was called 'dot #4'.

3. PARAMETER TUNING

Braille is normally produced according to strict geometrical specifications, but the manner in which these specifications translated into the VBD's parameters was not straightforward. For this reason, a first experiment was carried out to find the parameters that produced virtual Braille of appropriate dimensions. For the purposes of the feasibility study, only the width and the separation of dots were adjusted. The amplitude of the virtual dot sinusoid was set to the maximum that the system could provide. The amplitude and the wavelength of the texture were set empirically to values equal to $1/8^{\text{th}}$ those of the virtual dot sinusoid.

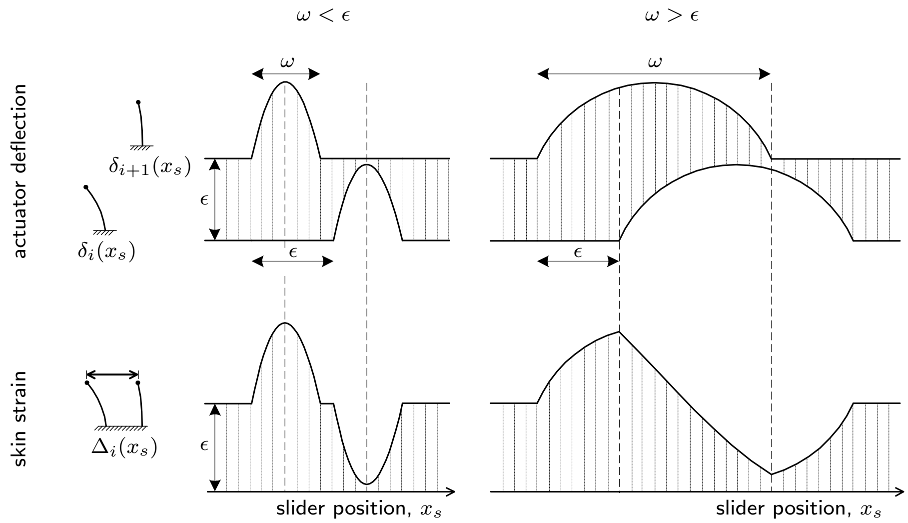


Fig. 10. Displacement of two consecutive actuators and corresponding skin strain patterns as functions of slider position, for width ω of virtual Braille dots smaller or greater than spatial period ϵ.

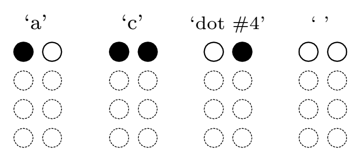


Fig. 11. Braille characters displayed by the VBD.

3.1 Method

With the help of the reference subject, the width of a virtual dot was first adjusted to match the sensation caused by a single physical Braille dot. Then, the distance between dots within a virtual character was adjusted. The inter-character spacing value was inferred from the value found for intra-character dot spacing.

The tuning experiment was conducted following a 2-alternative forced choice protocol, using the two-hand method in order to speed up the process and facilitate comparisons. The subject was asked to touch a reference stimulus produced by a conventional refreshable Braille display with her left index. She then immediately explored two stimuli on the VBD with her right index and selected the one that best matched the reference stimulus. Dots were always displayed with texture. After a short experimentation used to determine an appropriate range, the virtual dot width was varied among six equally spaced values from 0.5 mm to 3.0 mm. The intra-character dot spacing of the character 'c' (●●) was similarly varied from 1.0 mm to 2.5 mm. The dot width found in the first step was used in the second.

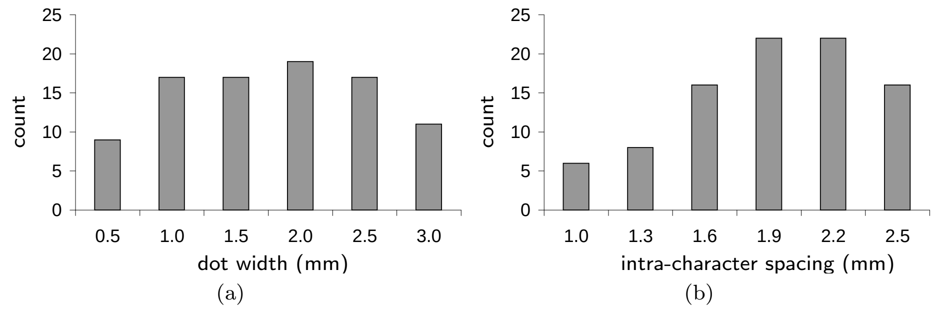


Fig. 12. Results of tuning steps: frequency distribution of (a) dot widths, and (b) intra-character dot spacings.

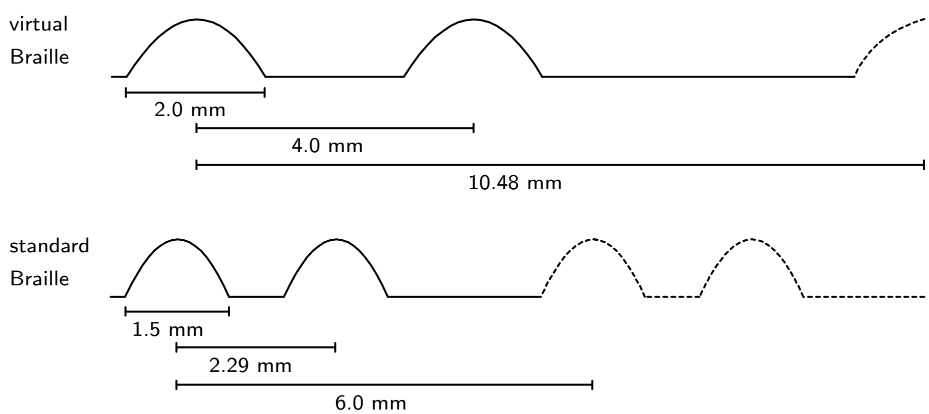


Fig. 13. Dimensions of virtual and standard English Braille.

3.2 Procedure

Both tuning experiments proceeded in the same manner. The reference subject moved the VBD toward the left, waited for an audible signal, explored the two different Braille dots or pairs of Braille dots, and verbally reported the stimulus that best matched the reference stimulus. Answers were logged by the experimenter. Each of the 30 possible ordered pairs of non-identical stimulus were presented to the subject 3 times, for a total of 90 trials. The different pairs of stimuli were presented in randomized order.

3.3 Results

Figure 12 shows the results of the two tuning experiments. The preferred virtual dot width was found to be 2.0 mm, the most frequently selected parameter during the first step. The virtual intra-character separation was also found to be 2.0 mm, between the two most frequently selected values during the second step.

These parameters corresponded to a intra-character dot spacing of 4 mm, compared to 2.29 mm for standard English Braille. The standard horizontal character-to-character distance of 6 mm was scaled accordingly to a virtual distance of

10.48 mm as illustrated by Figure 13.

3.4 Discussion

The preferred virtual dot width of 2.0 mm turned out to be greater than the spatial period ϵ of 0.7 mm, leading to a strain pattern similar to that shown on the right-hand side of Figure 10. Moreover, since the dot width was more than twice the spatial period, the peak strain was lower than the maximum achievable. Assuming that loaded actuator deflections are half those measured without load (Section 2.1.1), this pattern resulted in strains in the order of $\pm 20\%$.

Although the tuning experiments allowed us to find reasonable parameters, the tuning should ideally have been done either with a representative population of Braille readers or individually for each subject. Moreover, the use of texture on the dot may have contributed to an overestimation of the virtual dimensions. The two-hand comparison method may also have introduced errors, but constantly switching from a conventional Braille display to the VBD was impractical. Finally, the inter-character distance should have been tuned too. These coarse results were found to be sufficient given the scope and the aim of this study.

4. VIRTUAL BRAILLE LEGIBILITY

The next step needed to evaluate the feasibility of the tangential skin deformation approach for reading Braille was to determine whether blind subjects could read the subset of characters that could be displayed by the VBD. Here, we hoped to also begin identifying the strengths and weaknesses of the concept.

4.1 Method

4.1.1 *Participants.* Two females and three males, experienced Braille readers, volunteered for the study. All subjects were blind from birth. Their ages varied between 22 and 55. The subjects' primary reading finger was the right-hand index. All subjects except the reference subject had never experienced the VBD or heard about our efforts.

4.1.2 *Task.* The reading task was designed to evaluate the legibility of sequences of first-row characters displayed on the VBD. Subjects were asked to read individual 4-character strings using their dominant reading finger. The first and last characters of each string was always 'c' (●●). The two middle characters could be any of the 16 combinations of the characters 'a' (●○), 'c' (●●), 'dot #4' (○●), and ' ' (○○): "●● ●○ ○● ●●", or "●● ○○ ●● ●●" for example. The character 'c' (●●) was chosen as the string delimiter to avoid confusion.

4.1.3 *Procedure.* The subjects were given written Braille instructions and had supervised practice trials until they felt comfortable with the task. They were presented with strings to read in block trials. They placed the slider to the left, waited for an audible signal, read the string, and reported verbally the two middle characters. There was no time limit but they were strongly encouraged to answer quickly. In case of doubt, they were asked to give their best guess. Subjects could stop at any time if they no longer felt comfortable (e.g. loss of tactile sensation, fatigue). They were given the choice of doing the trials with texture, without texture, or in both conditions. Some subjects were tested in both conditions while

Table I. Summary of results from legibility experiments. Results from the first experiment (VBD, Section 4) are presented in columns 'nominal' and 'textured'. Results from the second experiment (conventional Braille, Section 5) are presented in the column 'control'. Trial durations are shown with their standard deviation.

	number of trials			legibility (%)			average trial duration (s)		
subject	nominal	textured	control	nominal	textured	control	nominal	textured	control
CN	80	160	80	97.5	88.1	100.0	4.8 ± 2.7	4.6 ± 2.2	3.4 ± 0.7
RB	0	80	80		95.0	100.0		10.8 ± 7.0	7.4 ± 1.4
ML	80	0	80	98.8		100.0	4.6 ± 3.2		2.3 ± 0.6
AB	40	80	80	45.0	86.3	100.0	18.6 ± 12.2	10.5 ± 6.3	2.4 ± 0.7
MS	80	80	80	71.3	66.3	100.0	8.0 ± 2.7	9.1 ± 3.0	5.8 ± 1.7
average	56	80	80	78.1	83.9	100.0	9.0	8.8	4.3

others decided to experiment with only one type. A trial block comprised 80 strings with each of the 16 possible combinations appearing 5 times in randomized order.

4.1.4 *Data Collection.* The experimenter logged the subject's answer for each trial. The slider trajectory was automatically recorded by the system. It was analyzed off-line to compute the duration of trials. A trial was considered to begin when the rightmost actuator first arrived at the leftmost virtual dot, and to end when it crossed this dot again for the last time in the opposite direction. In other words, the leading and trailing parts of the slider trajectory for which no actuator was affected by the Braille string were discarded.

4.2 Results and Discussion

The main results of this legibility experiment as well as those of a control experiment with conventional Braille (Section 5) are summarized in Table I.

4.2.1 *Legibility.* Legibility was defined by the proportion of correct identifications of 2-character strings. Results suggest that the effect of adding texture was idiosyncratic (see Table I). A dramatic improvement in performance was seen in one subject while a loss was observed in two other subjects. Retaining the best conditions for each subject, the legibility rates were between 71.3% and 98.8%.

Legibility rates were also plotted over time to assess the effect of fatigue. Without texture, no significant change with time could be noticed. However, for some subjects, performance tended to decrease noticeably after about 50 trials when texture was used (see Figure 14 for one of the worst-case examples).

4.2.2 *Character Pairs Legibility.* Regardless of the string, individual characters having one dot, '•○' or '○•', were harder to read than characters having no or two dots, '••' or '○○' (see Table II). The legibility also varied with the 2-character string (see Table III). Except for special cases such as the pair "○○ ○○" which was read perfectly, no insight could be gained regarding the cause of variations in reading difficulty. It is not clear, for example, why the string "•○ ○•" has much lower legibility than "○• •○".

Table IV shows the confusion matrix for individual characters. No clear pattern emerged, except perhaps that '••' and '○○' were rarely mistaken for one another. Similarly, Table V shows the confusion matrix for pairs of characters. Again

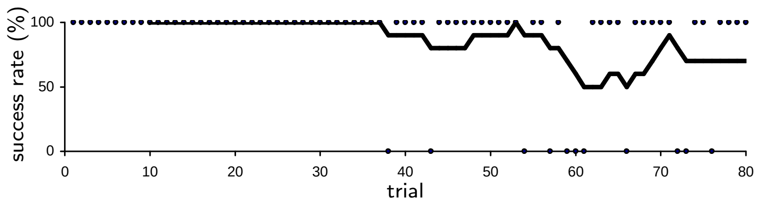


Fig. 14. Worst-case example of gradual decrease in performance over time (subject AB, with texture). Dots indicate individual trial results. The curve is a moving average over the past 10 trials.

Table II. Average character legibility (%). The average was computed across all subjects using individual subject means to compensate for the unequal number of trials under the different conditions.

●○	○●	●●	○○
83.3	88.9	92.2	98.1

Table III. Average 2-character string legibility (%). The average was computed across all subjects using individual subject means to compensate for the unequal number of trials under the different conditions.

●○ ○●	●○ ○○	○● ●●	●○ ●●	●● ●○	○● ○●	●● ○●	●○ ●○
66.0	74.0	76.0	77.5	78.0	81.0	81.7	84.5
○○ ●○	○● ●○	●● ○○	○● ○○	○○ ●●	○○ ○●	●● ●●	○○ ○○
85.0	90.0	92.0	92.0	94.0	95.0	98.0	100.0

there was no clear pattern. However, it does seem that the most frequent errors ($n = 3, 4, 5$) generally corresponded to the insertion of a single extra dot or to the incorrect localization of a dot within a character.

4.2.3 *Reading Patterns.* Table I shows the average duration of trials. The reading speed was far from the expected Braille reading speed of 65 to 185 words per minute [Legge et al. 1999], but the conditions are so different that a direct comparison is not possible.

Correlations between reading speed and string legibility were also investigated but none could be found, even though there could be important duration variations between trials of a same subject. If it is assumed that the time taken to read a pair of characters is an indication of the confidence the subject has in her or his answer, the characters that the subjects thought were hard to read were not necessarily the ones they had difficulty reading.

The recorded trajectory of the slider was used to investigate the reading pattern used by the subjects. Three classes of patterns were identified (see Figure 15). Subjects often used one or two straight passes over the dots. On other occasions, they would explore the virtual Braille string with short back-and-forth motions. In all cases it appeared that subjects read from left to right since they moved slower in that direction.

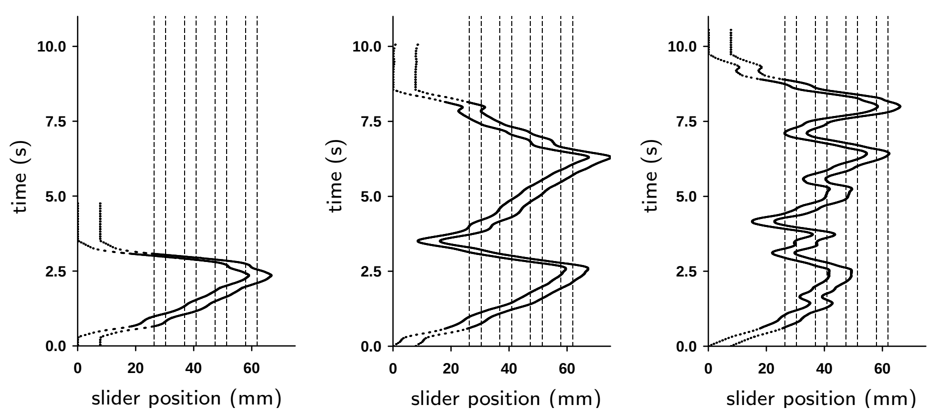
4.2.4 *Verbal Reports.* All subjects reported that reading requires concentration, mostly because the dots were subtle (possibly due to the limited range of motion of

Table IV. Confusion matrix for individual characters. Answers from all trials were pooled together.

		answered			
		●○	●●	○○	○●
presented	●○	284	17	23	20
	●●	11	315	0	13
	○○	7	1	327	0
	○●	22	9	13	298

Table V. Confusion matrix for pairs of characters. Answers from all trials were pooled together.

		answered															
		●○ ●○	●○ ●●	●○ ○○	●○ ○●	●● ●○	●● ●●	●● ○○	●● ○●	○○ ●○	○○ ●●	○○ ○○	○○ ○●	○● ●○	○● ●●	○● ○○	○● ○●
presented	●○ ●○	37	·	·	·	·	1	1	·	2	·	·	·	·	·	3	·
	●○ ●●	1	34	·	3	·	1	·	1	·	2	·	1	·	1	·	·
	●○ ○○	·	·	29	·	1	·	5	·	·	·	1	·	·	·	5	·
	●○ ○●	2	1	2	25	·	·	·	2	2	1	·	4	1	·	1	1
	●● ●○	·	·	1	·	35	2	3	·	·	·	·	·	2	·	·	·
	●● ●●	·	·	·	·	1	39	·	·	·	·	·	·	·	·	·	·
	●● ○○	·	·	2	·	2	·	37	·	·	·	·	·	·	·	·	·
	●● ○●	1	·	·	·	4	1	2	33	·	·	·	·	1	1	·	·
	○○ ●○	·	·	·	1	·	·	·	·	37	1	·	5	·	·	·	·
	○○ ●●	·	·	·	·	·	·	·	·	·	41	·	2	·	·	·	·
	○○ ○○	·	·	·	·	·	·	·	·	·	·	42	·	·	·	·	·
	○○ ○●	·	·	·	1	·	·	·	1	2	·	·	38	·	·	·	·
	○● ●○	·	·	·	1	·	·	2	·	·	·	·	·	37	1	·	1
	○● ●●	·	1	·	·	·	·	·	·	1	2	·	·	4	35	·	2
	○● ○○	1	·	1	·	·	·	·	·	1	·	·	·	·	·	37	·
	○● ○●	1	·	·	·	·	1	·	·	1	·	·	2	2	1	1	35



(a) (b) (c)

Fig. 15. Typical reading patterns: (a) one pass, (b) two passes, and (c) character re-scan. The band between the two curves indicates the span of the display. Dotted sections were not taken into account when computing trial durations. Vertical dashed lines indicate the location of the eight Braille dots.

actuators) and differed in perceived shape from physical Braille dots. Adding texture seemed to facilitate the perception of the dots for some subjects, while others found the sensation unpleasant. Some subjects also complained of loss of tactile sensation over time in both nominal and textured conditions. The occasionally-observed decrease in performance over time seems to confirm that a loss of tactile sensation was occuring with the textured representation and was likely due to the adaptation of tactile receptors.

Subjects also reported difficulties with locating the stationary Braille dots on the virtual Braille line. Most subjects mentioned that the display of characters with more than one row of points and having meaning would help reading.

Finally, contrary to our expectations, subjects reported that scanning constrained by a slider was beneficial because it guided their hand movement. They found it to be an advantage over paper Braille.

5. CONTROL EXPERIMENT

The reading task performed in the legibility experiment was not representative of typical Braille reading. It was hypothesized that the reading difficulties experienced by some subjects were inherent to reading a single row of Braille dots. The dots found in the bottom rows of most Braille characters could facilitate the localization of the dots within the cell. Without this extra information, locating a dot completely depends on evaluating the length of the spaces between dots.

A follow-up experiment was designed to test the subjects' ability to read single-row Braille characters on a conventional Braille medium: Braille embossed on vinyl tape.

5.1 Method

5.1.1 *Participants.* The experiment was conducted with the same five participants, one year after the original experiment.

5.1.2 *Materials and Tasks.* The reading task was identical to that used in the original experiment. Subjects were asked to read sequences of four single-row Braille characters starting and ending with '••'. The Braille strings were embossed on 1/2" adhesive vinyl tape using a Braille labeler. The non-existent 'dot #4' character was produced by sanding down the extra dot on character '.' of the embossing wheel.

The resulting Braille has smaller, sharper dots than paper Braille but is still easily readable and commonly used. Vinyl was preferred over paper because it afforded better control on the uniformity of the test plates.

Sixteen Braille labels (one per string) were produced. Each was affixed to a thin, right-angled metallic plate. The placement of the tape was carefully controlled to minimize differences between the plates and allow sufficient space for the finger. During trials, the plates were held down by a switchable magnetic clamp that allowed us to change the strings quickly, see Figure 16(a). A single flattened dot was printed on the extreme-left of the tape to serve as a starting point for reading.

5.1.3 *Procedure.* The subjects were read written instructions and had supervised practice trials until they felt comfortable with the task. They were presented with strings to read in block trials. They placed their finger to the left of the plate, waited for an audible signal, slid their finger over the flattened positioning dot, read

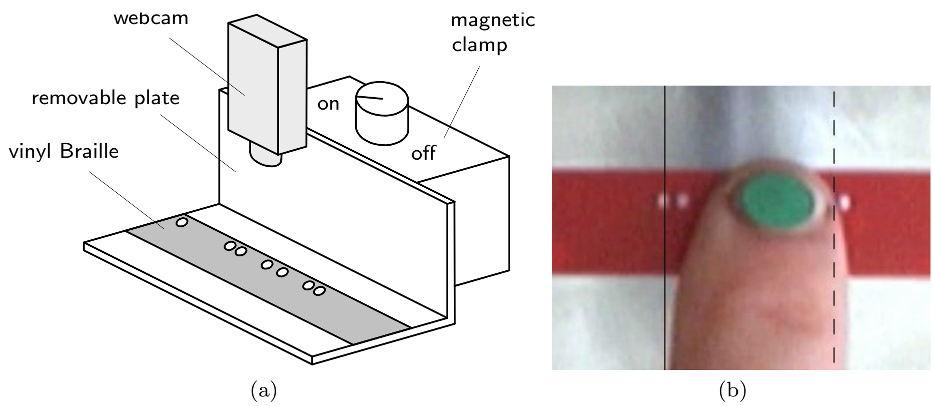


Fig. 16. Control experiment with conventional Braille: (a) apparatus, and (b) example of image processing. The location of the leftmost Braille dot is indicated by a solid line. The right edge of the finger is indicated by a dotted line. A green dot was affixed to the nail but not used for processing.

the string, reported verbally the two middle characters, slid their finger back over the tape, and removed it from the plate. They were instructed to read only with their right-hand index finger and to keep their other fingers against their palm. There was no time limit but they were strongly encouraged to answer quickly. In case of doubt, they were asked to give their best guess. The experimenter logged the result of each trial. A trial block comprised 80 strings with each of the 16 possible combinations appearing 5 times in randomized order.

5.1.4 *Data Collection.* A camera was positioned above the reading surface and was used to record color movies of the finger movements at a rate of 30 frames per second. The movies were compressed and stored for later analysis. A single, uncompressed image of the plate was also taken. The reading patterns and trial durations were analyzed from the movies captured during the experiment. Simple image processing operations were applied on the plate image to extract the position of the leftmost dot of the 4-character string. The absolute difference between the saturation levels of each frame with the background frame was then used to locate the fingertip in the image sequence. In order to approximate the definition of trial duration used in the original experiment, the trial was considered to begin as the rightmost part of the index crosses over the leftmost dot, and to end when it crosses it again in the reverse direction for the last time. The automated measurements were inspected visually and corrected for 75 of the 400 trials. The precision was estimated to be within 3 frames (± 0.1 s).

5.2 Results and Discussion

5.2.1 *Legibility.* All five subjects read the 80 strings presented to them with 100% accuracy. It is thus clear that the reading difficulty experienced by the subjects with the VBD cannot be explained solely by the inherent difficulty of the task.

5.2.2 *Reading Patterns.* Table I shows the timing measurements. The subjects read faster on vinyl Braille than on the VBD, more than twice as fast on average.

However, one of the slowest subjects on the VBD (AB) is also one of the fastest on vinyl Braille. The reading patterns were also inspected visually to assess their naturalness. Some subjects clearly slowed-down when sliding over dots and frequently returned to previous dots, or to the beginning of the string. This suggests that the reading strategies used by the subjects were different from those used in normal Braille reading [Millar 1997; Schiff and Foulke 1982; Bertelson et al. 1985].

5.2.3 *Verbal Reports.* Most of the subjects mentioned spontaneously that the reading task was easier on embossed plastic than it was on the VBD. Upon questioning, however, some acknowledged that the reading task was more difficult than typical Braille reading due to the lack of context (meaningless strings) and the absence of cues on the bottom rows. Subjects were also uncomfortable reading with a single finger, and particularly with keeping the other fingers in a fist.

6. CONCLUSION AND FUTURE WORK

This study showed that experienced Braille readers could read sequences of first-row Braille characters using the VBD with a legibility ranging from passable to excellent. This is encouraging considering that most subjects had little prior training with the device and that the character strings were meaningless.

Reading with the VBD was nevertheless difficult. The control experiment showed that subjects could read faster and with perfect accuracy when the strings were presented on embossed vinyl tape. This observation is confirmed by the subjects' verbal comments during both experiments.

Adding texture to the dots was found to increase performance for some subjects but was rejected by others. Prolonged use also seemed to cause tactile fatigue (numbness in the reading finger) as reported by subjects for both nominal and textured stimulus. This phenomenon was sometimes confirmed by an increase in the number of reading errors over time in the case of textured stimulus.

While this study was conducted with too few subjects to make it possible to draw final conclusions, it suggests nevertheless that reading Braille characters with devices based on the principle of the VBD could be possible. The study also helped identify the strengths and weaknesses of the current prototype and, more importantly, provides indications as to how it could be improved.

The strength of the dot sensation must be increased to realistically convey the illusion of a Braille dot. This issue involves the improvement of the actuators used and of their configuration. On-going work concerned with the micro-mechanical properties of the skin and the means to deform it at a very small scale is expected to yield an improvement in the performance of piezoelectric benders for this application [Wang et al. 2004]. Further experimentation with deflection functions could also lead to better approximations of the sensation of scanning over Braille dots. Designing deflection functions for maximum strain variations at skin mechanoreceptors may, for example, increase the strength of the dot sensation. Indeed static mechanical models of the skin designed by Phillips and Johnson [1981] and Van Doren [1989] suggest that deformation of receptors, as opposed to their displacement, is likely to determine sensation. The strain experienced by slowly adapting (SA) receptors may be particularly important to resolve the spatial details of scanned Braille [Phillips and Johnson 1985].

The cause of tactile fatigue must also be addressed. It is not clear what causes it and how it can be avoided. It is likely however that replacing the contact line by a more uniform contact surface could significantly delay the onset of tactile numbness.

Reading with the VBD requires a scanning movement. While this allowed the VBD to render adequately the dynamic sensation of sliding over dots, it prevented the user from stopping over a region as is sometimes done when reading physical Braille. Display without net movement could be possible if the magnitude of the strain produced by the device was made to depend on the force applied by the subject. This not only could make the sensation of sliding over a dot more realistic, but also allow the subject to stop and press against virtual dots.

The results of the tuning experiment and of the legibility experiment conspire to indicate that perhaps the greatest problem with the current display design is the difficulties experienced by subjects in evaluating the distance between dots. This is suggested by the distortions in perceived Braille dimensions introduced by the VBD when compared to standard English Braille. This is also consistent with observed reading errors and verbal reports of the legibility experiment.

Finally, the VBD should be extended to display complete Braille characters. Packing 4 rows of actuators capable of displaying forces and displacements similar to those of the VBD within the height of a Braille cell will be a significant technical challenge.

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