Sensing Directionality in Tangential Haptic Stimulation

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Abstract. Few studies have explored haptic sensing on a finger pad as a means of transferring complex directional information. Stimuli presentation using Braille or tactile vibrators use binary ("on/off") signals which require large areas to adequately represent data. Our research seems to support that tangential motion on a finger pad is a promising means of transmitting tactile information more compactly at equal or better rates than current methods. The index fingertips of 62 subjects were stimulated using random pattern of tangential motion in eight directions over two distances. An ANOVA found that distance was statistically significant, and direction was significant for 0.5 mm displacements, but not at 1.5 mm. Age also significantly affected perception of tangential motion. These results suggest tangential motion could transmit certain type of haptic information effectively; but its effectiveness may decrease with user age.

Keywords: tangential motion, directional haptic sense.

1 Introduction

From infancy we explore and actively manipulate our world through haptic's dynamic two way interactions. Yet despite the importance of touch, its use as a method of information transfer has been relatively untapped, with the exception of Braille, introduced in 1821 (1). More recently, more complex stimuli presentation through lateral forces, vibration, and finger positioning have been explored as means of haptic information transfer.

1.1 Normal Force Stimulus

Braille essentially uses normal forces to transmit information. Single tactile elements are raised dots; each providing 1 bit of information (touch or no touch), placed in 3 × 2 cell arrays, spaced 2.5 mm apart (from their centers); provide up to 6 bits (2^6 = 64 symbols) of information (Fig. 1). An earlier design, from which Braille evolved, used 6 × 2 arrays that were difficult to read because symbols were not felt all at once (1).

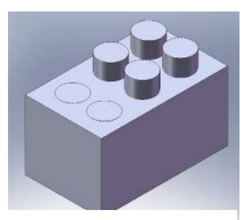

Fig. 1. Braille Element

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Recently, it was found that the perceptual "frame" through which humans distinguish tactile information is largely confined to the area of contact (2). This means tactile symbols are difficult to resolve when not completely felt. A visual analogy is to read the English letter "Q" in two parts (Fig. 2). We recognize the symbols "Ø," "O" or "Q" reading the upper part, but only distinguish "Q" after reading the lower part.

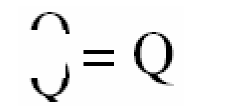

Fig. 2. Cell Analogy

Because of Braille's proven usability, many efforts have sought to recreate or augment it using small actuators located at the fingertip. But these elements are expensive, limited to small scale normal forces and require a great deal of spatial acuity; a fundamental limitation of Braille encoding.

1.2 Lateral Force Information

Lateral motion sensing has been used to implement Braille elements with limited usability (Fig. 3). Its effectiveness improves by increasing motion strength and contrast (3). Theoretically such elements emulate the information capability of traditional 1–bit Braille elements using motion/no motion to produce up to 64 symbols.

However lateral motion traverses two axes, allowing at least 2 bits of information: front–back and left–right. Furthermore angular thresholds for lateral motion have been found from 16º– 28º (4), (5). For 360º motions, a single lateral motion element can theoretically transmit:

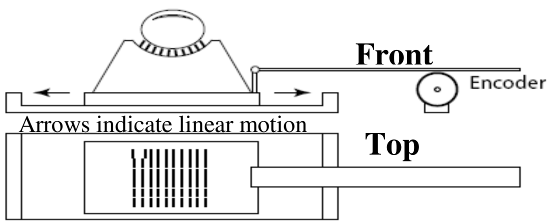

Fig. 3. Lateral tactile display
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$$\begin{aligned} 360^\circ/16^\circ &= \lfloor \log_2(22.5) \rfloor = 4\ \text{bits} = 16\ \text{symbols} \\ 360^\circ/28^\circ &\approx \lfloor \log_2(12.9) \rfloor = 3\ \text{bits} = 8\ \text{symbols} \end{aligned} \tag{1}$$

1.3 Sensing Vibration

Vibration elements usually generate 1 bit of information (vibration – no vibration). For this reason they are often strategically placed on the body to convey spatial information, e.g. (6), (7). More advanced elements like Vibratese (8) used three normal intensity levels and three vibration levels at different locations around the chest to create a simple haptic "alphabet." Recently such elements have been incorporated into cell phones with Immersion Corp's *Vibetonz* system which is capable of 5 distinct vibration channels – shape (steady – ramp), duration (constant – varied), speed (slow – fast), style (sharp strong – sharp), and magnitude (high – low) – that can be used individually or in combination (9).

1.4 Finger Position Information

Finger position has also been used to transmit haptic information. One early effort was the "reverse" typewriter (Fig. 4) that pushed user fingers in the *x*, *y*, and *z* axes (10). By replicating typing motions a finger received about 3 to 4 characters (1–2 bits) of information. Using 8 fingers, the entire contents of a 1960's QWERTY keyboard could be transmitted.

The Tactuator (Fig. 5) was a generalized form of the reverse typewriter that used movable rods to transmit force amplitude, frequency, and relative motion of varied durations to three fingers (11). In those studies, multiple dimensions provided greater sensational contrast than multiple levels within a dimension. This indicated how tactile signals are masked unless distinctly separated (11).

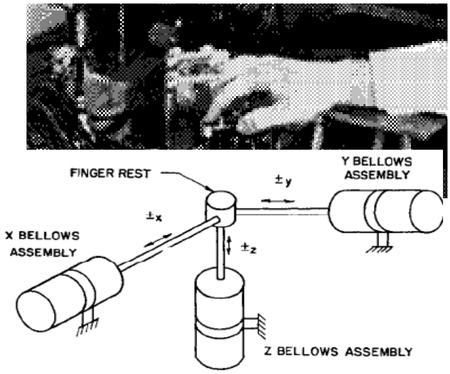

Fig. 4. Finger stimulator with detail © 1962 IEEE; reprinted with permission (10)

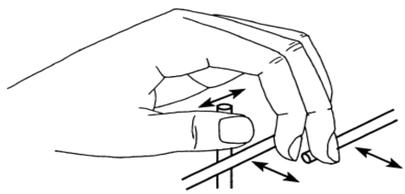

Fig. 5. Tactuator finger position and motions © MIT; reprinted by permission (11).

1.5 Factors of Accurate Tangential Information Transfer–Distance, Direction, and Age

Tangential motion can transmit complete signals to reduce confounding (2). It uses 2 dimensional axes to increase perceptual contrast (12), especially when paired with varied distance. Studies have suggested that lateral motion enhances tactile information transfer (13). Finally, prior studies have established force and angular thresholds for lateral motion (3), but have not examined its interaction with other factors.

We identified direction and distance as possible main effects influencing accurate signal perception of an applied directional stimulus. To our knowledge, tangential motion with distance interaction has not been studied. We therefore wanted to test the perceptual effects of varied distance on tangential motion, in order to examine displacement restrictions so as to understand how compactly we could make signal representations. When matching tangential forces to normal ones, direction was not found statistically significant (14). However, when judging angular Just Noticeable Differences (JNDs) versus different references, statistical differences were found (4), (5).

While we could not explicitly control age, we chose to examine this effect as a covariate factor. Tactile (15) and vibration thresholds (16), (17) increase significantly with age, indicating that there might be a substantial affect on tangential motion perception.

2 Methodology

We tested three haptic factors: 2 directions; front–back (distal–proximal) and left–right (radial–ulnar) and distance (0.5 mm and 1.5 mm). While up to 22 tangential directions could be distinguished (equation **(1)**, we chose to use only 8 in order to increase contrast while maximizing available motion. Distance corresponded to > 75% recognition of distal–proximal motion for probes glued to forearms (18) with additional compensation for decreased lateral sensitivity at the fingertip (14).

We developed an automated, tangential motion device that stimulated subject fingertips using a round nylon probe (μ_s = 0.25–0.5N; contact area ~ 6 mm diameter × 1.25 mm deep) moving approximately 5 mm/sec (Fig. 6). To ensure consistent fingertip stimulation, subject hand and finger were immobilized during testing. Probe motion was aligned to correspond to body position (axes) so as to reduce spatial confounding effects. A one N normal force was applied during testing using a weighted plunger (Fig. 6) to help subjects calibrate the force with which they touched the probe. We calculated that this generated a 0.33–0.45 N tangential force during testing; which roughly corresponded to the 0.5 N tangential force used in (14) as baseline perception.

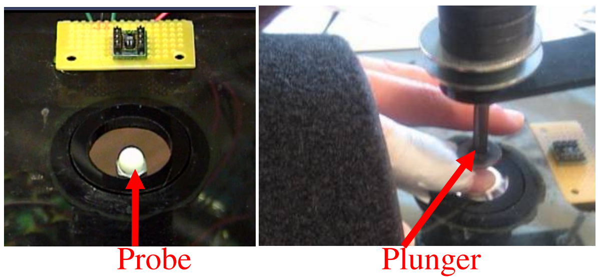

Fig. 6. Stimulus Interface

Sixty two subjects were subjected to 32 randomized, inter–subject trials (2 distances × 8 directions × 2 replicates). Subjects indicated their gender and age category in response to a questionnaire. The questionnaire screened subjects for possible illness or injury that could affect perception. Subject breakdown is shown in Table 1:

Table 1. Demographic Breakdown of Study

Gender		Age Category				
Male	Female	1:18-34	2: 35–44	3: 45–54	4: 55–64	5: 65+
28	34	17	11	12	14	8
45%	55%	27%	18%	19%	23%	13%

Subjects were familiarized with test procedure and probe motion prior to testing. During testing, subjects wore a blindfold and a noise cancellation headset (Creative HN–700) to negate visual and audio cues, and were seated in an ergonomic chair with the option to have their arm supported to reduce fatigue. Trials started with the probe at a neutral (center) position of the finger pad. Subjects were prompted to lower their fingertip onto the probe and prepare for stimulation using two separate tones played through the headset. The probe moved in a random direction and distance followed by another tone signaling subjects to lift their finger off the probe and report their percept scores. The ensuing 20 – 60 second delay during scoring allowed the skin to unload to mitigate confounding between sequences. The probe was then reset for the next trial.

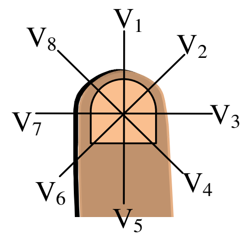

Fig. 7. Finger pad directions (top view)

Subjects reported their perception after each trial using a ten point Likert scale to describe perceived strength (magnitude); from 1 (no perception) to 10 (strongest perception) in one or more of the eight possible directions: "front" (V_1 – towards the fingertip), "back" (V_5 – towards the palm), "left" (V_7), "right" (V_3), plus the four in-between diagonals (Fig. 7). Scores were not restricted to single directions in order to measure complete perception. This resulted in the ith percept generating a vector $\vec{v}_i$:

$$\vec{v}_i = \begin{bmatrix} v_{i1} & v_{i2} & v_{i3} & v_{i4} & v_{i5} & v_{i6} & v_{i7} & v_{i8} \end{bmatrix} \tag{2}$$

2.1 Dimensional Reduction–The Percept Vector

Approximately 42% of responses reported 2 or more values for each direction. We therefore needed to accurately represent single as well as multiple responses in terms of both stimulus direction and strength (magnitude). Details of our heuristic procedure are provided in **(19)**, but are outlined here. Our intuition was to align subject percepts to the actual stimuli then break down the magnitudes of the ith percept into their *x* and *y* values (Fig. 8), so as to generate a *percept vector* (V_{ip}). A simpler form of this was used to calculate a mean vector from a series of unit vectors representing mechanoreceptor responses in **(20)**. In our case V_{ip} was a function of directional (V_{ixy}) and magnitude (M_{ip}) components. Direction was defined as:

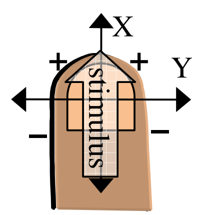

Fig. 8. Fingerpad axes with example stimulus (top view)

$$V_{ixy} = \begin{bmatrix} \vec{v}_{ix} \\ \vec{v}_{iy} \end{bmatrix} = \begin{bmatrix} v_{i1}\cos\alpha_{ij1} + v_{i2}\cos\alpha_{ij1} + \ldots + v_{i7}\cos\alpha_{ij7} + v_{i1}\cos\alpha_{ij8} \\ v_{i1}\sin\alpha_{ij1} + v_{i2}\sin\alpha_{ij1} + \ldots + v_{i7}\sin\alpha_{ij7} + v_{i1}\sin\alpha_{ij8} \end{bmatrix} \tag{3}$$

where α_{ij} was determined by the directional stimulus during a trial as:

$$.A = \begin{bmatrix} \alpha_{i1} = front \\ \alpha_{i2} = front - right \\ \vdots \\ \alpha_{i7} = left \\ \alpha_{i8} = front - left \end{bmatrix} = \begin{bmatrix} 0 & 45 & \cdots & 270 & 315 \\ 315 & 0 & \cdots & 225 & 270 \\ & & \ddots & & \\ 90 & 135 & \cdots & 0 & 45 \\ 45 & 90 & \cdots & 315 & 0 \end{bmatrix} \quad (4)$$

Larger magnitudes contributed more significantly than smaller ones thereby "weighing" the vector towards their direction. The resulting angle was retrieved using:

$$\alpha_i * = \arctan(V_{ixy}) \quad (5)$$

which can easily be retrieved using the ATAN2 function (or its equivalent) in any spreadsheet programs or dedicated statistical analysis programs. When two or more scores were reported they tended to reinforce each, generating magnitudes greater than the largest reported value when we calculated $|v_i|$. Instead, we "averaged" the magnitude of M_{ip} as a weighted sum of v_i:

$$M_{ip} = \sum_{j=1}^{8} v_{ij} * w_{ij} \quad (6)$$

We were interested in finding the perceived magnitude in the actual stimulus direction. We therefore used α_i* to estimate the value of M_{ip} in that direction using the transformation:

$$V_{icp} = M_{ip} * \cos \alpha_i^* \quad (7)$$

to generate the *corrected percept vector* (V_{icp}) which ranged from 10 to -10. Positive values indicated accurate perception, while 0 and negative values indicated motion was perceived perpendicular or opposite the actual stimulus respectively (Fig. 8). Results from these transformations compared favorably with established JNDs in **(14)**, **(21)**, and **(5)**, and are detailed in **(19)**.

3 Analysis

A breakdown of V_{cp} by direction and distance is shown as a star diagram in Fig. 9**.** and in Table 1. An ANOVA found direction ($p=0.004$), distance ($p<0.001$), and their interaction ($p=0.007$) all statistically significant.

A Tukey's test showed distance significant ($p<0.001$). For direction, significance was only found between forward motion versus back–right ($p<0.001$), back–left ($p=0.003$), and front–left ($p=0.002$). Direction was also

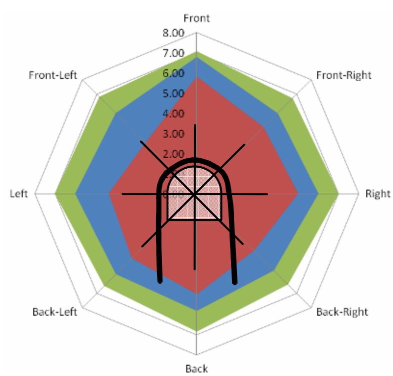

Fig. 9. Median V_{cp} by Direction (top of finger)

found to be of borderline significance for left motion versus back–right (p=0.05). The F test used in ANOVA simultaneously considers all possible contrasts of treatment means, not just pair–wise comparisons (22). Further examination of 0.5mm data and 1.5 mm data using one–way ANOVA showed that direction is significant (p<0.001) for the shorter distance, but not for the longer (p = 0.88). This corresponds with results reported in (14), (21), and (5).

Table 2. Corrected Magnitude Perception (V_{cp}) by Direction

		Front	Front-Right	Right	Back-Right	Back	Back-Left	Left	Front-Left
■ Overall	Average	5.97	4.97	5.25	4.29	5.01	4.62	5.36	4.57
	Median	6.79	5.65	6.00	5.39	5.83	5.65	6.00	5.66
■ 0.5 mm	Average	5.60	4.10	4.22	2.87	4.12	3.75	4.29	2.90
	Median	5.81	4.66	5.00	4.00	5.00	4.54	4.35	3.58
■ 1.5 mm	Average	6.34	5.83	6.23	5.64	5.85	5.41	6.42	6.14
	Median	7.07	6.69	7.00	6.36	6.84	6.47	7.00	6.80

3.1 The Effects of Age

A general linear model found age to have a statistically significant effect on V_p (p<0.001). This effect is illustrated for distance in Fig. 10 with similar results found for direction.

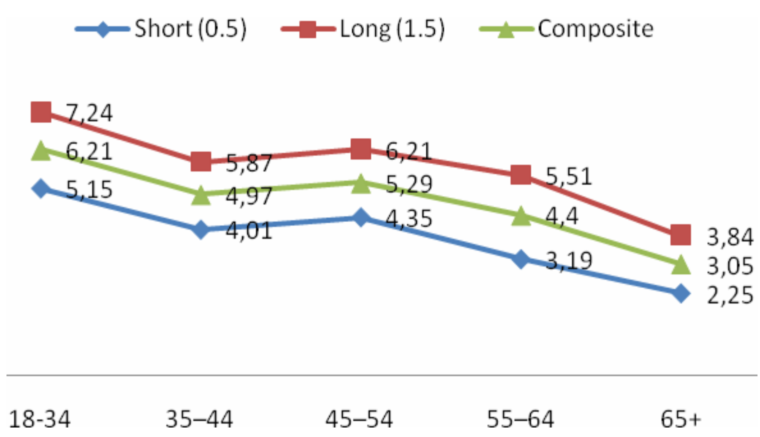

Fig. 10. Average V_p by Age Category and Distance

4 Discussion

Our analysis showed accuracy of perceived tangential motion is related to the distance of the stimuli. This effect was so pronounced that when incorporating direction, shorter distances displayed significant differences between forward motion and diagonal motions; back – right, back – left, and front – left; while longer distance did not. This finding in conjunction with (14) suggests distances 1.0mm or greater transmit at least 3 bits (8 direction) of information accurately provided we use 45º separation. In contrast, distances less than 1.0mm appear to transmit less information – slightly more than 2 bits – particularly when moving diagonally.

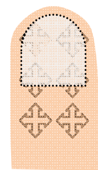

Fig. 11. Proposed Augmented Braille Design(top view)

A practical application of these results could augment the results of (3) which sought to replicate Braille elements using 0.1 mm radial–ulnar motion with limited results. While Braille elements are typically 2.5 mm apart, our results suggest that increasing motion at such small scales can improve perception. Tracing outlines of Braille characters, as suggested by (23), using 2–axial motion is another possibility. A third option is generating an enhanced Braille alphabet using 2–axial motion; which could effectively double, if not quadruple, the information a single element can transmit (Fig. 11).

However, development of any such paradigms must consider the age of the user. Our covariate analysis showed that older subjects perceived tangential stimuli less accurately than younger ones, particularly after 55 years of age. This finding in conjunction with (15), (16), and (17) suggest research in "haptic amplifiers" may be warranted, especially when 1 in 8 of the earth's population is predicted to be 65+ years by 2030 (24). Haptic amplifiers improve tactile perception much like hearing aids augment audition. For example, (25) suggested larger contact areas reduced pressure thresholds. We therefore used a large, low friction probe rather than the "pin–like" probe in (14), (21), and (5). This allowed our interface to be more comfortable for subjects, while producing similar results within the parameters of our test. Such research would increase overall usability, thereby inducing users to adapt such technologies more readily.

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