Numerosity Identification Used to Assess Tactile Stimulation Methods for Communication

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Abstract—Finger-Braille is a tactile communication method used by people who are Deafblind. Individuals communicate Finger-Braille messages with combinations of taps on three fingers of each of the hands of the person receiving the communication. Devices have been developed to produce Finger-Braille symbols using different tactile stimulation methods. Before engaging in communication studies based on technologically-mediated Finger-Braille, we evaluated the relative efficacy of these methods by comparing two devices similarly constructed; the first based on widely employed eccentric rotating-mass vibrating motors and the other using specifically designed tapping actuators. We asked volunteers to identify the numerosity of presented items and for each device we measured (1) error-rate, (2) reaction time, (3) confidence ratings, and (4) a comparison of confidence ratings to actual performance. The four measures obtained for each device showed a net advantage of the tapping stimulation method over the method of vibrations. We conclude that the tapping stimulation method is recommended for use in the design of tactile communication devices based on Finger-Braille and fingerspelling methods reliant on finger tapping actions. The results did not demonstrate clear evidence for tactile subitising with passively experienced stimulation on the fingers.

Index Terms—Tactile communication, Finger-Braille, Numerosity, Passive touch, Haptic interfaces

1 Introduction

Finger-Braille is a tactile communication method developed by the Deafblind Community [1]. It is distinct from other tactile communication methods used by people who are Deafblind such as the Italian Malossi, German Lorm, British Deafblind Manual, or Australian Deafblind Tactile Fingerspelling because it uses only six discrete contact points regardless of the underlying language. Finger-Braille maps the six dots of a standard Braille character to simultaneous taps between homologous fingers of the communicating person and the receiving person. This system resembles the use of a "chorded keyboard" where the characters of an alphabet are represented by simultaneous combinations of keystrokes [2]. Finger-Braille is thus analogous to a "Braille Keyboard" that maps the dots of each column of a Braille cell, from top to bottom, to the fore, middle, and ring fingers of each hand respectively.

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The Finger-Braille tactile communication system is one of several widely used communication methods of the Japanese Deafblind community [1], [3]. It is applicable for communicating with people who have dual impairments of both vision and hearing, as well as those who have a single sensory impairment of vision. This practice motivated us to develop the "HaptiBraille" device described in Section 2.2. This device was designed to enable computer-mediated communication via Finger-Braille. Other than the "HaptiBraille", the "HoliBraille" system [4] was the first Finger-Braille electromechanical device reported in the literature. Introduced in 2013 [5], this device uses six eccentric rotating mass (ERM) motors to map standard Braille code into Finger-Braille. A two-way communication device was also recently described to transmit Finger-Braille using ERMs [6].

Our hypothesis is that ERM motors, widely used in tactile studies and applications, are maladapted to conveying distinct and well-contrasted tactile signals to the fingertips. In the present study we sought to investigate, on equal footing, the comparative efficacy of tactile stimulation methods: ERMs, Fig. 1(a), vs. tapping actuators, Fig. 1(b), specifically developed for tactile manual alphabet methods [7]. Doing so, we strove to decouple our study from human-related performance factors.

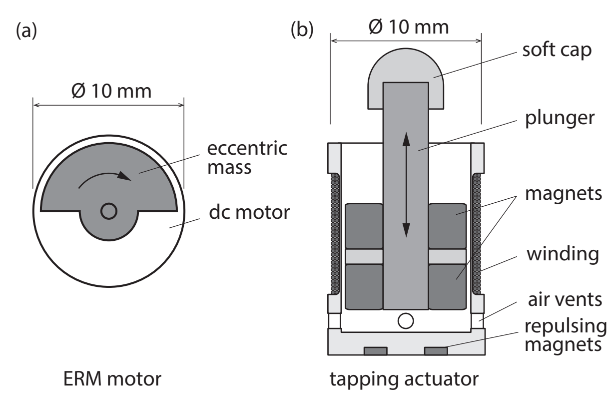


Fig. 1. Two tactile stimulation methods.

Tapping actuators operate by propelling upward a three-gramme plunger on a course of four to six millimetres terminating in a near-inelastic impact against the volar side of the hand. The impact intensity is of the order of 0.2 mJ. When the current pulse duration exceeds 20 ms, the tip of the plunger remains in contact with the skin, exerting

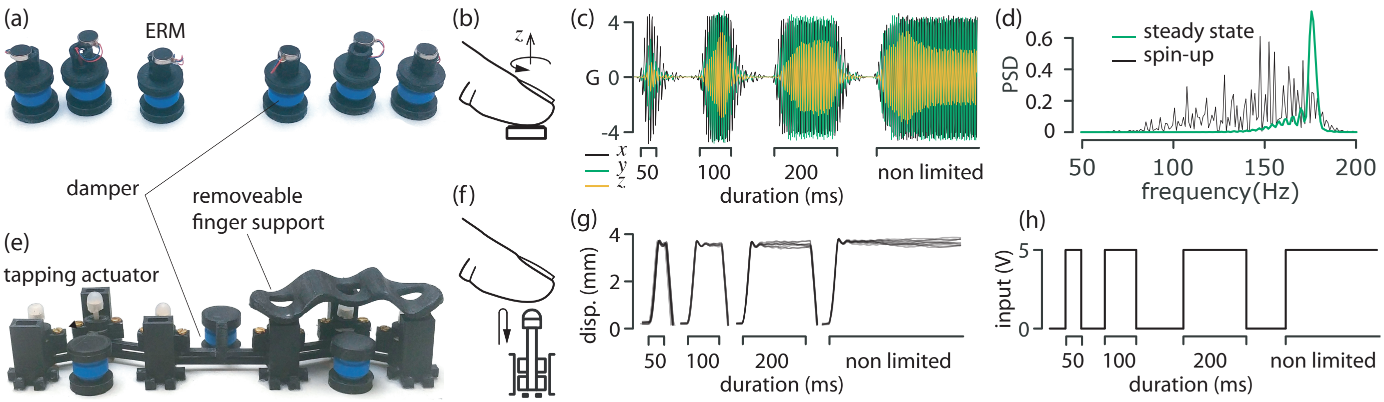


Fig. 2. (a) Vibration device. (b) Direct contact with a finger. (c) Vibration acceleration profile for different durations. (d) Frequency content. (e) Tapping device. (f) Interaction with the finger. (g) Plunger displacement for different durations. (h) Common inputs.

a persistent load of 50 mN (the gravity load of a 5 g, 14 mm diameter silicon ball). The resulting sensation resembles that of being touched by the fingertips of a person executing tapping-dwelling contacts lasting for the remaining duration of the current pulse.

The ERM motor used in the study had a nominal steady-state spinning speed of eleven thousand rpm, corresponding to a 180 Hz vibration (Adafruit, product 1201). We selected this model because its spin-up time is 20 ms, which is the same duration as the lift time of our motors. This model is also frequently used in tactile perception studies. The two stimulation methods could therefore be compared fairly with comparable stimulation exposure times.

To compare the relative advantages of the two stimulation methods prior to engaging in communication studies, we constructed two nearly identical devices, described in greater detail in Section 2, that differed only by the type of tactile stimulation method. With these two devices, volunteers performed a numerosity identification task with four different stimulus durations, resulting in eight different conditions. For each condition, we measured (1) error-rate, (2) reaction time, and (3) confidence rating the volunteers placed in their judgements. The confidence measure enabled us to compute a fourth measure, (4) discrepancy, that gauged the correspondance between self-evaluation of performance and actual performance. Discrepancy measured the capacity of a display to give to its user the ability to judge the effectiveness of the transmission of information.

A numerosity identification task had the advantage over general communication tasks of minimising the dependence of the results on the skills of the persons using the devices.

2 Method

2.1 Volunteers

Twenty-one volunteers were recruited (nine female, three left-handed, mean age 27.5 years with standard deviation of 5.25). They declared no known history of finger insensitivity. No Blind or Deafblind individuals participated in the study. The volunteers gave informed consent to test the devices and could withdraw from the study at any time.

2.2 Apparatus

The two devices were constructed out of 3D printed plastic. One device included six ERMs, the other six tapping actuators. The actuators were arranged to face the fingertips of the fore, middle, and ring fingers of both hands. The tapping device had removable finger supports, shown in Fig. 2(e). The devices were configured to place the hands at rest in a comfortable, ergonomic posture. The locations of the actuators were selected from the data reported in [8]. The electronics and software refreshed the actuator signals at 10 kHz.

2.2.1 *Vibration device*

Referring to Fig. 2(a), this device used mini motor discs ERMs (model 10B27.3018) popular in tactile studies. These motors were housed in individual casings supported by soft damping elements, visible in blue in Fig. 2(a). The upper surfaces of the motors were in direct and continuous contact with the fingers as shown in Fig. 2(b). The signal contrast between activated and inactivated sites was evaluated by running five hundred random combinations of actuator activations and by measuring acceleration at the activated and inactivated contact surfaces. Signal power measured at the inactivated sites was on average $2.9 \pm 1\%$ of the signal power measured at the activated sites, corresponding to a contrast ratio of 34:1. Upon activation, the vibration stimuli, see Fig. 2(c), had a spin-up phase of 20 ms, followed by a steady-state phase and a spin-down phase. During steady state, the vibratory power was concentrated in a narrow band centred on 180 Hz, see Fig. 2(d).

2.2.2 *Tapping device*

Referring to Fig. 2(e), the device employed the electrodynamic tapping actuators described in [7]. Upon a pulse of current, the plunger travelled upward for four millimetre to impact the finger, see Fig. 2(f). If the pulse was longer than 20 ms, see Fig. 2(g), the plunger applied a steady load of 50 mN onto the skin. The actuators were housed in a casing placed below the finger supports, recessed for optimal operation. The casing was supported by the same damping elements used in the vibration device. Using the same method, signal power measured at the inactivated sites was on average $1.7 \pm 1\%$ of the signal power measured at the activated sites, corresponding to a contrast ratio of 49:1. The tips of the plungers were covered by hemispherical silicone caps (EcoFlex 00-30) of 5.0 mm in diameter. They evoked sensations of contact similar to human fingers.

2.2.3 Response logging

Responses from volunteers were recorded by microphone and saved as WAV files. The recordings started within one millisecond of the actuator activations. To reduce the experimental bias introduced by different onset delays of utterances [9], [10], the volunteer's vocalisation patterns were characterised to correct the individual response time measurements. Cued by a tap on the index finger given by a 20 ms current pulse, each volunteer vocalised the French words for the numbers one to six as quickly as possible whilst maintaining clear diction. Each vocalisation was repeated ten times in a randomised order during trials separated by varying intervals. Across all volunteers the word for 'one' was enunciated with a delay of 383 ± 79 ms after cueing, the word for 'two' with a delay of 410 ± 78 ms, 'three' 333 ± 57 ms, 'four' 383 ± 73 ms, 'five' 326 ± 67 ms, and 'six' 322 ± 68 ms, which revealed that individual delay differences were not to be neglected.

2.3 Stimuli

The electromechanical properties of the devices and a brief pilot study served to determine appropriate durations for the pulse input commands. For the vibration motor, a pulse of 50 ms was found to be the shortest command signal. It allowed for a 20 ms spin-up phase, a minimal steady-state phase, followed by an unpowered spin-down phase. For the tapping actuator, a 50 ms pulse corresponded to an impact with an equivalently minimal dwelling time against the finger. For the vibration motor, a 100 ms pulse corresponded to its nominal operation comprising a spin-up phase and steady-state phase of duration in excess of the spin-up time. For the tapping actuator, a 100 ms pulse gave a dwell period that could be felt distinctly. A 200 ms pulse resulted in twice the duration for the nominal operation for the two stimulation methods resulting in a stronger sensation [11]. This set was completed with a continuous activation condition only limited in duration by the volunteers response. This case provided a control condition under which both devices were expected to provide optimal performance in error-rate and confidence ratings. The duration-limited conditions could thus be compared to this optimal condition.

Six fingers, each presented synchronously with an item or not, allowed for a set of sixty-three distinct stimuli (2^6-1). This number prevented us from testing a uniform distribution of all stimuli with a sufficient number of repetitions. Instead, we broke down the set of all possible stimuli into subsets with members of equal numerosity. A random selection of ten members of each subset for each duration furnished testing blocks of reasonable size comprising two hundred and forty trials where the presentation of each item numerosity was repeated ten times. All stimulus durations were equality represented in a block for each item numerosity. The blocks of randomised stimuli were the same for the two stimulation methods and comprised 240 trials (6 combinations of 1 to 6 items $\times$ 4 durations $\times$ 10 repetitions).

2.4 Procedure

The volunteers sat at a table, were blindfolded, and donned headphones playing white noise to mask the sounds emitted by the actuators. They rested the fore, middle, and ring fingers of both hands on the device. If desired, they could use a support for their forearms. Once ready, they were presented with 100 ms stimuli for each finger in turn to ensure that the fingers were correctly placed and that the stimuli were distinctly felt. The volunteers received the stimuli in two blocks, one per device. Eleven volunteers out of twenty-one began testing with the vibration device. They were encouraged to respond as quickly and as accurately as possible and received no feedback about their performance. To minimise the effects of learning and tiredness, a break of at least one hour was taken between the two blocks. The volunteers familiarised themselves with the task during a preliminary set of twenty trials comprising randomly selected stimuli.

For each trial, the volunteers were instructed to estimate the number of items they felt; responding verbally; and rated the confidence in their answers on a scale of 0 to 100 %. They were told that 0% meant not certain at all, 25% not very certain, 50% somewhat certain, 75% certain, and 100% completely certain. They could report any percentage they wished. Inter-stimulus intervals were randomly set within a 2.5–4.0 s bracket. Testing one block of trials took twenty minutes. Volunteers completed one block in the course of one day and a second block the next day. Order was random.

3 Results

3.1 Overall Results

Figure 3 shows the overall error-rates, reaction times, confidence ratings, and a measure of discrepancy between task performance and confidence ratings defined as the error-rate discounted by the complement of the confidence rating. The discrepancy measure was low for a low error-rate combined with a high confidence rating. It was also low for a high error-rate combined with a low confidence rating. It had a large positive value when the error-rate and the confidence rating were both high (overconfidence) and a large negative value when the error-rate and the confidence rating were both low (under confidence).

Table 1 shows the mean and standard error of the four measures for each condition. Excluding the continuous exposure condition, the error-rate measure showed a considerable advantage for the tap condition. Participants responded consistently faster under the tap conditions with an average advantage of 182 ms. The discrepancy between performance and confidence was also considerably lower, especially for short exposures. For the tap condition, optimal performance in error-rate and in discrepancy were obtained with 200 ms stimuli. In terms of reaction time, optimal performance with taps was with the 50 ms stimuli with a penalty of 9% in error-rate. With vibrations, the penalty in error-rate for shortening the stimuli from 200 ms to 50 ms was 22%, and the reaction time increased by 100 ms instead of decreasing.

3.2 Results by Outcomes

A two (stimulation-method) $\times$ four (stimulus-duration) analysis of variance (ANOVA) was calculated on each type

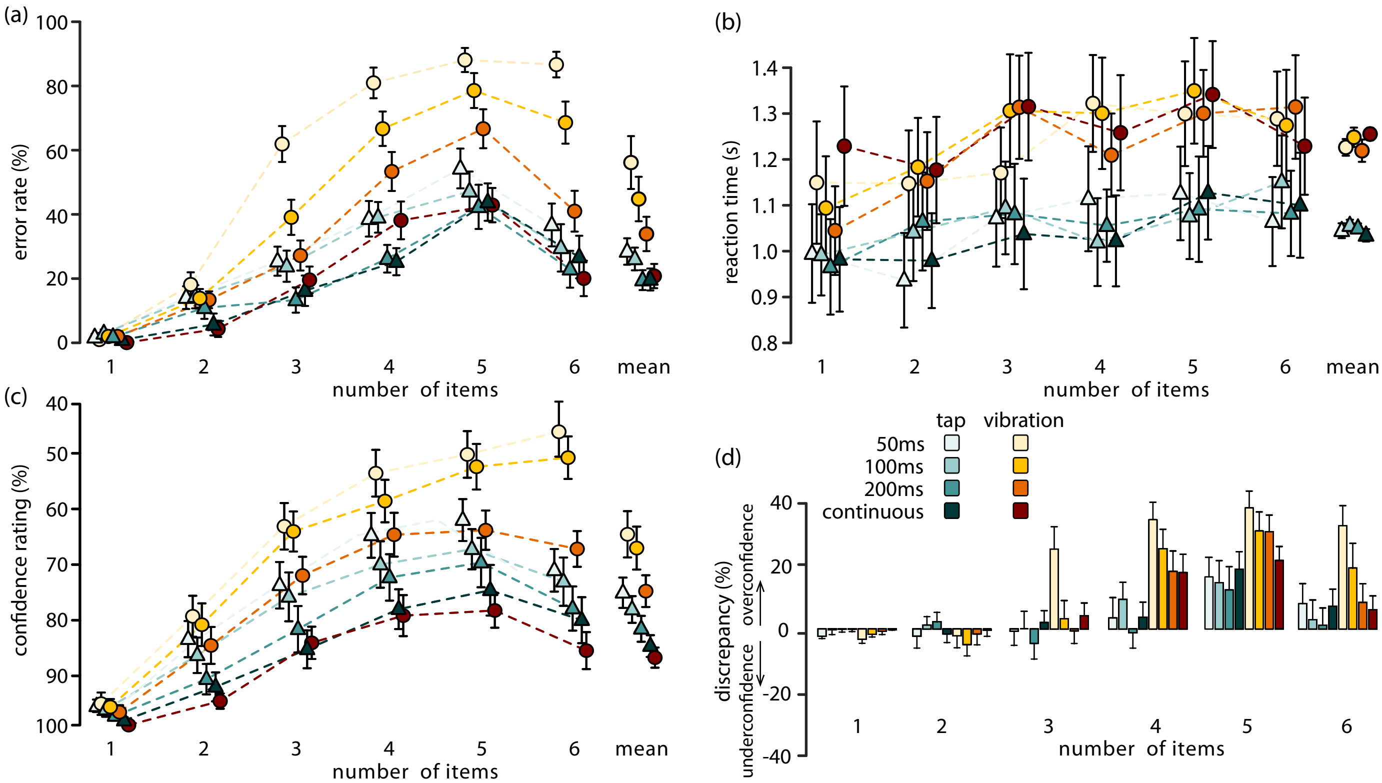


Fig. 3. (a) Mean error-rates across all volunteers. (b) Reaction times across all volunteers. (c) Confidence ratings across all volunteers. (d) Discrepancy measure between confidence and performance across all volunteers. Error bars represent the standard error of the mean.

TABLE 1
Mean and standard error of error-rates, reaction times, and discrepancy across all volunteers.

	error-rate		reaction time		discrepancy	
exposure	tap	vibration	tap	vibration	tap	vibration
50 ms	28.33 ± 3.19	56.11 ± 2.87	1023 ± 110	1216 ± 126	6.06 ± 5.27	23.10 ± 6.03
100 ms	26.11 ± 3.56	44.76 ± 2.97	1104 ± 112	1276 ± 130	7.11 ± 5.25	14.10 ± 5.77
200 ms	19.60 ± 3.11	33.89 ± 3.38	1044 ± 101	1174 ± 109	4.37 ± 4.99	10.87 ± 5.05
continuous	19.76 ± 3.32	20.79 ± 3.06	1045 ± 113	1279 ± 121	6.79 ± 4.36	9.46 ± 4.16

of outcome. The one-sample Kolmogorov-Smirnov test was used to test the normality of the data. The worse case, $p < 0.0016$, was for the discrepancy measure with 200 ms vibration stimuli.

3.2.1 Error-rates

There was a significant main effect of stimulation method, $F(1,160) = 46.96$, $p < 1.5\,e^{-10}$ $(r = 0.17)$. In general, volunteers performed the task with greater of accuracy when receiving taps (M = 23.45, SD = 15.36) rather than vibrations (M = 38.89, SD = 19.08). There was a significant main effect of stimulus duration, $F(3,160) = 18.41$, $p < 2.6\,e^{-10}$ $(r = 0.20)$. In general, volunteers performed the task more accurately when the stimulation duration was longer, 50 ms (M = 42.27, SD = 19.68), 100 ms (M = 35.43, SD = 17.58), 200 ms (M = 26.70, SD = 16.31), and continuous (M = 20.26, SD = 14.40).

There was a significant stimulation-method $\times$ stimulus-duration interaction, $F(3,160) = 6.04$, $p < 0.0007$ $(r = 0.06)$. We ran an additional one-way ANOVA with stimulus duration as factor on both methods of stimulation. There was no significant effect of stimulus durations with the tap stimuli, $F(3,80) = 1.8779$, $p = 0.14$ $(r = 0.07)$, however, there was a significant main effect of stimulus duration with the vibration stimuli, $F(3,80) = 24.11$, $p < 4\,e^{-11}$ $(r = 0.47)$.

3.2.2 Reaction times

There was a significant main effect of stimulation method, $F(1,160) = 7.16$, $p = 0.0082$ $(r = 0.043)$. Volunteers generally answered faster when receiving taps (M = 1061.50, SD = 422.00) rather than vibrations (M = 1245.16, SD = 450.92). There was no significant effect of stimulus duration, $F(3,160) = 0.014$, $p = 0.99$ $(r = 0.0002)$. There was no significant stimulation-method $\times$ stimulus-duration interaction, $F(3,160) = 0.024$, $p = 0.99$ $(r = 0.0004)$.

3.2.3 Confidence ratings

There was a significant main effect of stimulation method, $F(1,160) = 10.26$, $p < 0.0017$ $(r = 0.048)$. In general, volunteers were more confident when receiving taps (M = 80.31, $SD = 14.50$) rather than vibrations (M = 73.60, SD = 15.42). There was a significant main effect of stimulus duration, $F(3,160) = 11.72$, $p = 5.5\,e^{-7}$ $(r =$

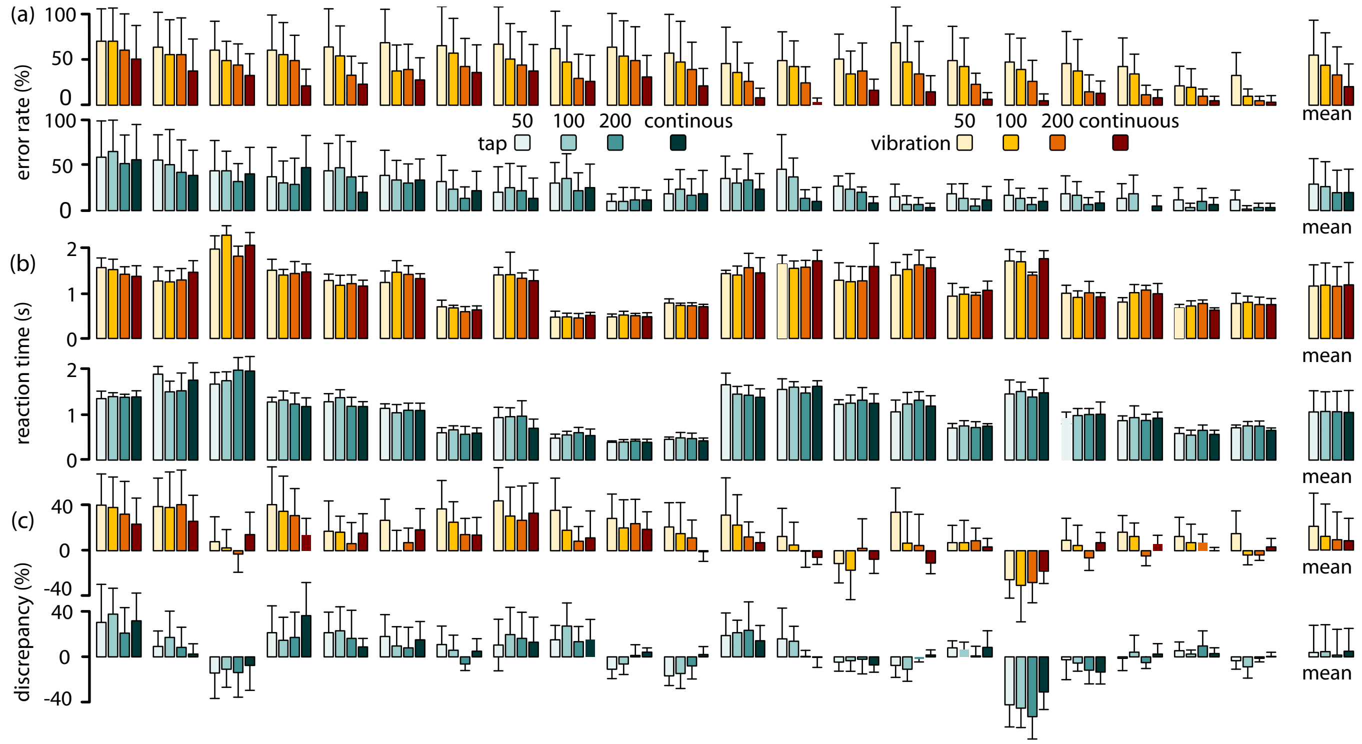


Fig. 4. (a) Individual error-rates. (b) Individual reaction times. (c) Individual discrepancy measures between confidence and performance. Error bars represent standard deviations.

0.17). In general, volunteers' confidence increased with stimulus duration, 50 ms (M = 70.06, SD = 15.76), 100 ms (M = 72.87, SD = 15.31), 200 ms (M = 78.60, SD = 13.73), and continous (M = 86.30, SD = 11.13). There was no significant stimulation-method × stimulus-duration interaction, $F(3, 160) = 2.19$, $p = 0.091$ ($r = 0.031$).

3.2.4 *Discrepancy*

There was a significant main effect of stimulation method, $F(1, 160) = 12.26$, $p < 0.0006$ ($r = 0.069$). In general, volunteers estimated more accurately their own performance with taps (M = 3.76, SD = 16.15) rather than with vibrations (M = 12.49, SD = 16.41). There was not a significant effect of stimulus duration, $F(3, 160) = 1.5$, $p = 0.21$ ($r = 0.025$). There was no significant stimulation-method × stimulus-duration interaction, $F(3, 160) = 1.36$, $p = 0.26$ ($r = 0.023$).

3.3 Individual Results

Figure 4 shows the three measures: error-rate, reaction time, and discrepancy for individual volunteers ordered by error-rates across all conditions, as well as the mean across volunteers. With only one exception (tenth from the left), all volunteers obtained better accuracy with the taps than with the vibrations. These results provide more detailed information about the variability of individual performances as a function of the eight conditions.

3.4 Most Effective Conditions

Another way to represent the results is to show which of the eight conditions achieved the lowest, second lowest, and third lowest error-rate, reaction time, and discrepancy measures across all participants, see Figure 5. Overall, the most effective condition was the 200 ms tap condition. The 50 ms tap condition tended to give the shortest reaction times and the smallest discrepancy between confidence and performance.

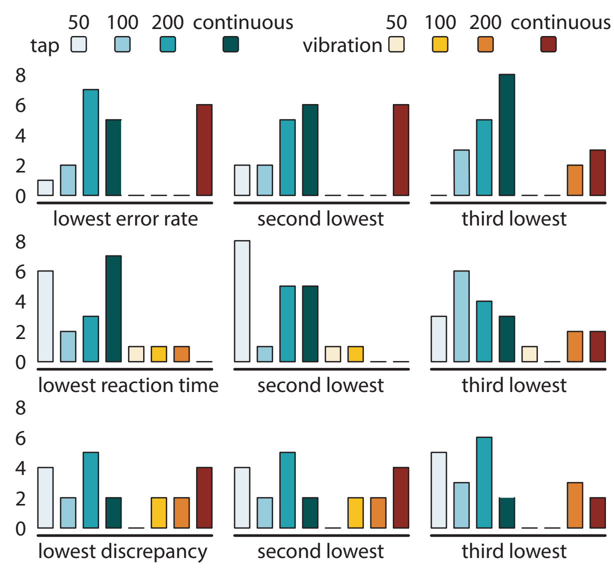
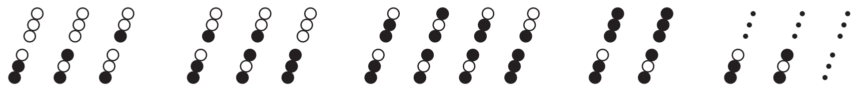


Fig. 5. Number of times conditions achieved the lowest, second lowest and third lowest error-rates, reaction times, and discrepancy measures between performance and confidence.

3.5 Influence of Patterns

Structure in item numerosity identification performance was difficult to identify among the sixty-three distinct patterns.

TABLE 2
Number of overestimated and underestimated counts by degrees of item contiguity.



		two items			three items			four items				five items		mean			totals
	estimation																
tap	over	1	11	10	7	10	0	5	2	8	5	2	19	15	42	15	152
200 ms	accurate	56	14	117	116	48	18	52	12	32	59	87	34	311	108	194	1258
	under	1	0	0	9	1	1	4	4	8	19	48	20	62	25	20	222
vibration	over	8	3	12	13	6	0	2	2	6	7	14	10	37	21	19	160
200 ms	accurate	49	18	115	94	41	18	35	7	20	36	49	21	227	87	169	986
	under	1	4	0	25	12	1	24	9	22	40	74	42	124	67	41	486
	subtotals	116	50	254	264	118	38	122	36	96	166	274	146	776	350	458	3264

Table. 2 shows the possible effect of contiguity on accuracy for 200 ms stimuli. The responses were sorted according to whether the stimuli included pairs of contiguous items or whether they were spaced apart by one place on a single hand. Overall, the configurations where items where distant tended to influence the volunteers to overestimate item numerosity. The volunteers tended to underestimate numerosity when both hands were stimulated and underestimation was twice as high for vibration than for taps.

4 Discussion

Any particular communication technique should be tested for its ability to convey clear and unambiguous messages independently from the skills of the users before being assessed in the field. Item counting is a task which, for most people, requires no training. It can therefore be used to compare different techniques on a level playing field. We hypothesised that eccentric-rotary-mass vibration motors, frequently employed in touch perception studies, were poor tactile stimulus generators.

Vibration motors made available by the mass-manufacturing industry are based on the assumption that 'intense' is equivalent to 'distinct'. There is a long tradition for this assumption. In 1927, Gault noticed that a vibrotactile frequency of 200 Hz in a tactile communication device gave the lowest detection threshold [12], which was later confirmed by Verrillo [13]. Since this time, it has been widely accepted that a frequency of 200 Hz is the gold standard for vibrotactile devices and nearly all commercial and experimental vibrotactile devices operate on this basis, e.g. [14], [15].

We questioned the assumption that stimulation methods should be based on a particular frequency. We predicted that a stimulation method based on the reproduction of naturally occurring signals, rather than artificial monochromatic oscillations, would bring about advantages for tactile communication. Having devised a tactile transducer that delivered naturalistic sensations resembling contacts with real fingers, it was pitted against the conventional ERM motor in an item numerosity identification task.

The overall error-rate results, Fig. 3(a) and Table 1, show that short-duration vibration stimuli led the volunteers to incorrectly estimate numerosity by a much larger margin than tap stimuli. The five-item case led to an error-rate of 90%. The error-rate was generally reduced with exposure time, but with tap stimuli the same measure was independent from exposure time.

This result can be explained by the fact that the longer vibratory stimuli gave volunteers the opportunity to engage in cognitive strategies to improve performance. This view is supported by the possibility that it is only in the control condition with continuous vibration stimulation that performance was similar to that obtained with tap stimuli. It follows that tap stimuli could have constituted a genuine sensory task, whereas vibration stimuli forced the volunteers to recruit cognitive resources to complete the task successfully.

The overall reaction times, Fig. 3(b) and Table 1, were hardly influenced by item numerosity. The volunteers however responded by a significant margin with more delay to the vibratory stimuli than to the tap stimuli. The individual results suggest that volunteers had vastly different reaction times but intra-individual reaction times were highly consistent.

The confidence ratings, Fig. 3(c) and Table 1, revealed that short duration vibrations caused confusion, leading to confidence ratings that diverged from performance ratings. It is only with the continuous stimulation condition that confidence ratings reached and even exceeded those obtained with tap stimuli. This trend is seen more clearly in Fig. 3(d), Table 1. The volunteers were frequently overconfident in their ability to identify the numerosity of items when they were presented as vibrations and when numerosity exceeded three. It is only in the case of five items that the tap stimuli induced overconfidence.

In comparison with previous research, our results replicated those of Riggs et al. [16] who used a stimulation method similar to our tapping motors. They found accuracies of 99, 98, and 93%, accuracy for items number one, two, three, respectively and reaction times of 490 ms plus 270 ms per item for item numerosity of one, two, and three. Riggs et al. also explained the decrease in reaction time between five and six items by the easiness to identify the special pattern of six items.

Our results did not replicate the results of Cohen et al. [17] who used the vibration method to stimulate the fingers. Their results did not replicate those of Riggs et al. either. Unfortunately, Cohen et al. tested only numerosity from one to five experienced by a single hand, which changes the task considerably. They did not compensate for the vocalisation delays for different numbers, and used long exposure times of 800 ms as control. Despite these differences, the error-rate curve for 200 ms vibratory stimuli in our study resembled that of the 800 ms condition in Cohen et al.'s study under the assumption that the items of numerosity four assumed the role of the items of numerosity five of our study. This case corresponds to patterns of maximal expected numerosity minus one. This apparent coincidence for widely different stimulus durations reinforces the view that item numerosity identification performance is highly dependent on the stimulation method.

Jansson [18] offers an interesting explanation based on perceptual filling-in as to why some patterns lead to an overestimation of numerosity. Table 2 does suggest that it is those patterns with more distant items that tend to be overestimated.

Although it was not an objective of the present study, we observed scant evidence for subitisation behaviour with either of the two stimulation methods when stimuli comprising synchronous items were presented on the fingertips. Subitisation normally entails correctly identifying the numerosity of items in constant response time up to a threshold where the response time begins to rise. Subitisation is observed in vision [19], [20], [21], [22]; or in audition when stimuli have certain metrical properties [23]. Our results support the view held by Gallace et al. and also by Iida et al. that subitising in touch is not a unitary phenomenon and that tactile numerosity identification might appeal to different mechanisms [24], [25], [26]. Tactile item numerosity identification thus is subjected to many factors to which we now can safely add the method of stimulation.

Our comparative study sought to determine a preferred manner to transmit symbols based on combinatorial codes applied to the fingers. Tap stimuli, which phenomenologically resembled contacts with human fingers, led to shorter reaction times, fewer errors, and relative independence from exposure time in a numerosity identification task. Among all conditions, 200 ms tap stimuli led to better performance according to the four measures.

Despite the fact that tactile numerosity identification was poor above two or three items, we anticipate that our results will generalise to linguistically-based systems of communication such as Finger-Braille or Fingerspelling. These systems are found by their users to be very effective. This effectiveness is explained by the fact that communicated messages normally convey meaning, whereas the task of identifying numbers is free of context and devoid of significance. This effectiveness could also come from the fact that certain classes of patterns are easier to identify than others. This point is left to future studies since the design of these studies would have to account for the languages used to support communication.

The present study did not include conditions with intensity variations. Intensity variations are impossible to command with ERMs but are possible with certain types of electrodynamic vibration motors, including our tapping actuators. The latter can combine vibrations and taps, allowing for even more possibilities.

We informally tested the devices with volunteers who were not sighted. The present study however was conducted with sighted volunteers. A properly designed study with individuals who have sensory impairments would not have necessarily provided more information regarding the method of tactile stimulation. For example, people who are Deafblind tend to be faster and require less movement for a given perceptual task but are as accurate as the control group [27], [28], [29]. More generally, there is no evidence that the loss of a sensory modality systematically modifies the basic functions of another sensory modality, e.g. [30]. More specifically, Ferrand [31] showed that people with and without blindness performed similarly during a tactile enumeration task. We thus anticipate that our results will generalise to most target populations.

Finger-Braille is an appealing tactile communication tool for use by people who are Deafblind. Like Fingerspelling, Finger-Braille enables variations of speed, weight, and length of contact to add prosody, nuance, expression, tone, timbre to the tactile communication [32], [33]. Braille globally relies on six dot patterns regardless of which language it is representing, allowing for simple and universally applicable hardware design and realisation. These factors make Finger-Braille a desirable candidate system for implementing computer-mediated tactile communication devices. Communicating with Finger-Braille can be laborious, but with practice, communication can become fluid and effective. We therefore expect that devices properly designed to produce Finger-Braille would provide the same advantages.

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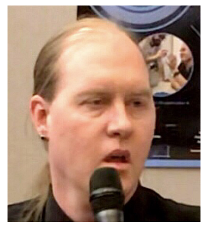

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