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Vibrotactile Alphabets: Time and Frequency Patterns to Encode Information

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***Abstract*—Although many tactual communication methods have been developed over the past decades, few of them have been widely adopted in everyday lives. In this paper, we investigate the ability to deliver text messages using patterns of vibrations. By manipulating the duration and frequency of vibrations, we designed two vibrotactile alphabets, i.e. 3F Vibraille and 2F Vibraille, along with their corresponding numbers and symbols. The main difference between 3F Vibraille and 2F Vibraille is the number of frequency levels utilised. Both alphabets were evaluated through human experiments in terms of training time, learning process and recognition accuracy of words and symbols. For both alphabets, the results demonstrated that participants were able to recognise words and symbols at an accuracy of over 90% after 6-8 hours of training. The main difference between the alphabets was that 3F Vibraille achieved a higher transmission rate while 2F Vibraille required less training time.**

***Index Terms*—Vibrotactile, tactual communication, haptics.**

I. Introduction

There is no doubt that life of the visually impaired, i.e. people who are either completely blind or have poor vision, is now relatively convenient due to the popularisation of assistive audio technologies, such as screen-reading systems, text-to-speech capabilities and audio books. However, there are circumstances under which the audio sense is compromised or overloaded. For instance, the visually impaired are in a noisy environment (markets, streets, pubs, etc.) or in circumstances that require keeping silence (chapel, library, meeting, etc.). Using headphones can solve above problems to some extent, but it isolates the user from the ambient environment and may thus put the user in danger or interfere communication with others. Besides, audio technologies are not able to help the visually impaired with writing and spelling. Apart from receiving information, inputting is actually important for the visually impaired in a variety of scenarios, such as taking notes in a meeting, entering passwords, etc. Furthermore, literacy is reported to be closely related to the educational level, employment, income and quality of life of the visually impaired [1]. Consequently, it is essential for the visually impaired to access information using the tactile sense.

Braille is the main tactual communication among the visually impaired. Sadly, the popularity of braille has significantly declined over the last decades. Currently, less than 10% of the visually impaired use braille in the US [1], while fewer than 1% of people who have sight loss are braille users in the UK [2]. One of the main reasons is that the six-dot structure restricts the use of braille in the mobile era today. Due to the requirements of spatial resolution, paper braille textbooks are normally bulky and costly. To reduce the size, refreshable braille displays that normally have 40-80 alterable cells have been invented. The cost of the displays, however, is still very high. It is reported in [3] that the price ranges from $\$5000$ to $\$15000$. The reason of such high price is that each dot requires an actuator. It is hard to cut down the cost due to the six-dots structure of braille; therefore, an alternative method for tactual communication is required.

To design the tactual communication that fits the mobile era, the following requirements need to be considered:

- Coding capacity: this stands for the total amount of information that the method is able to encode, including letters, numbers, punctuations, symbols, etc. Since standardised Unified English Braille (UEB) is quite mature, it can be treated as a benchmark. The alternative method should be able to code almost the same amount of information that UEB contains.
- Portability: considering that a visually impaired normally needs to hold a cane or a guide dog with one hand, the tactual display should be accessible and controllable with one hand only. The portability is affected by the type, size and number of actuators.
- Input: braille is important for the literacy of the visually impaired because it serves as both reading and writing media. It is reported in [4] that the employment rate of braille users is much higher than that of the visually impaired who do not know braille. Input is key to the employment of the community; therefore, the alternative tactual communication should be capable of assisting the users in input.
- Cost: as the majority of visually impaired people live in developing and poor countries [5], the price of the tactual communication should be as low as possible.
- Comfort: since the tactual communication is supposed to be used in everyday life, the corresponding device should be comfortable to wear at any season. Besides, it should be easy to wear and should not disturb the users' normal activities.
- Training: another reason for the decline of braille is that people think it is hard to learn. Hence, the alternative tactual communication should be friendly to new users. Primal training time should be as short as possible, so that users can start using it as quickly as possible and get more familiar as they practice.
- Transmission Rate: nowadays the majority of the braille users utilise braille for practical purposes, such as, labelling, taking notes, recording phone numbers, etc., rather than reading books [4]. What the community really needs is a tactual tool to access short messages. Consequently, the transmission rate of the coding method

can be compromised as long as it meets the need in daily life.

Reading braille heavily relies on the Merkel cells that are sensitive to edges and points [6]; therefore, braille is somewhat a static way to present information. Instead, we utilise vibration that stimulates another type of mechanoreceptor, i.e. Pacinian corpuscles, to code information. In this way, only one actuator is required; hence high portability, high comfort and low cost are easy to achieve while designing the tactual displays. By manipulating the frequency and duration of the vibration, we can use consecutive vibration signals to code almost the same amount of information that braille contains. For simplicity, this method of tactual communication is denoted as Vibrational Braille (Vibraille). Since the frequency and duration are chosen and arranged carefully and regularly, the user is also able to input information with just a few buttons. As the spatially distributed dots shift to consecutive vibrations, a transformation from the spatial to the temporal domain is realised. In order to investigate the performance and efficiency of Vibraille, we conducted experiments regarding the identification of single letters, words, numbers and symbols. The results demonstrate that high recognition accuracy and considerable speed are achieved within short training time.

The remainder of the paper is organised as follows. Prior art tactual methods are discussed in Section II. In Section III, the attributes and coding of Vibraille are presented, while the two mappings of Vibraille code are proposed in Section IV. In Section V, experiments are conducted to assess the performance of Vibraille in terms of word and symbol identification. Next, the results are discussed in Section VI. Finally, this paper is concluded in Section VII.

II. Related Work

A variety of tactual communication methods have been developed over the past decades. Reviews of previous methods can be found in [7], [8]. Different locations of the human body are researched; such as, the back [9], [10], [11], the waist [12], forearms [13], [14], [15], [16], wrist [17], fingers [18], [19], [20], [21], etc. As for types of stimuli, the majority of research utilises vibration and a few employ stretch [17]. In terms of encoding methods, most of above research proposes novel encoding techniques, while only a few rely on existing coding techniques (braille or Morse code). For example, the authors of [20] used a tactual display to present the dots of braille sequentially. Results of experiments showed that a recognition accuracy of 92% was obtained with a reading speed of 0.27 characters per second (cps). Apparently, the reading speed was significantly limited by the use of braille, since braille was initially not designed to be presented dot by dot (typical reading speed of Grade I braille is 5.36 cps [22]). On the other hand, the tactile perception of Morse code was investigated in [21]. After 70-80 hours of training, the new user was able to recognise common words with an accuracy of about 90% at 12 words per minute (wpm), while experienced Morse code users were able to achieve the same accuracy at above 16 wpm. However, Morse code is only capable of encoding a few punctuations apart from letters and numbers. Besides, the duration of numbers and punctuations is much longer than that of letters, which significantly reduces the efficiency of tactual Morse code. Consequently, it is better to design original coding methods that satisfy the need of the visually impaired.

Currently, almost all of the research using original coding techniques employs multiple actuators. For instance, the authors of [15] attached an array of 24 actuators to one forearm of the participants. Then they used position, frequency, modulation and duration to encode phonemes. The results demonstrated that participants could recognise 39 phonemes with a mean accuracy of about 86% and a mean response time of about 4.2 s. The authors of [14] designed a wearable device that utilised vibration, squeeze and stretch to encode 23 phonemes. After 100 minutes of training, the participants achieved an 86% recognition accuracy for a 50-words identification in the manner of multiple-choice. In [11], the authors utilised a 3×3 array of vibrotactile tactors to deliver various types of information, such as alphanumeric characters, colours and verbs. To minimise the users' cognitive and memory overloading, the tactile patterns could be customised according to the users' characteristics. It was reported that the average recognition accuracy achieved for alphanumeric characters, colours and verbs were 86.76%, 95.33% and 90.50%, respectively. In [23], six actuators embedded in a glove were employed with five placed on five fingers and the sixth one located on the back of the hand. The authors activated different combinations of actuators to code letters. After about 5 hours of training, the participants achieved a mean recognition accuracy of 94% at about 78.1 wpm for word identification. However, only letters were considered in this paper. Besides, a multiple-actuators setup normally utilises spatial coding; hence, each actuator must be placed precisely at certain spots as otherwise the accuracy and efficiency of such methods significantly deteriorates. Also, a multiple-actuators setup is more likely to compromise portability, comfort and cost.

In summary, most of the previous tactual communication methods focus on achieving high transmission rate, but compromise on portability and comfort to a large extent. We also note that vibration is intrinsically not appropriate for accessing long text, since long vibrational stimuli cause uncomfortable numbness, thus reducing the recognition accuracy. However, as long as the transmission rate serves the purpose of reading short messages in daily life, portability and comfort ought to be considered preferentially. Besides, almost none of the previous research considers an all-encompassing solution of outputting but also inputting messages. In order to let the visually impaired input messages conveniently, the number of buttons involved for typing should be minimised. On the other hand, research using original coding methods has not rigorously studied nor verified the encoding of numbers and symbols which are important for tactual communication.

III. Vibraille

In order to deliver various types of vibration, a linear voice coil actuator (LVCA) is used in our setting. As an electromagnetic device, the vibration of a LVCA can be precisely controlled through manipulating the input current. The cost of a LVCA starts from \$100, which is much lower than the refreshable braille display. A sinusoidal current is input into the LVCA to generate vibrations, since Pacinian corpuscles respond primarily to sinusoidal signals [24].

A. Attributes

In order to code different characters, we can tune three attributes of the sinusoidal signal:

- Amplitude: The larger the amplitude, the higher the intensity of the stimuli. If the amplitude is too small, it is hard to detect. On the other hand, too large of an amplitude causes numbness.
- Frequency: The moving time as well as displacement of the shaft decrease as the frequency increases. In other words, high frequency results in low intensity and low frequency leads to high intensity. The authors of [24] demonstrated that the just noticeable difference (JND) for frequency was about 18%. However, the duration of test signals in [24] was 500 ms, while the signals that we use is much shorter. According to the results of preliminary tests, we found that people can hardly distinguish more than three frequencies (which we will sometimes refer to as levels or bands of frequency). This is in accordance with the findings in [25], [26].
- Duration: In Morse code, the duration of a long signal is three times that of a short signal. Since the human tactile sense is less sensitive to change over time than the human auditory sense [27], the difference between long and short signals in the tactile domain is supposed to be larger than that in the audio domain. Although [21] showed that participants could discriminate the long and short signals in tactual Morse code, the results were obtained after 70-80 hours of training. As mentioned in Section I, it is important for tactual communication to deliver a smooth learning process. Our preliminary tests demonstrated that setting the difference as three units gave more promising results in terms of recognition accuracy and response time for new users. As users get familiar with this tactual coding method, they can reduce the duration difference between long and short signals accordingly.

It is clear that amplitude interferes with frequency, as both amplitude and frequency influence the intensity of stimuli. For example, both high amplitude and low frequency tend to present high intensity with respect to human perception; therefore, it is hard to tell the cause of the high intensity and to determine which character the vibration presents. We decided to keep frequency rather than amplitude, since frequency is more consistent when applied to other devices.

B. Coding

As presented above, frequency and duration are tuned to code different characters. Duration has two levels and frequency has no more than three levels. We propose two coding methods with the same number of levels of duration and different number of levels of frequency. As for duration, the duration of short signal was set as the basic unit of time (U) and the duration of long signals was set as four units (4U). It was reported in [21] that new users of tactual Morse code were able to discriminate short and long signals when the unit of time was longer than 100 ms; hence, our U was initially set to 100 ms. Next, informal observations on discrimination of short and long signals were conducted as U decreased. After an iterative process, we found that users were able to differentiate short signal from long signal when U was longer than 75 ms; therefore, U was set as 75 ms for all of the tests in this study. As for frequency, it is reported in [19] that people naturally categorise vibration into 'fluttering' ($10-70$ Hz) and 'smooth' (above 150 Hz). A similar adjustive process was conducted in our study. As for amplitude, the signal level for each frequency was adjusted to a comfortable level of sensation through an iterative process. The exact values of frequency and signal levels are presented in each coding method. The signal levels were specified in decibel (dB) relative to the maximum output of the system.

TABLE I: The coding table of a Vib for the 3F Vibraille.

Duration	Frequency	Code
short	low	1
short	medium	2
short	high	3
long	low	4
long	medium	5
long	high	6

1) 3F Vibraille: The first coding method is named 3F Vibraille, since three levels of frequency are employed (50 Hz, 100 Hz and 400 Hz). The corresponding signal levels are -14 dB, -14 dB and -12 dB, respectively. In this case, each slot of vibration (called a Vib) has six states (see Table I). Two consecutive Vibs have 36 possible combinations, which are enough to encode all the letters; hence two Vibs are set as a basic cell of 3F Vibraille and the duration between two Vibs (inter-Vib duration) equals U. The duration between letters (inter-letter duration) and between words (inter-word duration) equals 4U and 7U, respectively. Fig. 1 depicts an example of the 3F Vibraille.

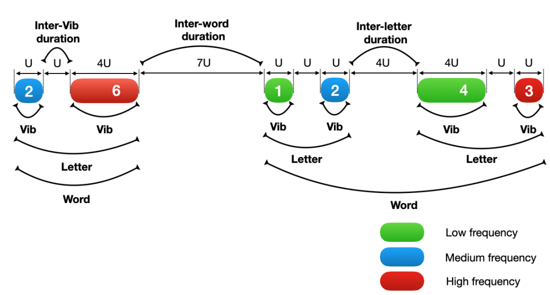

Fig. 1: An example of 3F Vibraille showing two words. Inter-Vib duration, inter-letter duration and inter-word duration equal U, 4U and 7U, respectively. The digits of Vibs correspond to the codes in Table I.

2) 2F Vibraille: The second coding method is named 2F Vibraille, since only two levels of frequency are utilised (50 Hz

TABLE II: The coding table of a Vib for the 2F Vibraille.

Duration	Frequency	Code
short	low	1
short	high	2
long	low	3
long	high	4

and 300 Hz). The corresponding signal levels are -14 dB and -14 dB, respectively. Each Vib contains four states (see Table II). Three consecutive Vibs (64 possible combinations) are required to code all the letters. The inter-Vib duration, inter-letter duration and inter-word duration of the 2F Vibraille are the same as that of the 3F Vibraille. An example of the 2F Vibraille is shown in Fig. 2.

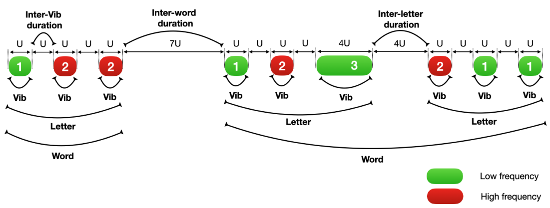

Fig. 2: An example of the 2F Vibraille showing two words. Inter-Vib duration, inter-letter duration and inter-word duration equal U, 4U and 7U, respectively. The digits of Vibs correspond to the codes in Table II.

Difference in levels of frequency results in difference in duration of the basic cell since U is kept the same for 3F and 2F Vibraille. 3F Vibraille uses two consecutive Vibs as a basic cell, while 2F Vibraille requires three consecutive Vibs to represent sufficient information. As a result, 3F Vibraille has advantages in efficiency. On the other hand, 2F Vibraille utilises only two levels of frequency. The users make two-alternative choices in terms of frequency; therefore it is expected that new users learn 2F Vibraille more quickly.

IV. Mapping of Vibraille Codes

Although the basic cells of both 3F and 2F Vibraille have more than 26 possible combinations, some of the combinations may be easily confused with others in terms of human perception. The only way to eliminate confusable combinations is to conduct human perceptual tests. After said tests, we kept the least confusable 26 combinations to encode the letters of the alphabet. During the mapping process, occurrence frequency of letters is considered to improve efficiency. More frequent letters are assigned to short codes. The specific mapping rules are described in Sections IV-B and IV-C. As for numbers and symbols, a method similar to contracted braille is designed and presented in each coding method.

A. Perceptual Tests

The experimental setup is shown in Fig. 3. Model NCM02-10-008-2JBA from H2W technologies was chosen as the vibrotactile display and an amplifier (MK190 from Velleman) was used to drive the actuator. The GUI interface was developed by ourselves for conducting the tests. Five normal-sighted participants (two females and three males) attended the initial perceptual tests. Such a sample size is typical for perceptual tests of tactual communication [21], [23]. All of the participants were right-handed and none of them had any problems with their sense of touch. None of them had any knowledge of the coding methods before the experiments. An initial mapping of Vibraille codes for each coding method was developed, so that participants could make decisions according to the mapping tables. Before the tests, the experimental setup and coding methods were introduced to the participants. Then they were given ten minutes to get familiar with the interface as well as the codes. As the tests began, each participant needed to complete two sessions of tests by holding the actuator with the left hand's thumb and index finger. In each session, a set of stimuli (the set covered all the Vibraille codes and each Vibraille code appeared three times) was presented one by one in a random order. After feeling a stimulus, the participants typed out which Vibraille code was presented according to the mapping tables without feedback. During the tests, the participants wore a headphone playing pink noise to exclude interference of the noise generated by the actuator.

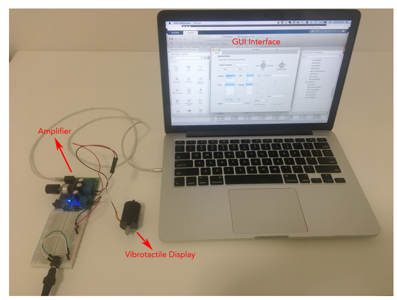

Fig. 3: The experimental setup consists of a vibrotactile display, an amplifier and a GUI interface.

B. 3F Vibraille

The initial mapping of the 3F Vibraille codes is shown in Table III. According to the results of the perceptual tests, a confusion matrix is built (see Fig. 4). There are 12 characters

TABLE III: Initial mapping table of the 3F Vibraille.

Code	11	12	13	21	22	23	31	32	33
Character	a	b	c	d	e	f	g	h	i
Code	14	15	16	24	25	26	34	35	36
Character	j	k	l	m	n	o	p	q	r
Code	41	42	43	51	52	53	61	62	63
Character	s	t	u	v	w	x	y	z	0
Code	44	45	46	54	55	56	64	65	66
Character	1	2	3	4	5	6	7	8	9

with recognition accuracy less than 80%, among which 'c' is only confused with 'b' and 'f'. If the Vibraille codes corresponding to 'b' and 'f' are removed, the recognition accuracy of the code corresponding to 'c' could be significantly increased. Hence we can keep the Vibraille code corresponding to 'c'. Besides, 'u' is only frequently confused with 't',

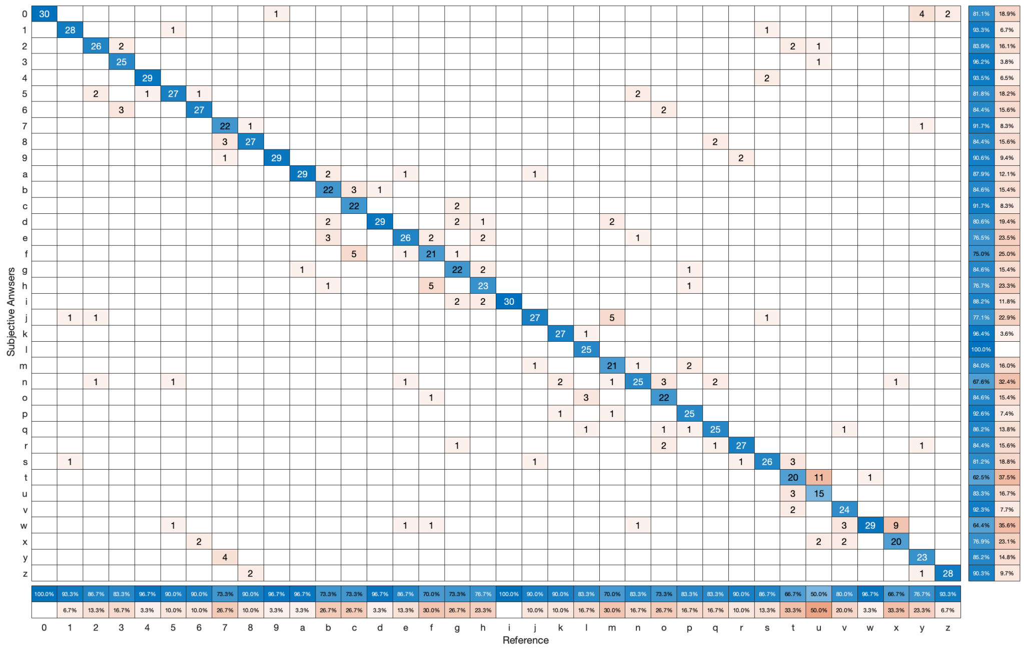

Fig. 4: The confusion matrix of the 3F Vibraille.

while ‘t’ is confused with several other characters; therefore, we can remove the code corresponding to ‘t’ and keep the code corresponding to ‘u’. All the other characters with a recognition accuracy of less than 80% are eliminated. After mapping the remaining 26 Vibraille codes to letters, another round of perceptual tests are conducted to confirm that the remaining Vibraille codes have a high recognition accuracy (see Table IV). It can be observed that almost all of the Vibraille codes have a recognition accuracy larger than 90%. In order to improve efficiency, the mappings are rearranged according to the frequency of occurrence of letters obtained from [28] (see Table V). The rules of reordering are as follows:

(i) More frequent letters are primarily assigned to Vibraille codes that have a short duration.
(ii) Within the same section of duration, more frequent letters are primarily assigned to Vibraille codes with a higher recognition accuracy.

For example, in Table IV, codes ‘11’ - ‘33’ have the shortest duration, codes ‘14’ - ‘63’ have medium duration and codes ‘44’ - ‘66’ have the longest duration. In the first section, codes are mapped to the most frequent letters ‘e’ - ‘a’. In the second section, as the accuracy varies with codes, rule (ii) is applied. For instance, ‘t’ is mapped to code ‘14’, ‘n’ is mapped to code ‘34’, etc. In the third section, the letters are mapped to codes using the same rules since accuracy varies with codes. The final mapping table of the 3F Vibraille for letters is shown in Table VI. As for numbers and symbols, two methods are designed as follows:

(i) A single-Vib cell is defined as a special indicator (SI); hence, there are 6 types of special indicators. An indicator is presented before a basic cell, so that the whole code can represent numbers, symbols or abbreviations. The interval between an indicator and a basic cell equals the inter-letter duration (4U).
(ii) An extra Vib is concatenated after a basic cell. The interval between the extra Vib and the basic cell equals inter-Vib duration (U). The integrated Vibraille codes are called special Vibraille codes that contain three Vibs.

TABLE IV: Second mapping table of the 3F Vibraille.

Code	11	13	21	22	33			
Character	a	b	c	d	e			
Accuracy	100%	100%	100%	100%	100%			
Code	14	15	16	25	34	35	36	
Character	f	g	h	i	j	k	l	
Accuracy	100%	93.3%	96.7%	90%	100%	96.7%	96.7%	
Code	41	43	51	52	62	63		
Character	m	n	o	p	q	r		
Accuracy	90%	96.7%	93.3%	100%	90%	100%		
Code	44	45	46	54	55	56	65	66
Character	s	t	u	v	w	x	y	z
Accuracy	100%	93.3%	83.3%	100%	100%	96.7%	93.3%	100%

TABLE V: The occurrence frequency of letters in descending order.

Rank	1	2	3	4	5	6	7	8	9	10	11	12	13
Letter	e	i	r	o	a	t	n	s	l	c	p	m	d
Rank	14	15	16	17	18	19	20	21	22	23	24	25	26
Letter	u	h	g	y	b	f	v	k	w	x	z	j	q

TABLE VI: Final mapping table of the 3F Vibraille.

Code	11	13	21	22	33			
Character	e	i	r	o	a			
Code	14	15	16	25	34	35	36	
Character	t	u	c	g	n	p	m	
Code	41	43	51	52	62	63		
Character	y	d	h	s	b	l		
Code	44	45	46	54	55	56	65	66
Character	f	z	q	v	k	x	j	w

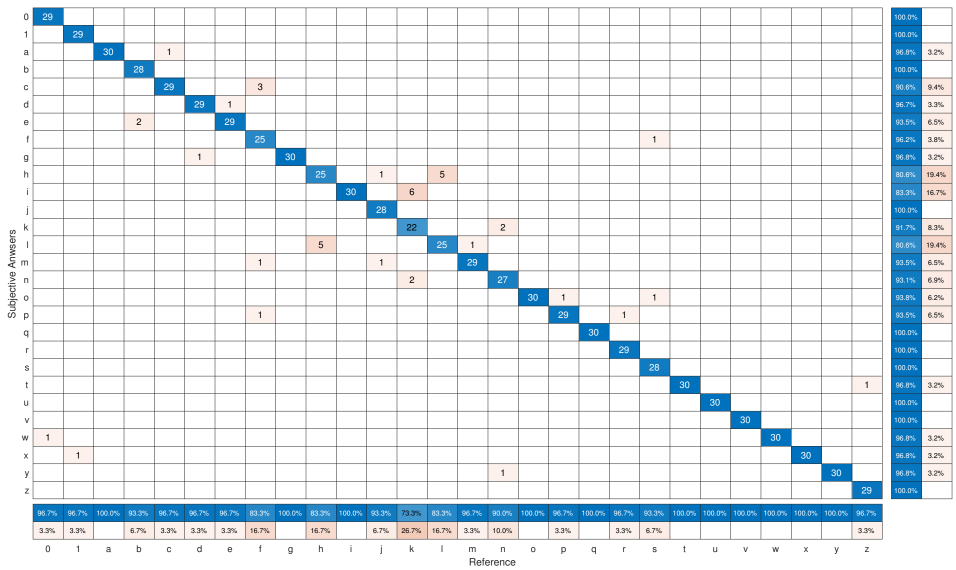

Fig. 5: The confusion matrix of the 2F Vibraille.

In order to increase the recognition accuracy of symbols and numbers, only the Vibraille codes that have high recognition accuracy, i.e. ‘t’, ‘y’, ‘f’, ‘g’, ‘s’, ‘k’, ‘m’, ‘l’ and ‘w’, are chosen. In total, there are 108 ($9 \times 6 \times 2$) special Vibraille codes that can be used to code numbers, symbols, etc. The first type of special Vibraille codes are particularly useful for representing continuous numbers or symbols. For instance, ‘t’ - ‘w’ with the special indicator are used to represent numbers ‘1’-‘9’. In other words, ‘SI w’ stands for ‘1’, ‘SI y’ stands for ‘2’, etc. To present continuous numbers, we only need to use one indicator. For example, ‘21357’ is presented using ‘SI y t f s m’ rather than ‘SI y SI t SI f SI s SI m’ (the in-between interval equals inter-letter duration). That is, any letters after the special indicator now represent numbers until an inter-word duration terminates the string of numbers. In this case, the efficiency is significantly improved. On the other hand, the second type of special Vibraille codes can be used to represent standalone symbols.

C. 2F Vibraille

For 2F Vibraille, there are 64 possible combinations to choose from. Through preliminary tests, we find that people are easier to recognise Vibraille codes with neighbouring Vibs having the same code, such as, ‘111’, ‘222’, ‘112’, ‘122’, etc. Hence, we only chose the Vibraille codes that have the form of ‘AAA’, ‘AAB’ and ‘ABB’, which gives us 28 possible combinations. After setting an initial mapping to these Vibraille codes (see Table VII), the confusion matrix is obtained through perceptual tests (see Fig. 5).

First, it is shown that Vibraille codes starting with ‘3’ and ‘4’ have a higher recognition accuracy than codes starting with ‘1’ and ‘2’. Second, there are four codes that have a relatively low recognition accuracy (‘f’,‘h’,‘k’ and ‘l’). ‘h’ and ‘l’ constitute a perfect confusable pair. If the Vibraille code of one of them is modified, the recognition accuracy of both codes can significantly increase. To this end, we change the Vibraille code of ‘h’ from ‘221’ to ‘232’ which is unlikely to be confused with other codes. On the other hand, the Vibraille codes corresponding to ‘f’ and ‘k’ are removed. Now there are 26 Vibraille codes left and they are used to build the second mapping table (see Table VIII). Another round of perceptual tests is conducted and the results show that all of the Vibraille codes have a recognition accuracy larger than 93.3%. The Vibraille codes are also divided into sections according to duration, so that it can be easily rearranged according to the occurrence frequency of letters. Besides, the occurrence frequency of bigrams is also considered, since it is found that people are more likely to recognise neighbouring Vibraille codes starting with the same Vib. The rules of the final mapping are as follows:

(i) More frequent letters are primarily assigned to Vibraille

TABLE VII: Initial mapping table of the 2F Vibraille.

Code	111	112	113	114	122	133	144
Character	a	b	c	d	e	f	g
Code	221	222	223	224	211	233	244
Character	h	i	j	k	l	m	n
Code	331	332	333	334	311	322	344
Character	o	p	q	r	s	t	u
Code	441	442	443	444	411	422	433
Character	v	w	x	y	z	0	1

TABLE VIII: Second mapping table of the 2F Vibraille.

Duration	5U			8U		11U		14U		
Code	111	112	122	113	114	144				
Character	a	b	c	d	e	f				
Accuracy (%)	100	93.3	96.7	100	96.7	96.7				
Code		222	211	232	223	233	244			
Character		g	h	i	j	k	l			
Accuracy (%)		100	100	96.7	93.3	100	96.7			
Code				311	322	331	332	333	334	344
Character				m	n	o	p	q	r	s
Accuracy (%)				96.7	100	100	100	100	100	100
Code				411	422	441	442	433	443	444
Character				t	u	v	w	x	y	z
Accuracy (%)				100	96.7	96.7	96.7	100	100	100

codes that have a short duration.

(ii) Within the same section of duration, more frequent letters are primarily assigned to Vibraille codes with a higher recognition accuracy.

(iii) According to the rank of bigrams [28], the letters ‘e’, ‘i’, ‘r’, ‘o’, ‘t’ and ‘n’ are assigned to Vibraille codes starting with ‘1’. The rest of the codes are rearranged accordingly.

The final mapping table of the 2F Vibraille is shown in Table IX. The same methods as for the 3F Vibraille are applied to code numbers, symbols, etc. The Vibraille codes used for this purpose are ‘e’, ‘s’, ‘k’, ‘q’, ‘i’, ‘n’, ‘a’, ‘f’, ‘v’, ‘p’, ‘c’, ‘l’, ‘m’, ‘x’ and ‘z’. In total, there are 120 ($15 \times 4 \times 2$) special Vibraille codes that can be used to code numbers, symbols, etc.

TABLE IX: Final mapping table of the 2F Vibraille.

Code	111	112	113	114	122	144	
Character	e	r	o	t	i	n	
Code	232	222	223	211	233	244	
Character	d	s	u	a	f	v	
Code	331	332	333	334	311	322	344
Character	h	g	k	w	p	l	x
Code	441	442	443	444	411	422	433
Character	y	b	j	q	c	m	z

V. Vibraille Codes Identification

To evaluate the legibility and performance of the Vibraille codes, eight normal-sighted volunteers were recruited to identify words of different lengths and symbols. Four participants (one female and three males) attended the tests of the 3F Vibraille and they were denoted as $F1-F4$, since 3F Vibraille was the fast Vibraille code. Another four participants (three females and one male) attended the tests of 2F Vibraille and they were denoted as $S1-S4$, since 2F Vibraille was the slow Vibraille code. This sample size was the same as that of the tests reported in [21], [23]. None of the participants had any problems with their sense of touch. Their ages ranged from 26 to 30 years old and they were recruited through advertisements. As the proposed Vibraille was a brand-new coding method, no participants had prior knowledge of it before the tests. Only participants F2 and S1 had experience of vibrotactile psychophysical tests before. All of the participants attended a training session to learn the Vibraille codes. The experimental setup is the same as the one presented in Section III except the GUI interface. The GUI interface is shown in Fig. 6. ‘Test1’ is for word identification and ‘Test2’ is for symbol identification. As for ‘Coding’, ‘Method 1’ stands for 3F Vibraille and ‘Method 2’ represents 2F Vibraille. Other functions are introduced in the following sections.

A. *Training*

The training session was divided into two phases. First, the participants were trained to identify individual letters. After this phase, the participants were able to distinguish 26 letters with short response time. However, we found that it was hard to identify words even if the participants passed the first phase of training. It turned out that the interval between letters was too short for participants to react as the first phase only required participants to identify a single letter each time. To help participants learn how to identify words, the second phase was designed to let participants get used to perceiving strings of letters. As to the number of letters in a string, we found that a two-letter string did not work, since the participants intended to first keep the pattern of Vibs in memory and only translated them into letters after perceiving the whole string. However, a word normally contained more than two letters. As the number of letters increased, it got harder to accurately remember all of the Vibs; therefore, word identification required the participants to rapidly and sequentially process letters one by one. According to our pilot tests, it was unlikely to retain Vibs of more than three letters. As a result, three-letter strings were chosen in the second phase of training.

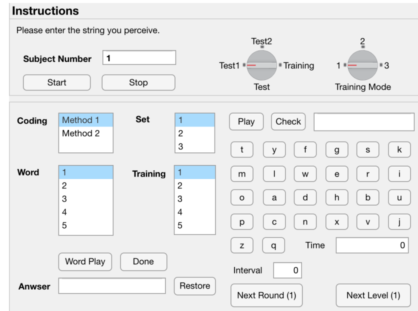

Fig. 6: The GUI interface of Vibraille codes identification.

1) Single Letter Identification: The Koch method is demonstrated to be one of the simplest and fastest ways to learn Morse code [29]. The participants start to learn a fundamental group of letters and conduct identification tests with correct answer feedback. If they achieve an accuracy of 90%, they can upgrade to the next level, in which another group of letters are added to the current group. They repeat this process until they learn all of the letters. For Morse code, the fundamental group normally contains two letters and only one letter is added at each level. Through the pilot tests, we found that this method worked for the Vibraille codes as well; however, learning all letters one by one was quite difficult and inefficient. Such exhausting tests resulted in a demotivation of learning and inaccuracy of identification. To improve the efficiency and learning experience of the training session, the letters were divided into 5 sets according to the perceptual characteristics. For instance, ‘e’,‘r’, ‘i’, ‘o’ and ‘a’ for 3F Vibraille containing only short Vibs are assigned to one set, so that the participants can easily learn how to distinguish them before these letters are mixed up with other letters. The size of the fundamental group and added groups of letters are chosen accordingly. The details of grouping for 3F Vibraille and 2F Vibraille are depicted in Table X and Table XI, respectively.

For 3F Vibraille, two Vibs of a letter in Set 1 have same frequency. Set 2 contains letters that only have short Vibs. The frequency of two Vibs of a letter varies in both Sets 3 and 4; however, the letters in Set 3 start with a long Vib, while the letters in Set 4 begin with a short Vib. Set 5 includes the remaining letters that only have long Vibs. Set 6 is a full set of all of the letters. As to 2F Vibraille, three Vibs of a letter are the same in Set 1. Both Sets 2 and 4 have the structure of 'ABB' with the letters in Set 2 starting with a short Vib and the letters in Set 4 beginning with a long Vib. On the contrary, Sets 3 and 5 have the structure of 'AAB'. The letters in Set 3 start with a short Vib, while the letters in Set 5 begin with a long Vib. Similarly, the last set covers 26 letters.

For each set, the participants learn the letters level by level. At each level, the participants firstly use 'Training Mode 2' (see Fig. 6) to freely explore the letters and then conduct tests in 'Training Mode 1'. The letters are presented in a random order and each letter appears twice. After perceiving a stimulus (participants can only perceive it once), the participants respond by picking a letter in the GUI interface and the response time of each trial is recorded. The measurement of response time begins at the offset of the stimulus and ends at the onset of the participants' input of answers. The participants upgrade to the next level only if the following criteria are met: i) two rounds of tests with a recognition accuracy over 90% are achieved; and ii) the mean response time is less than 1.5 s.

TABLE X: Grouping of single letter identification for the 3F Vibraille.

	Level 1	Level 2	Level 3	Level 4	Level 5
Set 1	t y f	g s k	m l w		
Set 2	e r	i	o	a	
Set 3	d h	b			
Set 4	u p	c	n		
Set 5	x j	z	q	v	
Set 6	t y f g s k m l w	e r i o a	d h b	u p c n	x j z q v

TABLE XI: Grouping of single letter identification for the 2F Vibraille.

	Level 1	Level 2	Level 3	Level 4	Level 5
Set 1	e s	k	q		
Set 2	i n	a	f	v	
Set 3	r o	t	u	d	
Set 4	p c	l	m	x	z
Set 5	h g	w	y	b	j
Set 6	e s k q	i n a f v	r o t u d	p c l m x z	h g w y b j

2) Three-letter Identification: Meaningless strings of three letters are used in this training phase. Through pilot tests, we found out that the participants were unable to identify strings if the inter-letter duration was set to be 4U; therefore, we applied the Farnsworth method [30]. The inter-letter duration was initially set to be twice as the response time, so that the participants could get familiar with perceiving consecutive letters. The inter-letter duration was then reduced gradually to increase the reading speed. The results of pilot tests showed that it got harder to decrease the inter-letter duration when the reading speed got higher. In other words, the inter-letter duration should not be reduced linearly. The interval between levels needed to decrease as reading speed increased (see Table XII). For a round of tests, the participants needed to perceive 26 strings of three random letters (each letter appeared exactly three times) and to respond by entering a string in the GUI interface without correct answer feedback. The participant started from level one and could upgrade to the next level only if the following criterion was met: one round of test with accuracy (identification of the whole string) over 90% was achieved. If the participants could not significantly improve the recognition accuracy over five rounds of tests, this training phase terminated and inter-letter duration at the last level was recorded for tests of word identification.

TABLE XII: Inter-letter duration of three-letter identification.

Speed	Level 1	Level 2	Level 3	Level 4	Level 5
Inter-letter duration	40U	35U	30U	25U	21U
Speed	Level 6	Level 7	Level 8	Level 9	Level 10
Inter-letter duration	17U	14U	11U	9U	7U
Speed	Level 11	Level 12	Level 13		
Inter-letter duration	6U	5U	4U		

B. Tests

1) Word Identification: The words used in this test were chosen from [31]. 90 common words were obtained and the length of words ranged from two to five. The ratio of word length accorded with the length-frequency statistics presented in [32] (see Table XIII). The words were evenly divided into three word groups and the participants needed to complete all of the groups one by one. On each trial, the participants clicked 'Word Play' in the GUI Interface (see Fig. 6) to perceive the stimulus of a word, then responded by typing out the word in the box of 'Answer'. No correct answer feedback was provided. Every word was presented only once and the words in each word group were arranged in a random order.

TABLE XIII: Ratio of word length for tests of word identification.

Word length	2	3	4	5
Number of words	21	30	24	15

2) Symbol Identification: As mentioned, there are 108 and 120 special Vibraille codes for 3F Vibraille and 2F Vibraille, respectively. However, these codes were not assigned to specific symbols at this stage. For the convenience of testing, the special Vibraille codes were temporally represented by the formation of the special Vibraille codes. For example, letter 't' followed by an extra Vib with short duration and low frequency (see Table I) is coded as 't1' for 3F Vibraille. Similarly, if a Vib with short duration and medium frequency is used as a special indicator before letter 't', the special Vibraille code can be expressed using '2t'. Before the tests, the structure of special Vibraille codes was introduced to the participants. As the tests began, the participants were exposed to three groups of special Vibraille codes one by one. Each group included the whole set of the special Vibraille codes arranged in a random order. On each trial, the participants perceived the stimulus of a special Vibraille code and responded by typing out the answer. No correct feedback was given.

VI. Results and Discussion

All of the participants attended the tests of word and symbol identification, although they spent different amounts of time in the training session. The details of their performance in terms of training process, word identification and symbol identification are discussed in this section.

A. Single Letter Training

As mentioned, sets 1-5 contained only a part of the letters while set 6 contained 26 letters. Sets 1-5 were to help participants to get familiar with the vibration and codes, whereas set 6 was to make sure that participants can recognise all of the letters. The learning process of sets 1-5 for 3F and 2F Vibraille is shown in Table XIV. For simplicity, only the last level that contains all of the letters in each set is depicted. The digits under each set demonstrate the number of rounds of tests it takes a participant to meet the criteria. First, participants S1-S4 conducted less rounds of tests on average than participants F1-F4. For 3F Vibraille, all of the participants completed set 3 easily, since it only contained three letters, while the other sets varied with participants. For 2F Vibraille, all of the participants finished all of the sets easily. It suggests that 2F Vibraille is easier to learn than 3F Vibraille (this will be further discussed in section VI-C where the total training time is presented).

Table XV demonstrates the learning process of set 6 for 3F and 2F Vibraille. There are 5 levels in set 6 (see Table X and Table XI). The digits under each level stands for the number of rounds of tests it takes a participant to meet the criteria. For both Vibraille coding methods, participants took only a few rounds to finish level 1, since level 1 was the same as set 1. Participants took relatively more rounds to meet the criteria in the following levels as more letters from other sets were added. In this case, participants needed to discriminate not only letters within a set but also letters among different sets. Although the total number of rounds of test varied per participant, all of the participants could recognise 26 letters with an accuracy of over 90%. The details of the learning process are depicted in figures which can be found in the supplemental materials.

TABLE XIV: For sets 1-5, the number of rounds of tests it takes a participant to meet the criteria in single letter training.

Participant	Set 1	Set 2	Set 3	Set 4	Set 5
F1	4	5	2	4	3
F2	2	2	2	3	3
F3	9	6	2	5	15
F4	4	5	3	8	4
S1	2	2	2	2	2
S2	2	3	3	3	3
S3	2	2	2	2	3
S4	2	3	2	3	3

TABLE XV: For set 6, the number of rounds of tests it takes a participant to meet the criteria at each level in the single letter training.

Participant	Level 1	Level 2	Level 3	Level 4	Level 5
F1	2	3	4	4	5
F2	2	2	3	2	3
F3	4	12	10	5	3
F4	6	5	10	3	8
S1	2	2	2	3	2
S2	2	2	3	5	7
S3	3	6	4	5	8
S4	2	4	9	6	5

B. Three-letter Training

Table XVI depicts the learning process of the three-letter training for 3F Vibraille and 2F Vibraille. Almost all of the participants took more than four rounds to complete the first level even though they could recognise single letters within a quite short response time. This is because recognising strings of letters is quite a different experience from single letter recognition. Participants needed to remember previous letters as they perceived current letter. However, they normally achieved a consecutive success in the following levels once they got used to perceiving continuous letters. Most participants mentioned that the increased speed was not obvious until the interval between letters was very low (at around level 8). It normally took quite a few rounds (2-5) for the participants to meet the criteria after level 8. Once a participant could not make significant progress over five rounds, the participant stopped training and the last level was recorded. The highest level achieved by participants were thus different. For instance, participant F2 achieved level 13, which meant that the inter-letter duration was 4U (see Table XII). The highest levels of all participants and corresponding inter-letter duration are shown in Table XVII. The details of the learning process of three-letter training are depicted in figures which can be found in the supplemental materials.

TABLE XVI: The number of rounds of tests it take a participant to meet the criteria at each level in three-letter training (‘L’ stands for ‘Level’).

Participant	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13
F1	5	1	2	1	2	1	3	3	4	5	4	3	
F2	2	1	2	1	1	4	2	2	4	3	5	3	5
F3	4	4	1	2	2	1	4	4	5				
F4	5	3	1	3	3	1	2	4	2	5	3	4	
S1	2	1	1	1	1	1	1	2	1	5	2	2	4
S2	5	1	1	1	2	2	1	5	4	5	5		
S3	5	1	1	4	1	1	1	5	2	4	2		
S4	5	1	4	2	1	3	2	1	2	1	1		

TABLE XVII: Highest levels achieved by participants in three-letter training.

Subject	F1	F2	F3	F4	S1	S2	S3	S4
Highest level	12	13	9	12	13	11	11	11
Interval	5U	4U	9U	5U	4U	6U	6U	6U

C. Word Identification

Table XVIII shows the word recognition accuracy and character recognition accuracy. The word recognition accuracy is calculated as the number of correct words (the entire word needs to be correct) over the total number of words, while character recognition accuracy is calculated as the number of correct letters (the letter needs to be in the right position in a word) over the total number of letters. As for 3F Vibraille, all participants achieved more than 90% word accuracy with an average above 95%. The character recognition accuracy was even higher. As for 2F Vibraille, all participants achieved high word recognition accuracy although the scores obtained by participants S3 and S4 are relatively low. The average word recognition accuracy was 92.50% and the average character recognition accuracy was 96.53%. Fig. 7 depicts the word recognition accuracy with respect to word length. It is shown that five-letter word has the lowest accuracy for both 3F Vibraille and 2F Vibraille. However, the lowest word recognition accuracy (80%) of a five-letter word is sufficiently high as the participants are only trained to recognise three-letter strings.

In terms of statistical analysis, a two-way 3×2 (word group $\times$ coding method) ANOVA test is applied. The results show that the effect of the encoding method is statistically insignificant ($F(1, 18) = 3.677, p = 0.071$). In other words, the word recognition accuracy of 3F Vibraille is not significantly larger than that of 2F Vibraille. The effect of word group ($F(2, 18) = 1.706, p = 0.210$) and interaction effect ($F(2, 18) = 0.356, p = 0.705$)) are also statistically insignificant. As to the number of letters in a word, however, the effect of word length is statistically significant ($F(3, 72) = 7.148, p \leq 0.005$).

Fig. 8 demonstrates the training time of 3F Vibraille and 2F Vibraille. As to single letter identification, the training time of 3F Vibraille ranges from 3.38 h to 4.19 h, while that of 2F Vibraille is from 2.65 h to 3.69 h. The average training time of 2F Vibraille is about 0.7 h less than that of 3F Vibraille. It suggests that it is easier to learn 2F Vibraille. However, the training time also depends on participants; as one can see, participant S2 has spent more time than participants F2 and F3. As to three-letter identification, the average training time of 2F Vibraille is also less than that of 3F Vibraille. Consequently, the average training time in total of 2F Vibraille is about 1.48 h less than that of 3F Vibraille. Besides, it is clear that experienced participants F2 and S1 have spent the least time in both training sessions, which accords with the findings reported in [21]. As to statistical analysis, the ANOVA test shows that the training time of 2F Vibraille is significantly less than that of 3F Vibraille ($F(1, 6) = 8.930, p = 0.024$).

TABLE XVIII: Results of word identification (the number in the bracket shows the standard deviation across three word groups).

3F Vibraille	F1	F2	F3	F4	Average
Word accuracy	97.78% (0.019)	97.78% (0.038)	94.44% (0.069)	95.56% (0.019)	96.39% (0.012)
Character accuracy	99.33% (0.006)	98.68% (0.023)	98.35% (0.021)	98.68% (0.006)	98.76% (0.004)
2F Vibraille	S1	S2	S3	S4	Average
Word accuracy	96.67% (0.033)	95.56% (0.051)	88.89% (0.038)	88.89% (0.077)	92.50% (0.033)
Character accuracy	98.34% (0.015)	98.34% (0.015)	95.38% (0.023)	94.06% (0.051)	96.53% (0.017)

D. Symbol Identification

Table XIX shows the recognition accuracy of both types of special Vibraille codes. All of the symbols are composed of basic cell and fundamental Vibs. As a result, all participants achieved high recognition accuracy even though they conducted the tests without specific training for symbols. The average recognition accuracy of 3F Vibraille is 93.34%, while that of 2F Vibraille is 93.33%. In terms of statistical analysis, the main effects of symbol group ($F(2, 18) = 1.105, p = 0.353$) and coding method ($F(1, 18) = 0.000068, p = 0.993$) are statistically insignificant.

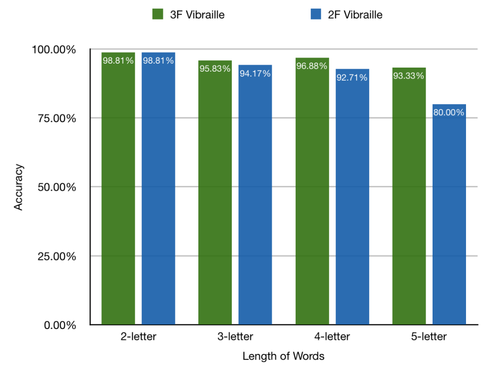

Fig. 7: Word recognition accuracy with respect to word length.

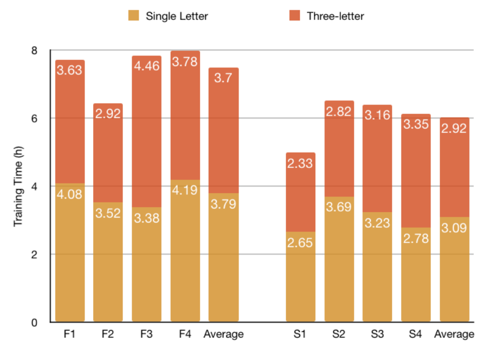

Fig. 8: Training time with respect to single letter and three-letter identification.

E. Comparison with Other Tactual Communication Systems

Multi-actuator systems normally achieve high transmission rate since they utilise an extra dimension of information (such as, space). For instance, [23] employed a 6-actuator glove to code letters using vibration. Experiments were conducted in the manner of free response. The results demonstrated that the participants could recognise common words with an accuracy of 94% at 13.33 characters per second (cps). However, such multi-actuator system requires each actuator to be precisely deployed on the human body. Displacement of any actuator affects the recognition accuracy. Due to the same reason, the portability and comfort of the device are also limited. Utilisation of multiple actuators increases the cost of the device as well. Considering portability and comfort, only one actuator is utilised in our methods; therefore we explicitly compare our methods with tactual communication that uses one actuator only [20], [21], [33].

The authors of [20] utilised a piezoelectric actuator to deliver vibration and to represent letters depending on braille. Two vibrational patterns were designed to stand for 'bumped' and 'flat' dots, respectively; therefore, it required six Vibs to present a letter. The experiments were conducted to evaluate the performance in the manner of free response. The participants spoke out the answers after perceiving a stimulus with correct answer feedback. The results showed that an 83% recognition accuracy of single letter identification and 0.41 cps were achieved. On the contrary, we proposed two new coding methods that did not rely on braille. Only three or two Vibs

TABLE XIX: Results of symbol identification (the number in the bracket shows the standard deviation across three symbol groups).

3F Vibraille	F1	F2	F3	F4	Average
Recognition accuracy	94.91% (0.017)	96.30% (0.011)	96.30% (0.021)	85.88% (0.028)	93.34% (0.018)
2F Vibraille	S1	S2	S3	S4	Average
Recognition accuracy	95.56% (0.035)	94.44% (0.032)	90.53% (0.032)	92.78% (0.025)	93.33% (0.026)

were required to present a letter. The speed of 3F Vibraille and 2F Vibraille was 2.10 cps and 1.39 cps, respectively. The recognition accuracy of single letter identification was above 90%. On the other hand, reading speed of traditional Grade I braille was about 5.36 cps [22]. Although the transmission rate of Vibraille was lower than that of traditional braille, we believe that this transmission rate is applicable to the scenario of conveying short messages. Words and symbols were not considered in [20], while our method achieved more than 90% recognition accuracy for both word and symbol identification.

Morse code in terms of vibrotactile signals was experimented in [21]. On each trial, the participant was presented with a string of Morse code and then typed out the answers in response. Immediate correct answer feedback was provided. It took more than 5.75 h for new users to achieve about 95% accuracy of single letter identification and more than 9 h to achieve about 70% accuracy of three-letter identification. Fig. 8 shows that the training time of our method was less than that of Morse code. This may be due to the consistency of our method: The letters of our methods have fixed number of Vibs, while the number of Vibs of different letters varies in Morse code. The recognition accuracy of single letter identification (more than 90%) was comparable to Morse code, while the recognition accuracy of three-letter identification (more than 90%) was much better than Morse code. In terms of speed, the "PARIS" standard was used in [21], while there is apparently no such standard for our method at this stage. However, we can compare the average duration of 26 letters: The average duration reported in [21] was about 600 ms, whereas 3F Vibraille achieved 476 ms and 2F Vibraille achieved 721 ms. For Morse code, the average duration significantly increases if numbers and symbols are included; this is because numbers and symbols consist of more than 5 Vibs. As to our method, numbers and symbols contain 4 Vibs at most, hence the average duration will only slightly increase.

Instead of vibration, the authors of [33] utilised stretch to code information. Three tactile alphabets were designed and single-letter identification was experimented in the manner of free response. The participants typed out the answer to respond to a stimulus without correct answer feedback. The results demonstrated that all of the tactile alphabets achieved high recognition accuracy ($80-97\%$) with speed ranging from 0.34 cps to 0.45 cps. It is clear that our methods significantly outperform the alphabets using stretch in terms of efficiency.

F. Discussion

We have shown that both 3F Vibraille methods and 2F Vibraille methods are capable of conveying information at a high accuracy. It took approximately $2.65 - 4.19$ h for participants to learn and recognise the alphabets. Participants reported that it was difficult at the beginning and it became easier as they got more familiar with the vibration patterns. After another training session of consecutive letters, the participants were able to recognise words. Some participants reported that three-letter words were easily recognised, while a few four-letter and five-letter words were obtained by deduction. This was because the training of strings is limited to three letters. In practice, the participants are supposed to learn and memorise Vibraille words directly once they can recognise the alphabet, just as what people do to learn a language. Furthermore, it has been demonstrated that almost all of the special Vibraille codes are recognisable without any further training. Currently, the special Vibraille codes are not assigned to specific symbols since the standardisation of symbols needs to take many factors into account and requires further work from a variety of people. Overall, our methods achieve good performance in terms of speed and recognition accuracy. 3F Vibraille is fast, while 2F Vibraille is friendly to new users. The participants can decide which one to learn accordingly. More importantly, we have designed recognisable symbols that almost none of the previous tactual communication has considered.

VII. Conclusions

Two methods, i.e. 3F Vibraille and 2F Vibraille, for representing letters and symbols were proposed in this paper. The former was more efficient, while the latter was easier to learn. Experiments were conducted to examine word and symbol identification. The results have shown that participants have achieved an average recognition accuracy of over 90% with 6-8 hours' training. In terms of future work, the training session can be optimised further to decrease training time. Another direction is to build a wearable device that can be connected with smartphones and design an app for people to learn Vibraille codes conveniently. Besides, only isolated word and symbol identification have been considered in this paper; identification of sentences that combines words and symbols at higher levels of abstraction needs to be investigated in a later study so as to fully assess the performance of Vibraille. Apart from consuming the Vibraille codes, the capability of expressing (inputting) is worth researching. Currently, the refreshable braille display has 6-8 buttons which requires users to use both hands for typing, while our methods require as few as four buttons. For 3F Vibraille, five buttons are required, with two representing duration and the other three representing frequency. 2F Vibraille requires only four buttons that represent four states of a Vib, respectively. However, the implementation, process, efficiency and accuracy of input require diligent future studies.

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