Designing and Evaluating a Vibrotactile Language for Sensory Substitution Systems

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Abstract. The sense of touch can be used for sensory substitution, i.e., to represent visual or auditory cues to impaired users. Sensory substitution often requires the extensive training of subjects, leading to exhaustion and frustration over time. The goal of this paper is to investigate the ability of the subjects to recognize alphanumeric letters on 3×3 vibration array, where the subjects can fully personalize the variables including spatial location, vibratory rhythm, burst duration and intensity. We present a vibrotactile device for delivering the spatiotemporal letter patterns while maintaining the high level of expressiveness. The results prove that this system is an effective solution with a low cognitive load for visually/auditory impaired people and for any context that would benefit from leaving the eyes/ears free for other tasks.

Keywords: Vibrotactile display · Sensory substitution · Wearables · Haptics

1 Background

The skin has been considered as a conduit for information [1, 2], where a vibrotactile display can be added by an array of vibration actuators, with the resolution varying from 2×2 to 64×64 [3] and mostly applied to the skin on the back, abdomen, forehead, thigh, or the fingers. In [4], a camera image is transformed into vibrotactile stimuli using a dynamic tactile coding scheme. The resolution of the image needs to be reduced to fit the low resolution of the *tactor array* as their system consists of 48 (6×8) vibrating motors. The authors also compared their method (M1) in tactilely displaying of the letter with two other typical continuous vibration modes [5, 6]. The first one is an improved handwriting pattern, and the actuation order is similar to handwriting. The vibrating duration time is overlapped between the adjacent motors (M2). In another approach, called scanning mode (M3), the motors are triggered in the lines from top to bottom. As an initial study in pattern identification task, the capital letters were displayed to experienced and inexperienced subjects, using a 20×20 matrix of vibratory tactors placed against the back [6]. Authors reported the results of four modes of stimulus presentation, each letter being presented 42 times under each mode. They found that the sequential tracing by a single moving point leads to the highest recognition accuracy. A tactile stimulator (M8) mounted on a wheelchair is presented in [7], to convert the capital letters into tactile letters using 17×17 Tactile Vision Substitution Systems (TVSS). The dark

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region of the visual display captured by a stationary camera activated the tactors in the corresponding areas of the tactile matrix. Each black line of a letter drawn on a white cardboard activated a line of two tactors wide in the tactile matrix. The experiments demonstrate that at least three independent basic letter features i.e. enclosing shapes, vertical parallel lines, and angle of lines play important parts in tactile letter recognition.

The possibility of differentiating letters by using only a 3×3 array of vibrating motors on the back of a chair has been examined in [8], by providing a sequential pattern for each letter with a “tracing mode.” This work (M9) could obtain high recognition rate in reading tactile alphanumeric characters. Recently, a system of spatiotemporal vibration patterns called EdgeVib, for delivering both alphabet (M10) and digits (M11) on wrist-worn vibrotactile display was presented in [9]. Each unistroke pattern longer than four vibrations is split into multiple 2/3-vibration patterns. The new patterns are consecutively displayed to assist the recognition of the alphanumerical patterns. The study revealed that the recognition rate is significantly improved by modifying the unistroke patterns in both alphabet and digits. Factors such as familiarity with the displayed character set, stimulus duration, inter-stimulus onset interval, type of vibration motors, number of trials, number of letters, and cognition load affect the quality of recognition. Therefore, different studies cannot be directly compared. The results along with some details are brought in Table 1. The discrepancy between studies is due to the differences in equipment, procedure, and style of letters. As summarized in Table 1, the subjects had no time limits for letter perception. Moreover, most of the previous studies only focused on a subset of alphanumerics, and the participants

Table 1. Previous published results.

Vibration modes	Average recognition rate	Cognition load (average repeated times)	Number of letters
M1	82.0% ± 23.3%	2.05	10
M2	76.8% ± 23.5%	2.1	10
M3	47.5% ± 27.5%	2.6	10
M4	34%	$1–2^{\alpha, \beta}$	26
M5	41%	$1–2^{\alpha, \beta}$	26
M6	47%	$1–2^{\alpha, \beta}$	26
M7	51%	$1–2^{\alpha, \beta}$	26
M8	67.53% ± 20%	$1^{\alpha, \gamma}$	26
M9	86% ± 9.7%	1^{α}	34
M10	85.9% ± 6.3%	NA^{δ}	26
M11	88.6% ± 10.4%	NA^{δ}	10

α: The subjects had no time limits for letter perception and they were given as much time to respond as they needed.
β: If the first response was incorrect, they responded with the second guess, after which they were informed of the correct response.
γ: The subjects were trained until they had acquired an identification accuracy of over 80% in each subset of alphabet. The error correction was given when the subjects misidentified. The number of trials per subject was not the same.
δ: After training session, a brief test was performed to ensure that each participant memorizes the patterns correctly. The participants could ask to repeat the questions if they were not confident of their answers. After they gave their answer, the screen prompted the actual answer.

were informed of the correct response. To overcome these limitations, we develop a customizable vibrotactile system to deliver any patterns including all alphanumerics under time constraints for letters perception.

2 The Proposed System

Our tactile display is implemented on an adjustable belt attached on the back of a human. The system comprises nine cylindrical Eccentric Rotating Mass (ERM) motors (8.7 mm in diameter and 25.1 mm in length), Fig. 1(a). The motors are glued to the belt with a spacing of 5 cm (see Fig. 1(c)). This gap between tactors is necessary to perform vibration localization robustly. The motors control the intensity and have fine temporal haptic characteristics (8 ms from off to a perceivable intensity, 21 ms from fully on to off using active breaking with H-bridges). The intensity of the tactors is controlled by Pulse Width Modulation (PWM) signals. The vibration intensity is set to 10 levels from very low to very high. To fully control each motor individually, we used Adafruit 16-Channel 12-bit PWM Driver Shield that can drive up to 16 motors over I2C with only two pins (see Fig. 1(b)). The on-board PWM controller will simultaneously drive all 16 channels with no extra processing overhead. Therefore, the system can incorporate the control of a vast number of different feedback devices into a single and unified interface. The shield plugs in directly into an Arduino device, which also provides the 5 V power to power and control the PWM signal.

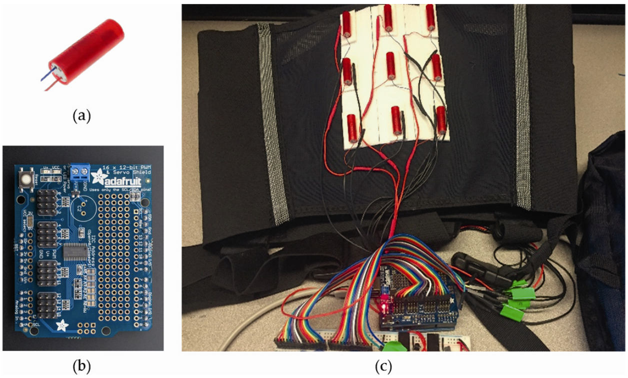

Fig. 1. (a) 9 mm vibration motor from Precision Microdrive, model: 307-103, (b) 16-Channel 12-bit PWM Driver Shield, (c) Back belt with 3×3 tactor array

In the proposed platform, the users have full control on the motors variables including spatial location, vibratory rhythm, burst duration, and intensity to generate vibratory patterns. For this purpose, a Graphical User Interface (GUI) is developed to create or revise the patterns and to optimize the temporal-spatial tactile coding according to human tactile perception. Two experiments are conducted with the 3×3 tactors array to evaluate the customizable tactile display perception. We report the recognition rate of letters with both default and personalized vibratory patterns.

Algorithm 1 describes the test cases, where each session contains a number of trials with randomly selected characters. Algorithm 2 extracts changes in the motors (events) from the input pattern (line 2). The events stored in an array control the motor operations and 10 intensity levels, defined in line 9. Tactors are activated based on the vibrating order, spatial and temporal properties in lines 10–12.

Algorithm 1. Test_Cases

```
Input: testCase, defaultPatterns, customizedPatterns; output: recognitionRate
alphaNumerics ← 'ABCDEFGHIJKLMNOPQRSTUVWXYZ0123456789';
numberOfRounds ← 3;
switch testCase {
    case: 'alphaNumericsRecognition_def' {
        targets ← randomPermutation (alphaNumerics(1:end));
          % Make a random order of alphanumeric
        hapticPatterns ← extractPatterns (targets, defaultPatterns); }
        % Extract the haptic patterns for the targets according to the default pattern
    case: 'alphaNumericsRecognition_per' {
        targets ← randomPermutation (alphaNumerics (1:end));
        hapticPatterns ← extractPatterns (targets, customizedPatterns); }
        % Extract the haptic patterns for the targets according to the personalized
          pattern through GUI
    for i = 1:1: numberOfRounds
        for j ← 1:1: length (hapticPatterns)
            runHaptic (hapticPatterns (j));
            % Generate each pattern on the vibration motors
    recognitionRate ←accuracy (confMat (targets, userResponses));
return recognitionRate;
```

Algorithm 2. runHaptic

```
Input: hapticPattern;
1. resetVibMotors (1:9); % Turn off all 9 motors
2. [events, intensities] = FetchEvents (hapticPattern);
   % Extract the events from the pattern (i.e. default pattern or customized pattern). Events is a
     time-sorted array. events(i): is 1 if a motor should be turned on at this time, events(i): is 0 if
     a motor should be turned off at this time. intensities(i): intensity of the vibration motor which
     is turned on at this time.
3. i = 0;
4. while (1) {
5.     i = i + 1;
6.     wait (t_i); % Wait till it is time for next event.
7.     selectedMotor = events (i).motor;
8.     if (events (i)) { % If at this time a vibration motor should be turned on
9.         intensity = (((maxPW – minPW) × (intensities (i)) / 10) + minPW;
10.        setPWM (selectedMotor, intensity); }
           % Turn on a vibration motor with the determined intensity
11.    else { % If at this time a vibration motor should be turned off
12.        setPWM (selectedMotor, 0); } % Turn off a vibration motor
13.    if (i == length (events))
14.        break; }
```

3 Experiment Setup

We first conduct an experiment consisted of two sessions of vibrotactile pattern identification tasks, before and the other after the development of each subject's personalized letters. The experiment is carried out with ten healthy volunteers (five males, five females) aged 18 to 46 with (Mean ± SD) 30.70 ± 8.87. The ethical approval was received from McGill Ethics Committee. The participants had no experience of vibro-tactile display devices, were asked to wear the belt in upright sitting position and to match felt sensations with the alphabets or digits. They had a time limit of 2 s for letter perception, and no chance to repeat the presented tactile stimuli. To have a more realistic scenario, they were not allowed to use any headset to block out the sound caused by the vibrators and environment. We wanted to analyze the results with a minimum cognitive load that is calculated by the average repeated time for the subject to conduct the letter's identification [4]. In the training phase, the subjects knew the characters they perceived through 3×3 tactile grid display. The training and testing phases are composed of 108 (3×36) trials with 3 sets of randomly selected characters. Figure 2 illustrates the sequence of tactors activated in the default patterns setting designed by a left-handed supervisor. There is no time interval between the onsets of stimuli, and the stimulus duration is set to 200 ms.

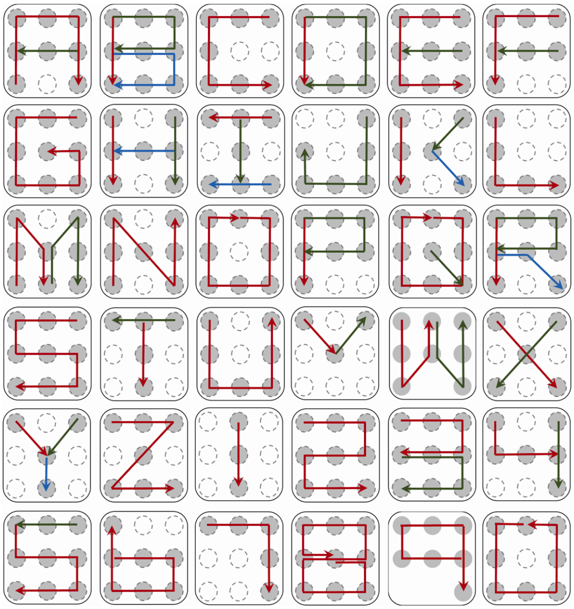

Fig. 2. The sequence of tactors to be activated 36 different alphabets and digits in the default version - The arrows orders: red, green, and blue. (Color figure online)

The default settings help the participants to perceive the letter as a continuous stroke. In the second session, the subjects could revise the default patterns through the GUI. Indeed, each subject can turn the motors on and off in succession and therefore they could customize the tactors' vibration patterns with any preferences such as following their own writing habit. Personalizing the spatiotemporal vibration patterns could deliver more information with easier interpretation and memorizing. Therefore, this property greatly facilitates the users to distinguish the letters.

4 Experimental Results

Figure 3(a) shows the participants' confusions between stimuli with the default patterns. Each cell value of the matrix C (i, j) shows the total number of trials that the response 'j' occurred upon the presentation of stimulus 'i'. The results show that the subjects readily recognize the patterns under mean identification rate of 70.83% ± 24.65%, with a low cognitive load. The subjects reflected that sometimes they had difficulty in distinguishing the patterns different from their own writing habit such as letter 'E'. The patterns 'E' and '7' presented to the participants tended to get highly confused with letters 'G' and '1', respectively. The letter 'O' and number '0' activated the same dot matrix patterns, but they can be discriminated by the direction of the activated tactors. Most participants reported that sometimes they judged a pattern according to their own writing habits. We expect they may be less likely to be confused by revising the spatial locations, stimulus duration and directions, etc. The subjects had a time limit of 2 s and no chance to repeat the stimuli. These constraints are beneficial for the multi-character words. In the second session, where each subject was allowed to make modifications to the default patterns, there is a more uniform confusion matrix (see Fig. 3(b)). For instance, letters 'X' and 'Y' have similar patterns directions, and subjects can apply an alternative writing sequence to create more differentiable patterns. Figure 4 shows some more effective alternative patterns for letters, where the participant used higher level of intensities for letters 'A' and '7' (tick arrows). As seen in Fig. 5, customizing the vibrotactile patterns improved the recognition accuracy by 22.49%. A student's t-test revealed that the customized patterns achieved significantly higher recognition rates than the default patterns (86.76% ± 9.44% vs. 70.83% ± 24.65%, $p\text{-value} \ll 0.01$). Among the numbers, the number '2' yielded the best accuracy (96.67%) and '5' was the worst (56.67%). For letters, 'I' and 'J' yielded the best accuracy (100%) and the lowest letter accuracies are: 'V' (70%), 'Y' (70%) and 'G' (73.33%). As seen in the confusion matrix, still some letters ('Q' and 'G') exhibited asymmetries. Although the updated patterns increase the total vibratory delivery time, they resolve the confusion between letters and reduce the misrecognition rates. The misidentifications are more likely due to time constraints for letters' perception. Contrary to other studies, the participants could not repeat the questions and the error correction was not given when the subjects misidentified. These constraints are beneficial for the multi-character words. Another observation worth highlighting is the reduction of 'Missed' answers (57.85%) after revising the letters. The subjects could judge the pattern in the first two seconds, and their performance would be improved by tuning the vibratory variables again and practicing them for a couple of more trials.

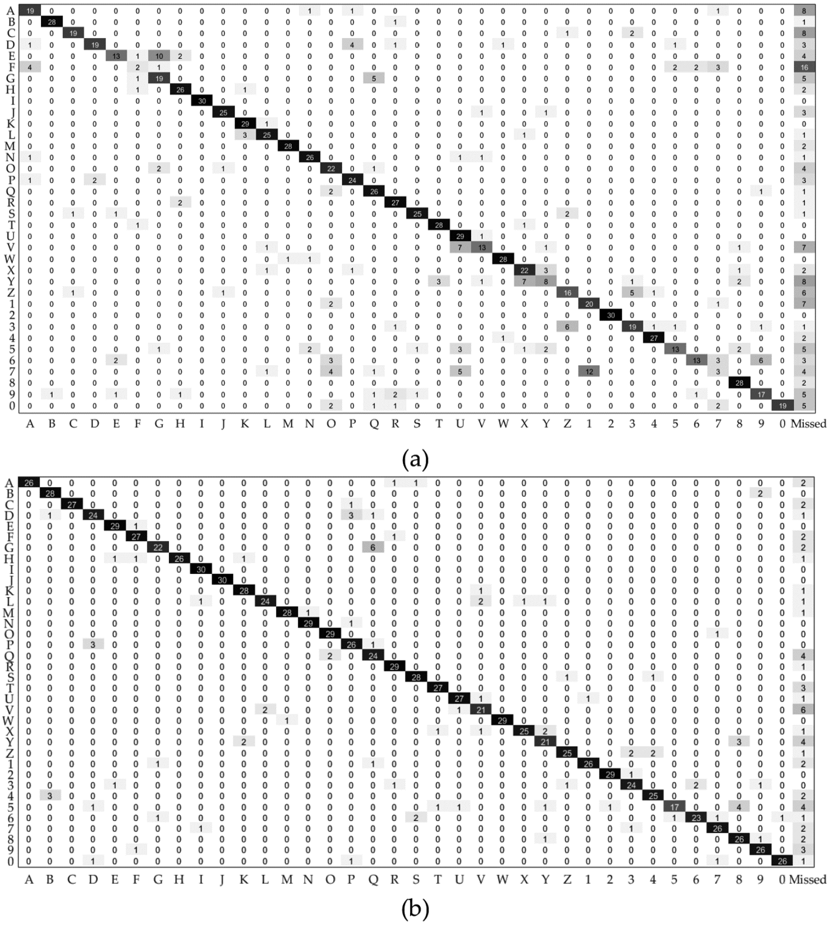

Fig. 3. Confusion matrices for the recognition of (a) default patterns, (b) customized patterns

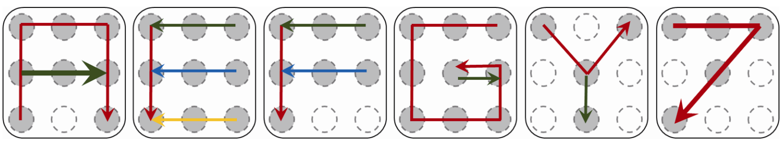

Fig. 4. Examples of customized patterns by one of the participants

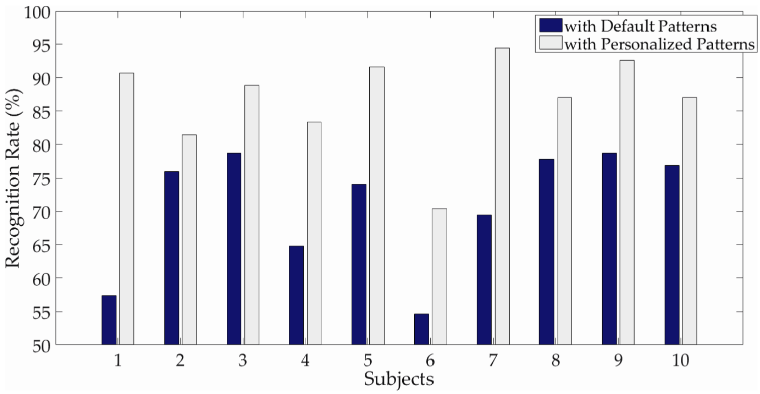

Fig. 5. Recognition rates with default and personalized patterns for each subject

5 Conclusion

We presented a tactile display and the experiments conducted to investigate its effectiveness. The results reveal that the customizable low-resolution vibrotactile display alleviates the perceptional and memory loadings of the users to recognize new patterns with no extensive training sessions. Personalized tactile instructions can be a major component of an assistive wearable device for people with hearing and visual impairments. The applicability and usability can be extended to color and multi-character messages identification tasks.

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