International Conference Interfaces and Human Computer Interaction 2017

# HANDS-FREE READING BRAILLE WITH A VIBROTACTILE WRISTBAND

Simon Schätzle[1], Bernhard Weber[1], and Benedikt Leichtmann[2]
[1]*German Aerospace Center (DLR), Institute of Robotics and Mechatronics,*
*Muenchener Str. 20, 82234 Wessling, Germany*
[2]*Universität der Bundeswehr München, Human Factors Institute,*
*Werner-Heisenberg-Weg 39, 85579 Neubiberg, Germany*

## ABSTRACT

In this paper, a new approach to display Braille is presented. Braille dots are mapped to six tactors of a vibrotactile wristband. The dot patterns of characters are displayed with adequate vibrotactile stimuli generated by the tactors. Compared to the conventional way of reading Braille, the advantage of the proposed approach is that there is no need to commit a hand to active Braille dot scanning and thus, the hand is still free for other activities or tasks.

In a user study, different methods of mapping Braille to the wristband with respect to the assignment of cell dots to tactors as well as temporal aspects were evaluated using objective performance data and subjective ratings. Even with little training, promising results were obtained. Sequential mapping methods performed better than parallel methods and characters could be correctly recognized in up to 97% of cases.

## KEYWORDS

Vibrotactile Feedback, Braille, Assistive Technology for Blind People.

## 1. INTRODUCTION

As a consequence of an impairment or loss of visual perception, blind or visually impaired people depend on their auditory and haptic channel for receiving information. It is well known that blind people can partially compensate the loss in visual channel by improving other senses like their haptic abilities. Several studies showed better tactile spatial acuity of blind in comparison to sighted people (Wong et al., 2011; Goldreich and Kanics, 2003; Goldreich and Kanics, 2006; Legge et al., 2008). Particularly for deaf-blind persons or when acoustic presentation of information to blind people is impossible or uncomfortable, using Braille is a common way to convey information. Braille is a tactile writing system with tiny palpable bumps used to represent letters through raised dot patterns. Each letter is coded with six dots in a matrix with two columns and three rows. Usually, embossed paper or electronic braille displays are used as output. In any case, the fingertip is necessary to feel the text which means that the hand cannot be used for other purposes while reading Braille.

In this paper, we introduce a new approach of presenting information to blind or visually impaired people without using their auditory channel and without blocking the hand for other activities or tasks. To this, tactile stimuli generated by a vibrotactile wristband are used. A review of the state-of-the-art reveals the potential of (vibro-)tactile feedback and the variety of applications such as sensory substitution, spatial orientation, navigation and motion guidance, exploration of virtual environments, communication, messages and multimedia in which tactile displays (Benali-Khoudja, 2004) have been deployed (Choi and Kuchenbecker, 2013; Jones and Sarter, 2008; Elliot et al., 2009). Depending on the application, the stimulation is applied to different locations such as fingertip (Galambos, 2012), hand (Yang et al., 2009), arm (Bark et al., 2011; Bosman et al., 2003; Kapur et al., 2010; Lehtinen et al. 2012; McDaniel, 2010; Piateske and Jones, 2005; Tadakuma and Howe, 2009), torso (Lindemann et al., 2006; Schroeder et al., 2015, Van Erp, 2004) or foot (Meier et al., 2015).

The design of vibrotactile displays and relevant issues such as the spatial and temporal resolution of the skin, the absolute and differential perception thresholds, spatial masking, apparent location, temporal enhancement, adaptation and frequency, amplitude and duration of stimuli have been intensively investigated and published in useful guidelines (Jones and Sarter, 2008; Cheung et al., 2008; Cholewiak and Collins, 2003; Cholewiak et al., 2001; Pongrac, 2006; Van Erp, 2002; Choi and Kuchenbecker, 2013). Furthermore, the conveyance of semantic information through vibrotactile stimuli has been explored with variations in the number and placement of tactors as well as in the modulation of signals (Pietrzak et al., 2009; Nicolau et al., 2013; Brown, 2007; Brewster and Brown, 2004; Yatani, 2009). The so-called "Vibratese" (Geldard, 1957) for example used five tactors on the upper body to encode information with variations in intensity and signal length. Similar to that, "Optohapt" used nine vibration motors that are scattered over the body (Geldard, 1966).

Besides the output of semantic information, displaying Braille with vibrotactile stimuli is not a novelty (Guerreiro, 2013). With UbiBraille, Nicolau et al. (2013) mapped Braille to six vibrotactile actuators that were attached to the user's index, middle and ring finger of both hands. Inspired by writing Braille characters, raised cell dots are displayed with vibrotactile stimuli on the fingers that are commonly used to write the given Braille character. Compared to this mapping, we pursue the idea of assigning cell dots to tactors based on a projection of the Braille cell into the cross section of the arm (see Fig. 1). Furthermore, in contrast to the simultaneously output of raised dots in the study of Nicolau et al., we also evaluated sequential and simultaneous methods.

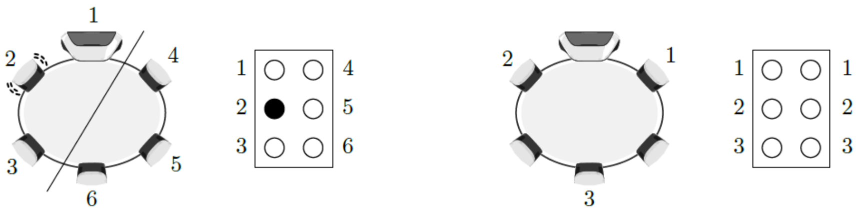


Figure 1. Assignment of Braille dots to the tactors if all tactors of VibroTac (left) or if only three tactors (right) are used

Other approaches known in the state-of-the-art uses touchscreens of mobile devices to display Braille vibrotactilly with the disadvantage that the hands are engaged in the reading process (Rantala, 2009; Jayant, 2010; Al-Quadah, 2011). Furthermore, individual encodings e.g. in the latter case (combinations of raised and unraised dots within a Braille character column is displayed through different encodings inspired by the Morse code) lead to high training effort.

In contrast to such approaches with own coding schemes, we use the well-known writing system Braille. Thus, only the mapping of the six dots to the six tactors of the wristband has to be learned. Compared to directly reading Braille with the fingertip, using VibroTac as a display for Braille is expected to be advantageous in situations where the user's hands need to be available for manipulative tasks (e.g. in the context of professional integration) or when usual tactile displays are complicated to use (e.g. while moving or as navigation hints e.g. "Caution, rotating door" on travel). Even though we expect the vibrotactile Braille reading to be slower than classical Braille reading, the proposed approach should be well suited to convey short messages.

This paper reports a user study we performed to evaluate the general usability of this approach and of VibroTac for displaying Braille characters. We designed different mapping methods that appeared reasonable to us and compared them in terms of performance data and subjective ratings. Due to the difficulty of recruiting blind people for such a time-consuming evaluation, we decided to conduct this study with sighted people. Consequently, the study was designed in a way that Braille literacy is not required: subjects had to reproduce the presented dot patterns on a print-out of blank characters without identifying the characters themselves. Though we expect better results for blind people as they are superior in tactile acuity and perception tasks than sighted people (Goldreich, 2003), further studies with blind people will be necessary (see section 6 for future work).

As the number of different methods claims high demand in terms of effort and required time of subjects, the evaluation experiments were split into two parts. In a pilot study (see section 4) with four subjects, we aimed at the evaluation of all presented methods in terms of usability and at the reduction of the number of methods. In the main study (see section 5), a selection of the best methods was investigated in detail with 18 subjects.

## 2. THE VIBROTACTILE WRISTBAND VIBROTAC

The vibrotactile output of Braille is realized with VibroTac (see Fig. 2), a tactile feedback device which was developed at the German Aerospace Center (DLR). This battery driven and wireless controllable wristband comprises six vibration motors (tactors) that are distributed around the arm in equal distances. Each of the tactors can be separately and continuously adjustable in frequency and shape (Schätzle et al., 2010).

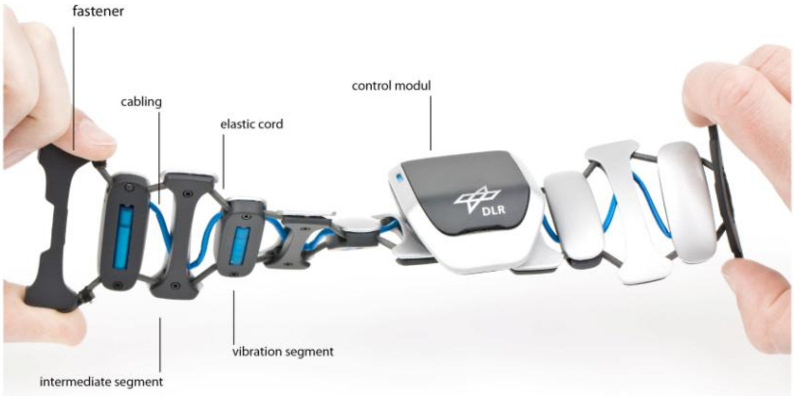


Figure 2. The vibrotactile wristband "VibroTac" with six tactors which is used to display Braille through vibrotactile stimuli

As the six dots of Braille cells are mapped to the six tactors of VibroTac, the spatial acuity with which the user is able to distinguish and localize the stimulation’s position is crucial (for the user’s performance). In a study with sighted people, even with very little training, a mean correct detection rate of approx. 95% was determined (Schätzle and Weber, 2015). It can be assumed that the tactile perception of blind people is more precise, resulting in even higher correct detection rates.

Besides the requirement of a reliable localization of activated tactors, the ability to present stimuli at different tactor locations that are perceived with equal magnitude is not less important. Information is not only transmitted by variations of signal shape and length but also by the intensity of the stimuli. As the perceived magnitude of stimuli with a certain frequency differ depending on the tactors’ locations e.g. on the ulna, radius, muscle or fatty tissue, calibration factors for VibroTac were determined (Schätzle and Weber, 2015). Applying these factors to the commanded intensities allows for similar perception magnitudes of vibrotactile stimuli at the six different tactor locations around the human wrist.

Due to the ability of VibroTac to present spatially separated stimuli with six tactors that can be distinguished reliably and that can be controlled individually in signal shape and intensity, the device is well-suited as a haptic display for Braille.

## 3. MAPPING BRAILLE TO VIBROTAC

Mapping Braille to the six tactors of VibroTac can be realized in different ways. On the one hand, this concerns the assignment of cell dots to the single tactors, on the other hand the temporal aspects of stimuli patterns can be varied. We designed eight different mapping methods that appeared reasonable. Prior studies on VibroTac revealed that impulses with a signal length of approx. $T_{on} = 0.3$ s and with 30 % of maximum available intensity were perceived as pleasant. The resulting frequency of the stimulus is approx. 90 Hz.

As described below, unraised dots are displayed with signals of less intensity, resulting in stimuli with approx. 50 Hz and a perceived magnitude of approx. 25 % compared to the stimuli of raised dots. In two of the following methods, only three tactors were used in order to compare two configurations with different distances between the tactors and to check for potential better results due to a more reliable spatial distinction of activated tactors.

### *A) Sequential Methods*

Braille cells are run through in a sequential way starting with the dot in the left column from first to third line followed by the right column from first to third line.

#### *1) Sequential (SQ)*

Raised dots are displayed with signal length $T_{on}$ = 0.3 s and a subsequent signal pause $T_{off}$ = 0.4 s. Before the next character is started, the output is paused for the duration $T_{wait}$.

#### *2) Sequential rotated (SQ-ROT)*

Analogous to method “SQ” but with VibroTac worn 30° rotated counterclockwise so that the separation line between the two columns is orientated vertically.

#### *3) Sequential raised/unraised (SQ-R/UR)*

Analogous to method “SQ” but additionally, unraised dots are presented with a signal of less intensity than the signal of a raised dot. Signal times for raised and unraised dots: $T_{on}$ = 0.3 s, $T_{off}$ = 0.15 s) and $T_{wait}$ between characters.

#### *4) Semi-sequential (SSQ)*

Analogous to method “SQ” but with a short break $T_{break}$= 0.4 s between the columns of a character.

### *B) Parallel Methods*

Several raised dots are displayed simultaneously.

#### *5) Parallel (P)*

All Raised dots are displayed with signal length $T_{on}$ = 1.0 s and a break $T_{wait}$ is inserted before the next character is started.

#### *6) Semi-Parallel (SP)*

First, all raised dots of the left column are displayed with signal length $T_{on}$ = 1.0 s and after a break $T_{break}$ = 1.0 s, all raised dots of the right column are displayed simultaneously and finally $T_{wait}$ is added before the next character is started.

### *C) Three Tactors-Methods*

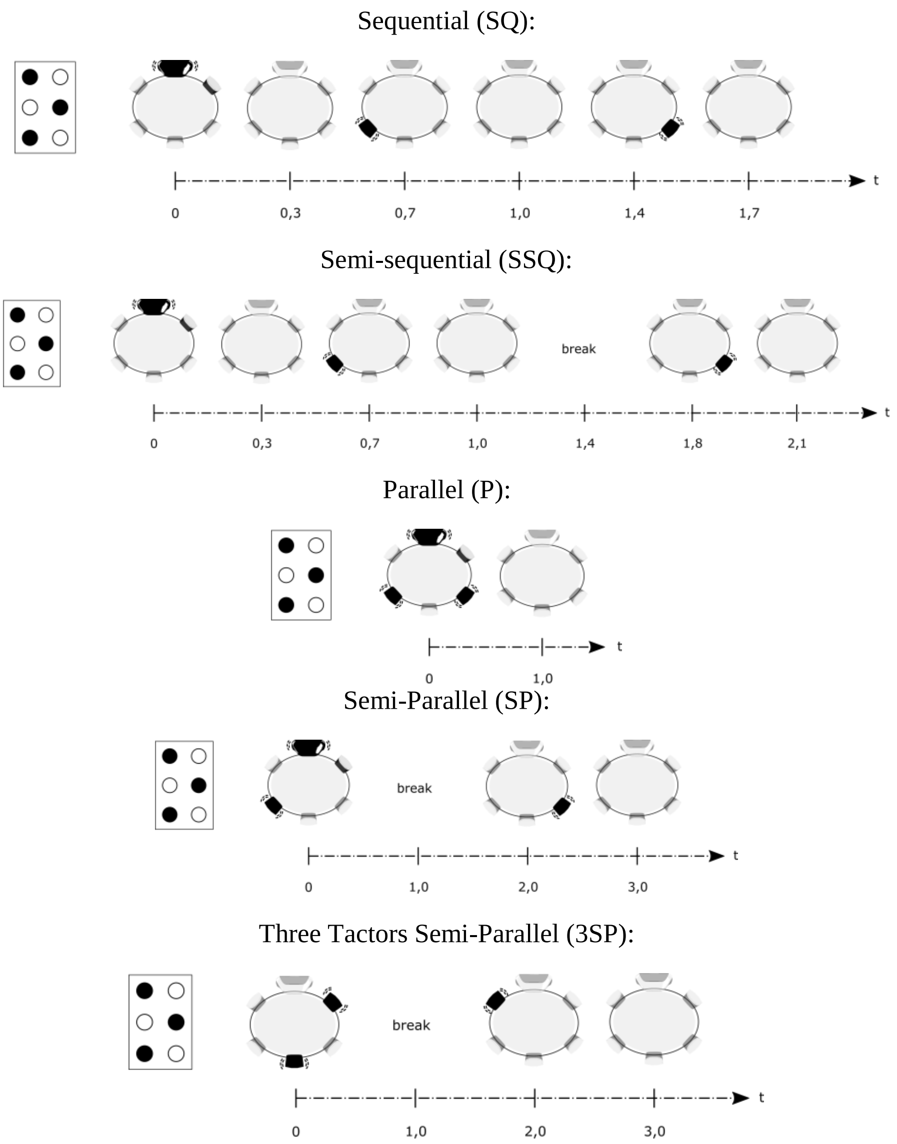
In these methods, only three tactors (see Fig. 1, right) of the device are used. In consequence, the distances between the tactors are larger and hence better result might be obtained due to a more reliable distinction of the activation patterns.

#### *7) Three Tactors Semi-Parallel (3SP)*

Analogous to method “SP”

#### *8) Three Tactors Sequential raised/unraised (3SQ-R/UR)*

Analogous to method “SQ-R/UR”



Sequential (SQ):

Semi-sequential (SSQ):

Parallel (P):

Semi-Parallel (SP):

Three Tactors Semi-Parallel (3SP):

Figure 3. Schematic representation of mapping methods with different timing aspects

## 4. PILOT STUDY

In the pilot study, four sighted subjects (1 female, 3 male, with ages ranging from 22 to 34) participated.

### 4.1 Methods

The VibroTac was worn close to the wrist. The subjects sat on a chair and laid their hand relaxed onto the table such that the VibroTac did not touch the table surface. Ear protection generating white noise was worn in order to avoid acoustical influence of vibrating tactors. Calibration factors determined in a prior study (Schätzle and Weber, 2015) were applied to adjust the single tactor intensities so that perception magnitudes of vibrotactile stimuli are similar at all six different tactor locations, as information is also coded with the stimulus intensity.

Subjects were familiarized with VibroTac with three short impulses displayed successively at each tactor. Subsequently, the six dots of the Braille cell were presented sequentially with vibrotactile stimuli on the corresponding tactors in order to familiarize subjects with the dot-tactor assignment (see Fig. 1). Then, the recognition of complete characters was trained ten times by displaying different characters (from the set of characters depicted in Fig. 4) with the sequential (SQ) and the parallel (P) methods respectively. Each character was repeated three times before subjects had to mark the detected raised dots into a printed blank Braille cell and feedback was given by the investigator. Ear protection generating white noise was worn in the training phase and in the studies to avoid acoustical influence.

Each subject ran through a test series with all eight methods in randomized order and with nine different characters randomly chosen from a set of characters (see Fig. 4). The upcoming method was demonstrated with an example and was trained three times analogously to the training described above. Afterwards, a randomly selected character from the set of characters was displayed and subjects were asked to mark the recognized dots on the printed blank Braille without feedback of the investigator.

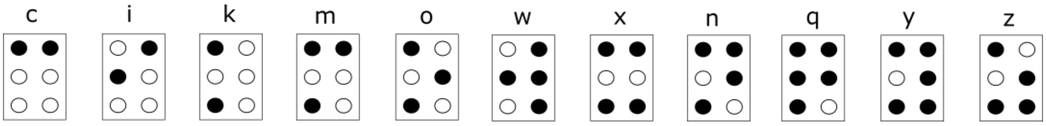


Figure 4. Braille codings of different characters as examples of dot patterns that were used in the studies. The characters were grouped into easy letters (only 2 raised dots) and in difficult letters (3 – 5 raised dots). Braille literacy is not required for the conduction of the studies as dot patterns had to be recognized only instead of identifying Braille characters

This procedure was conducted for nine characters per method. Besides objective data (e.g. correct recognition of raised and unraised dots), subjective ratings (e.g. difficulty and learnability) were gathered before the next method was started. After the third and sixth run, a recovery break was inserted in order to avoid adaptation effects and fatigue.

## 4.2 Results

As can be seen in Fig. 5, better results were obtained with sequential methods (1-4, 8) than with parallel methods (5-7) for the correct recognition of characters/dot patterns.

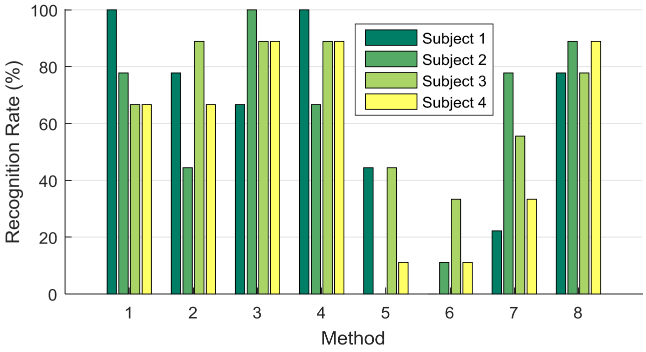


Figure 5. Correct recognition of vibrotactile displayed characters in Braille coding for eight different methods

Similarly, the subjective ratings of the different methods in terms of the difficulty to recognize characters (see Fig. 6, left) and the learnability (see Fig. 6, right) revealed the worst ratings for the parallel methods (5-7). Method 2 (SQ-ROT) with the rotated configuration of VibroTac did not improve performance compared to method 1 (SQ). Furthermore, the additional pause between left and right column in method 4 (SSQ) did not lead to a substantial improvement in the objective and subjective results.

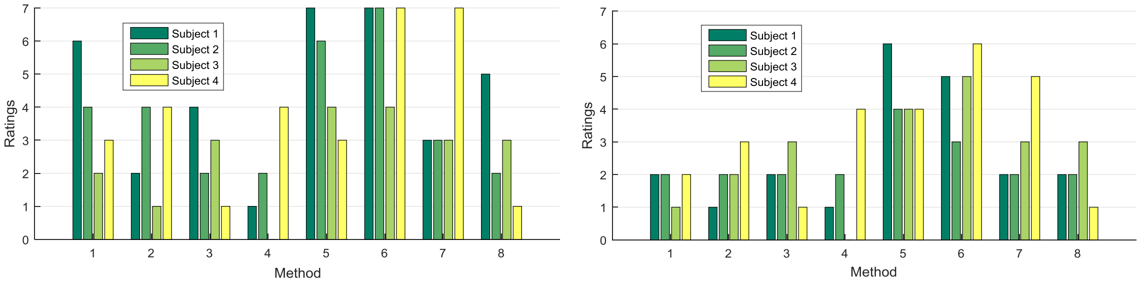


Figure 6. (left) Subjective ratings of the difficulty to recognize characters for different methods (Likert scale from 1 = very easy to 7 = very difficult) and (right) subjective ratings of the learnability to recognize characters for different methods (Likert scale from 1 = very easy to 7 = very difficult)

Method 3 (SQ-R/UR) and method 8 (3SQ-R/UR) yielded similar results. The increased distances between tactors when using three tactors only (method 8) compared to the method with same temporal condition but with six tactors (method 3), had no significant effect on the correct character recognition. The results indicate as expected that the parallel methods are more difficult to process and learn compared to the sequential methods.

## 4.3 Conclusion

In the pilot study, encouraging results were obtained for the mapping of Braille to a vibrotactile wristband with six tactors. With some methods very high recognition rates were obtained even without extensive training. The results indicate that the two sequential (SQ and SQ/R-UR) as well as the semi-parallel (3SQ) methods are the most promising methods and thus should be further evaluated in more details and with more subjects.

Despite of the moderate results in terms of character recognition and rated learnability obtained with parallel and semi-parallel methods, these variations of mapping should not be discarded completely. After initial difficulties, intensive training might lead to good results with the advantage of a high reading rate. Therefore, the method “Three Tactors Semi-Parallel” is also further investigated in the main study.

# 5. MAIN STUDY

In the main study, the mapping of Braille to the VibroTac is evaluated for three methods that have been selected in the pilot study. These are: “sequential”, “sequential raised/ unraised” and “Three Tactors Semi-Parallel”. Furthermore, the difficulty of the characters was varied to explore potential Method x Difficulty interaction effects.

## 5.1 Method

For the main study, N = 18 (7 female, 11 male) sighted individuals (employees of the German Aerospace Center; $M_{age}$ = 28.4; SD =7.2 with an age range from 16 to 48 years) were recruited. None of them participated in the pilot study. First, a written description of the experiment was handed out and subjects signed an informed consent document. The experimental setup (posture, hand positioning and calibration factors) was the same as described in the pilot study.

Subjects were familiarized with the VibroTac and its tactor positions: successively, three impulses were displayed at each tactor ($T_{on}$ = 0.6 s and $T_{off}$ = 0.5 s) and a second time with $T_{on}$ = 0.3 s and $T_{off}$ = 0.4 s. Afterwards, vibrotactile stimuli according to method “SQ” were displayed in order to learn the assignment of Braille dots to the corresponding tactors. After this, each single dot was displayed in randomized order and had to be marked on a printed blank Braille cell. The experimenter fed back whether the answer was correct or not.

In a within-subject design with randomized condition order, eight randomly chosen characters were presented in each condition, two of those characters being easy (only two raised dots) and six being difficult (more than two raised dots). Again, subjects were asked to mark the detected dot pattern on the printed blank Braille without feedback of the experimenter. Before the test series was started, each upcoming method was demonstrated by an example and four different characters were trained with feedback of the investigator. As in the pilot study, ear protection generating white noise was worn in order to avoid acoustical influence. At the end of each condition, a questionnaire on mental workload and method appropriateness had to be filled out. For measuring mental workload, the item "mental demand" of the NASA-TLX (Hart and Staveland, 1988) was used ("How mentally demanding was the task? Was it simple or complex?"; Likert scale from 1 (very low/simple) to 20 (very high/ complex)). Method appropriateness was measured with the item "How appropriate is the method for displaying Braille characters?" (Likert scale from 1 (inappropriate) to 7 (very appropriate)).

## 5.2. Results - Objective Data

First, the number of correctly identified points for each character (see Tab. 1) was analyzed as the overall performance parameter. Repeated measures ANOVA with Method and Difficulty as within factors revealed a significant main effect of Method (F(2, 34) = 5.27, p < .05) and Difficulty (F(1, 17) = 6.99, p < .05) as well as a significant interaction of both factors (F(2, 34) = 4.97, p < .05). Pairwise comparisons with Bonferroni correction showed that the average number of correct points was significantly higher in the "SQ-R/UR" condition compared to the "SQ" (p < .05) and "3SP" condition (p < .01). As assumed, performance was better in the easy compared to the difficult character conditions. Interestingly, the significant interaction indicated that this difficulty effect varies across methods. Paired-samples T-tests indicated no significant difficulty effect for method "SQ" (t (17) = .6, ns.), a marginal trend for the method "SQ-R/UR" (t (17) = 1.37, p <.10, one-tailed testing) and a significant effect for method "3SP" (t (17) = 4.18, p < .001).

Table 1. Correctly identified points

| Method | Difficulty | Mean (%) | SD (%) |
|---|---|---|---|
| SQ | Easy | 0,92 | 0,12 |
| SQ | Difficult | 0,90 | 0,09 |
| SQ-R/UR | Easy | 0,98 | 0,05 |
| SQ-R/UR | Difficult | 0,97 | 0,06 |
| 3SP | Easy | 0,96 | 0,05 |
| 3SP | Difficult | 0,88 | 0,09 |

## 5.3 Results - Subjective Ratings

First, the subjective ratings listed in Tab. 2 were analyzed regarding mental workload ("How mentally demanding was the task? Was it simple or complex?"; Likert scale from 1 (very low/simple) to 20 (very high/ complex)). Repeated measures ANOVA with Method as within factor yielded a significant effect (F(2, 34) = 12.68, p < .001). Subsequent pairwise comparisons with Bonferroni correction showed that method "SQ-R/UR" was rated as being significantly less demanding or complex as the other methods (both ps < .01). No meaningful difference was found between "SQ" and "3SP" (see Tab. 2, left).

Finally, the overall appropriateness of the three methods for displaying characters was rated ("How appropriate is the method for displaying Braille characters"; Likert scale from 1 (inappropriate) to 7 (very appropriate)) and results are listed in Tab. 2, right). Again, ANOVA indicated a significant overall effect (F(2, 34) = 5.34, p = .01) and pairwise comparisons revealed that ratings for method "SQ-R/UR" were significantly higher compared to the other conditions (both ps < .05). The ratings for the other methods did not differ significantly.

Table 2. Subjective rating of mental workload (Likert scale from 1 (very low / easy) to 20 (very much / complex)) and of method appropriateness (Likert scale from 1 (inappropriate) to 7 (very appropriate))

| Method | Workload | | Appropriateness | |
|---|---|---|---|---|
| | Mean | SD | Mean | SD |
| SQ | 10,94 | 4,77 | 4,83 | 1,38 |
| SQ-R/UR | 6,83 | 4,16 | 5,78 | 0,88 |
| 3SP | 11,67 | 4,97 | 4,72 | 1,27 |

## 5.4 Discussion

The data of the main study showed clear evidence that the best performance is reached with the sequential method that presents all (raised and unraised) cell dots (SQ-R/UR). Recognition rates of 97-98% were obtained for easy as well as for difficult characters. In line with the objective data, subjects also rated this method best in terms of mental workload and appropriateness. Similar results (96%) were achieved with the semi-parallel method that uses 3 tactors (3SP) at least for easy characters whereas the recognition of characters with more than two raised dots within a column led to significant lower recognition performance.

Despite of the reliable distinction and localization of VibroTac's tactor positions (correct detection rate of approx. 95% for single tactor positions, determined in previous studies by Schätzle and Weber (2015)), the sequential method did not lead to convincing results. Obviously, subjects had problems to identify and memorize the single dot positions when these were presented in a quick sequence of vibrotactile stimuli. Perhaps intensive training could lead to similar results for the method "SQ" and "SQ-R/UR". Besides the difficulty to localize activated tactors, memorizing the sequence might also be challenging.

In the sequential method that presents all (raised and unraised) cell dots (SQ-R/UR), most information is transmitted to the user. This might be the reason for the superior results obtained with this method. Since unraised dots are also represented haptically, another recognition strategy is possible: subjects memorize the full haptic sequence (like a rhythm) rather than localizing the individual tactor positions. It seems that the haptic sequence can be recalled easily. This might work even retrospectively assumed that there is a short break before the next character is started. The disadvantage of the "SQ-R/UR" method is the additional time in comparison to method "SQ" in order to present the unraised dots.

Regarding the semi-parallel method "3SP", the correct detection of activated tactors is a major challenge. In comparison with the other two methods, the difficulty and thus the number of raised dots has a significant effect on the performance. The assignment of cell dots to the three tactors is not quite intuitive. However, this seems not to be the reason for the moderate results obtained for difficult characters as with the same method, convincing results are reached for easy characters.

# 6. CONCLUSION AND FUTURE WORK

In this paper, a new approach of displaying Braille through vibrotactile stimuli at the wrist was presented. Each of the six Braille cell dots is mapped to one of the six wristband's tactors. As the Braille coding itself is not altered, only the mapping between cell dots and tactors has to be learned. We performed a user study that aimed at evaluating the general usability of this approach and at the comparison of different mapping strategies (assignment of cell dots to tactors and temporal aspects). Due to the difficulty of recruiting blind people for such a time-consuming evaluation, the study was designed in a way that Braille literacy is not required. Thus, for a first evaluation of the approach we conducted the study with sighted people.

Even with little training, very promising results were obtained. The evaluation of eight different mapping methods with different assignments of cell dots to tactors as well as temporal aspects revealed significant differences in terms of objective performance (activation pattern recognition) and subjective ratings. The sequential presentation of raised and unraised dots turned out to be the best method. However, in further studies with more intensive training it should be investigated whether similar results can be achieved with the method using sequential presentation of raised dots only or with the method based on semi-parallel output of raised dots with three tactors or based on parallel output.

The results of this study indicate that the mapping of Braille code to six tactors at the wrist is a reasonable approach and that reading Braille without using the fingertip seems to be possible. We expect better results for blind people as they are superior in tactile acuity and perception tasks than sighted people. The feedback we received from a blind person in a preliminary test was positive and encouraging to further proceed with the presented approach. Anyway, future studies with blind subjects are essential to optimize and investigate relevant issues. First of all, the required time to output characters or words has to be shortened to allow for a natural communication. If stimuli are displayed in a fast sequence, one should have in mind that effects such as spatial masking, apparent location or temporal enhancement may affect correct localization of stimuli and deteriorate the performance. Furthermore, the recognition of several words or sentences and the robustness of vibrotactile Braille cues in the presence of distractors e.g. when engaged in another task or when lifting objects should be investigated. In addition, reading performance of blind people should be compared with a baseline condition e.g. traditional fingertip Braille reading or vibrational Morse code.

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