Learning the Vibrotactile Morse Code Alphabet

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Learning the Vibrotactile Morse Code Alphabet

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Vibrotactile Morse code provides a way to convey words using the sense of touch with vibrations. This can be useful in applications for users with a visual and/or auditory impairment. The advantage of using vibrotactile Morse code is that it is technically easy to accomplish. The usefulness of tactile Morse code also depends on how easy it is to learn to use without providing a visual representation of the code. Here we investigated learning of the vibrotactile the Morse code alphabet without any visual representation of the code and whether the learned letters can immediately be used to recognize words. Two vibration motors were used: one was attached to the left arm (dots) and the other to the right arm (dashes). We gave the participants a learning session of 30 minutes and determined how many letters they had learned. All participants managed to learn at least 15 letters in this time. Directly afterward, they were presented with 2-, 3-, 4-, or 5-letter words consisting of only the letters they had learned. Participants were able to identify words, but correct rates decreased rapidly with word length. We can conclude that it is possible to learn vibrotactile Morse code using only a vibrotactile representation (15 to 24 letters in 30 minutes). After the learning session, it was possible to recognise words, but to increase the recognition rates extra training would be beneficial.

CCS Concepts: • **Human-centered computing** → **Empirical studies in HCI**;

Additional Key Words and Phrases: Haptic communication, vibration, Morse code

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1 INTRODUCTION

Vibration is an easy way to transfer tactile messages to a user. A very common use in mobile phones is to alert the user that there is an incoming message. However, it can be necessary to convey more complex messages, for instance, in assistive technology for individuals with a visual and/or auditory impairment. There exist many tactile languages. The most well known is probably Braille, but there are others such as tactile sign language, Moon, or finger spelling. Although tactile sign language relies in practice mainly on an interpreter, for some of the others digital displays have been developed. There are numerous commercially available Braille displays and recently displays to deliver finger spelling have been designed such as the Hapticomm [5] and the Lorm glove [8].

What these aforementioned languages have in common is that they are not hands-free. So the user cannot receive a message if the hands are otherwise occupied. Also some, such as Braille, can be difficult to learn. Some forms of deafblindness (i.e., a combination of auditory and visual impairment) are acquired over time, and it can be difficult to start using Braille at a later age, see, for instance, Reference [12]. Tactile Morse code provides a possible alternative. Morse code is international, and it is potentially easy to display, as it is made up of only dashes and dots. There are several ways to display tactile Morse code. The most commonly used way of displaying tactile Morse code is with vibration (see, for instance, References [14, 16–18]), but it can also be done using proprioceptive information by manipulating the height of a finger [17], skin stretch on the finger tip [7], or via embossed images [9]. In a direct comparison by Tan and colleagues, it was found that vibrotactile Morse led to better performance than proprioceptively presented Morse code [17]. There are also practical advantages of vibrotactile Morse code; it can be displayed with just a single vibration motor, and the motors do not have to be placed on the hands, allowing for hands-free communication. Vibrotactile Morse code can thus be easily displayed using a smart watch or fitness bracelet. In fact, in a study with experienced Morse code users it was found that vibrotactile Morse code was perceived better when displayed on the wrist than on the abdomen [14].

Given these advantages, there have been several initiatives to develop apps or other platforms to incorporate vibrotactile Morse code using vibration in human–computer interfaces (HCI) [1, 2, 11, 19]. Often these were designed especially for individuals with deafblindness. However, if vibrotactile Morse code proves difficult to learn, then it might not have much of an advantage over Braille in that respect. Also, the pace at which vibrotactile Morse code can be reliably perceived is slower than auditory Morse code [17]. Although the pace might increase with training, it makes vibrotactile Morse code most suitable for shorter messages. Despite the interest in developing technological means for displaying tactile Morse code, not much is known about learning tactile Morse code.

A few studies have focussed on the learning of vibrotactile Morse code. Tan and colleagues compared novices and experienced auditory Morse code users in learning to use vibrotactile Morse code [17]. They showed that vibrotactile Morse code can indeed be learned and that experienced auditory Morse code users learned using vibrotactile Morse code faster than novices. In this study, however, participants were shown a visual representation of the Morse code alphabet and were allowed to write down the code. This means that participants did not learn Morse code in a tactile way and also did not have to memorize the code while it was being displayed as they could write it down. If not able to do this, then it might be very hard or impossible to learn and use haptic Morse code. Learning Morse code from a visual representation is not practical for individuals with a visual impairment. Also, writing the code down is not practical in general, because the message might be transferred while someone is walking around. So Tan and colleagues have shown that vibrotactile Morse code can be used to display words. However, one might wonder whether the Morse code alphabet can be learned without a visual representation and whether it is possible to recognize words without writing the code down. Both of these factors would severely limit the usefulness of tactile Morse code in HCI.

There is a case study with a user with deafblindness who used vibrotactile Morse code for communication with a smartphone [2]. In that study, it was reported that the user did find the vibrotactile Morse code useful but only

after a long period of getting used to it. One of the bottlenecks that is mentioned is how to learn the Morse code alphabet. While vibration patterns were used to display the message from the smartphone, they familiarised the user with Morse code via an embossed representation of the Morse code alphabet. The user indicated that it was difficult to understand the connection between the embossed code and the code presented with the vibrations. Can vibrotactile Morse code can be learned without referring to a visual or embossed representation of the alphabet? Doing so might actually make it easier to learn to use vibrotactile Morse code, because it is learned in the same representation as in which it is displayed in practice.

It has been shown that it might be possible to learn vibrotactile Morse code in a passive way [15, 16]. Seim and colleagues let participants play a computer game while also displaying vibrotactile Morse code using a Google glass's bone conduction transducer [16]. While playing the video game, participants heard words from the sentence "The quick brown fox jumps over the lazy dog" accompanied by the vibrotactile Morse code. Afterward, participants were able to recognize letters from the Morse code alphabet with high accuracy and were also able to recognize the words from the used phrase. Participants performed passive learning sessions with many active testing sessions performed in between. The results of a study by Pescara and colleagues suggest that actually active learning during these testing sessions was largely responsible for the learning curves [13]. They show that passive learning of vibrotactile Morse code is possible but very limited.

Another study on learning vibrotactile Morse code focussed on finding the best way of presenting the code [18]. In this study, only 12 Morse code characters were included, and recognition of words was not tested. The authors compared using a single vibration motor, two motors on the same arm, or two motors distributed over both arms to indicate dashes and dots. They found that presenting tactile Morse code by using a vibration motor on each arm was perceived the best. In that study, however, they focussed on comparing different vibration motor configurations and not on learning the whole alphabet.

Overall, the number of studies that have tested learning and using of tactile Morse code in general, and vibrotactile Morse code in particular, is very limited. Some were not focussed on learning the whole alphabet and recognizing words [18]. Others used experienced auditory Morse code users and/or allowed participants to write the code down and use a visual representation [14, 17]. Only in studies into passive learning of vibrotactile Morse visual representations were not used to learn the Morse code alphabet [13, 15, 16]. In the current study, we are interested in how fast the vibrotactile Morse code can be learned, and therefore we chose an active learning paradigm. One of the advantages of using a tactile language based on the alphabet, as opposed to haptic sign language, is that one only has to learn the mapping between the regular alphabet and the corresponding Morse code. In theory, learning the alphabet is enough to recognize any word. We set out to determine how many letters of the vibrotactile Morse code alphabet can be learned in a fixed amount of time and whether this training with letters only is enough to recognize words.

In the current study we set out to test how many letters of the vibrotactile Morse code alphabet can be learned in 30 minutes without providing participants with a visual representation of the Morse code alphabet. Here we focussed on individuals with no prior experience using Morse code. We never showed them a visual representation of the code, and they were not allowed to write it down. After learning the letters, we tested their performance on recognising words containing the letters they had learned.

2 METHODS

2.1 Participants

Ten participants (4 male and 6 female, age range 20–26) were recruited from the student population of Eindhoven University of Technology. All students were Dutch native speakers and had experience with learning foreign languages. None of the participants had prior experience with using Morse code. All participants signed informed consent prior to participating in the experiment. The experiment was approved by the ethical committee of the Human Technology Interaction group at Eindhoven University of Technology.

2.2 Set-up and Stimuli

Morse code was provided using two coin-style vibration motors (Adafruit mini motor disc, diameter 10 mm, thickness 2.7 mm) controlled with a micro controller (Arduino Nano). One vibration motor was taped near the wrist on the volar side of the left forearm and the other one on the same location on the right forearm. The motor on the left arm was used to represent dots, and the one on the right to represent dashes. A dot was represented by a vibration pulse of 103 ms and a dash by a vibration pulse of roughly 3 dots lengths (307 ms). A break of roughly 7 dot lengths (730 ms) was used between letters. This timing ratio is consistent with the ratio used in auditory International Morse Code, but the pace is lower.

Letters were not learned in alphabetical order but in an order that was chosen such that Dutch words could be made even after learning only five letters. The order in which the letters were learned was as follows: “A,” “F,” “K,” “M,” “O,” “T,” “I,” “S,” “B,” “C,” “D,” “E,” “G,” “H,” “J,” “L,” “N,” “P,” “Q,” “R,” “U,” “V,” “W,” “X,” “Y,” and “Z.”

2.3 Experimental Procedure

Participants first performed a 30-minute session in which letters were learned (Letter session). During this session letters were learned in blocks of three letters at the time. This means that in the first block “A,” “F,” and “K” were learned. First each letter was presented using vibrotactile Morse code while the experimenter announced which letter was being presented. This means that only a vibrotactile representation of Morse code was provided, and they were never shown a visual representation of the Morse code alphabet. Then each of the three letters was presented two times in random order (practice phase). The participant was asked to respond which letter was presented and the experimenter provided feedback on what the presented letter was. If their answer was incorrect, then the experimenter informed them of what the correct answer was. This was directly followed by a test phase in which each letter was presented in random order. If they answered with a correct rate of 100%, then they continued to learning the next block of three letters. If they made a mistake, then the test phase continued with the block of three letters being presented again in random order until a 100% correct rate was achieved in one block of three letters before continuing to the next block. Each time two blocks of letters were learned a repetition phase occurred. During a repetition phase, all letters that had been learned up until that point were presented a number of times in semi-random order. The number of repetitions depended on the total number of letters learned. After learning the first six letters, they were all repeated 2 times, during the next repetition phase each of the letters was repeated 4 times, then 6 times, and so on. Also during repetition phases and test phases participants were asked to respond which letter was presented and the experimenter gave feedback on what the presented letter was. The Letter session continued until all letters had been learned or until 30 minutes had passed. A schematic overview of the Letter session is shown in Figure 1. Using this procedure does mean that letters that were learned in the beginning of the session were repeated more often than those toward the end. We chose to do this because we wanted to prevent the participants from forgetting previously learned letters after learning new ones. This way all letters learned were fresh in memory when the Word session started.

After a short break the Word session was started. The Word session lasted 20 minutes. During this session, words (two, three, four, or five letters) were presented that consisted of the letters that were learned by the participant. All letters up to the last test phase they had passed were considered learned. So they did not necessarily have to finish the whole repetition phase that followed the last test phase. The set of words therefore differed between participants. Also the number of words presented in the 20 minutes session differed, because some participants answered quicker than others. Participants were asked to answer which word was presented and again feedback was given on what the presented word was. A full list of all words used with their English translation can be found in the Supplemental information.

Fig. 1. Schematic overview of the experimental procedure. Here the first learning cycle up to the first repetition phase is depicted. The green boxes indicate the very first time the three letters to be learned in that phase are displayed to the participants. After this initial display the three letters are repeated two times in block random order (blue boxes). This is followed by a test phase that continues until a correct rate of 100% is achieved (red boxes). This is followed by a second round of learning and test phases. After a total of six new letters has been learned, a repetition phase is started (purple box). This cycle was repeated for the whole sequence of letters to be learned or until 30 minutes had passed. Note that the repetition phase included all previously learned letters and became increasing longer as the experiment progressed.

3 RESULTS

3.1 Letter Session

For 2 of the 10 participants, the data files of the letter learning session were corrupted. Therefore, these participants' data were left out of the analysis of the Letter session but included in the analysis of the Word session. For the remaining eight participants, the correct rates of the repetition phases are shown for each letter individually as a function of the number of times this letter was presented (Figure 2). The panels are ordered in the same way as the order in which the letters were learned. It can be seen that toward the end of the sequence of letters, the number of times these letters were presented was smaller than in the beginning of the sequence. Not every participant learned the same number of letters, and therefore the number of participants included in each data point can vary. One participant reached the repetition phase with up to letter "X," while the other seven reached the repetition phase up to the letter "P." It can be seen that overall the correct rate during the repetition phases was quite high. Note that Figure 2 also includes data from incomplete repetition phases as the learning session was ended after 30 minutes regardless of whether a phase was finished. Because letters were presented randomly during the repetition phase, by chance some letters were presented more often in the final repetition phases than others.

To analyse which confusions between letters occurred most often, a confusion matrix was calculated. This was done by calculating the percentage of confusions that occurred between each possible letter combination for each participant individually. The individual confusion matrices were then averaged over participants. The result is shown in Figure 3(a). It can be seen that most answers fell on the diagonal, indicating that the answer was correct. The only two-letter combinations that occurred above 10% that were not on the diagonal were "L"–"F" and "G"–"J." The first letter combination makes sense, because "L" and "F" are very similar in terms of pattern (· – · · vs · · – ·). They are both four characters long, and the only difference is that a dash and a dot in the center are swapped. The "G" and "J" are more dissimilar, because they differ in length (three vs. four characters). To see whether mistakes between letters of different numbers of characters occurred often, we calculated a second confusion matrix. Here the percentage of confusions between presented letter lengths and responded letter length are shown (Figure 3(b)). It can be seen that confusions between letters with different numbers of characters were actually quite rare.

3.2 Word Session

The Word session always lasted 20 minutes per participant. For each participant, a set of words that contained only letters they had learned was presented. A letter was considered learned if they had entered the test phase in which that letter was learned. Four participants learned up to the letter "X," one learned only up to the "J,"

Fig. 2. Percentage correct as a function for the number of times the letter was presented in the repetition phase. Each panel shows a letter and the panels are presented in the order in which the letters were learned. Dots indicate the median over participants, and the error bars indicate the 25th to 75th percentiles. The colours indicate the number of the repetition phase.

and the others somewhere in between. Note that in the Results of the Letter session it was concluded that all participants learned up to “P” or more. This discrepancy is due to the fact that the data from two participants in the letter section were not saved correctly, and these data were omitted from the analysis. The data from these participants in the Word session were, however, included, and one of these two participants learned only up to the letter “J.” So the minimum number of letters learned was 15. The number of words that were presented during this session varied between participants, because some took much longer to answer than others. The minimum number of words presented was 14, and the maximum was 72. For each participant, the proportion of correctly identified words was calculated per word length. The median and 25% to 75% interval over participants are shown in Figure 4(a). It can be seen that the correct rate rapidly decreased with word length, and it was

Fig. 3. Confusion matrices for the Letter session with the percentage of confusions averaged over participants. (a) Confusions between the different letters. (b) Confusions between letters depending on letter length.

difficult to correctly recognise four- and five-letter words. However, a word was only counted as correct if all letters were identified correctly. So a word with only one letter mistaken was counted as incorrect.

To analyse how dissimilar the answers of the participants were from the presented words, we calculated the Levenshtein distance. This is a measure for the minimum number of actions needed to transform one word (or sentence) into another. The minimum value is 0 (all letters correct), and the maximum value is the number of letters in the word. The actions available are deletion, substitution, or addition. Here we normalised the Levenshtein distance by dividing by the word length. This means that the maximum Levenshtein distance was 1 for all word lengths. For each participant, the average Levenshtein distance per word length was calculated. The median and 25% to 75% intervals over participants are shown in Figure 4(b). It can be seen that the normalised Levenshtein distance seems to increase with word length. To test whether this increase was statistically significant, linear regression was performed on the individual participants' data. This yielded a slope of 0.88 ± 0.06 (*mean* $\pm$ *se*). A *t*-test on the values of these slopes showed that these were significantly larger than zero ($t = 15, p < 0.001$). Given that the Levenshtein distance was normalised for word length, this indicates that the answered words became more dissimilar to the presented words with increasing word length.

4 DISCUSSION AND CONCLUSION

Our results show that it is possible to learn a substantial part (participants learned at least 15 letters) of the vibrotactile Morse code alphabet in only one session of 30 minutes without using any visual representation of Morse code. This was without any prior experience with using Morse code (tactile or otherwise), and the Morse code was thus learned in a vibrotactile way. So participants were never given a visual representation of the Morse code and only experienced the vibrotactile Morse code. In previous studies on vibrotactile Morse code participants were often given a visual representation of the Morse code alphabet and/or were allowed to write down the code they received [17, 18]. This can be highly impractical for individuals with perceptual and/or motor disabilities. One study that involved a user with deafblindness resorted to use an embossed representation

Fig. 4. Results of the Word session. (a) Proportion of correct answers as a function of word length. (b) The normalised Levenshtein distance between the presented word and the participant's response as a function of word length. Dots indicate the median over participants, and the error bars indicate the 25th to 75th percentile.

of Morse code to learn the code [2]. One of the difficulties was that this knowledge of the embossed representation of the code had to be transferred to recognising Morse code that was displayed using vibration pulses. The current study shows that it is possible to quickly learn the vibrotactile Morse code alphabet by learning it directly using vibration pulses.

After the 30-minute learning session, they could recognise words using vibrotactile Morse code, but the number of errors did increase rapidly with word length. Also, the normalised Levenshtein distance increased with word length. This indicates that their answers became more dissimilar from the presented word with increasing word length. One reason for this could be that they had to keep a longer sequence in memory before answering. This could give rise to errors.

In addition to vibrotactile Morse code being easy to display, we here show that it is also relatively easy to learn. Here we opted to optimise the presentation of vibrotactile Morse code. Based on the study of Walker and Reed, we presented dashes and dots to the left and right arms, respectively [18]. Also the speed at which the vibration pulses were presented was chosen based on a previous study, indicating that this presentation speed works well. Both of these factors probably influence how fast the Morse code can be learned. The correct rates for four- or five-letter words were quite low, and, to be able to reliably use vibrotactile Morse code in an application, these should increase. Note, however, that in this study participants only received 30 minutes of training, and this was just learning the alphabet. There was no training with words. The correct rates for words will likely increase with training. In a study by Seim and colleagues, participants learned the Morse code alphabet by presenting words from a sentence containing all words of the alphabet. Recognition rate of the words used in that sentence were quite high [16]. However, they did not test with words that were not used during learning. Still, training with words might improve recognition of words in general and not only words that were used during training.

There is also a way to communicate via touch without the need for learning a new language. This is done with tactile vocoders [3, 4, 10]. A vocoder analyses the speech signal and presents it via vibration. Varying numbers of vibration motors can be used for this. This might seem an easy solution: Just display a tactile version of the speech signal and the user does not have to learn a language. However, there are many hours of training associated with learning to recognise speech through a tactile vocoder. For instance, in a study by Lynch and colleagues, it took 41 hours of training to learn 50 words [10]. Even after this many hours of training the correct rate still was only 42%. A recent study in which the speech signal was decomposed into phonemes seems to be more promising [6]. After 100 minutes of training a correct rate of 45% for recognising words was achieved. Overall, it can be concluded that this approach does involve a long training process, and based on the results in the current study learning vibrotactile Morse code does seem easier to learn. For displaying longer messages, however, vocoders might have an advantage, as displaying vibrotactile Morse code is relatively slow. Even trained auditory Morse code users need vibrotactile Morse code to be displayed at a much slower pace than auditory Morse code to be able to use it [17].

In addition to Morse code being universal and it being technically easy to present using vibration, we show here that it can be learned very quickly and without any visual representation of the Morse code alphabet. Importantly, we show that words can be recognized directly after learning the alphabet without writing the Morse code down. This makes vibrotactile Morse code a good option as a way of communication to implement in assistive technology. This is especially the case when displaying short messages and while doing activities that do not leave the hands available to receive communication.

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