Karlsruher Institut für Technologie

Institut für Telematik
Pervasive Computing Systems / TECO
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Bachelor's Thesis/Master's Thesis

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Department of Informatics

Responsible Supervisor: Prof. Dr. Michael Beigl

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1. Implementation of your Project

1.1 Design

This section presents the design and the key design decisions we made for this project. We begin by describing the hardware apparatus, which includes the actuators and the gloves themselves, as well as the design iterations undertaken during the development of the glove. Next, we outline the software components, detailing the encoding of the actuators, the communication protocol, and providing a brief introduction to the associated software elements. Finally, we conclude this section by introducing the study design of the two studies conducted to address our research questions.

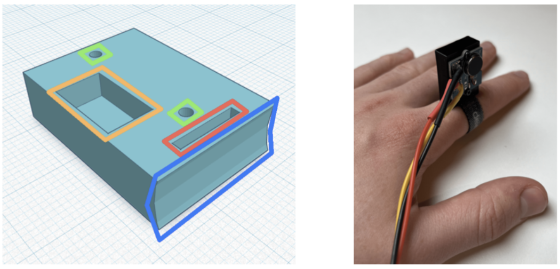
1.1.1 Hardware

We have divided this subsection into two parts: the first focuses on the actuators used, while the second discusses the design of the Velcro gloves.

1.1.1.1 Actuator Design

For the actuators and their setup, we adopted the design and configuration proposed by Fang et al. [8], using Velcro straps. This decision was informed by prior research [21, 15, 13, 7], which highlights the importance of design factors such as weight, breathability, flexibility, and coarseness for user comfort, particularly during extended wear. Velcro straps effectively meet these criteria while enhancing dexterity, a recognized advantage of fingerless glove designs [12]. This design facilitates everyday tasks and accommodates a range of finger sizes, making the gloves adaptable for different users. Furthermore, using the same actuators enables a direct comparison with Fang et al.'s prior work [8], which employed identical actuators in a one-handed, non-chorded piano learning setup.

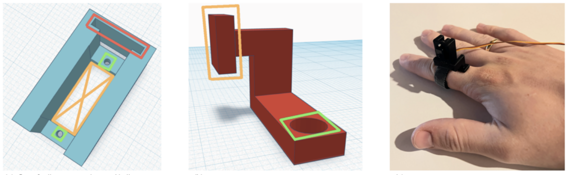
The actuators consist of six vibration systems (three per hand), with one shown in Figure 1.1. Each system includes a vibration motor (Brand: Grove Seed; Model: ANDA-B1020) housed in a 3D-printed PLA case and secured with Velcro bands. Operating at a frequency of approximately 200 Hz, the vibration motors are directly



(a). Case for the vibration motor used in the vibration system. Red: bottom, space for the velcro bands. Green: Screw holes for fixing the vibration motor. Orange: Space for the back end of the pins. Blue: curved bottom as a contact to finger.

(b). Vibration motor and case fixed on the index finger of a user using a velcro band.

Figure 1.1: 3D model, and the implementation on a users finger of one element of the vibration system from [8]



(a). Case for the servo motor used in the tapping system. Red: bottom, space for the Velcro band. Green: Screw holes for fixing the servo motor. Orange: Space for the servo motor.

(b). 3D model of the contactor for the tapping system. Orange: hammerhead that touches the skin. Green: cutout for the counterpart to the output shaft of the servo motor.

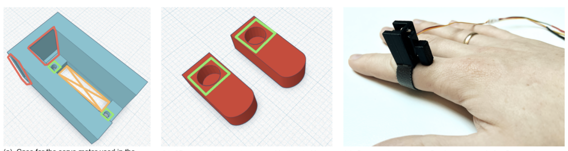
(c). Servo motor and case fixed on a user's index finger using a velcro band with a contactor attached. Contactor in "down" position.

Figure 1.2: 3D models for the case and hammer-shaped contactor, and the implementation on a user's finger of one element of the tapping system from [8]

connected to the glove for control. Each system is mounted in a curved-bottom 3D-printed case for optimal fit, as illustrated in Figure 1.1, where it is demonstrated on a single finger. Consistent with Fang et al.'s design [8], larger contact areas were used to allow easier adjustment for individual comfort. The actuators operate at an amplitude of 1.03 G and weigh 6.6 grams each.

For the tapping and stroking systems, we employed six actuators for each system, utilizing mini-servo motors (Master DS208). These motors provide an actuating force of approximately 0.1–0.2 kg and complete a 45° movement in approximately 0.1 seconds. The actuators draw around 5V and 1.75A for stroking, and 5V and 2A for tapping, based on our measurements using a USB Current Voltage Capacity Tester (Model: KWS-V20/V21). Both systems are controlled via Pulse Duration Modulation (PDM) through the glove. The cases for these systems are 3D-printed using PLA. The design of the stroking system is shown in Figure 1.3, while the tapping system is depicted in Figure 1.2.

To enhance wearer comfort during prolonged use, we added a small cushion to the actuator casings for both the tapping and stroking systems. This cushion, which



(a). Case for the servo motor used in the stroking system. Red: bottom space for the velcro band. Green: Screw holes for fixing the servo motor. Orange: Space for the servo motor itself.

(b). 3D model of the contactor used in the stroking system. Green: Cutout for the servo output shaft.

(c). Servo motor and case fixed on a user's index finger using velcro band. Contactor is placed in the center of the total movement range.

Figure 1.3: 3D models for the case and the contactor, and the implementation on a users finger of one element of the stroking system from [8].

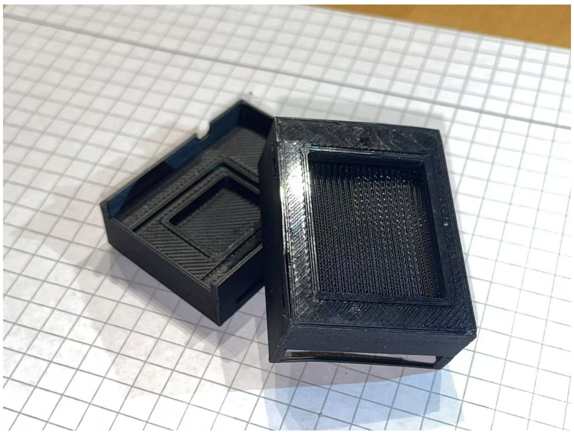


Figure 1.4: Final Glove- Case Design on a squared Din A5 paper for size reference.

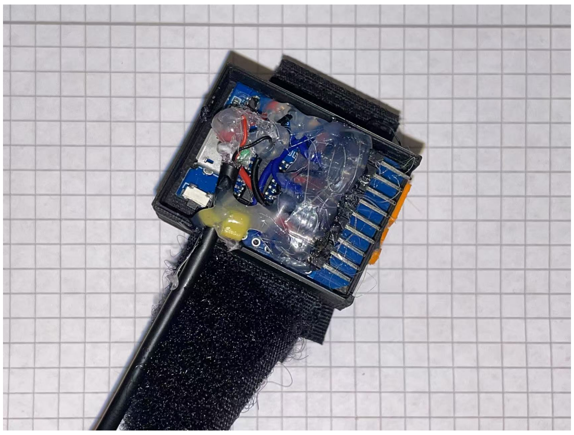


Figure 1.5: Final Glove Design opened on a squared Din A5 paper for size reference.

was not included in Fang et al.'s original design [8], and is only used for the contact area of the non-moving part of the actuator and the skin.

The tapping system delivers equal force at the same rate by applying and removing contact from the user's skin [8]. Its design follows a hammer-like structure, consisting of a servo motor housed in a PLA case and a contactor. The contactor is an 8×8 mm square plate that presses against the skin, connected to the servo motor's output shaft via an L-shaped support. The design is illustrated in Figure 1.2.

The stroking system, shown in Figure 1.3, features a contactor that moves across the user's skin while simultaneously indenting it slightly, similar to the tapping system. The contactor is a $15 \times 7 \times 5$ mm square with a rounded bottom and is housed in a design similar to the tapping system. The servo motor is mounted on the participant's hand, and by rotating the motor, the contactor performs a stroking motion across the skin.

All actuators are positioned near the interphalangeal joints of the fingers.

1.1.1.2 Glove Design and Design Iterations

Our final glove design, shown in Figure 1.6, incorporates the actuators described above along with a wristband. The wristband consists of a Velcro strap mounted onto a 3D-printed PLA casing with a cushion on the bottom to enhance comfort

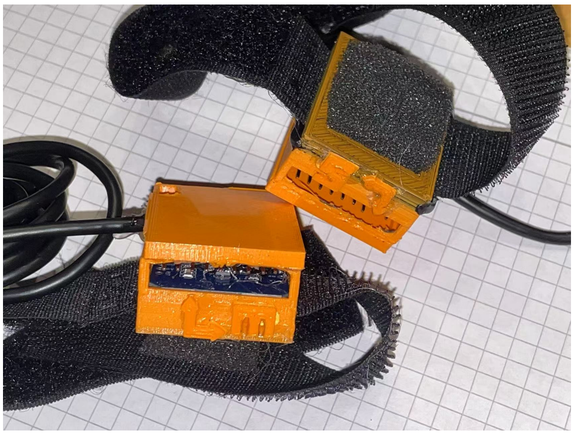


Figure 1.6: Final Glove Design on a squared Din A5 paper for size reference.

Protocoll	**Range**	**EE (R)**	**EE (T)**	**Throughput**	**Latency**	**Overhead**	**OSI-Layer**
ESP-NOW	220m	489 mW	1042 mW	**1 Mbps**	**1ms**	**Small**	Layer 2
TCP / UDP	100m	214 mW	538 mW	**54 Mbps**	3.3ms	Medium	Layer 4
Bluetooth	60m	141 mW	441 mW	784 Kbps	6ms	High	Layer 2

Table 1.1: Comparison of Wi-Fi, Bluetooth and Esp-Now [6].
EE stands for Energy Efficiency, R stands for receiver and T for transmitter.

during extended wear. Herefore, we left a small hole in the bottom to fit the cusion into it due to the cushion being not soft enough due to the clue if not placed within a small indentation as showed in Figure 1.4.

The casing measures 37.6 mm × 28.75 mm × 15 mm, making it comparable in size to the Xiaomi Mi Watch Lite smartwatch (dimensions: 41 mm × 35 mm × 10.9 mm, weight: 35 g with strap, 21 g without strap)[1]. Also the bottom is fitted, so that the ESP8266 can fit even without glue in there and won't move. With a open case the design is depicted here Figure 1.5. The 9 outputs are the same as depicted in the circuit diagram in Figure 1.8.

This design achieves our goal of creating a compact wearable device comparable to a modern smartwatch.

For the microcontroller, we chose to use devices from the ESP family due to their compatibility with the ESP-Now protocol. This decision was based on the protocol's advantages in terms of latency, overhead, and throughput, as highlighted in the comparison by Eridani et al. [6], with their results shown in Table 1.1. As we identified those as the most important criteria for solving our soft-real time[2] requirements, as we need to get the ms timings right and in order.

In our initial design iteration, we used the ESP8266 microcontroller, but it was later replaced with the ESP8266 D1 Mini due to several advantages. These include its low cost (approximately €1), lightweight design (3 g)[3], and compact size. Both microcontrollers offer built-in Wi-Fi capabilities that provide sufficient connectivity for the entire software system. The affordability and accessibility of the ESP8266

[1]https://www.mi.com/de/mi-watch-lite/specs/
[2]Soft-Real Time as defined in computational theory such as by Shin et al. [32]
[3]https://www.smart-prototyping.com/Mini-D1-PRO-Development-Board-ESP8266-4M-16M

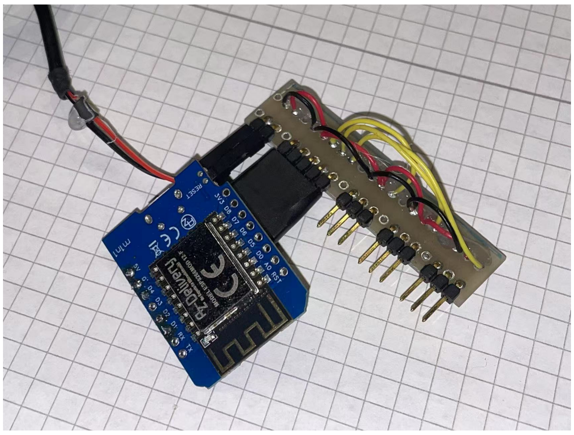


Figure 1.7: Old design of the circuit.

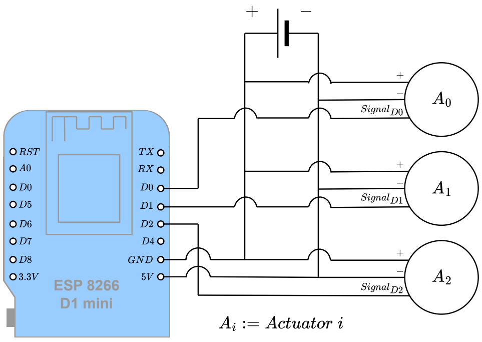


Figure 1.8: Glove Circuit Diagram.

D1 Mini make it particularly suitable for use in low-income households, enhancing the device's feasibility and reach.

The first alpha prototype version with the esp8266 D1 mini is shown in Figure 1.7. As it is the Minimal Viable Prototype (MVP), it is rather bulky with the cables attached to it. Nevertheless, the same circuit diagram as in Figure 1.8 applies for it, and it is fully operational.

Due to the high current demands of the tapping and stroking systems, the on-board power supply of the ESP8266 was insufficient. To resolve this, we soldered an additional USB cable to the board to provide an external power supply, as shown in Figure 1.8, that can also be seen on Figure 1.7 for the MVP and in Figure 1.5 for the current one. In the first experiment, the actuators were interchangeable and could be of the vibration, tapping, or stroking type. We utilized the pins D0, D1, and D2 because of their PDM capabilities.

The USB cable was connected to a standard phone charger. For testing, we used the original 10W Xiaomi USB-A charger (model: MDY-09-EW), which has a maximum output voltage of 5V and 2.0A. This served as the general power source for the system, with one charger used per glove. The design also works with a powerbank, however due to our extended experiment times we didn't use a powerbank in our study.

Furthermore, we added additional wiring to simplify mounting the actuators onto the wristband glove, ensuring better usability and stability during operation. Which can be seen in the open version of the glove design depicted in Figure 1.5, so that we can fit the actuators directly on it.

1.1.2 Software

This software section is divided into two parts, the webistes created for the experiment (one on the glove and one on an external laptop for testing) as well as the communication protocoll used between the gloves.

1.1.2.1 Website

Two websites were developed for the study, adhering to the Material Design guidelines for button design and usability[4]. One website was displayed on a mobile phone (Xiaomi A2 Lite), which was hosted by the glove to control the experiment and play audio data, while the other was used to assess the participants' knowledge.

The website for controlling speech output and vibrations is shown in Figure 1.9. It was designed using a responsive framework, enabling compatibility with other devices capable of running modern browsers. During the study, we used the Google Chrome browser on the smartphone.

The website could be accessed within the "Master Glove" Wi-Fi network (SSID: Master Glove) using the URL 192.168.4.1. The preset buttons on the website correspond to those used in the studies. Upon pressing a button, the master controller receives the associated word or letter, as well as whether Prioritized Overlapping Spatiotemporal Sequence (OST)-Encoding is activated (inactive for sequential input). The master controller then sends this data to the slave controller.

The website plays the corresponding audio for the selected character using a JavaScript text-to-speech converter, as the master controller was not connected to the internet. After the specified offset detailed in the audio-vibration offset section, the vibration begins, aligned with the encoding chords and tailored to finger sensitivity. Both, the audio and vibrations automatically stop after five minutes, providing a break for the conductor to test the participant, as outlined in the study protocol.

The second website, shown in Figure 1.10, was designed solely for testing participants' knowledge. It ran on a Firefox browser on a Fujitsu laptop (model: VFY A5440M15B70E) with Ubuntu.

Additionally, instead of displaying the pressed character, we only showed asterisks ("*") to avoid distracting the user. This approach followed the idea of the "stars-only feedback" condition from Seim et al. [29], allowing participants to focus on the order rather than the specific characters.

The same laptop was also used to run Gwelled, the game employed in Fang et al.'s study [8], during the learning session.

[4] https://m3.material.io/

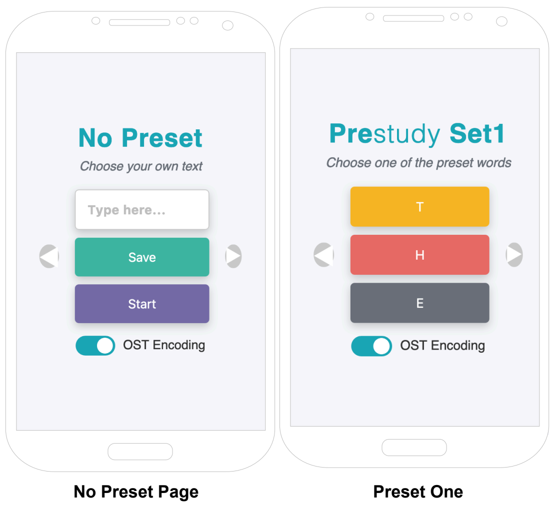


Figure 1.9: Website Design in a Mobile Phone.

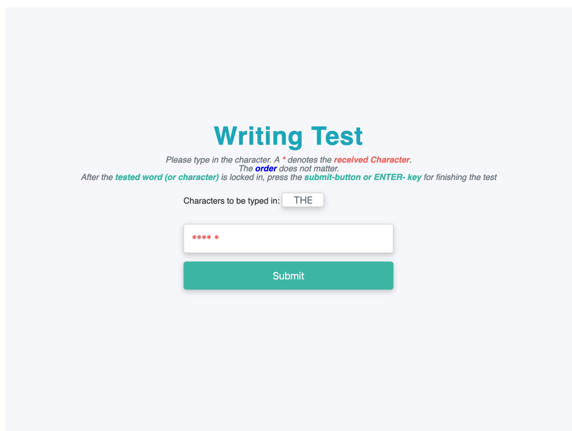


Figure 1.10: Testing Site for the Writing Test.

1.1.2.2 Communication between the gloves

Both gloves operate using a master-slave configuration, with the left glove functioning as the master and the right glove as the slave. To ensure flexibility in actuator motor types and encoding schemes, we implemented a layered architecture within both the master and slave gloves.

For communication, the slave glove employs a listener that, upon receiving a message, triggers a callback function to determine how the data should be processed.

The slave glove can receive two types of data. The first type is the activation sequence, which consists of a series of activation requests and pauses in between. Once this sequence is received, the slave waits for the second type of data—a timing index indicating when the next character should be played.

This approach ensures precise synchronization, as the timing index is transmitted during the pauses between characters, preventing significant timing discrepancies. To meet the requirements of low overhead, fast latency, and high throughput, as outlined in section 1.1.1.2 and illustrated in Table 1.1, we leverage this speed to maintain accurate timing without the need to wait for a connection to be fully established.

1.1.3 Encoding Scheme

This section provides an overview of the encoding methods used in our study. First, we introduce the encoding of chords, which we employ in both of our studies. Here, we differentiate between the sequential approach that we use and the OST encoding approach.

The section also discusses the finger activation sequence to ensure alignment with previous works. The second subsection addresses the offset between the audio and the activation sequence that we employ, explaining which method we use and the rationale behind our choice.

The third part focuses on the selection of isograms for the words used during training. We explain why we believe these words to be the most appropriate and demonstrate, using information theory, that they have similar entropy. This selection ensures that the words used for learning are of comparable complexity. Additionally, we explain why our chosen words form a partial pangram.

1.1.3.1 Encoding Chords

Encoding Braille words as tactile chords is not straightforward because several considerations must be taken into account, such as how to encode a chord in a way that prevents all fingers from vibrating simultaneously, as this was shown to be ineffective by Seim et al. [29], who demonstrated that participants often struggle to distinguish stimuli. Additionally, when offsetting each of the tactile sensations, further considerations must be made, such as: "How long are the sequences activated?" "In which order are the tactile sensations delivered to the fingers?" "How long and where are breaks placed during activation?" and "What activation protocol should we use?" To address these questions, we orient ourselves based on previous works.

For the activation protocol, we use two different encodings, which we compare against each other in the second study. We employ the OST encoding developed by

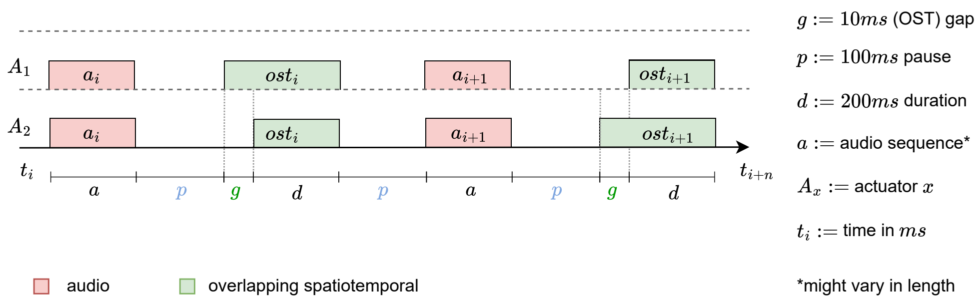


Figure 1.11: Audio vibration offset.

Luzhnica et al. [18, 19, 16, 17], as shown in **??**, to encode the chords. The OST encoding uses a gap p of 10 ms, following the value named (g) used in [18], with the same finger stimuli order and tactile thresholds that align with the findings of [5]. Additionally, we incorporate the sequential encoding approach used by Seim et al.

The OST encoding has several advantages, such as enhanced throughput, as previously outlined. Furthermore, compared to simultaneous encoding, which often leads to difficulties in distinguishing stimuli [29], the OST encoding has proven more beneficial for learning [18]. In the first study, we use only the OST encoding.

Luzhnica et al. [16] found that the order in which tactors are activated during overlapping spatiotemporal stimulation impacts the ability to accurately identify stimuli. Prioritizing the activation of tactors, starting with the most sensitive areas, significantly improves accuracy. Building on these findings, we prioritize the fingers according to their known sensitivity order (from index to ring finger), as described by [16], [11], [35], and [5]. This prioritization follows the approach outlined by [16] to enhance perception accuracy.

Studies on temporal acuity indicate that individuals can discriminate between successive taps on the skin with a gap as small as 5 ms [16, 14]. Luzhnica et al. found that gaps of 10 ms and 20 ms between taps did not significantly impact perception accuracy. Based on this, we chose a gap of 10 ms, as shown in Figure 1.11, which is greater than the minimum discriminative gap of 5 ms established by [16]. This 10 ms gap has been used for OST encodings in previous studies [18, 17].

During both studies, we use the same intensity for vibration, as [16] found that varying vibration intensities between tactors does not lead to higher accuracy, even when prioritization by sensitivity is applied. Therefore, we maintain consistent intensities across all tactile sensations.

For the base duration d, we use 200 ms, with a between-letter gap (bl) based on the average durations of dots (100 ms) and dashes (300 ms) from [28] and dots (200 ms) from [22]. The 200 ms duration aligns with the recommendations of [18], who suggest this interval to separate subsequent letters. While this duration is shorter than those used in some language-teaching studies, such as [25], it fits well within the 100–300 ms range used for keypad learning chords by Seim et al. [26].

1.1.3.2 Audio-Chord Offset

For the offset between audio and vibration, we adopt the same value as used in [26] for Braille learning, which is 100 ms, as shown in Figure 1.11.

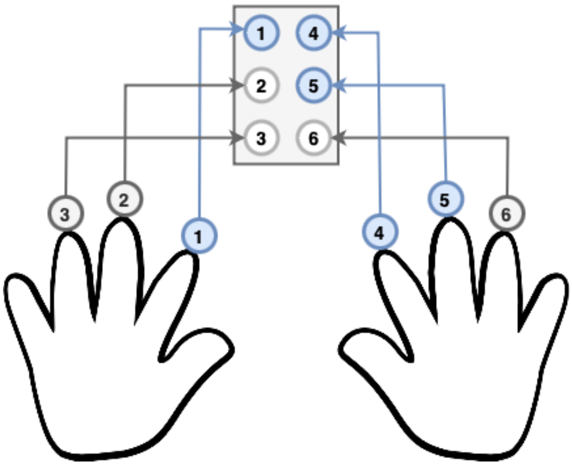


Figure 1.12: Encoding of the character D as an example for hand encodings.

For stroking and tapping, we follow the setup described by [8], where each finger is stroked or tapped once. However, we use the OST encoding with the same OST gap and pause time, as illustrated in Figure 1.11, so the only difference between the affective and discriminative touch setups lies in the base duration d. Since this is the first study, to our knowledge, investigating OST with stroking or tapping for affective touch, we use this pattern without any additional prior timing guidelines, except for the passive learning encoding found in Fang et al. [8].

1.1.3.3 Isogram Selection and carry-over effect minimisation

When participants are passively learning to type using different actuators, we use a segment of a pangram [2], following the methodology of Seim et al. [28, 27]. This approach is intended to mitigate the "carryover effect" [20, 3], which occurs when participants are influenced by previously learned data, either through stress or prior knowledge.

To ensure a fair comparison and avoid the carryover effect, we taught participants different characters with equal complexity for each actuator. Pescara et al. [22] defined complexity by creating patterns of equivalent length and difficulty, based on the number of dash and dot transitions in Morse code. Inspired by this approach, we use entropy, as defined in information theory [9, 30, 31], to quantify the underlying complexity.

To achieve this, we encoded each Braille dot with a number from 1 to 6, following the methodology of [36]. The dots correspond to positions on the left hand (index to middle finger) and right hand (index to middle finger), as illustrated in Figure 1.12 for the Braille character "D". Each character is thus represented as a set of numbers corresponding to the Braille dots.

Using this encoding, we calculated the probability $P(d)$, where d represents a "dot at position i." We used the standardized English Braille alphabet, consisting of 26 characters. The probability distribution for each dot being present in a character is calculated as:

$$P(d = X) = \frac{\|\{d \in c \mid c \in A\}\|}{\|A\|}$$

where A represents the 26-letter English alphabet. The results are summarized in Table 1.2, showing the occurrence of each Braille dot and its corresponding probability across the alphabet.

Dot d	①	②	③	④	⑤	⑥
Occurrences	20	14	15	15	13	6
$P(d)$	0.7692	0.5384	0.5769	0.5769	0.5	0.2307

Table 1.2: Probability for each dot occurring.

Using these probabilities for each dot $P(d)$, we then computed the entropy $H(c)$ for each character c using the entropy formula:

$$H(c) = \sum_{d \in C} P(d) \times \log_2 P(d)$$

This measures the amount of information in bits per character. The calculated entropies for each character c are presented in Table 1.3.

We evaluated words used in previous studies, such as "add," "a," and "bag" from Seim et al. [25, 29], with entropy values of 2.7891, 0.2912, and 2.793 bits, respectively, and the words "The," "Lazy," and "Dog" from Seim et al. [28], with entropy values of 3.9597, 5.4531, and 4.2278 bits, respectively.

Next, we searched for a partial pangram composed of three words for the three actuators by going through the English dictionary with word-length of 3[5], while ensuring that the words did not share the same characters and had similar complexity and character length, and are commonly used[6]. We selected the words "the," "old," and "pub," as shown in Figure 1.13, with entropy values of 3.9597, 3.728, and 3.6969 bits, respectively. These words were deemed more suitable for our task due to their similar entropy values and simplicity, as many of our participants are non-native English speakers. These words were used in the first and second studies (for the second study, we used "old" and "pub" due to their closer similarity in entropy).

1.2 Study design

Our study is inspired by the work of Pescara et al. [22] and Fang et al. [8], and it is divided into two distinct phases. The first phase addresses our first research

[5]https://www.dictionary.com/e/word-finder/3-letter-words/

[6]As we didn't interview native speakers we needed to ensure they knew the words

Character c	⠁ A	⠃ B	⠉ C	⠙ D	⠑ E	⠋ F	⠛ G	⠓ H	⠊ I
$H(c)$ in bits	0.2912	0.6458	0.749	1.249	0.7912	1.1036	1.6036	1.1458	0.8124
Character c	⠚ J	⠅ K	⠇ L	⠍ M	⠝ N	⠕ O	⠏ P	⠟ Q	⠗ R
$H(c)$ in bits	1.3124	0.749	1.1036	1.2068	1.7068	1.249	1.5614	2.0614	1.6036
Character c	⠎ S	⠞ T	⠥ U	⠧ V	⠺ W	⠭ X	⠽ Y	⠵ Z	
$H(c)$ in bits	1.2703	1.7703	1.2372	1.5918	1.8006	1.695	2.195	1.7372	

Table 1.3: Entropy for each Braille letter rounded to 4 decimal places.

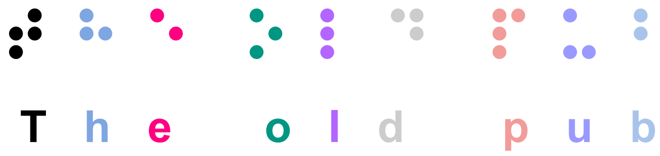


Figure 1.13: Sentence used in the pre-study and its braille part.

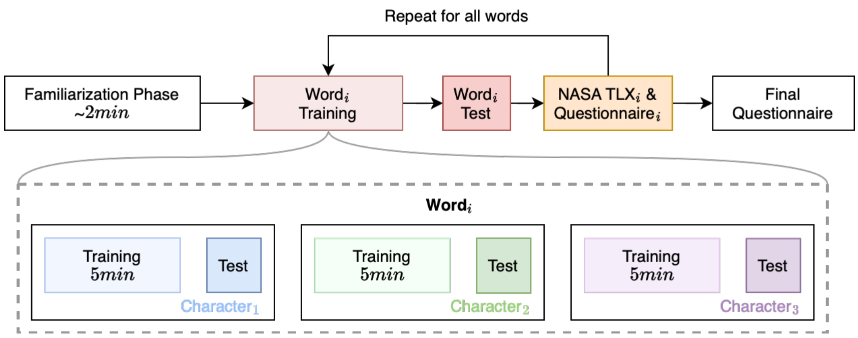


Figure 1.14: Study design.

question: "RQ1: Is there a difference between affective and discriminative touch for both hands using the OST?" This phase is followed by a pre-study. The second phase aims to answer our second research question: "RQ2: Is there a significant difference between using the OST and the SEQ encoding?" In both studies, we focus on teaching uncontracted, alphabetic English Braille, known as Grade One Braille [33, 1].

Similar to Seim et al. [27, 28], our studies focus on learning words. However, we use a different set of words than those employed in their research. In the first study, we aim to assess the effectiveness of various stimuli and examine the impact of affective versus discriminative touch using the OST encoding. This will be combined with different stimuli to teach Grade One Braille. In the second study, we investigate the differences between using the OST and Sequential encoding (SEQ) encodings.

For both studies, we employed a balanced randomized Latin square design, similar to the method used by Huang et al. [13], a technique frequently applied in educational and psychological research [23]. The study procedures are illustrated in Figure 1.14. As shown in the figure, each study begins with a familiarization phase lasting approximately 2 minutes. This phase includes using the testing website Figure 1.10 and its input method to familiarize participants with the setup, followed by a brief session of the game Gwelled to help participants acclimate to the game.

The familiarization phase is followed by word training, during which participants use the specific actuator attached to their fingers. For this, we used a Velcro band, similar to the setup used in previous studies [34, 8], enabling comparability with [8], which also investigated discriminative and affective touch. For the first study, we used the respective actuator according to the balanced Latin square design, consisting of vibration, tapping, and stroking, with the OST encoding employed. In the second study, we used only the vibration actuator, but the encoding was changed according to the balanced Latin square design to either SEQ or OST.

During word training, each word is taught letter by letter. The training phase for each letter is followed by a test. In the letter training phase, participants play Gwelled, which was used in previous studies by Fang et al. [8], Donchev et al. [4], and Pescara et al. [22] for 5 minutes. This serves as a distraction task while they receive their respective stimuli. Throughout this phase, we log user inputs, clicks, game scores, and the time played. This data allows us to assess participant focus in relation to the type of actuator used and evaluate the test results.

To ensure data validity, we monitored the average click count to avoid significant drops between letters with the same stimulus. For the character test, we use the testing site shown in Figure 1.10.

After participants learn three characters, they complete a word test consisting of a word formed from the three learned characters. The word test is conducted on the same website.

During the testing phase, participants do not see their typed information to minimize distractions and encourage better performance, as detailed in subsubsection 1.1.2.1. For each test, participants are given three attempts to reproduce the Braille character chord, following the setup used in previous works [8, 24, 7]. After all three characters of a word (as shown in Figure 1.13) have been learned, participants complete a NASA TLX [10] questionnaire, as well as our own questionnaire assessing the perceived usefulness of the system. Once all conditions (each actuator for the first study or each encoding for the second) are completed, participants fill out a final questionnaire directly comparing the conditions to each other. This final questionnaire aims to gather objective scores for the conditions and determine participants' preferences and feedback. The questionnaires are provided in the appendix.

Since we only have two conditions for the second study, we used only the two Braille words ⠕⠇⠙ (OLD) and ⠏⠥⠃ (PUB), as depicted in Figure 1.13, for learning/testing.

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