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Design and Validation of the *Readable* Device: a single-cell Electromagnetic Refreshable Braille Display

Gemma Carolina Bettelani[1*], Giuseppe Averta[1,2], Manuel Giuseppe Catalano[2], Barbara Leporini[3] and Matteo Bianchi[1]

***Abstract*—Blindness represents one of the major disabling societal causes, impacting the life of visually impaired people and their families. For what concerns the access to written information, one of the main tools used by blind people is the traditional Braille code. This is the reason why in the recent years, there has been a technological effort to develop refreshable Braille devices. These consist of multiple physical dots that dynamically change their configuration to reproduce different sequences of the letters in Braille code. Although promising, these approaches have many drawbacks, which are mainly related to costs, design complexity, portability, and power consumption. Of note, while many solutions have been proposed for multi-cell devices, the investigation of the potentialities of single-cell refreshable systems has received little attention so far. This investigation could offer effective and viable manners to overcome the aforementioned drawbacks, likely fostering a widespread adoption of such assistive technologies with end-users. In this paper, we present the design and characterization of a new cost-effective single-cell Electromagnetic Refreshable Braille Display, the *Readable* system. We also report on tests performed with blindfolded and blind expert Braille code readers. Results demonstrate the effectiveness of our device in correctly reproducing alphanumeric content, opening promising perspectives in every-day life applications.**

***Index Terms*—Blind users, Single Cell Refreshable Braille, Electromagnetic Actuation**

Fig. 1: A participant "reading" through the *Readable* device.

I. Introduction

In the world there are 285 millions of Visually-Impaired People (VIP), 39 millions of which are blind [1]. Blind and VIP life is tougher compared to the one of normal sighted under several aspects, as it is the case of accessing to digital, textual and graphical contents. Indeed, as of today, personal computers, tablets, smartphones and other portable devices mostly deliver information to users through vision. Blind and VIP can access text information relaying on voice synthesizers perceived via speakers or headphones [2]. However, aural feedback could be masked by other sounds and noise, and it could have a negative societal impact, since it can annoy other people present in silent spaces, such as libraries or workplaces. In addition, the usage of headphones is not completely satisfactory, since users might be isolated from the surrounding environment.

On the contrary, the sense of touch represents a more promising solution for surrogating visual content to blind people, also considering the many similarities between touch and vision, resulting e.g. in supramodal cortex organizations [3]. For these reasons, haptic devices have been developed targeting VIP usage to: (i) render general graphic information (geometrical shapes and figures) [4], (ii) allow the development of mental maps from virtual objects [5] or (iii) convey textual cues through Refreshable Braille displays. The latter are based on the Braille code, which is characterized by raised dots to represent the letters of the alphabet, each character being represented by a cell of 3x2 dots, or a cell of 4x2 dots. The particularity of Refreshable Braille displays is that the raised dots change dynamically, enabling to represent different texts with the same device. Braille devices are usually well-received by users, which can actively use their sense of touch to read and learn informative cues. Indeed, as it has been demonstrated in [6], an active mode of accessing textual information, such as through haptic exploration, generally leads to greater comprehension compared to the case where blind people only passively listen a text being read [7].

In literature, several different mechanisms have been proposed for the actuation of Refreshable Braille displays pins.

Piezoelectric actuators represent one of the most common technologies used in commercially available devices. Displays with such an actuation strategy have some positive aspects, e.g. proper distance between pins and fast refreshing rate, yet they also show several drawbacks. Indeed, although they have reasonable reliability due to their sophisticated mechanical elements, the proposed design solutions typically require considerable cell dimensions, a very high operating voltage (100-300V) and the final product is typically very expensive [8], [9].

Other approaches presented in literature propose the use of shape memory alloy (SMA) coils, or thermo-pneumatic/pneumatic actuators, but they can also come with not-negligible costs. Furthermore, these technologies may exhibit low portability [10], they can be complex to control, and the dynamics of the actuation is typically slow [11], [12]. Moreover, other negative aspects can be the relatively high working temperatures, which could result in repetitive cooling phases during the usage, and the high power consumption due to continuous powering of the actuators also in static conditions [9].

Finally, there are devices that employ electromagnetic linear actuators. The operating principle consists in a static magnetic field, usually generated by a permanent magnet, which interacts with a variable magnetic field, produced by electrical current flowing into one or more coils. In this case the force exerted by the coil on the magnet can be regulated by modulating the current. For example, in [13] the authors propose a flapper mechanism for each dot of the Braille cell, enabling to arrange the voice coil actuators horizontally beneath the cell surface, and to transmit the movement

[1] G. C. Bettelani, M. Bianchi and G. Averta are with Research Center "E. Piaggio", University of Pisa, Pisa, Italy and with the Department of Information Engineering of University of Pisa, Pisa, Italy. {gemma.bettelani1} at gmail.com

[2] M. G. Catalano and G. Averta are with the Soft Robotics for Human Cooperation and Rehabilitation, Fondazione Istituto Italiano di Tecnologia, via Morego, 30, Genova 16163, Italy.

[3] B. Leporini is with the Human Interfaces In Information Systems Lab, Istituto di Scienza e Tecnologie dell'Informazione (ISTI) "A. Faedo", Area della Ricerca del CNR di Pisa, Via G. Moruzzi, 1, 56124, Pisa, Italy.

[*] Corresponding author.

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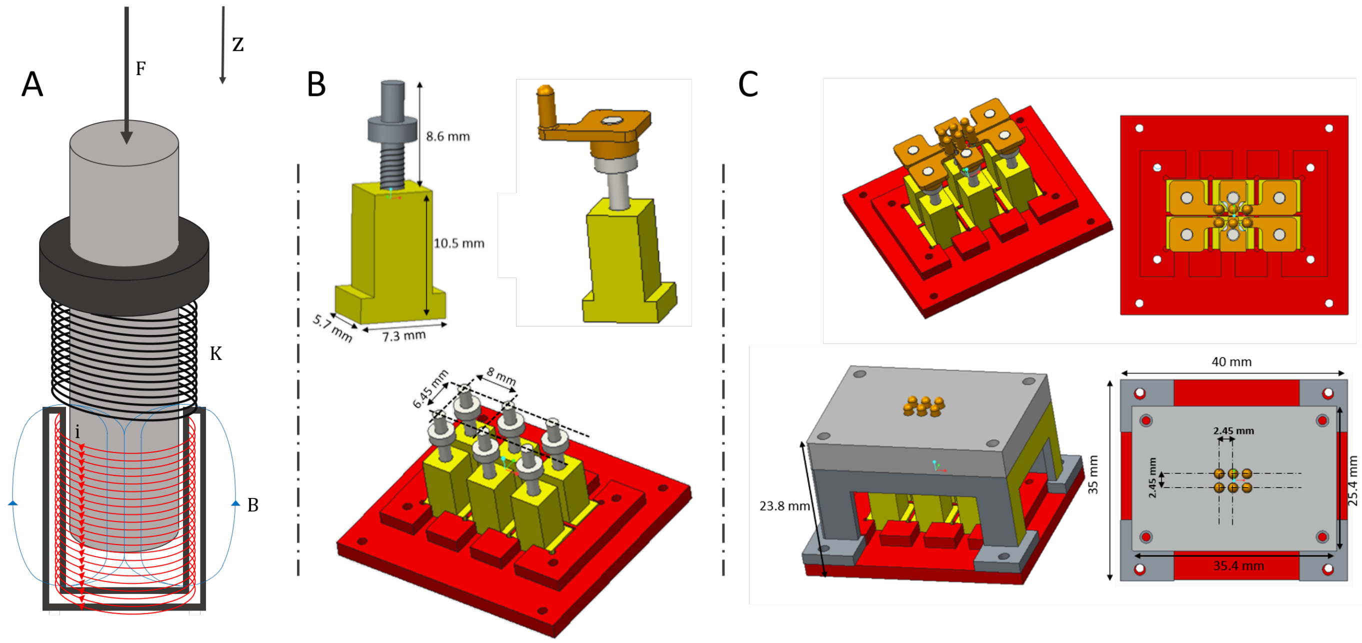

Fig. 2: **(a)** A single solenoid with the ferromagnetic element and the linear spring (elastic constant k). A current i flows in the red solenoid and generates a magnetic field B. The bar is then attracted downwards with a force F. **(b)** The structure used to arrange six solenoids in a 3x2 matrix. On the top right, in orange the adapter. **(c)** On the top, the adapters mounted on the six pins. On the bottom, the complete architecture of the Braille cell.

with convenient leverages. However, cells designed with this type of actuation are considerably large. and the resulting system can be cumbersome [14]. In [15], the linear motion electromagnetic actuator is equipped with two identical coils connected in series, in such a way that they generate a magnetic flux of opposite directions in the inner region, where a permanent magnet is positioned. In this way, in accordance with the polarity of the power supply, the permanent magnet will move either up or down. Using this type of actuation the dots spacing is 3.5 mm [16], which is 1 mm larger than the standard Braille dimensions [17].

All the previous solutions report on multi-cell/multi-line devices, witnessing for a great scientific and technological interest in these topics. However, such interest is not matched when we look at the investigation of the potentialities of single-cell refreshable Braille devices. This investigation could offer effective and viable manners to overcome the limitations of Braille systems, which are mainly related to costs, design complexity, portability, and power consumption. Furthermore, tactile reading on a single cell display could potentially increase reading speed and user's comfort [18]. In [19], a preliminary study on a single-cell device that consists of linear actuators driven by electromagnetic relays is reported. However, no quantitative data on the experiments with blind users interacting with this system, neither a characterization of its dynamics, thermo-electrical behavior and cost information are provided. A similar approach is also in [18]. In [20] a piezoelectric single cell solution integrated within a complete display is described, but in this case the dot spacing is larger than the standard Braille code dimensions. A similar problem can be found in [21] where six PWM (Pulse Width Modulation) servos are used.

In this work we present the design and characterization of a new cost-effective single-cell Refreshable Braille device, *Readable*, based on electromagnetic actuation [22]. This device can reproduce all the letters of the Braille code. Our mechanical solution ensures a spacing between the dots equal to 2.45 mm, in accordance with standardized Braille cell parameters [17], while the refresh rate is up to 4Hz. Our implementation resulted in a light, portable (comparable

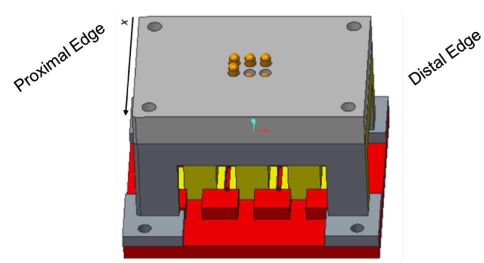

Fig. 3: *Readable* reproducing the "v" letter; x is the axis parallel to the frontal plane of the reader. The Proximal Edge is the closest to the subject own body. The tactile exploration for letter identification occurs along the direction of the x axis. In this case the device has four dots in the down configuration and two in the up configuration

with reduced layout single cell solutions see [20], and energetically efficient solution, with low working voltage (<5V) also compared to e.g. [18] or to [23] - in the latter case, dividing the required voltage for the entire display per the number of cells, which may enable the usage in everyday life with dedicated battery-based supply. To validate our system, we performed an exhaustive experimental campaign, carrying out two sets of experiments, one with 8 sighted blindfolded participants, and one with 8 blind expert Braille readers. Results demonstrate the effectiveness of our device in correctly reproducing alphanumeric content, opening promising perspectives in every-day life applications.

II. System Architecture and Control Strategy

The design of the cell relies on a set of commercial solenoids [24], organized in rectangular boxes of 5.7mm x 7.3mm x 10.5mm. The solenoid internal available diameter is 2mm.

Our implementation exploits as actuation strategy the magnetic field generated by the solenoid to move a ferromagnetic bar equipped with a surrounding spring (see Fig. 2–a). The pin is allowed to freely move along the vertical direction (z), while a spring counteracts the movement along positive z direction. Six elements are arranged in a 3x2 matrix (see Fig. 2–b), and adapters are used to allow a

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distance between the pins coherent with standardized Braille design requirements [17] (Fig.2–b and Fig.2–c). The functionalities and design strategies for each of the above components are described in the following.

A. Actuation Strategy and System Layout

The current i, flowing into the coils of the solenoid, generates a magnetic field B inside the solenoid itself [25]. If a ferromagnetic material (or pin/bar) is positioned in the center of the solenoid, it experiences a downward attraction force as depicted in Fig. 2.

Considering the design of Fig. 2–a and the depicted direction of the applied current, the bar is attracted inside the hall of the solenoid and the spring, wrapped around the bar, is compressed. We refer to this as *down configuration*. Instead, in the case of no current in the solenoid, the bar is released and the spring maintains the pin position, based on its rest configuration. We refer to this as *up configuration*. Therefore, each dot mechanically connected to the pin (see next subsection) can be controlled in two different configurations (see Fig. 3):

- *up configuration*, with spring in rest position and the tip of the dot being at 0.6 mm from the reading surface [17];
- *down configuration*, with compressed spring and dot just below the reading surface.

The device is controlled with an `Arduino-Micro` micro-controller. The current applied to each solenoid is conveyed through a relay, whose activation is commanded through a dedicated output port of the micro-controller. When the port is activated, the corresponding relay commutes, the current flows into the coils of the solenoid and the corresponding dot is commanded in the down configuration. When a pin is deactivated, the corresponding relay commutes again, the current stops flowing into the coils of the solenoid, and the dot is in the up configuration. Note that such design requires an applied voltage only for the commutation (and holding) of the down configuration, while the up configuration does not require any voltage, since it is maintained by the spring. To overcome the spring resistance and bring the dot to the down configuration, a voltage of 4.30V and a current of 240mA are required. This means that the power consumption is 1W.

III. System Characterization

As previously discussed, one of the major technical requirements of Braille cell design is the specific distance between dots. Furthermore, their resistance against a vertical applied force needs to be carefully considered. Typical vertical forces during Braille display reading range between 5 and 15g [26]. To ensure a correct perception of the pin stimulus - in up configuration - by the fingertip, its elevation with respect to the base of the cell needs to be ≥ 0.25mm [26]. This results in a constraint on the spring characteristics. Indeed, the balance of the forces acting on the pin are:

$$F_e - mg = F_a, \tag{1}$$

where $F_e = K\Delta z$ is the elastic force of the spring, K ($0.82\ \frac{\mathrm{N}}{\mathrm{mm}}$) is the elastic constant, Δz the displacement along z axis of the spring when the external force F_a is applied on the pin along the vertical direction and, finally, m and g are the pin mass and the gravity acceleration respectively. Considering the force ranges observed in [26], and a pin mass equal to 0.42g, we have that Δz will vary in the range $[0.06, 0.2]$mm, thus maintaining a pin elevation with respect to the surface always higher than 0.4mm [26].

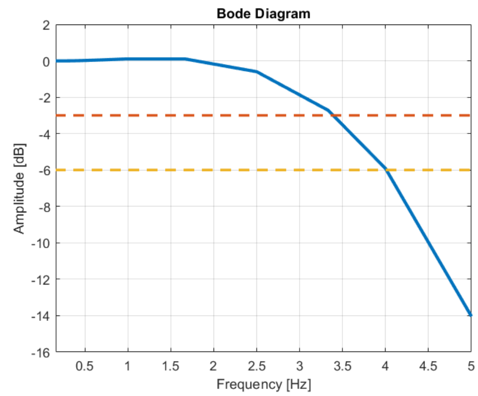

Fig. 4: Bode diagram of the estimated transfer function (red and orange dashed lines mark a gain equal to -3 and -6 dB respectively.)

To quantify the maximum refresh rate of the designed cell, we evaluated the capabilities of the device to properly commute at different desired frequencies. In other terms, we performed an identification experiment to determinate the input-output characteristics. More specifically, we tested the pin commutation at different desired frequencies, ranging from 0.16 to 5 Hz. For each input frequency, we video-recorded the vertical displacement of the dot. Then, the movement of the dot was tracked using the Kinovea software [27].

For each frequency, applied for five complete waves, we then evaluated the ratio between the module of the output sinusoidal function and the maximum pin elevation. Results are depicted in Fig. 4. Note that the system exhibits an expected low pass behaviour, which could be approximated as a transfer function with two poles. More interestingly, it is worth noticing that the system is able to follow the desired frequency with negligible gain loss (6 dB bandwidth) up to a frequency of 4 Hz, in agreement with the highest refresh rates for refreshable Braille [9].

Since the magnetic field generated by the solenoid is minimal outside it, the electromagnetic actuators can be places close to each other. However, the distance between the actuator centers, and hence between the pins, is 8 mm, greater than the requirements in [17]. To implement the required spacing between dots, we designed suitable adapters in ABS with a customized geometry, see Fig.2-B. We used lubricant to minimize the influence of the friction on the pins. These adapters are connected to the ferromagnetic pins and, when the device is operated in the up configuration, enter the holes and emerges from the surface of the device (in ABS) as dots, with an inter-dot distance equal to 2.45 mm [17]. The total dimensions of the cell with the case are 40 x 35 x 23.8 mm, see Fig. 2-C.

A. Thermal Variations in Normal Use

To evaluate the variation of temperature of the case and inside the device, we performed a set of experiments in which *Readable* was controlled to cyclically commute the pins between the up and the down configurations. We used a duty cycle equal to 3 seconds. Tests were performed considering a continuous working time equal to 30 seconds, 1, 2, 3, 6, 10, 20 and 30 minutes. At the end of these periods, we measured the temperature through a thermal camera (accuracy 0.05 °C). The test for each working duration was repeated three times. In Fig. 5 we report the average temperature values at the pin level for all the considered experimental conditions. Snapshots of exemplary thermal cameras views are reported in Fig. 6.

It is worth noticing that also in the case of the longest duration we considered, the steady-state working temperature inside the case was around 50 °C (environmental temperature 21 °C). The reading surface exhibited a temperatures around 30 °C. These results suggest

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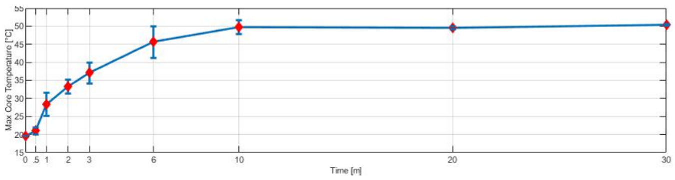

Fig. 5: Pins temperature over working-time (mean and standard deviation). Pins were commuted up-down with a duty cycle equal to 3 seconds (similar to classical use). Values were recorded through a thermal camera.

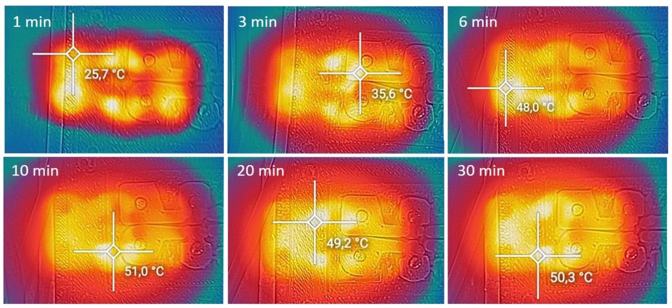

Fig. 6: Sample pictures of the temperature at the level of the ferromagnetic pins (inside the case) after 1, 3, 6, 10, 20 and 30 minutes of continuous usage. Pictures were recorded through a thermal camera (Accuracy 0.05 °C).

a comfortable usage of the device, also for long-use experiences. Furthermore, these experiments allow to exclude potential thermal effects on the mechanics (i.e. thermal expansion of the pins).

B. Cost Analysis

Current commercially available implementations of Braille devices usually results in prices between 500$ and 2000$ [28]. This represents a major limitation for the development and the diffusion of such technologies for everyday life. For this reason, our design strategy takes into account also the economic impact of the components. More specifically, the overall cost of the complete cell presented in this work is equal to 42.74$. It is worth noticing that a large part of the cost is associated to the electromagnetic solenoids, which could be further reduced with custom-made solenoids. Note that the resulting price of our implementation is comparable to analogous cost-aware devices presented in literature [28], [29]. For additional details on these aspects the reader is invited to refer to Tab. I.

TABLE I: Costs of the *Readable* cell components

Product	Quantity	Cost
`Arduino-Micro`	1	6,28$
Relay (G5LE-1 5DC)	6	8,48$
Solenoids	6	26$
Batteries	1	2$
Total	one cell	42,74$

IV. Experimental Validation with Sighted Blindfolded Participants

A. Participants

Eight sighted and blindfolded participants (4 female, age 29.1 ± 2.33 y.o.) were enrolled in the experiment, for the quantification of the performance of the single cell Braille in reproducing the Braille code. None of the participants reported any physical or cognitive impairment, which may have affected their haptic perception and the results of the test. Participants were naif to Braille code. The experimental procedure was approved by the Ethical Committee of the University of Pisa, in accordance with the guidelines of the Declaration of Helsinki for research involving human subjects. The subjects signed an informed consent to participate in the trials.

B. Protocol of the Experiment

Participants were asked to seat on an office chair in front of the device. They were blindfolded and isolated from external audio disturbances via pink noise through headphones. They were instructed to explore the surface proposed (either paper-printed - traditional tools for VIP communication, see Fig. 7 - or device-coded Braille letter of the Italian alphabet), laterally moving their index fingertip as in [7], and to recognize the reproduced letter. In particular, when they thought to have understood the dot configuration, they took off the blindfold and looked at the paper-printed letters, to identify the one corresponding to the stimulus perceived. All the twenty-one letters of the Italian alphabet were randomly proposed twice for the two modalities, i.e. for the paper letter modality and for the device modality (the order of stimulus presentation for these two conditions was counterbalanced across participants). It is also worth mentioning that, before the beginning of the experiment, the participants performed a training phase of five minutes both with the paper-printed letters and with the device.

The letter exploration was recorded to keep track of the correctness of the provided answers and of the time participants employed. Note that participants had no time limitation to accomplish the experimental task.

C. Data Analysis

To assess the performance of the participants, we evaluated the accuracy per subject in recognizing the letters, in the two reading modalities. Furthermore, we also considered the average exploration time used by participants with the device and the paper letters. Data Gaussianity was tested using a Lilliefors test, and a paired t-test was used to compare the performance in the two experimental cases.

V. Experimental Validation with Blind Participants

A. Participants

Eight blind participants (2 female, 52.6± 20 y.o) were enrolled in the experimental validation. All of them were expert Braille readers, and 5 out of 8 used commercially available Braille displays in their every-day life. The aim of this experiment was to test the effectiveness of our system, to receive a feedback from real end-users, and to identify possible application areas where the single cell device would be preferable with respect to the complete Braille display. The experimental procedure was approved by the Ethical Committee of the University of Pisa, in accordance with the guidelines of the Declaration of Helsinki for research involving human subjects. The participants signed an informed consent to participate in the trials.

B. Protocol of the Experiments with Blind Participants

The participants were asked to seat on an office chair in front of the device and to recognize alphanumeric stimuli, either paper-printed or reproduced via the device. The experimental protocol consisted of three sub-tasks: the recognition of twenty-one letters of the Italian alphabet presented twice for the two modalities; the recognition of two meaningful anagrams of two words (i.e. "SENTITO/INSETTO" and "SORTE/RESTO"), and the recognition of two anagrams of one number (854/485). The order of stimulus presentation within sub-tasks, the order of the sub-tasks was randomized, and the reading modality counterbalanced across participants. More specifically, if one participant experienced the words "SENTITO", "SORTE" and

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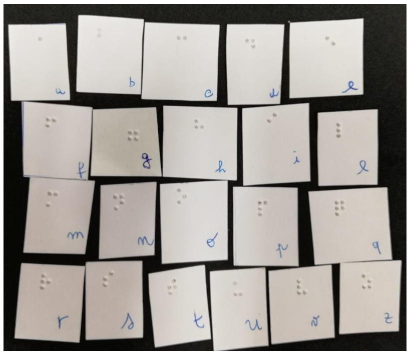

Fig. 7: Paper Braille letters used to perform the experiment. Samples were generated using a commercial 4 Lines 28 Cells Braille Writing Slate and Stylus.

the number ”854” via paper-printed letters, he/she experienced the words ”INSETTO”, ”RESTO” and the number ”458” via the device. The choice of using anagrams was motivated by the need for maintaining the same level of difficulty of stimulus recognition in the two reading modalities. Before the start of the experiments, blind participants underwent through a training of five minutes with the device to familiarize with it. We used a duty cycle equal to 3 seconds for rendering words and numbers. The experiment was recorded to keep track of the correctness of the provided answers and of the time participants employed. Note that participants had no time limitation to accomplish the experimental sub-tasks. At the end of experiment, blind participants underwent through a subjective quantitative evaluation - using a 5 point Likert scale (from 1: totally disagree to 5: totally agree). The questions (see Table II) were related to participants’ knowledge and use in every-day life of Braille code (Q1, Q2), to the performance (readability, comfort, refresh rate and elicited sensation on the fingerpad: Q3, Q5, Q4, respectively), and to the acceptance of the device (Q7, Q8). Finally, we collected general participants’ impression on the system and open-answers on possible usages of *Readabale* in everyday life.

C. Data Analysis

The same methods reported in Section IV-C were used to evaluate participants’ accuracy in stimulus recognition and the average exploration time for the two reading conditions. Data Gaussianity was tested using a Lilliefors test, and a paired t-test was used to evaluate the exploration time, and the Wilcoxon test to assess the accuracy, in the two reading modalities.

VI. Results

A. Experiment with Blindfolded Sighted Participants

Considering the time required by blindfolded subjects to recognize the letters, we found a statistically significant difference between the two reading modalities, i.e. via paper and via device ($p = 0.003$). More specifically, results showed that the time required to complete the task via the device is - on average - lower ($312s$) than the time required to complete the same task with the traditional modality on paper ($450s$). Regarding the total accuracy in giving the correct answers for the whole experiment, we obtained a total accuracy for the case of reading via device and for the traditional modality of 94 % and 90%, respectively. Performing a statistical analysis on the total number of correct answers provided by each blindfolded subject, we verified – via t-test – that there was no statistical difference between the two reading modalities ($p = 0.08$). These outcomes suggest similar performances – in terms of correctness in the detection of the Braille letters – of our device with respect to traditional Braille communication. *Readable* outperformed the paper-printed stimuli in terms of the average recognition time.

	Questions	mean±std
Q1	How much do you know the Braille code?	4.9±0.3
Q2	How much do you use the Braille code in your daily life?	4.6±0.78
Q3	How readable were the letters performed by the device?	3.78±0.78
Q4	How much the feedback of the dots on the fingertip was comfortable?	3.9±1.1
Q5	How was the refresh rate of the device?	3.25±0.7
Q6	How cheap do you think the cost of the device is?	3.24±0.89
Q7	How much do you think this device can be useful?	4±0
Q8	How much did you like the device?	3.71±0.95

TABLE II: Questions Likert scale (from 1 to 5) relative to Blind participants

B. Experiment with Blind Participants

We verified via t-test that there was no statistical difference between the time required by participants to recognize the stimuli in the two reading modalities ($p = 0.13$). Regarding the total accuracy in giving the correct answers for the case of letter recognition, we obtained a total accuracy for the case of reading via device and for the traditional modality of 94 % and 97%, respectively. Performing a statistical analysis on the total number of correct answers provided by each subject, we verified – via Wilcoxon signed rank test – that there was no statistical difference between the two reading modalities ($p = 0.06$). Considering the sub-tasks related to the reading of the words and the numbers, all participants provided the correct answers via the traditional paper-letters; on the other hand, there was one case of a participant incorrectly reading only one letter of a word via the device.

1) Subjective Quantitative Evaluation: Results of the Likert scale are reported in Table II. The participants knew very well the Braille code and they often used it in everyday life (Q1, Q2). Moreover, they considered the letters well readable (Q3), the feedback of the dots on the fingertip comfortable (Q4) and the refresh rate appropriated (Q5). Regarding the costs, they considered the device cost-aware (Q6). Finally, they judged the device useful (Q7), and they gave a positive impression on it (Q8).

2) Possible usage in everyday life: The participants suggested several possible applications of our device in everyday life, where *Readable* would be preferable to a complete multi-cell Braille display. Here a collection of the most frequent suggestions:

- displaying the status of the household appliances;
- displaying the current floor of an elevator;
- integration in a cordless phone for a first call notification;
- showing the temperature measured via the thermometer;
- showing the light status on/off.

Finally, we asked blind participants if they would have preferred an acoustic feedback for this type of applications compared to tactile cues provided through the Braille code, observing a general consensus for the latter one.

VII. Conclusions and Future Developments

In this work, we have presented *Readable*, a new electromagnetic refreshable single Braille cell. The main objective of this manuscript is to propose a reliable, effective, cost-aware device, which enables to codify the alphabet letters according to the Braille code. Our implementation is characterized by six independently-controlled dots actuated via electromagnetic field, with no noticeable magnetic cross-talk effect between dots, and negligible thermal variation of the pins during the normal usage of the device. The design enables contact points at the fingertip level comparable with the standard Braille coding [17], and it is able to properly work up to a frequency rate of 4Hz.

To test the performance of the *Readable* device, we carried out a series of experiments with a cohort of eight sighted blindfolded participants, and eight blind users, who were expert Braille code readers. Results show that participants' capability in recognizing alphanumeric information in Braille code via the *Readable* device is comparable to the performance achievable with traditional paper letters, with no significant statistical difference. Furthermore, it is worth reporting that blindfolded participants employed an average time significantly lower in the case of device-coded letters, while no difference was observed in the exploration time for blind subjects. This seems to testify in favor of the intuitiveness of Readable in delivering textual content.

Moreover, the blind participants evaluated the device as intuitive, cost-aware, useful and well-accepted. Looking at the open answers they provided, it is interesting to note that blind users identified the usefulness of the system in everyday activities such as displaying the status of the household appliances, showing the current floor of an elevator, or of the light status in integration with a cordless phone, where the usage of the *Readable* would be preferable with respect to the complete multi-cell Braille display or audio feedback. In addition, the estimated overall cost of the cell is around 42.74$, which was considered as cost-aware by the blind participants.The outcomes of this work open interesting perspectives for the investigation of new technological solutions for the single-cell Braille displays, which could help to overcome the main drawbacks of the complete Braille devices. Our future work will be directed toward an overall dimension reduction of the design, with specific focus on the external case and the electronics, and toward a more in depth analysis of the applicability of *Readable* in every-day life.

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