FLight: A Low-Cost Reading and Writing System for Economically Less-Privileged Visually-Impaired People Exploiting Ink-based Braille System

Tusher Chakraborty, Taslim Arefin Khan, and A. B. M. Alim Al Islam
Bangladesh University of Engineering and Technology, Dhaka, Bangladesh.
tusherchakraborty@matholympiad.org.bd,arefin612@gmail.com,alim_razi@cse.buet.ac.bd

ABSTRACT
Reading printed documents and writing on a paper pose a great challenge for visually-impaired people. Existing studies that attempt to solve these challenges are expensive and not feasible in low-income context. Moreover, these studies solve reading and writing problems separately. On the contrary, in this study, we propose *FLight*, a low-cost reading and writing system for economically less-privileged people. *FLight* uses ink-based Braille characters as the medium of textual representation. This helps in keeping a compact spatial representation of texts, yet achieving a low-cost status. Additionally, *FLight* utilizes a low-cost wearable device to enhance ease of reading by visually-impaired people. We conduct a participatory design and iterative evaluation involving five visually-impaired children in Bangladesh for more than 18 months. Our user evaluation reveals that *FLight* is easy-to-use, and exhibits a potential low-cost solution for economically less-privileged visually-impaired people.

Author Keywords
Assistive technology; Wearable device; Braille; Economically less-privileged people

ACM Classification Keywords
K.4.2 Social Issues: Assistive technologies for persons with disabilities

INTRODUCTION
Access to printed text is always a challenge for people having visual impairments. According to WHO, there are approximately 285 million visually-impaired people worldwide, and 90% of them live in low-income settings [6]. While technological advancements have reaped benefits to the sighted peers, challenges involved in reading and writing by visually-impaired people still remain an open problem. Recent development in smart phones and computer vision algorithms have paved paths to new solutions. However, these solutions are expensive which make them unfeasible for economically less-privileged people.

CHI 2017, May 6-11, 2017, Denver, CO, USA.

http://dx.doi.org/10.1145/3025453.3025646

The palpable dot based conventional Braille system has been perceived as a difficult and arduous process because of the effort necessary to learn Braille [18]. Consequently, the popularity and literacy rate of Braille generally remains low [3, 17]. The wide market penetration of smart phones and gadgets is one of the reasons behind the fall of Braille's popularity. Ironically, Braille has its influence in the later part of a visually-impaired person's life. Visually-impaired adults having prior Braille literacy exhibit 56% employment rate compared to 23% observed for individuals habituated with plain texts [27, 28]. Moreover, a report from the US Department of Education [22] states that youth with visual impairment are more likely to attend post-secondary school than those with other disabilities. Since this group shows more inclination towards education, a number of research studies have been conducted to solve their reading and writing problems.

There are attempts to ease reading process in both smart phone and wearable form-factor [9, 24, 30]. Computer vision and OCR based algorithms have solved plain text based reading problems. There are applications which offer text writing exploiting speech input or multi-touch gesture input [1, 4, 5]. However, they certainly do not help writing on paper. Braille is often used for writing using embossing kits, so Braille-like smart phone writing applications aim to both help in learning Braille, and rely on existing expertise in writing Braille for faster input [11, 20]. The ease of text based reading and the compactness of Braille based writing have developed two disjoint groups of research studies. Even though smart phones provide alternative solutions to reading and writing problems, it is far from ideal for economically less-privileged people to afford smart phones [21].

Since smart phones and gadgets alone cannot solve this problem, we attempt to investigate whether reviving Braille can help. There are two arguments why Braille is still important. First, Braille has a relationship with employment as discussed before. Second, a study reveals that non-visual free-form handwriting by the visually-impaired is often messy and space inefficient, because, they lack necessary spatial feedback and shape awareness [25]. Since existing solutions also rely on Braille-based writing for faster input, a coherent solution for reading and writing problems is less likely without Braille.

It is now necessary to establish why this coherent solution is important for economically less-privileged people. Developing countries account for 97% of the total world population growth [13]. While it is true that technology penetration is moving fast, people in this region tend to avoid complex functionalities of smart phones [19]. For example, they struggle with navigating through hierarchical organization of information in smart phones. They even struggle with choosing contacts from contact book. They use mobile phones mainly for voice communication [19]. However, the socio-economic infrastructure to support Braille education is also appalling. For example, as a developing country, Bangladesh has only one government run Braille printing press. Palpable Braille printing is expensive. Our investigation in this study reveals that printing Braille book is 65× expensive than printing plain text book (see Table 1). A quick solution to printing problem is utilizing existing normal ink-based printers available in our homes and offices. Two mutually related problems arise here - first, ink-based printing provides no haptic means of reading, second, even if we print using ink-based printers, most state-of-the-art solutions rely on computer vision or OCR techniques, which are unaffordable in low-income settings.

Our study here encompasses solving these two design challenges, plus ensuring a common ground for both reading and writing problems, and yet maintaining a low-cost status. To address these challenges, we take advantage of the reflective characteristics of visible light and employ a novel technique to discern textual patterns. With no camera to capture and analyze the pattern for us, we exploit a simplistic and spatially compact pattern that visually-impaired are already familiar with - Braille. In this study, we undertake a participatory design process involving visually-impaired people, develop a novel low-cost (<$10) wearable device that helps in reading, and a custom-off-the-shelf (COTS) pen that enables writing exploiting ink-based Braille system. Our proposed system exploits finger-held devices, and light plays a cardinal role in reading. As a result, we name our system *FLight*. We also refer the reader to our prior work that presents a simple pen for the visually-impaired to ease reading process [7]. In this paper, our contributions are as follows -

- We design and develop a low-cost (<$10) novel system that helps visually-impaired people in reading and writing ink-based Braille characters. Our solution exploiting ink-based printing reduces cost by more than 80% compared to palpable Braille printing system.
- We undertake a participatory design process involving five visually-impaired children. In a more than 18 months long study, we iteratively design *FLight* from a pen to a wearable form-factor based on their feedback. We also demonstrate culture-specific system design as a use-case study in human-computer interaction design.
- To contrast with our prior work [7] - (a) we make transition in design space - from a commodity pen to a wearable glove, (b) we improve the reading speed from 2 words per minute (wpm) to 13 wpm, (c) we lessen the cognitive stress of identifying Braille dots and recognizing the character, and (d) we introduce Braille writing feature that coherently work with the wearable (reading tool).

RELATED WORK

A number of research studies have been carried out in both academia and industry to solve reading and writing problems of visually-impaired people.

Reading Aid and Technique

Reading devices and techniques vary in the nature of interaction with the users and the modality of their usage. We categorize them here based on the latter.

Mobile Applications: The era of smart phones helped researchers to quickly develop applications that provide audio feedback to the users. Shen and Coughlan [29] describe a prototype smart phone application that reads printed texts. ZoomText [31], SayText [8], etc., are similar examples of text-based readers. Contrary to these applications, VBraille [15] helps in reading by virtually dividing the smart phone screen into six zones corresponding to six dots of a Braille character. It uses vibration when user touches different screen zones to convey presence of a raise dot.

Wearable Solutions: Wearable solutions here are mostly accompanied by a camera to assist in vision, and generates either haptic or audio output, or in some cases both. OrCam [24](price $2,500) is a smart wearable eye glass designed to assist visually-impaired people in reading printed texts. FingerReader [30] is a smart finger-worn device that helps blind users with reading. However, FingerReader may not work under poor lighting condition. HandSight [32] addresses this problem by introducing a self-illuminating finger-worn device.

Braille Based Devices: Conventional Braille reading utilizes haptic senses of the readers. In refreshable Braille displays, the dots of a Braille cell are formed by pins independently controlled by actuators [12]. UbiBraille [23] is a vibration based Braille reading device that actuates the six fingers mapped with six dots of a Braille character.

Writing Aids and Techniques

McSig [25] explores non-visual free-form hand writing by visually-impaired students. No-Look Notes [4] is a pioneering work on the first multi-touch enabled phone screens, which revealed that arranging characters in 8-segment pie menu is less erroneous and more faster than speech based input. Similarly, MTITK [5] is a mobile keyboard where users tap to enter a text, and gesture to edit it. Touchplates [16] is a low-cost acrylic board overlay on a touchscreen providing tactile cues to the soft keyboard displayed underneath. Among the Braille based inputs, BrailleTouch [11] takes Braille input on six virtually divided zones corresponding to six dots on a smart phone. TypeInBraille [20] uses touch-based gestures on smart phones to input one row of a Braille character at a time. In both cases, an audio feedback is provided. Azenkot et al., [2] mapped fingers with Braille dots, and experimented with single hand input versus both hands input. Another work [1] explored speech input by blind people. Their study revealed that participants were satisfied with speech input, however, they spent an average of 80.3% of their time editing the texts.

What is There for the Economically Less-Privileged?

Medhi et al., [21] showed that more than half of the existing mobile phone subscribers live in low-income countries, and most of them are subscribers of low-cost feature phones. Consequently, it is far from ideal for people having low per capita income to afford smart phones. Moreover, apart from

(a) A Braille book (b) Plain print book

Figure 1. English language book for Class 5 in Bangladesh

	Braille print	Plain print
Dimension (l×w×h) cm	27×24×4	25×21×0.7
Number of pages	203	104
Cost (USD)	50	0.76

Table 1. Comparison between Braille and plain text books

standalone devices, some solutions (e.g., FingerReader, HandSight) come with expensive companion computing devices, such as a computer or tablet. We now refer the reader to our first attempt on designing a low-cost reading solution for economically less-privileged people. EyePen [7] is a commodity pen that helps visually-impaired people in reading Braille printed from regular ink-jet printers. The reading process of EyePen is slow. In this paper, we address improvement in reading speed and incorporate writing as a new feature.

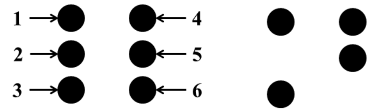
RESEARCH CONTEXT

Our more than 18 months long study was conducted at the National Foundation for Betterment of the Disabled at Mirpur, Dhaka. This organization supports basic education and rehabilitation program for different forms of disabilities. As of September 2016, this organization has 30 boys and 18 girls in its school for visually-impaired. We chose this school because of suitable geo-location and it also reflected problems of low-income settings. The monthly tuition fee varies by classes. We report here the average \$3.75 per students. All students reside at the on campus dormitory. The school has ten teachers; five of them have different forms of visual impairment and are quite fluent in Braille. Students of Class 5 are the seniors in this school. After that, they continue high school in other government-run or private schools. The school authority reported that approximately 20% of these students no longer continue education because of various reasons such as poverty, difficulties with Braille, etc.

Books: Braille embossers are expensive [10]. There is only one government run Braille printing press in Bangladesh. Figure 1a shows a Braille printed English book under the national curriculum of Bangladesh. Figure 1b shows the corresponding print for sighted peers. Table 1 demonstrates a comparison between these two books as an example. Here, considering only printing cost, Braille book is 65× costlier than plain print book. Although students in this school receive Braille books free of cost from the government, our primary concern here is the massive cost involvement in printing Braille books. Moreover, the only Braille press struggles to supply academic books in time. Students once spent at least half of their academic year without books [14].

Supporting Tools: The conventional writing system in Braille is complex because it is done from *right to left*. In order to read the same, they flip the paper and read from left to right. Figure 2 shows a supporting tool that assists them

Figure 2. Supporting tool for writing in Braille



(a) A Braille cell (b) Braille representation of 'N'

Figure 3. Printed form of Braille in our system

Participant	Category	Initial Braille learning period	Age (years)	Writing hand
P1	Blind	1.5 months	8	Left
P2	Blind	4 months	9	Right
P3	Blind	1 months	10	Right
P4	Low vision	5 month	10	Right
P5	Low vision	1.5 months	11	Right

Table 2. Demography of participants

while writing. It has 30 Braille cells per line. Each cell has six small notches for six Braille dots. Visually-impaired people use a small stylus with metallic tip to bore holes at appropriate notches. They use heavy paper such as art paper while writing and are able to utilize only one side of the paper.

Use of Technology: While conducting our study in that school, we found that none of the students were using a smart phone. Some of them used feature mobile phones having physical keyboard. Physical keyboard played an important part because it provided necessary tactile feedback while dialing numbers for voice call. This on-site experience also motivated us to think beyond smart phones.

FLIGHT

FLight evolved through a collaborative evaluation and feedback from a dedicated and strong focus group. Over a period of more than 18 months, this focus group helped us in shaping and outlining *FLight*.

Focus Group and Design Goals

We targeted one primary group and two secondary groups as focus group participants. The primary group consisted of five children from the school. We collaborated directly with the primary focus group to study the usability of our developed system and received feedback for further improvement. The two secondary focus groups consisted of school teachers and two visually-impaired undergraduate students from University of Dhaka (DU). These groups participated in design discussions, idea generation, and also provided feedback. Table 2 shows a demography of primary focus group participants. Following the classification provided by WHO [6], we group moderate and severe visual impairment under 'low vision', and complete vision loss under 'blindness'. Conforming with WHO standard, we refer low vision and blindness together under the umbrella term 'visual impairment'.

Underlying Operational Mechanism

To remind the reader, our endeavor here is to design a system that coherently solves reading and writing problems exploiting

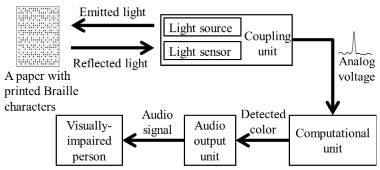


Figure 4. Block diagram of underlying mechanism

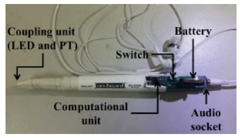
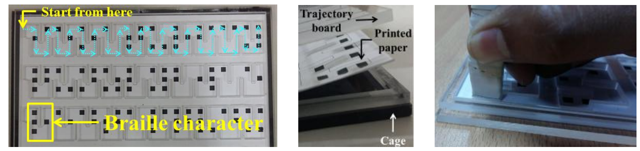


Figure 5. Pen-shaped active sensing body developed in phase 1



(a) Trajectory board with printed page (b) Closer look (c) Tip fits the drilled hole

Figure 6. Modified printed page and trajectory board used in phase 2

ink-based Braille system. Figure 3a shows an ink-based form of a Braille cell with six filled-circular (or square) dots. Figure 3b shows the character 'N' in Braille format in our system. Using ink-based printers, we wish to print each character in Braille format as shown. With no haptic feedback and no camera to help, how exactly are we going to provide feedback to the user? Here, we present the underlying operational mechanism that works at the core of our system, followed by a simplified operational block diagram.

A black-colored surface absorbs most of the incident light energy, whereas, a white-colored surface reflects most of the incident light energy. As a result, the intensity of light reflected from a white-colored surface is significantly higher than that from a black-colored surface. To corroborate this phenomenon, we conduct a testbed experiment in different ambient lighting conditions. The experimental setup consists of a white paper having printed black colored region on it, and a coupling of LED and phototransistor (PT). Experimental results confirm that there is a significant difference between the voltages generated by PT for two different colored regions [7].

Figure 4 represents a simplified block diagram of the underlying operational mechanism of our system. The system consists of four units: (1) A paper with printed Braille characters, (2) A Coupling unit, (3) A Computational unit, and (4) An audio output unit. In our proposed system, we print Braille characters in black ink over white papers using normal ink-jet printers. Components $2-4$ are used to recognize Braille characters and generate an audio output to visually-impaired people.

Using the underlying system design, we develop our system phase by phase. In each phase, we accumulate user feedback and revise our system accordingly in the next phase.

PRELIMINARY WORK

For simplicity of exposition, we summarize here the first two iterative phases presented in our prior work [7]. Although we summarize here key points in terms of design and user evaluation, we refer the reader to our prior work for details.

Phase 1

The initial design presented in our prior work was mostly intuition driven. We summarize here our first design followed by the user feedback.

Tangible Object Design

Designing for visually-impaired is always challenging. The social model of disability [18] and the demand for portable assistive tools helped us understand the subtlety involved while designing assistive tools for the visually-impaired. Consequently, our design evolved as a pervasive portable pen-shaped body. Figure 5 shows a snapshot of the pen. This pen generates an audible beep when it detects the presence of a black-colored region on the white paper placed beneath the pen tip.

Using this pen, we intended to read Braille characters similar to that presented in Figure 3. To do so, a visually-impaired person needs to perceive the relative positions of Braille characters and their dots. We facilitated this process by designing a predefined trajectory to drag the pen tip on the printed paper. Here, the visually-impaired participants perceived this trajectory through audio-feedback generated by the pen instead of haptic feedback. We would like to refer the reader to our prior work [7] for the details on reading procedure.

Usability Analysis

Analyzing the feedback from the first user evaluation involving our focus group, we pointed out several crucial aspects:

- Following the predefined trajectory exploiting the audio-feedback is strenuous for a visually-impaired person.
- Since the threshold demarcating black and white region depends on ambient lighting condition [7], the pen undergoes an initial calibration to set the threshold value. This calibration process makes the reading procedure cumbersome. Nevertheless, the threshold could also change with the change in ambient lighting condition while reading.

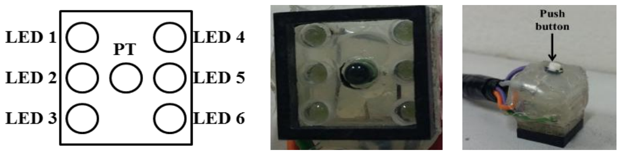
Phase 2

In the second phase, we addressed the problems and integrated the improvement suggestions provided by the focus group after the first deployment. Although we summarize here key points in terms of design consideration and user evaluation, we encourage the reader to our prior work for details [7].

Solving The Alignment and Calibration Issues

The first user evaluation allowed us to contemplate at the way visually-impaired people behave and perceive information. One of the key aspects of conventional Braille reading system is that, it leverages the haptic sense of the reader by tiny palpable bumps or raised dots. However, our preliminary system depended on the correctness in dragging the pen along a predefined trajectory by leveraging the auditory senses only, which was difficult and error-prone. Consequently, we needed to produce a way that could make use of the haptic sense.

We attempted to leverage the haptic sense through using a hard thick board. To do so, we developed a novel board that contained a trajectory drilled along the thickness and guides tip of the pen-shaped body to follow a predefined path (as shown in Figure 6). Besides, the hole on trajectory board and the tip were shaped in such a way that the hole fits the tip (as shown in Figure 6c). To do so, an opaque boundary was



(a) LED, PT placements (b) Front view (c) Entire view

Figure 7. Modified Coupling unit in phase 3

built around the LED and PT. The modified design of the tip implicitly solved the calibration problem, as the opaque wall kept the Coupling unit out of the influence of ambient light.

User Evaluation

We conducted a second user evaluation based on the improvements made in phase 2. Due to space limitations, based on the user feedback, we outline here only two crucial aspects that can drive us towards further improvement.

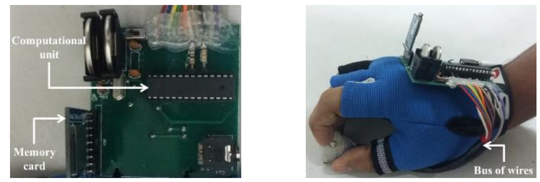
- **Escalating Reading Process:** Using the current prototype of our system, one can read as much as 2 words per minute. When we asked the participants to comment about our system, P2 and P5 used their imagination and said that, *"It would have been better if this pen could tell me the character, or at least enumerate the dot positions"*.
- **Potential for Aiding in Writing:** Although the temporal disadvantages of our system was a concerning issue, the focus group expressed interest on exploiting the aiding capability of ink-based Braille in writing. P3 opined that our system could be more useful during writing.

PHASE 3

The second deployment turned our focus towards two pivotal aspects: escalating reading process and potential of ink-based writing. In this section, first, we delineate how we develop the wearable solution *FLight* to speed-up the reading process. Second, we delineate our proposed ink-based Braille writing feature that coherently work with this wearable.

Improvements

Up until phase 2, our system could detect only one Braille dot at a time. The previous user evaluation revealed that it required around 5s to recognize a single Braille character, since a visually-impaired person have to scan all the six dot positions of a single Braille character through placing the pen-tip (i.e., the Coupling unit) on six different dot positions in sequence. This extent of time required for recognizing a character is significantly higher than the conventional palpable system. Here, though it merely takes 5ms to detect a dot, the time consuming part in recognizing a character is the manual movement of pen-tip to six different dot positions of a Braille character. An intuitive idea to address this problem is to detect all the six possible dots of a single Braille character without any manual movement, i.e., by keeping the tip of *FLight* fixed at one position. Driven by the same intuition, one might think of incorporating six pairs of LED and PT to detect six different dots at the same time. However, from the pragmatic point of view, there will arise several problems in such a design: (1) integration of five more PTs will demand five more analog to digital converter (ADC) channels of microcontroller and that will give rise to both power consumption and hardware redundancy, (2) the expensive part of the Coupling unit is PT which costs around 60 times more than the cost of an LED and thus the integration of five more PTs will demand colossal cost, (3) integration of six pairs of LED and PT will increase the size of the Coupling unit, which can result in much lower character density than current implementation, and (4) since power consumption is a crucial issue here, it will not be a wise decision to turn six LEDs on at a time.



(a) Modified circuit board (b) Wearable glove

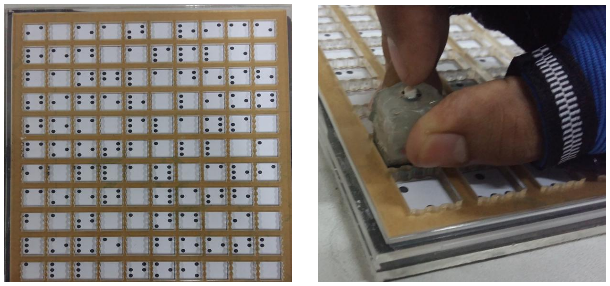
Figure 8. Modified *FLight* and its circuit board in phase 3

Modified Coupling Unit: As a remedy, we modify the Coupling unit in such a way that it escalates the reading procedure and does not give rise to the aforementioned problems. Our new design of the Coupling unit subsumes only one PT and six LEDs, as shown in Figure 7. The six LEDs are positioned in such a way that whenever the Coupling unit is placed over a Braille character, all six LEDs are placed exactly on top of corresponding six dots of the Braille character. Therefore, the six LEDs are arranged in 3×2 matrix as shown in Figure 7a, where the PT is placed in between the two columns. Here, using one PT in a judicious manner, we make six pairs of LED and PT in the temporal domain. To further elaborate, we do not simultaneously keep all the LEDs turned on, rather we turn the LEDs on one by one. Thus, when we turn any one of the six LEDs on, the region beneath the LED is illuminated only, and the light reflected from that region hits the PT. Consequently, the voltage generated by the PT represents color of the region situated directly beneath the LED. Iterating the same process for all the six LEDs, we can get color of the regions beneath the LEDs and thus, the system recognizes the absence/presence of all six dots.

The Wearable: We explore the design space of wearables and employ our changes in a comfortable and lightweight hand glove. Such a wearable form-factor offers portability, ease-of-access, and impacts social interaction positively [33]. Figure 8a shows the new circuit board of *FLight*, which we affix on the glove. Since our intention is to recognize a Braille character and dictate the corresponding audio clip to the user, we also include a memory card (available in local market at price below $1.5) to store all alphanumeric audio clips. Figure 8b shows the complete wearable glove for reading.

Modified Trajectory Board: The modified trajectory board is much simpler than the previous one. It consists of 130 rectangular shaped holes and each hole covers a Braille character printed on a paper, which is attached beneath the board (as shown in Figure 9a). The hole on trajectory board and the Coupling unit are shaped in such a way that the hole fits the Coupling unit (as shown in Figure 9b).

While reading a Braille character, a visually-impaired person places the Coupling unit in the corresponding rectangular



(a) The board with printed paper (b) Coupling unit fits the board

Figure 9. Modified trajectory board used in phase 3

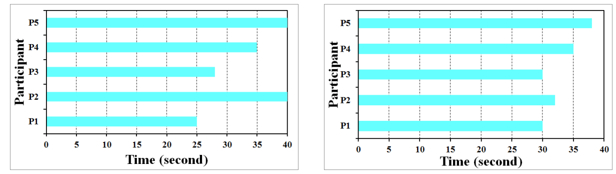
Figure 10. Writing system design and procedure

drilled hole of the trajectory board (as shown in Figure 9b). Since power consumption is crucial here, we design the system such that the system reads only when the reader wishes to read. This is done by introducing a push switch as shown in Figure 7c. The push button is placed in such a position that when a visually-impaired person holds the Coupling unit, the index finger automatically comes over the push button (as shown in Figure 9b). Upon placing the Coupling unit in a hole, the visually-impaired person presses the button to activate the reading procedure. Next, the Computational unit turns the LED on, which corresponds to the Braille dot '1', on for 5ms and takes reading of voltage generated by the PT. Then, the voltage is compared with a pre-defined threshold, which is set experimentally as discussed earlier, to detect the presence/absence of dot '1'. After that, the Computational unit turns that LED off and turns the next LED on, which corresponds to the Braille dot '2'. In a similar manner, it scans all six dots of the Braille character within only 60ms and recognizes the alphanumeric character represented by that Braille character. Upon recognizing the Braille character, the Computational unit searches the database for corresponding sound and plays it.

Note that, our current prototype allows us to print 130 Braille characters on each side of a page, making it 260 overall per page. Here, for prototyping purpose, we used Dual in-line package(DIP) of LED and PT. Commercial production subsumes Surface Mount Device(SMD) which is 3 to 4 times smaller in dimension than DIP. This can significantly increase char density ($\sim$ 600 characters/page).

Ink-based Braille Writing

Up to this point, we have delineated the evolution of *FLight* as a reading tool for visually-impaired people exploiting ink-based Braille system. Keeping alive our central motivation to design a common ground for reading and writing, we design a low-cost COTS writing aid for visually-impaired people exploiting ink-based Braille system. In our design, we attempt to leverage the haptic sense of a visually-impaired person ensuring a low-cost status. Here, we use a retractable marker available in local market at less than $1. It is important to ensure that visually-impaired writers place dot exactly where they intended. To ensure swift writing movement and alignment, we design a small frame made of acrylic (as shown in Figure 10a), which we attach at the tip of this marker (as shown in Figure 10b). The writing procedure subsumes the existing trajectory board used in phase 3 with a small modification. Note that this modification does not influence the reading procedure described in phase 3. We make 6 mini concave notches on two vertical walls of a single hole on existing trajectory board (as shown in Figure 10c). Each vertical wall contains 3 concave notches keeping same relative positions corresponding to the Braille dot positions. While writing a Braille dot, a visually-impaired person fits one of two convex mountings of the frame with a concave notch which corresponds to that Braille dot (as shown in Figure 10d), utilizing the haptic sense.



(a) For reading (b) For writing

Figure 11. Training period

SYSTEM EVALUATION

We conducted a series of evaluations to explore whether *FLight* can provide a coherent reading and writing support for visually-impaired people. In this section, we delineate the results of evaluations followed a usability survey.

Reading

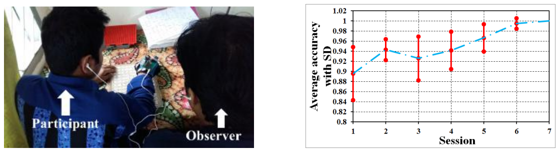
The most interesting aspect of working with visually-impaired children was their enthusiasm and intuition towards a new object. In this phase too, we followed these steps while evaluating our system - (1) introduce the system to each participants individually, (2) let the participants touch and feel the system and hear from them what they are touching, (3) a hands-on demonstration to the participants on how to operate the system, and (4) let the participants use the system on their own.

Training Period

We consider steps 3-4 as the training period. We define training period as the time during which the participants were completely able to demonstrate by themselves on how to use *FLight*. Figure 11a shows the training time for reading. Surprisingly, the maximum training time period for any participant was 40 seconds. Two issues accounted for such a small time. First, we found their perception and intuition towards haptic sense very strong during step 2. Second, their prior experience with the previous iterations [7] helped them anticipate the behavior of our system. Note that, we reserved steps 1-2 for informal training time. While sighted peers can use vision to understand the behavior of a system, non-sighted people mostly use their haptic sense to understand a system. Hence, we kept provision for informal discussions during steps 1-2.

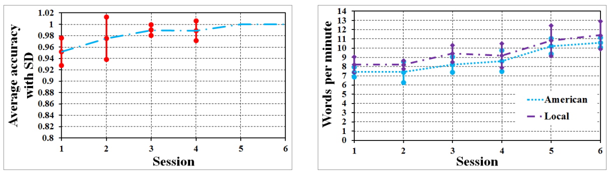
Reading with FLight

We organized the reading sessions in gradual improving order - (1) reading (listening) to every audible character using *FLight*,



(a) Sharing earphone to observe errors (b) Accuracy of recognizing characters

Figure 12. Experimental process and accuracy of reading characters



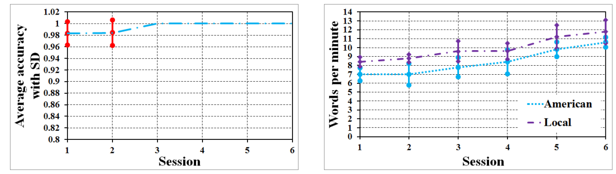
(a) Accuracy of forming word (b) Words formed per minute

Figure 13. Statistics while forming word by recognizing individual character(s)

(2) forming words from just read characters. In doing so, we took note of two important errors - **system error** is an error generated by our system, and **human error** is an error on behalf of the human, for example, the system outputs 'B' when there is an actual 'B', however, the human mistakenly perceives that as 'D'.

Reading (recognizing) Single Character: We asked participants to read aloud characters as they hear them. This is called oral reading. To cross-check for errors while reading, we asked them to put one earphone in their best ear, and used the other for ourself, as shown in Figure 12a. In Figure 12b we report the accuracy of reading simple characters in Braille using *FLight*. In each session, we provided a set of 100 alphanumeric characters that were randomly organized. We continued until Session 7, where all the participants correctly enunciated the characters. It led us to an interesting finding - **accent** played an important while participants struggled to perceive the system dictated character. The default audio clip that we used here dictated characters in American accent. P4 complained, *"It's a bit strange. 'T' and 'P' sounds similar. Why?"* As shown in Figure 12b, in Session 1, the accuracy of recognizing characters was 89% (SD=5). With each session, they became more habituated and adapted themselves with the nuances of this accent. For example, in Session 6, only P2 made mistakes in 3 characters. Here, the **system error** was 0% for all sessions.

Forming Word: We then asked the participants to form word as they read the characters. We conducted this experiment in oral mode. To remind our readers, *FLight* provides audible dictation of the characters to participants, and provides no audible sound when a space was found. We provided printed documents with meaningful words in the form of sentences. We started counting reading time using a stopwatch whenever a participant was ready to read. In six consecutive sessions that lasted for ten minutes each, the accuracy of forming word peaked in the last two sessions, as shown in Figure 13a. It clearly shows that participants adapted to *FLight* with time and practice. During these sessions, P3 and P5 made personal best of 11 wpm. We provided regular and age appropriate dictionary words that had diversity in word-length, such as words so small as 2 characters to words so large as 12 characters.



(a) Accuracy of forming word (b) Words formed per minute

Figure 14. Statistics while forming word by recognizing character(s) all together at the space interval

	Standard Braille	Using FLight
Silent reading (wpm)	33 (± 9)	25 (± 4)
Oral reading (wpm)	19 (± 7)	12 (± 1)

Table 3. Standard Braille reading speed vs. reading speed using *FLight*

Preliminary Feedback on Reading: We summarize here the preliminary feedback from the participants on reading.

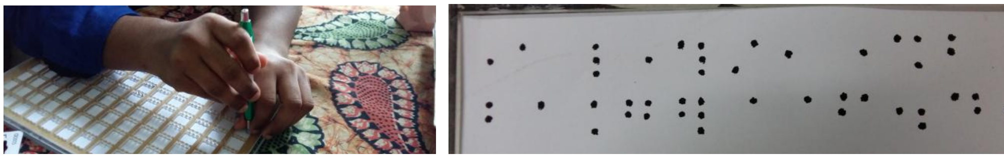
1. Participants had to memorize just-read characters in order to form words which was cumbersome. All the participants raised this issue upon completing the six sessions.
2. The default audible sound having American accent was troublesome. The participants were habituated with local accent. Consequently, their accuracy of recognizing characters improved slowly (Figure 12b).

Recognizing Characters at Space Interval: We address the preliminary feedback and modify *FLight* for the second time in phase 3. This time *FLight* does not dictate the character immediately after scanning it, rather it provides a smooth audible tone as a feedback and saves the characters in a run-time queue. When a space is scanned *FLight* dictates just-read audible characters from the queue. The visually-impaired person can hear these characters repeatedly by pressing the push button at space. However, when *FLight* starts to scan a new character after scanning a space, it overwrites the queue. The relative advantage of this arrangement is clear from Figure 14a, where accuracy improved than that in Figure 13a. Figure 14b illustrates the advantage over temporal domain.

Our endeavor in this phase was to escalate the reading procedure using *FLight*. Here, we achieved up to 13 wpm while reading, which is 6× more than that of previous phase. Additionally, in Table 3, we show a comparison between standard Braille reading speed and the reading speed using *FLight* in wpm. Pertaining to other studies such as [26] that quantifies reading speed, we also report here silent reading and oral reading. In silent reading, the reader is allowed to read silently with sustained attention, concentration, and comfort. In oral reading, the reader is asked to read aloud. Since our primary goal was to evaluate the accuracy of *FLight*, our sessions were conducted in oral reading mode to measure wpm and the errors while reading. Additionally, we conducted two more informal sessions in silent reading mode to report a quantitative comparison in Table 3.

Writing

The adoption of writing was very quick after a short training session. They intuitively started to use one hand to move the



(a) A visually-impaired person while writing (b) Small portion of a paragraph written by P4

Figure 15. Deployment of writing tool involving the focus group

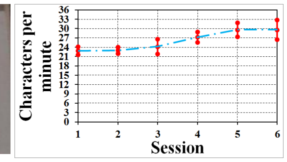


Figure 16. Characters written per minute

marker and another hand to press the push button of marker (as shown in Figure 15a). We noted down the time during which the participants were able to achieve a spatial awareness required for writing using the marker and our trajectory board. We again found their perception towards haptic senses very strong, the results of which were reflected in Figure 11b.

We asked the participants to write a paragraph for ten minutes in each session, topics included but not limited to their country, their favorite hobby, their parents, etc. Figure 15b presents a snapshot showing small portion of a paragraph written by P4. We then shuffled each piece of writing among the participants and let them read what others have written. We report here characters written per minute in Figure 16. This session was lengthy because we cross-checked with the writer what he actually intended to write. Nevertheless, when we asked them to read back the written pieces, we evaluated based on what was written only. Owing to previous practices, the participants were able to read and understand the written characters. This time the accuracy of reading was 100%.

Usability Survey

In addition to performing user evaluation, we perform a usability survey that explores both formal and informal comments and reviews from focus group participants.

Ease of Use: Our iterative design method helped us to gain generous feedback from focus group participants. Our reading technique evolved from an object (pen) [7] to a wearable form-factor, with significant improvement. All of the participants liked our wearable glove. P3 said, *“Well, I like this glove-thing more. It tells me the character, not that irritating beep like before.”* We found them happy knowing that they can read printed materials from regular printers. *“Really? You can do that?”*, exclaimed P5 in a surprising tone. P3 explained why his friend was surprised, *“We do not have Braille versions of any non-academic books, so we do not read story books, we listen to radio sometimes.”* The audible character feedback generated some concerns. The initial American accent appeared to be difficult for them. They struggled with alphabets having closely related phonetic sounds in American accent. For example, {‘B’, ‘P’, ‘T’}, {‘B’, ‘D’}, and {‘I’, ‘Y’}. The error rates were discussed in section “Phase 3”. We later experimented with a local dialect of English alphabets. They were also curious about writing when we said they can write with a pen too. However, P2 said, *“I would love a shorter pen for writing that fits my fist.”* Shorter retractable pen, although available in other countries, were unfortunately absent in the local market of Bangladesh.

Will Grown-ups Accept *FLight*?: We made formal and informal discussions with two visually-impaired undergraduate students at the University of Dhaka (DU). We asked them to try out *FLight*. We found them excited in the beginning, however, we felt that they were reluctant to try out further after two sessions. We then asked them how they manage their daily academic activities. Three important facts evolved here - (1) they do not have Braille books in the university although DU own one Braille embosser which has been out of service for some years, (2) they rely on audio recitations made by their fellow sighted peers, and (3) none of them own a smart phone or gadget, rather they find feature phones easy to use. These facts are important, particularly because other low income countries reflect them as well. Nevertheless, when we asked them how they appear in examinations, they replied, *“We bring a junior as a writer; we dictate, they write.”* Consequently, it became clear to us their apparent disinterest to use *FLight*, because they had long deserted reading and writing in Braille, and were more used to with audio based activities. This led us to focus on children as primary participant, because, early adoption of a system always plays a vital role in its future uses.

Statement	P1	P2	P3	P4	P5
The wearable was comfortable	5	5	5	4	4
I prefer gloves over previous pen	5	5	5	4	5
Reading was easy	5	3	5	4	3
Writing was easy	4	3	5	4	4
Writing was intuitive	5	5	5	5	5
I enjoyed *FLight* overall	5	5	5	5	5
I will use *FLight* in future	5	3	3	2	4

Table 4. Results from the questionnaire on 5-point Likert scale

Summary: We summarize the user feedback in Table 4. We let the participants answer or express their opinion based on the 5-point Likert scale. Here, ‘1’ referred to ‘strongly disagree’, ‘2’ referred to ‘disagree’, ‘3’ referred to ‘undecided’, ‘4’ referred to ‘agree’, and ‘5’ referred to ‘strongly agree’.

DISCUSSION

In this section, we discuss the reading speed, Braille proficiency, and the cost effectiveness pertinent to *FLight*.

Reading Speed: From Table 3 we see that wpm count using *FLight* is close to that of the standard Braille reading speed in both cases for the same set of participants. Although wpm count using *FLight* appear as a concerning issue, note that, our participants are students from Class 1 to 5 whose average wpm is less than adults’ wpm measure. Moreover, the reported values in Table 3 conform with [26] for the same age group. Besides, one of the teachers at the school also commented about the reading speed, *“The last time a student said your devices could read 2 wpm, right? And now its 13 wpm! This*

	Using Braille	Using FLight
Dimension (l×w×h) cm	27×24×4	29.7×21×4.5
Number of pages	203	542
Printing cost	$52	$8
Paper cost (500 pages)	$31.93	$3.83

Table 5. Comparison between Braille printing and printing for *FLight*

is great improvement. You see, people take a month long to grasp Braille itself, so with practice they can improve with your device as well."

Braille proficiency: While we argue that Braille is important, it might appear to the reader that *FLight* is penalizing Braille proficiency while reading. There are two reasons why *FLight* facilitates such reading process. First, from [7], we know that perceiving the relative positions of six dots and simultaneously recognizing the character was slow and stressful. *FLight* addressed these two issues by automating the character recognition process and providing an audio-feedback based on the recognized character. Second, *FLight* offers a coherent solution to address reading and writing problems. Writing with *FLight* requires as much proficiency in Braille as required in standard Braille. Therefore, *FLight* does not penalize Braille proficiency as a coherent solution. As a low-cost tool with an inclusive design addressing both reading and writing problems, *FLight* encourages Braille proficiency similar to standard Braille.

How Low is Our Low-cost?: In Table 5 we show a comparison between conventional Braille printing and printing for *FLight* for the same text book of Class 5. In terms of only printing cost, our system is 80% more cost-effective than Braille printing. Note that, we have excluded here other variable and fixed cost involved in production, such as labor cost, transport cost, maintenance cost, etc. The press owners were reluctant to share these information with us fearing us to be journalists or other private competitors. We therefore reserve from reporting *unsure* and *approximate* numbers. Moreover, visually-impaired people use art papers while writing by boring holes. While using *FLight*, a visually-impaired person can use normal paper, which is 8× cheaper than art paper. Note that, our current implementation is fashioned by hand-made lab equipments and limited to DIP package only. Character density is influenced by the size of our reading device. This has been discussed in section "Phase 3". Overall, *FLight* is a cost-effective system than state-of-the-art practices.

FUTURE WORK

We summarize here the potential future work in this section.

Continuous Reading: The current difficulty in temporal domain is due to a limitation in tactile representation and feedback. Contrary to existing implementation, a system with continuous scan and read will improve reading time and words per minute count.

Multi-button Retractable Pen: Instead of a single button retractable pen, we wish to explore the use of six-button (corresponding to six dots) retractable pen. The size of the tip will be similar to the size of the current Coupling unit, having six independent nib corresponding to six buttons.

CONCLUSION

In this study, we propose *FLight*, a low-cost system comprising a wearable device for reading, a retractable pen for writing, and a tactile trajectory board for assisting reading and writing. *FLight* uses Braille as the underlying medium of textual representation. In this system, Braille characters are printed using normal ink-based printers available in our homes and offices. We exploit the classical reflection model of light, design a low-cost (<$10) wearable device for recognizing Braille characters, and provide audible feedback. Besides, the retractable pen with COTS frame at the tip serves tactile grip while writing using the trajectory board. The entire design process evolved in a participatory fashion involving focus group members. We evaluated our system with the focus group members consisting five visually-impaired children. Using our system, participants achieved up to 13 words per minute (wpm) in reading and 33 characters per minute (cpm) in writing.

We observed an uncompromising importance of accents in the audible feedback. Participants favored local accent English over American accent. We also observed significant improvement on reading speed (wpm) over successive sessions. The least time period a participant in our focus group took to learn conventional palpable Braille system is 1 month; consequently we believe that with improvements in the device and practice by the participants, reading wpm and writing cpm will improve. On top of everything, *FLight* is cost-effective, as printing Braille characters based on normal ink can reduce printing cost by more than 80%. Such a cost-saving system is very important and significantly impacts the lives of less-privileged visually-impaired people.

ACKNOWLEDGMENT

We sincerely thank our shepherd AC and the reviewers for their insightful comments and feedback.

REFERENCES

1. S. Azenkot and N. B Lee. 2013. Exploring the Use of Speech Input by Blind People on Mobile Devices. In *Proceedings of the 15th International ACM SIGACCESS Conference on Computers and Accessibility*. ACM, 11.
2. S. Azenkot, J. O Wobbrock, S. Prasain, and R. E Ladner. 2012. Input Finger Detection for Nonvisual Touch Screen Text Entry in Perkinput. In *Proceedings of Graphics Interface 2012*. Canadian Information Processing Society, 121–129.
3. American Foundation for the Blind. 2015. School Experience for Children and Youth with Vision Loss. (January 2015). Retrieved February 21, 2016 from `http://goo.gl/1Np4m2`.
4. M. N Bonner, J. T Brudvik, G. D Abowd, and W K. Edwards. 2010. No-look notes: Accessible Eyes-free Multi-touch Text Entry. In *International Conference on Pervasive Computing*. Springer, 409–426.
5. M. C. Buzzi, M. Buzzi, B. Leporini, and A. Trujillo. 2014. Designing a Text Entry Multimodal Keypad for Blind Users of Touchscreen Mobile Phones. In *Proceedings of the 16th international ACM SIGACCESS Conference on Computers & Accessibility*. ACM, 131–136.

6. Media Center. 2014. Visual impairment and blindness. (August 2014). Retrieved February 15, 2016 from `http://goo.gl/BG8XTG`.
7. T. Chakraborty, T. A. Khan, and ABM Islam. 2016. EyePen: Ease of Reading for Less-Privileged Visually-Impaired People. In *Proceedings of the 7th Annual Symposium on Computing for Development*. ACM, 13.
8. DocScanner. 2010. SayText. (June 2010). Retrieved March 23, 2016 from `http://goo.gl/aLvPBS`.
9. Be My Eyes. 2016. Be My Eyes | Lend your eyes to the blind. (2016). Retrieved September 15, 2016 from `http://goo.gl/wiBP0B`.
10. American Foundation for the Blind. 2016. Braille Printers. (2016). Retrieved September 18, 2016 from `https://goo.gl/C14WYk`.
11. B. Frey, C. Southern, and M. Romero. 2011. Brailletouch: Mobile Texting for the Visually Impaired. In *International Conference on Universal Access in Human-Computer Interaction*. Springer, 19–25.
12. T. Fukuda, H. Morita, F. Arai, H. Ishihara, and H. Matsuura. 1997. Micro Resonator Using Electromagnetic Actuator for Tactile Display. In *Micromechatronics and Human Science, 1997. Proceedings of the 1997 International Symposium on*. IEEE, 143–148.
13. Carl Haub. 2012. Fact Sheet: World Population Trends 2012. (2012). Retrieved September 18, 2016 from `https://goo.gl/LvZ2Hr`.
14. Mansura Hussain. 2012. Delayed supply of books for visually-impaired. (2012). Retrieved September 15, 2016 from `https://goo.gl/4xzrnP`.
15. C. Jayant, C. Acuario, W. Johnson, J. Hollier, and R. Ladner. 2010. V-braille: Haptic Braille Perception Using a Touch-screen and Vibration on Mobile Phones. In *Proceedings of the 12th International ACM SIGACCESS Conference on Computers and Accessibility*. ACM, 295–296.
16. S. K Kane, M. R. Morris, and J. O Wobbrock. 2013. Touchplates: Low-cost Tactile Overlays for Visually Impaired Touch Screen Users. In *Proceedings of the 15th International ACM SIGACCESS Conference on Computers and Accessibility*. ACM, 22.
17. R. M. Leonard. 2001. *Statistics on vision impairment: A resource manual* (5th ed.). Lighthouse International.
18. Vincent Lévesque. 2005. Blindness, Technology and Haptics. *Center for Intelligent Machines* (2005), 19–21.
19. I. M. Thies. 2015. User interface design for low-literate and novice users: past, present and future. *Foundations and Trends in Human-Computer Interaction* 8, 1 (2015), 1–72.
20. S. Mascetti, C. Bernareggi, and M. Belotti. 2012. TypeInBraille: Quick Eyes-free Typing on Smartphones. In *International Conference on Computers for Handicapped Persons*. Springer, 615–622.
21. I. Medhi, M. Jain, A. Tewari, M. Bhavsar, M. Matheke-Fischer, and E. Cutrell. 2012. Combating Rural Child Malnutrition Through Inexpensive Mobile Phones. In *Proceedings of the 7th Nordic Conference on Human-Computer Interaction: Making Sense Through Design*. ACM, 635–644.
22. L. Newman, M. Wagner, R. Cameto, A. Knokey, J. A. Buckley, and D. Malouf. 2009. The Post-High School Outcomes of Youth With Disabilities up to 4 Years After High School. (2009). Retrieved September 18, 2016 from `https://goo.gl/eLOaxg`.
23. H. Nicolau, J. Guerreiro, T. Guerreiro, and L. Carriço. 2013. UbiBraille: Designing and Evaluating a Vibrotactile Braille-reading Device. In *Proceedings of the 15th International ACM SIGACCESS Conference on Computers and Accessibility*. ACM, 23.
24. OrCam. 2016. OrCam - See for Yourself. (2016). Retrieved February 20, 2016 from `www.orcam.com`.
25. B. Plimmer, A. Crossan, S. A Brewster, and R. Blagojevic. 2008. Multimodal Collaborative Handwriting Training for Visually-Impaired People. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, 393–402.
26. D. Radojichikj and D. Blagoj. 2015. Students with visual impairments: Braille reading rate. *International Journal of Cognitive Research in Science, Engineering and Education (IJCRSEE)* 3, 1 (2015), 1–5.
27. Ruby Ryles. 1996. The Impact of Braille Reading Skills on Employment, Income, Education, and Reading Habits. *Journal of Visual Impairment and Blindness* 90 (1996), 219–226.
28. Ruby Ryles. 1999. New Research Study: Early Braille Education Vital in Establishing Lifelong Literacy. *Future Reflections* 18, 2 (1999).
29. H. Shen and J. M. Coughlan. 2012. Towards a Real-Time System for Finding and Reading Signs for Visually Impaired Users.. In *ICCHP (2)*, Vol. 7383. Springer, 41–47.
30. R. Shilkrot, J. Huber, W. Meng Ee, P. Maes, and S. Nanayakkara. 2015. FingerReader: A Wearable Device to Explore Printed Text on The Go. In *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems*. ACM, 2363–2372.
31. Ai Squared. 2016. ZoomText. (2016). Retrieved on March 22, 2016 from `http://goo.gl/LFLQSj`.
32. L. Stearns, R. Du, U. Oh, C. Jou, L. Findlater, D. A Ross, and J. E. Froehlich. 2016. Evaluating Haptic and Auditory Directional Guidance to Assist Blind People in Reading Printed Text Using Finger-Mounted Cameras. (2016).
33. H. Ye, M. Malu, U. Oh, and L. Findlater. 2014. Current and future mobile and wearable device use by people with visual impairments. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM, 3123–3132.