PRET Printer: Development and Evaluation of a Passive Refreshable Tactile Printer

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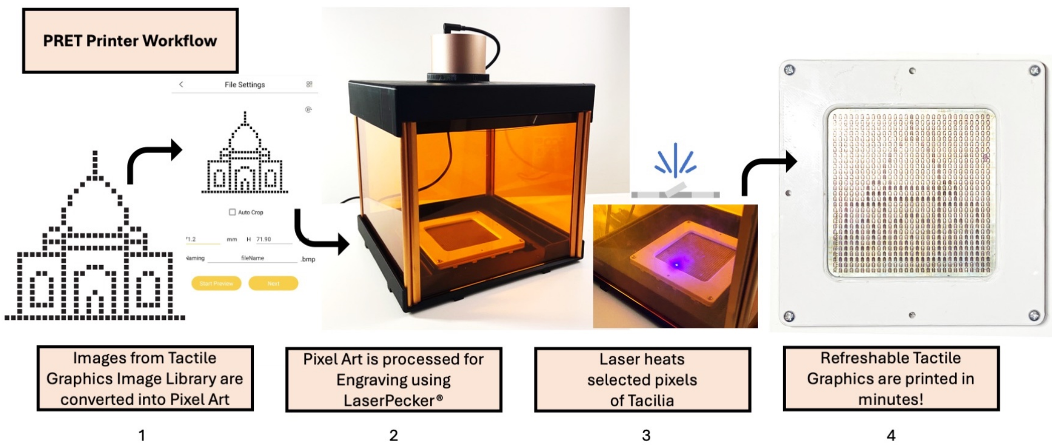

Figure 1: Workflow using the PRET Printer prototype to convert Pixel Art graphics into refreshable tactile graphics on Tacilia.

ABSTRACT

While audio-based interfaces make information accessible to people with visual impairments, some information, such as diagrams, graphs, and charts, can be better interpreted tactilely. We introduce a new Passive Refreshable Tactile (PRET) Printer concept. Using off-the-shelf components of a laser engraver and the nascent Tacilia technology, the prototype enables the creation of refreshable tactile graphics. By leveraging Pixel Art as a rendering process, we enhance the diversity of image production on this medium. We contribute technical specifications, open-source files to make the PRET printer and a qualitative evaluation of the concept by tactile learners. The prototype facilitates rapid and cost-effective development of refreshable tactile media, crucial for improving comprehension. The work builds upon existing research, furthering the groundwork to address the needs of tactile learners worldwide and establishing a foundation for further innovation and development in this domain.

CCS CONCEPTS

• **Hardware**; • **Emerging technologies**; • **Emerging interfaces**;

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KEYWORDS

Tactile Display, Tactile Graphics, Laser, Shape Memory Materials

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1 INTRODUCTION

Visualisations, images, diagrams, and graphs are critical mediums of education and communication but are often inaccessible to people with visual impairments. While braille and text-to-speech interfaces have made textual information accessible, they do not fully address the need for accessible graphics [17, 23]. These tactile graphics are haptic translations of visualisations that provide a way to access and understand visual information through touch [47]. Accessing tactile materials is critical in the education of students with visual impairments and offers significant benefits in learning concepts [42]. Traditional methods for creating tactile graphics use thermoforming, heating microcapsule swell paper, digital manufacturing and manual crafting using foam, glue, clay, and threads. More recently, McDonald et al. [32] and Stangl [49] highlight the potential for 3D printers and laser cutters in creating tactile aids. Serrano-Mira [45] demonstrate the feasibility of using 3D-printed molds for thermoforming tactile images. However, these static methods are time-consuming to make and yield static tactile graphics, making them redundant after use.

Refreshable tactile displays with an array of selectively controlled reciprocating pins can create and enable interaction with many tactile images on a single display [8, 18]. However, they have a limited surface area composed of tactile dots, which may be insufficient for complex graphics, and they are prohibitively expensive ($15,000 to $56,000), making them unaffordable to most people [37].

Here, we introduce a novel Passive Refreshable Tactile Printer (PRET Printer). It aims to combine the advantages of reconfigurable displays with the cost-effectiveness of static tactile displays to enhance access to affordable tactile media. It harnesses the capabilities of Tacilia, a passive reconfigurable tactile display technology made from a single sheet of Nitinol [2]. The PRET printing system actuates selected tactile pixels Tacilia using a single laser (LaserPecker 1) [56]. The actuation is intrinsic to the material's mechanical structure. Hence, no external energy is required to keep the intended pixels actuated while the graphic is read. A simple workaround to translate line diagrams into Pixel Art ensures only the intended pixels are actuated and image conversion is consistent, demonstrating the ability to print diverse reconfigurable tactile graphics in minutes.

Using this proof-of-concept system (Figure 1), five tactile readers with visual impairments qualitatively evaluate usage scenarios and discuss details of the eventual product. This establishes essential requirements for future iterations of a user-centred tactile printer device [21]. Hence, our key contributions are the proof-of-concept and open-source files of a new product archetype – passive refreshable tactile printer and exploration of design requirements for its realisation into a usable product.

2 RELATED WORK

We discuss the state-of-the-art refreshable tactile interfaces, Tacilia's technology, and the mechanism of actuating Nitinol using laser irradiation.

2.1 Refreshable Tactile Interfaces

The desire for an affordable two-dimensional pin-array tactile display device is shared globally, especially among students with visual impairments, their educators, and professionals [36]. Such a device holds immense potential as it can translate vast amounts of digital information into Braille and tactile graphics, enabling independent learning [43] and reducing dependence on seldom available and bulky printed books. In 2007, Vidal-Verdu and Hafez [50] introduced the concept of a virtual tactile screen, mapping each pixel of a GUI through tactile pixels as a way to represent graphical information tactually. Today, several interactive pin-array displays, such as HyperBraille [57], Graphiti [58], DotPad [59], Braille Pad [60] and NewHaptics [61], have emerged, opening new avenues for tactile interactions. These vary in technical specifications, including screen size, pins' resolution, refresh rates and pin heights and utilise a wide variety of mechanisms to selectively reciprocate a compact array of hundreds to thousands of pins [3, 50]. Digital information can be easily shared, stored and presented on these refreshable interfaces and these devices are effective in accessing graphics information [38], supporting mobility and orientation training [12, 28, 29], collaborative interactions [9, 10] feeling movement and actions [19, 41] and in displaying games [25]. The HCI community has assessed the utility of refreshable tactile displays across a broad spectrum of applications encompassing the display of tactile maps [13, 20, 44, 53], tactile shapes [4, 39], symbols [27], graphical user interfaces [8, 10, 39], and animations [18]. These user-centred explorations have provided an improved understanding of the value and use of refreshable tactile devices.

However, the cost associated with these refreshable devices (ranging from $15,000 to $56,000) remains a significant barrier to widespread adoption, for which there has been constant research exploration in the materials and engineering design [1, 7, 30, 51, 52]. It is essential to avoid the "engineering trap," as discussed by Modhrain et al. [36] which occurs when design decisions prioritise engineering principles and technological capabilities over factors related to the display's practical use and the tasks intended to support it. Innovations like Tacilia [2] have begun to disrupt how the core tactile technology is designed, focusing more on the accessibility and affordability of the solution. Its lightweight, silent, robust, and cost-effective fabrication process for hundreds of tactile pixels, combined with its slow refresh rates, can offer a unique opportunity for semi-permanent applications to access affordable yet refreshable tactile media.

2.2 Tacilia

Tacilia is a passive refreshable tactile display made from a single sheet of shape-memory Nitinol that retails at $40 from Fuxus [62]. The prototype used in this work features 841 independently addressable tactile pixels organised in a 29x29 matrix, providing Braille resolution with a 2.5mm spacing between pixels both vertically and horizontally. This configuration results in a usable area of approximately 72x72mm^2 [2].

Each pixel of Tacilia is subjected to a thermal training process that enables shape transformation, causing it to bend out of plane when exposed to temperatures exceeding 40℃. This shape-changing capability employs a thermomechanical training process [2]. Initially, the laser-cut pixels are bent out-of-plane at room temperature and held in place by inserting a 0.25mm diameter steel wire between the bent pixel and the base surface. This fixture is placed in a furnace at 550℃ for 30 minutes, followed by immediate quenching. This process trains the material to memorise its new austenitic state, corresponding to the bent state of the pixels. The sheet is subsequently annealed to enable malleability and reconfigurability by maintaining it at 550℃ for 48 hours and allowing it to cool within the furnace. This process softens the material, permitting the pixels to be pressed back into their flat state without undergoing permanent deformation, while memorising their bent state.

The thermal transformation can be achieved through various energy transfer mechanisms, including conduction, convection, or radiation. Irrespective of the methods, when fully actuated, the pixels can bend up to 0.4mm out of plane and require a minimum of 0.6 seconds to complete the actuation process. After cooling to room temperature, the pixels maintain their bent position, serving as their memorised state, until they are mechanically pressed back into their flat state.

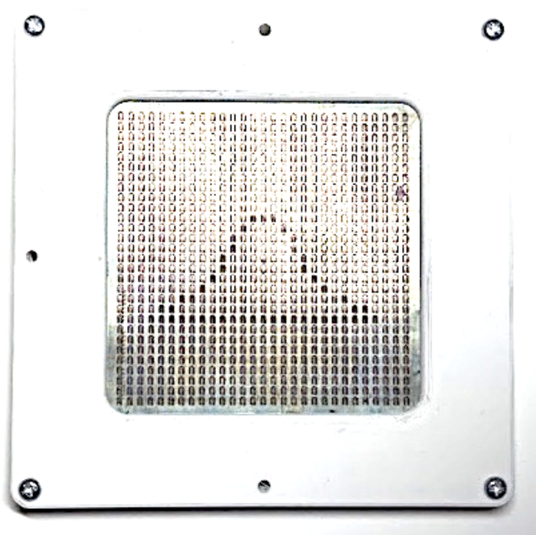


Figure 2: Prototype of Tacilia with 29x29 reconfigurable tactile pixels. A curve is displayed to represent a tactile graphic on Tacilia.

Importantly, the pixels exhibit a blocked force of 0.25kg when actuated, which proves sufficient for direct tactile reading and eliminates the need for external power to maintain actuation. Consequently, once configured, the display appears similar to a printed tactile page, capable of presenting information without needing external power sources. Furthermore, the thermomechanical cycle of heating for actuation and mechanical pressing for reconfiguration can be executed thousands of times, endowing Tacilia with a prolonged and sustainable operational life. In this refreshable way, many graphics and tactile information can be made available without the high cost of a refreshable tactile display device or cumbersome and expensive printing equipment. Finally, Nitinol is a biocompatible material extensively used in medical applications, which is an essential consideration for its use as a tactile interface [46].

2.3 Laser Irradiation to Activate Shape Change

Lendlein et al.'s work on light-induced shape memory polymers hints at utilising a laser to induce shape change [26]. However, shape change in Nitinol due to laser irradiation has not been discussed in depth before. Laser irradiation has been used to cut Nitinol [6], heat treat the material and shape setting [5], melt [48], for surface modification [34] and 3D printing with Nitinol powder [35]However, no literature exists on using low-power lasers to activate Nitinol for its shape-changing effect. Hence, the onward work is purely experimental.

Nitinol is a metal alloy. The interaction between a pulse laser and metal reflects a certain amount of laser energy from the top surface. Some energy gets absorbed within a shallow depth of the metal surface [31]. The availability of free electrons in the metal dominates the absorption of photons [16]. The absorbed energy is transferred through the lattice by collisions that create the thermal effect in the metal. The absorbed laser energy is directly transferred into heat. This is called a photothermal (pyrolytic) response resulting in the metal's elevated temperature, which can trigger a thermally activated process. Hence, laser irradiation on Nitinol can activate processes that reorganise the crystal structure and can create a rapid transformation to the high-temperature austenitic phase of the shape memory material [14].

Therefore, a laser beam can become a source of actuation for Tacilia. Laser irradiation on selected areas of Tacilia will heat a localised area and cause the pixels to bend out-of-plane to attain their actuated state. The selection of areas to be laser irradiated can be controlled by commonly available laser engraving systems that can control the movement of the laser beam. This is experimentally developed next.

3 TECHNICAL DEVELOPMENT

3.1 Prototyping

An off-the-shelf laser engraver called LaserPecker is used [56] to develop the PRET Printer prototype and to test the concept's technical feasabilty. LaserPecker is a portable laser engraver with a movable beam system. This makes the laser module compact and can engrave an area of 100x100mm. The laser engraver is based on a 500mW 405nm blue laser diode with a luminous power of 1.5W and a 0.15mm beam diameter. It works on 5V and 2A and can engrave materials that are kept 200mm from its laser's window. The laser is accompanied by a free smartphone app with which any photograph, image or graph can be loaded into the laser to be engraved [56]. The software has a custom software that can process the image for the laser [63]. It also allows the user to control the power of the laser and its depth.

The PRET prototype (Figure 3) keeps the laser 200mm from Tacilia. Four sheets of orange acrylic absorb the reflected laser beams, covering the laser area. A 3D-printed frame keeps Tacilia under the laser while another part keeps the laser in place. The mechanical design[1] calibrates the laser beam so that the centre aligns with the centre pixel of Tacilia and can cover the entire area symmetrically. The laser beam is calibrated for further centring adjustments using the LaserPecker app.

3.2 Optimization

The tactile graphic must be fully printed in the least possible time for optimal printing. Therefore, this study aims to find the optimal settings for complete and accurate actuation in a single pass (the laser will go only once to create the graphic). Power and depth are two parameters that are controllable by the LaserPecker App. The documentation on LaserPecker is limited; hence, the power parameter seemed to determine the intensity of the laser output. The depth parameter seemed to determine the speed at which the beam moves over the plane. The depth will increase the time it takes to create the graphic in a single pass. Therefore, optimal values are required so that the tactile pixels rise to their maximum height (0.4mm), they have no mis-actuated tactile pixels, so the tactile graphics are visually identical to the digital graphics and actuates the targeted tactile pixels in the least possible time.

[1]Link to the files with the 3D model: http://tiny.cc/50c5yz

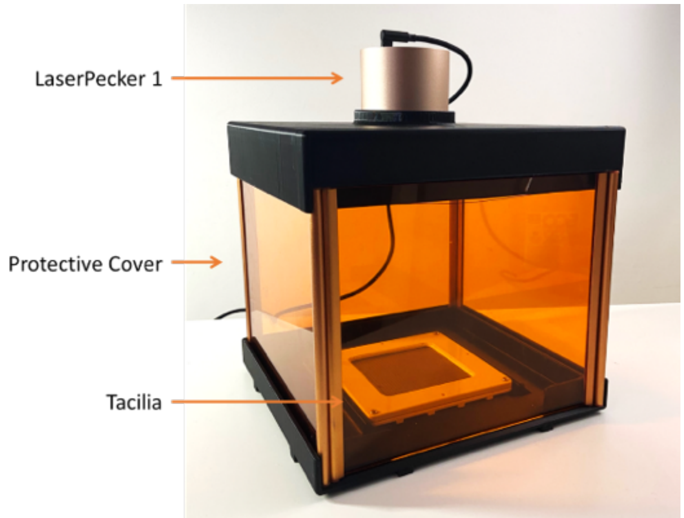
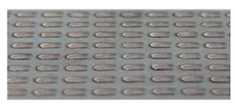
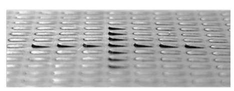
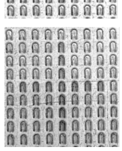
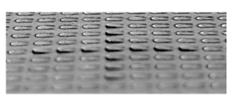
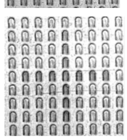
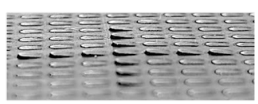
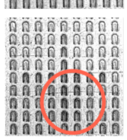
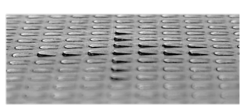


Figure 3: Prototype of PRET tactile printer

Table 1: Trial and error experimentation to calibrate the laser power and depth setting for accurate printing.

Power	Depth	Results	Height (mm)	Time (sec)
10%	10%	 	0mm	0.28
100%	10%	 	0.29	0.28
100%	20%	 	0.31	0.31
100%	30%	 	0.36	0.33
100%	40%	 	0.4	0.36
90%	40%	 	0.4	0.36

To calibrate the laser beam with the tactile pixels, the central tactile pixel is manually marked, and the centre of the laser beam is calibrated to point directly at the mark.

A trial-and-error experiment is conducted to find the optimal values of the power and depth parameters of the laser to actuate the tactile pixels of Tacilia. Starting from 10% power and 10% depth, the laser parameters are increased till the graphical cross is clearly and fully printed at the centre of Tacilia. First, the power increases while the depth remains at 10%. The actuation time did not change with increased power. Even at 100% power, the tactile pixels are not fully actuated. Therefore, using 100% power, the depth value is sequentially increased. With the increase in depth, the time to complete the job rises, but the more extended beam irradiation at a location improves the actuation performance of the tactile pixels. As the depth increases, the actuation improves from 0.2mm at 10% to full height (0.4mm) at 40%. However, at the intersection of the cross, mis-actuations are observed at 100% power and 40% depth. This may be due to heat accumulation that spreads to the nearby tactile pixels. The power is then reduced to 90% to avoid this, resulting in a clear and accurate tactile graphic. Therefore, 90% power and 40% depth were set to render tactile graphics on Tacilia (Table 1).

3.3 Testing

To test the replicability of the system, 21 graphics from the Tactile Graphic Image Library (TGIL) [55] that can be translated into a small area of 29x29 tactile pixels. The graphics examples explore a variety of complex scenarios that the printer should be able to render. Pixel Art is used to redesign the graphics to make them suitable for the pin-array type display of Tacilia [4]. The graphics are recreated manually using Pixel Art guidelines in Adobe Illustrator.

Graphics made in Illustrator[2] are saved in .jpg format, and the .jpg file is transferred to the LaserPecker app. The necessary parameters for depth and power are set, and then the image is printed using PRET. The results of this exploration can be seen in Table 2. Each output is then analysed for rendering issues such as misactuations and incomplete actuation of the tactile pixels. The graphical conversion of images from the TGIL to Pixel Art captured key features of the graphic, and the centre point calibration procedure repeatedly provided accurate results. The laser beam only heated desired tactile pixels, and the accuracy is consistent for simpler tactile graphics, such as the constellation, and denser graphics, such as the kidney diagram.

The depth and the power were sufficient to actuate a single tactile pixel accurately but were not overheating to cause mis-actuation. The average actuation height of the pixels reached the desired 0.4mm, demonstrating total accuracy and complete actuation. Time measurements were conducted through video recordings of the printing process. The time to print a graphic depends on the surface area, the number of tactile pixels to be actuated and the depth setting of the LaserPecker. It took approximately 1.3 seconds to actuate a single tactile pixel at the given settings. Consequently, the time required for printing varied, ranging from 5m33s to print Big Ben in an area of 7x29 pixels to 22m2s to print a piano key with braille labels in an area of 28x28 pixels.

4 CONCEPT EVALUATION

The primary objective of the concept evaluation workshop is to establish the essential requirements for interactions with the PRET Printer and to delineate the various scenarios in which it can be potentially used.

[2]Link to the graphics: http://tiny.cc/jzb5yz

4.1 Participants

Five students with visual impairments from Delhi, India, participated (P1 - P5) in the concept evaluation session (Table 3). All male participants were recruited using convenience sampling, primarily through personal relations. Each participant has a proficient understanding of Braille, although their usage of Braille in everyday life varied. However, every participant has prior experience with tactile graphics, particularly in subjects such as mathematical plots and geometrical shapes, through tactile books. Additionally, they are technologically savvy and regularly use laptops and smartphones daily. The participants' mean age was 25.4 years.

4.2 Procedure

The participants were seated around a table for approximately two hours during the session. Given their familiarity, a brief informal icebreaker session facilitates casual conversation. Following this, the workshop's context is explained, and ethical consent was obtained to record the conversation for research purposes. The study has been approved by the UCL Research Ethics Committee Project ID 18925/001.

To identify PRET's scenarios of use, the participants are then asked, one by one, to share scenarios from their recent experiences where they felt the need for a tactile interface but did not have access to one. Subsequently, the concept of the refreshable tactile printer was introduced, and the participants' initial reactions were recorded. Explaining the concept of the printer and its working principle involved describing the principle of the laser and how it operated with the printer.

The printer prototype is then made available for participants to explore haptically (Figure 4). Any immediate questions or curiosities that arose were discussed and recorded. Participants were then encouraged to brainstorm various scenarios for the device's use in their everyday lives and consider the associated requirements and needs. These discussions encompass the limitations of the current workflow and ways to make it more accessible. The team also prompted participants to consider using audio descriptions during the printing process to develop their ideas further.

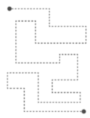
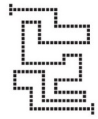
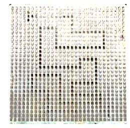
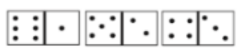
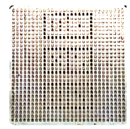
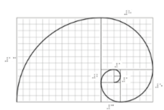
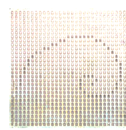
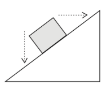
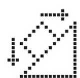
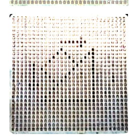
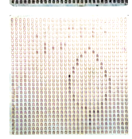
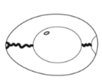
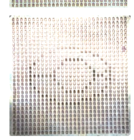
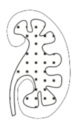
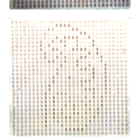
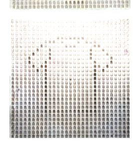
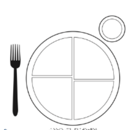
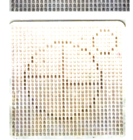
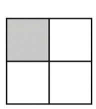
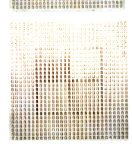
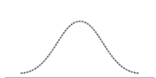
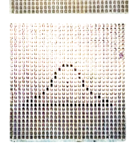
As participants discussed, the researchers set up the printer to demonstrate its working capabilities. Once the tactile graphic was printed, participants physically examined the outcome and provided feedback and suggestions regarding their experience with Tacilia. The session ended by summarising the insights drawn from the workshop.

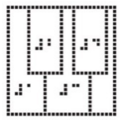
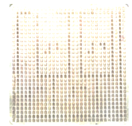
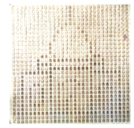
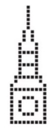
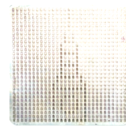
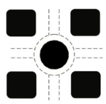
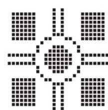
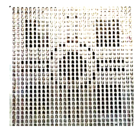
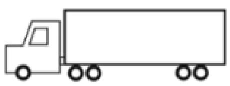
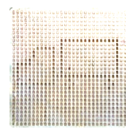
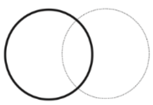
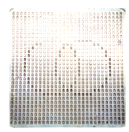
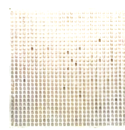
The audio recordings are thematically analysed using an inductive approach [11]. This analysis identified the requirements for the product's features that extend beyond the current design and are iteratively grouped into themes that specify the product and interaction design requirements for PRET's next iteration.

4.3 Findings

The five participants expressed a strong need for tactile graphics as they play a critical role in helping students understand concepts more effectively. It became evident that tactile interfaces are essential tools for comprehending concepts, and the purpose of tactile graphics, in general, is to support conceptual understanding. For instance, P4 emphasised the importance of tactile graphics in his study of historical architecture and art, in which relying solely on

Table 2: The 21 tactile graphics from the TGIL that are converted into Pixel Art and printed on Tacilia, along with the time it took to print.

Image from the Tactile Graphic Image Library	Pixel Art image adjusted to the size of PRET Printer	Printed tactile graphic on Tacilia	Time to print (minute: seconds)
			10:39
			8:37
			9:40
			3:45
			6:17
			6:6
			7:25
			10:52
			7:55
			11:30
			9:27
			3:54

			22.2
			14:3
			5:33
			16:57
			8:57
			8:49
			1:13
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		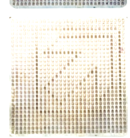	14:32

Table 3: Participants in the concept evaluation workshops

Participant	Age	Education	Braille Literacy	Vision
P1	32	PhD Student in History	Yes, proficient	Congenital Blindness
P2	18	BA in Economics, First Year	Yes, intermittent use	Congenital Blindness
P3	21	BA in Economics, Third Year	Yes, intermittent use	Congenital Blindness
P4	27	MA in History	Yes, intermittent use	Low Vision
P5	29	PhD in English Literature	Yes, proficient	Low Vision

Braille and audio materials provides only a theoretical understanding of the subject. It falls short of fully comprehending the intricate concepts on which P1 commented:

"Whatever you take as a subject, once you get the image in your head, then solving questions is much easier. Otherwise, you must memorise things. If you don't get the picture or don't understand it, it becomes a challenge." – P1

Tactile graphics bridges a key knowledge gap and offers students a more comprehensive educational experience.

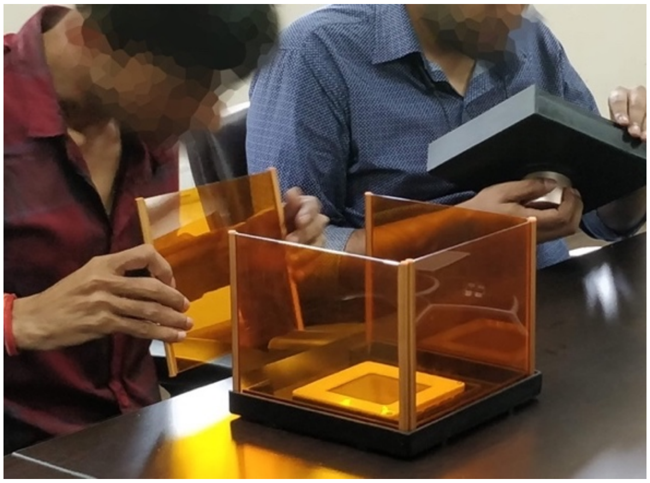

Figure 4: Participants explored the form and prototype of the PRET Printer.

4.3.1 Need for On-Demand Tactile Information. In schools, students can access basic tactile graphics of geometric shapes printed using Braille printers in standard textbooks. However, these tactile resources fall short of adequately supporting the educational experience. Consequently, a significant portion of the curriculum remains untaught and unexamined. This issue leads to frustration among students, as exemplified by the following quote from P2.

"I don't use Braille that much, but I need graphs. Books are usually available only to a certain extent and only basic shapes and some content is provided and that too only in a few schools. So, we end up skipping a large part of the syllabus, and we don't learn things fully." – P2

In higher education, some universities have addressed the need for tactile graphic materials by establishing contracts with third-party organisations, as was the case for P3. While this approach can help meet the demand for tactile materials, it has limitations, particularly in courses requiring numerous graphics. Printing tactile graphics through a service is both costly and time-consuming. As a result, students often must proactively manage their courses by requesting instructors to provide learning materials well in advance and coordinating with the university's special education unit to have the materials printed. It's also worth noting that not all universities offer such facilities, and teachers can fail to give the materials in advance, exacerbating the situation.

P3 highlighted the need for customised tactile media on demand and envisioned that a personal, tactile printer could streamline and simplify this process for students.

"At present, we need to wait for one to two weeks for the tactile graphics compared to which, it is fine if it takes 20 minutes to print it." – P3

4.3.2 Need for Accessible Creation of Tactile Content. The participants presented a clear need to integrate their creativity through tactile media into the printing workflow to make something manually, and an approximate image can be printed. The printer's software or application is the potential point of interaction for fostering this creativity. Developing accessible Braille and graphic creation tools within the app will empower students to create bespoke tactile media digitally.

For instance, P5 pointed out the need for Braille notes to be readily available on the spot when delivering seminars. Current approaches require materials to be prepared days in advance, making it challenging to incorporate last-minute corrections, as Braille printing services typically have long turnaround times. While refreshable Braille displays are one solution, P5 expressed frustration with their regular ticking noise and limited word count per line in the restricted 20-character line-by-line Refreshable Braille device.

The participants also considered ways to print multiple pages using the PRET Printer. Multiple-page printing can be accomplished on separate or both sides of a single sheet; both are considered exciting options. It will enable printing numerous graphics to enhance understanding of a single concept. These graphics could be printed alongside sheets of Braille text, providing more information about the graphic and the concept instantly and on demand.

"If we can print and keep the sheets, then it will be helpful. Like an affordable embosser because there is nothing else available. We can analyse two to three images together or print an entire file like a PDF on some pages. Keep the refreshable option also but permanent printing will drastically increase its use." – P5 and P3

Participants envisioned an integrated refreshable and static tactile printer to address these challenges. Such a device could print on a refreshable display for quick access and editing while allowing users to print the final version permanently on paper. This integration would allow users to create, print, iterate, and refresh until they are satisfied with the output. Once satisfied, they could print the information onto paper for remote use. This integrated approach could provide a more accessible, affordable, and convenient way to access tactile information as needed.

"Both options should be there. For people who want to print and understand a concept can use the refreshable part and for those who want to preserve the information can use the paper part. Many people just want text, and this can be a very cost-effective way." – P5

This integration could be technically feasible using Swell Paper [15], another heat-responsive tactile interface. Swell Paper can expand and create tactile patterns when exposed to heat, offering a complementary approach to tactile representation. While the feasibility of this approach wasn't evaluated in our study, there have been demonstrations of such integration in hobbyist settings [54].

4.3.3 Need for Multi-Modal Interactions. The group considered the integration of audio and generative AI-based systems to make productive use of the time during printing. This can take the form of functional feedback, providing an audio description of a progress bar to indicate when the print is nearing completion, verbally announcing when the printer is ready, and signalling its completion. In addition, participants discussed the incorporation of educational value by providing audio descriptions while printing. For instance, if a tactile graphic of a boiled egg is being printed, the audio description can offer relevant facts and information about the graphic. These features can be integrated into the accompanying app to enhance the user experience.

"Generative descriptions can be of any length and if it is converted into audio that can easily fill in the time the print is taking place." – P3

One noteworthy point highlighted by P1 was the noise level of existing thermoforming and embossing equipment. P1 observed that these conventional machines tend to be exceedingly noisy. In contrast, with its silent operation and static laser head, the PRET printer provided a more favourable and quiet printing experience. This difference in noise level could significantly enhance the user experience and create a more comfortable printing environment with an option to integrate audio descriptions.

5 DISCUSSION

5.1 Tactile Laser Printing

By utilising Tacilia's capabilities, this work introduces a novel concept that offers the advantages of reconfigurability and customisation while providing a print-like interface and overcoming the cost associated with refreshable tactile devices. This archetype branches out from the prevailing refreshable tactile display research approach, which is to create tablet-like devices, focusing on portability and rapid reconfigurability [24, 36, 59, 61]For less than $250, we could print several tactile graphics and a single laser pointer from an off-the-shelf laser engraver, providing sufficient power to actuate the intended pixels fully.

In addition, inducing a shape memory effect of Nitinol through laser irradiation for a tactile display is a novel contribution. The demonstration proves that it is possible to heat Nitinol with a laser to activate its shape memory effect, contributing another example of how materials science influences the field of HCI [40].

5.2 Accessing Bespoke Graphics

Jones et al. have studied the need for bespoke tactile graphics to enhance understanding. [22], who emphasise the potential of these interfaces in supporting communication, coordination and learning. The current landscape of tactile information generation and refreshable tactile interfaces presents several challenges. Mukhiddinov and Kim [33], and several others [8, 24, 43] highlight the need for cost-effective and efficient methods for creating tactile graphics. While computer vision and artificial intelligence algorithms hold the potential to make images more accessible through audio descriptions, the high cost of refreshable tactile displays remains a significant barrier to accessing tactile graphics [51].

The printer's evaluation reiterated that the primary function of any tactile interface is to bridge the gap in understanding concepts. Essential to this is the capability to produce bespoke tactile graphics as needed. This also validates the need for a cost-effective interface. Such an interface should be personal and affordable while also being capable of refreshing content. The PRET Printer archetype can be an effective alternative until refreshable tactile interfaces become more mainstream and economically viable. PRET Printers can be used at home, in the office, and classrooms, enabling students and professionals to access bespoke tactile graphics anytime.

5.3 Limitations

The exploration into developing a more accessible tactile graphic system has revealed promising directions and several limitations that need to be addressed in future iterations. The project, primarily an experimental endeavour, has provided initial qualitative technical observations and feasibility validation of the concept.

The initial prototype's display area, confined to a 29x29 pixel grid, limits the complexity of tactile graphics that can be effectively represented. Although 21 instances of tactile printing were demonstrated, none were thoroughly evaluated within the current scope of work. Tacilia, while innovative, presents its own set of challenges. Its output is limited to a height of 0.4mm and offers limited tactile contrast due to its binary output nature. The dot-based approach facilitates the approximation of line segments and Braille presentation but needs to convey detailed representations due to its resolution limitations. Additionally, being a 2D tactile display, it cannot provide 3D representations and textural nuances important for conveying certain concepts through tactile graphics.

Moreover, the absence of an extensive user study to assess the clarity and readability of these graphics highlights an area for further research. Future efforts will aim to expand the tactile display surface and evaluate the effectiveness of more complex tactile media. The current printing system, which utilises a hobby laser, suggests improvements. More powerful lasers could expedite the heating process, reducing printing times. The workflow, currently dependent on the proprietary LaserPecker App, faces accessibility challenges, marking another area for enhancement. In addition, the users did not operate the device as the workarounds were inaccessible, and gauging holistic, independent interaction was out of the scope of this work. Furthermore, the limited number of users who evaluated the product provides a limited perspective on the requirements. With future iterations, we will invite more volunteers to co-design and evaluate the concept.

5.4 Future Work

The PRET printer's future interactions are intended for independent use, with which tactile learners can print their own bespoke pieces of information. In addition, future developments will focus on creating a larger, reconfigurable printer that handles A4-sized tactile graphics. This expansion will involve a larger Tacilia sheet and an upgraded laser system to accommodate more extensive tactile graphics. An accompanying goal is to develop a custom, accessible software application to streamline the conversion of images into pixel art and subsequently into a format compatible with the laser's firmware. Furthermore, generative AI systems may be integrated into the system to provide information about the graphic, making the wait time more engaging.

Participants also expressed interest in a tactile output that could be preserved in paper format, akin to embossed printing, pointing towards another avenue for innovation. Ensuring the technical feasibility of permanent printing and devising an interactive workflow for this process will also be essential in future works. In addition, the robust repeatability of Tacilia's display technology requires no additional maintenance, which enables printing many pieces of graphical information. This will eventually include facilitating the translation of digital files into pixel art for display and enabling line drawing onto swell paper, thereby broadening the system's applicability and utility.

6 CONCLUSION

This paper introduces a pioneering refreshable tactile printer archetype, utilising Tacilia technology, a commercial laser engraver, and a manual workaround for Pixel Art conversions to produce accurate tactile graphics swiftly and economically. While the prototype offers the potential to effectively bridge a significant gap in accessing custom tactile graphics, it requires enhancements in display size, graphic clarity, permanent printing capabilities, and a user-friendly accessible interface. Future work will focus on these improvements and conduct extensive evaluations to solidify the system's utility in refreshable tactile technology, aiming to meet user needs comprehensively.

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