The Effect of Orientation on the Readability and Comfort of 3D-Printed Braille

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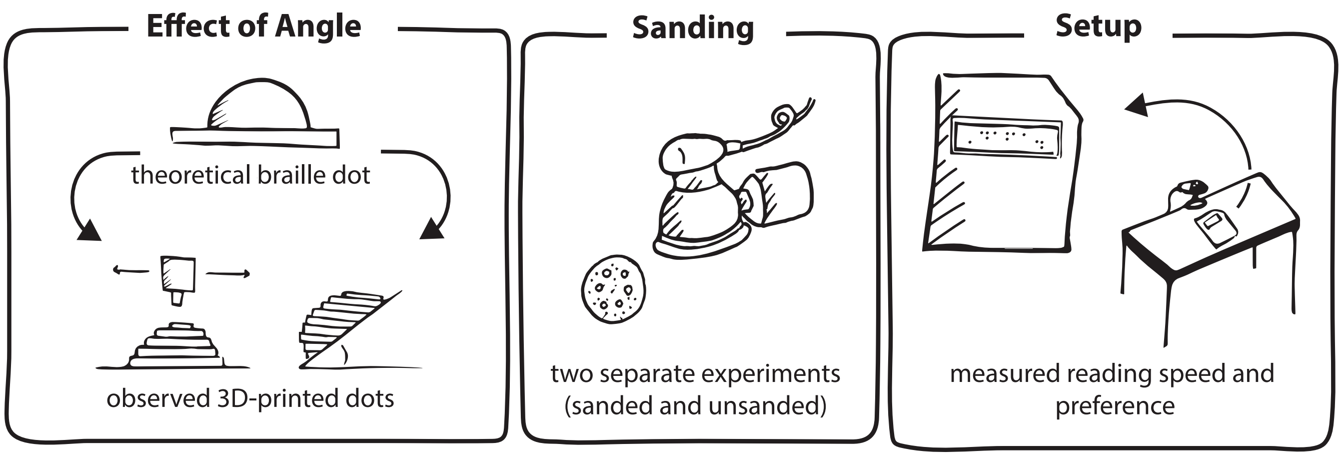

Figure 1: The angle at which an object is 3D printed impacts its geometry and surface quality, as demonstrated by the illustration on the left. This quality difference may influence the tactile properties of braille, affecting its comfort and readability. Therefore, we conducted two experiments evaluating the effect of printing braille at different angles. For one experiment we sanded the prints and for the other one we did not. We taped braille prints onto a stock paper page and recorded participants' responses, including reading time and preference, as seen in the illustration on the right.

ABSTRACT

Fused Deposition Modeling (FDM) is a low-cost method of 3D printing that involves stacking horizontal layers of plastic. FDM is used to produce tactile graphics and interfaces for people with visual impairments. Unfortunately, the print orientation can alter the structure and quality of braille and text. The difference between printing braille vertically and horizontally has been documented. However, we found no comprehensive study of these angles or the angles in between, nor any study providing a quantitative and qualitative user evaluation. We conducted two mixed-methods studies to evaluate the performance of braille printed at different angles. We measured reading time and subjective preference and performed a thematic analysis of participants' responses. Our participants were faster using and preferred 75° and vertical braille over horizontal braille. These results provide makers with guidelines for creating models with readable 3D-printed braille.

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CCS CONCEPTS

• **Human-centered computing** → *Empirical studies in accessibility*.

KEYWORDS

3D Printing, Visual Accessibility, Braille

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1 INTRODUCTION

Three-dimensional (3D) printing has been explored as a relatively inexpensive and customizable medium to produce tactile interfaces for people with visual impairments. Examples range from tools in education [6, 7, 38], orientation and mobility [19, 24], and medicine [1, 14]. Relevant textual or auditory information must often accompany these interfaces to make them usable [45]. There are many advances in technologies to label such models like infrared tags [13], Quick Response (QR) codes[2], and clicking devices [48] that all trigger audio labels. However, while using braille has limitations, its familiarity and universality make it an accessible system for presenting contextual information. Therefore, it is important to understand the benefits, limitations, and best practices of 3D printing as a medium to produce braille.

While there are many types of 3D printing, Fused Deposition Modeling (FDM) is considered among the most widespread and economically accessible [12]. FDM 3D printing works by stacking horizontal layers of molten material, most often plastic, meaning that a model is created from horizontal slices. Therefore, a print's structure and surface quality are related to print orientation [8]. These challenges can impact the readability and comfort of braille. Fabrication techniques, which include 3D printing, have had a meaningful impact on the development of general assistive technology, including tools for people with visual impairments [17, 18]. For example, Hurst and Tobias explore the potential of Do-It-Yourself (DIY) techniques via case studies [26]. They describe modern 3D printers as comparatively inexpensive tools, and more accessible than other traditional fabrication methods. They also praise their cultural impact and community access in public spaces like libraries and disability centers. Similarly, Buehler et al. investigated how online communities share these models, including tactile graphics and other tools designed for people with visual impairments in mind [5]. The space to share models and ideas is considered one of the strengths of 3D printing.

A white paper by the DIAGRAM Center noted the difference between *vertical* and *horizontal* braille based on the printing angle [10]. In both cases, the braille is added onto a back surface akin to a sign, referred to as a *plate* in our experiment. For *vertical* braille, this plate is printed to stand vertically upwards with braille to its side. Correspondingly, a plate with *horizontal* braille is printed to lay flat with the braille cells at the top. Figure 2 illustrates the model of a braille dot printed *vertically* on the left and *horizontally* on the right. They describe how *vertical* braille was preferred over *horizontal* braille. However, the report provides only general recommendations and no details about the results of an empirical evaluation. In this work, we expand upon the DIAGRAM Center's findings to investigate the relationship between print orientation and reading experience with a more granular evaluation and analysis. Specifically, we conducted two mixed methods experiments that measured participants' preference and performance for stimuli 3D printed at different angles.

These experiments were designed to answer the following research questions.

- **RQ1** What is the impact of printing angle on the reading speed of 3D-printed braille?

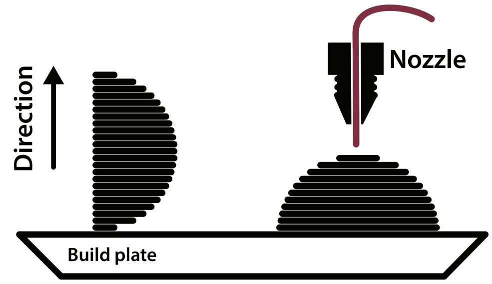


Figure 2: The print on the left is oriented at 90 degrees from the plate, whereas the right one is at 0 degrees. The former has to deal with overhangs for the first several layers, which are printed partially above the air instead of being supported by the lower layer.

- **RQ2** How do printing angles affect readers' reported ease of discerning individual characters?
- **RQ3** How do printing angles affect readers' reported comfort when reading the 3D-printed braille?

We evaluate and report quantitative metrics, namely reading time and Likert preferences, and report a qualitative analysis of common themes brought up by participants during the experiments. The two experiments test sanded and not sanded, referred to as unsanded, stimuli. Namely, sanding allows us to ask participants to read fast while minimizing the risk of injury, whereas not sanding provides a *"straight-from-the-machine"* perspective. The purpose of the study is not to compare the impact of sanding across both experiments but to provide a multifaceted analysis by exploiting the strengths of each design.

To summarize, this paper contributes:

(1) the design and results of two studies comparing the usability of 3D-printed braille at various angles:
   (a) a controlled experiment in which we measured the reading speed at which participants read braille and
   (b) semi-structured interviews and Likert-style questionnaires in which participants rated reading character discernment and comfort.
(2) design and implementation recommendations for using braille in 3D-printed interfaces based on these results.

2 BACKGROUND AND RELATED WORK

We first provide a summary of FDM 3D printing, which is the specific technology we are investigating. Then, we recapitulate the relevance of its applications in tactile graphics and other interfaces. Finally, we explore similar evaluations of 3D-printed braille.

2.1 FDM 3D Printing

Fused Deposition Modeling is a method of 3D printing that consists of creating a model by building upon it in horizontal layers [42]. A nozzle is attached to an arm that moves in continuous paths where it deposits the molten material on its trail. Note that higher layers in the model rest on lower ones to prevent warps or defects from overhangs. Many experts such as Prusa Research, our printer's manufacturer, suggest avoiding overhangs angled at less than 45°

from the horizontal [47]. 45° is geometrically relevant since it is the angle at which at least half of the upper layer makes contact with the lower layer, meaning better adhesion and less impact from gravity.

Weeren et al. identified a few problems that affect the surface quality of FDM printed objects [54]. They describe how the horizontal slicing creates a *staircase* effect from layers stacked upon each other. This *staircase* effect is different based on the slope of an object [52], as illustrated in fig. 2. This means that its orientation during print will impact the dimensional accuracy– how close the object resembles the theoretical model– and the surface roughness. Weeren et al. also describe how defects at the start and end of the nozzle's path lead to imperfections on the surface. For example, the gaps in between braille dots might have small nubs from plastic that increase the roughness of the text. Among other physical limitations, the size of the nozzle constrains the width of a line of extruded material [23, 47]. FDM printers have lower resolutions and surface quality than other printing methods [27]. However, FDM is still considered one of the most affordable commercial types of 3D printing, including initial equipment purchases and per-model costs [12].

2.2 3D-printed Tactile Graphics and 3D Models

Tactile graphics are tactile representations of two-dimensional images, such as textbook graphics in STEM education and mathematics testing [30]. However, they can also have recreational applications like in art [32, 57]. There are many documented guidelines and good practices for developing tactile graphics [15, 44]. 3D models often aim to represent something inherently embedded in 3D space, like monuments, buildings, or chemical particles [53]. Holloway et al. evaluated some differences between tactile graphics and 3D models for orientation and mobility maps [25].

Over the last decade, several studies have focused on understanding the educational uses of 3D printing for accessible graphics and models [28]. Buehler et al. identified some of the benefits and limitations of 3D printing in special education classrooms, including for children with visual impairments [6, 7]. Similarly, 3D printing methods have been used in other contexts such as for the production of orientation and mobility tools [24], the customization of circuit engineering instruments [11], and labeling medicine [1, 14]. 3D printing also provides customization that allows to design for different visual conditions [42]. For example, Gotzelmann proposes a combination of a smart device and their 3D-printed graphic to visually enhance parts of tactile graphics for users with low vision [19]. There is also work addressing the limitations of Computer-Aided Design (CAD) modeling software, which is often used in 3D printing [40, 49]. These examples highlight the use and potential of 3D printing as a medium to create tactile interfaces.

2.2.1 Labeling Methods. The use of braille in tactile graphics is standardized, and organizations like the Braille Authority of North America (BANA) have guidelines for it [44]. Among others, the Round Table advise on the benefits and limitations of different tagging techniques including braille, *basements* (which are separate signs containing labels and a model outline), and audio notes triggered by QR codes or NFC tags. Similarly, the 3D Printing for Visually Impaired (3D4VIP) project coordinated by the Royal Dutch Visio recompiled standards and best practices for the use of 3D printing for tactile graphics [55]. Namely they specify important parameters to consider when 3D printing models including the importance of print orientation. However, they also do not provide an empirical evaluation or mention angles beyond *horizontal* and *vertical* braille.

There are some challenges to the use of braille in tactile graphics and 3D models. For example, braille cannot be resized (which prevents re-scaling models), it takes a significant amount of space, and it requires that users know how to read it. These can impose constraints on the text length that can be added onto models. However, the community has developed several tools and methods to circumvent some of these limitations. For example, devices like The Tactile Talking Tablet allow users to mount raised graphics onto a tablet for auditory feedback [29, 30]. Baker et al. proposed embedding QR codes to encode audio labels that could be read with another device, such as a smartphone [2]. However, they also found that braille-literate participants preferred braille and read it faster. Shi et al. propose *Tickers and Talkers* [48], which use physical triggers to encode audio labels for 3D models which may not have large flat areas to include braille or QR codes. Other methods, such as The Tactile Graphic Helper by Fusco and Morash [16], use computer vision to identify where a user might be pointing. While these methods can be very effective, many of them require an external device to use. In the case of devices that need to be connected to a computer, this can hinder its portability. Similarly, other programs may pose other software requirements that might not be viable in the long term or may need to be maintained. This also poses a barrier to entry via the use of cameras or smartphones, which, while expansive might not be available in some settings or adopted by all populations. Therefore, while braille has its limitations, there are also valuable reasons for its continued use.

2.3 Evaluations of Braille Displays

While outside the scope of this project, we note that many kinds of tactile displays are used for graphics and other texts [9, 50, 56]. Morash et al. conducted an evaluation proposing one such interface. To evaluate the performance of their high density pin display, they tested the reading speed and reported the difficulty of their various pin configurations to emulate braille patterns with multiple pins. While their proposed display was not 3D printed, the stimuli they used for their studies were. Minatani explored the usability of 3D-printed braille for embossing tactile graphics, namely geographical maps [39]. They proposed a design pipeline and highlighted some of the practical obstructions they faced in their prototyping. Namely, they describe problems with the inferior surface quality and the readability of city labels. Loconsole et al. compare two low-cost FDM 3D printing techniques for producing braille as well as with a professional printer [33]. The techniques consist of the layer-by-layer FDM approach discussed above, and a novel method named *continuous flow*. For this method, they programmed an FDM printer to continuously extrude plastic by moving up and down in between layers to avoid residual filament in between cells. A study of their method seemed to improve the comfort of users reading braille, but they highlight how commercial software often limits the ability to program arbitrary pathways. Neither of these evaluations consider print orientation and the ones using FDM printers describe the high surface roughness of the braille.

Finally, the DIAGRAM Center conducted a series of studies to determine standards for adding braille to tactile graphics, including testing printing [10]. They tested a variety of printers to determine that braille printed perpendicular to the printing bed, which they call *vertical* braille, was better than braille printed parallel to the printing bed. In their report, they mention testing other angles and recommend avoiding them, but no further explanation is devoted to this argument.

3 METHODOLOGY

Our study consisted of two within-subject experiments with similar stimuli and study conditions. Both experiments were comprised of a subjective Likert scale and qualitative evaluation of the impact of angle on participant responses. The first experiment contained sanded stimuli and also used reading speed as a proxy for performance. In the second experiment we did not sand the stimuli, and so we refer to it as the *unsanded* evaluation. This separation was made as initial pilot studies suggested that some of the prints straight from the printers would have nubs that could hurt participants when asked to read as fast as possible.

We tested seven print angles from 0 degrees (*horizontal*) to 90 degrees (*vertical*) from the print plate in 15-degree intervals and included a control consisting of braille embossed on 80# stock paper and produced by the National Braille Press in Boston, MA. For both experiments, participants did not know the angle of print or sentence of a presented plate. All the plates were printed with removable supports so that they could be laid down flat after printing. A flexible casing was also made to hide the slope in the plates printed at angles, and this casing was glued onto a piece of stock paper so that participants could easily find and move the stimuli. The supplemental materials of this study can be found in https://osf.io/t2rbq/ and the preregistration in https://osf.io/mcyv5.

3.1 Participants

We recruited thirteen adults through the Carroll Center for the Blind. One was excluded from the analysis since a stimulus was presented to them more than once. Of the twelve participants, seven self-identified as female and five as male. Participant ages ranged from 29 to 81 (median= 59). Ten participants identified as having complete or total blindness; one identified as "almost completely blind with some light perception", and another one as having significantly low vision. Similarly, eleven participants started reading braille before the age of eleven with the other at 38. Experimental procedures were approved by our Internal Review Board, and informed consent was acquired from all participants. Participants were compensated with a $40 US gift card.

3.2 Reading Stimuli

The braille was modeled in OpenScad by adjusting the specification of existing code found online [51]. For the dimensions, we followed BANA's guidelines for signage which are shown in table 1. We used the smallest values in each of their intervals as pilot studies suggested that higher dots could be more uncomfortable. The braille dots were modeled as hemispheres with truncated tops to make them flat. The characters were added on top of a rectangular plate with a slope on its long side for the angles to print. The models were then exported as STL files and added onto a slicer software (Prusa Slicer) to generate the instructions for how to print them. To avoid the plates warping in our experimental stimuli, we add support structures. Figure 3 exemplifies the stimuli used and shows the printing angle.

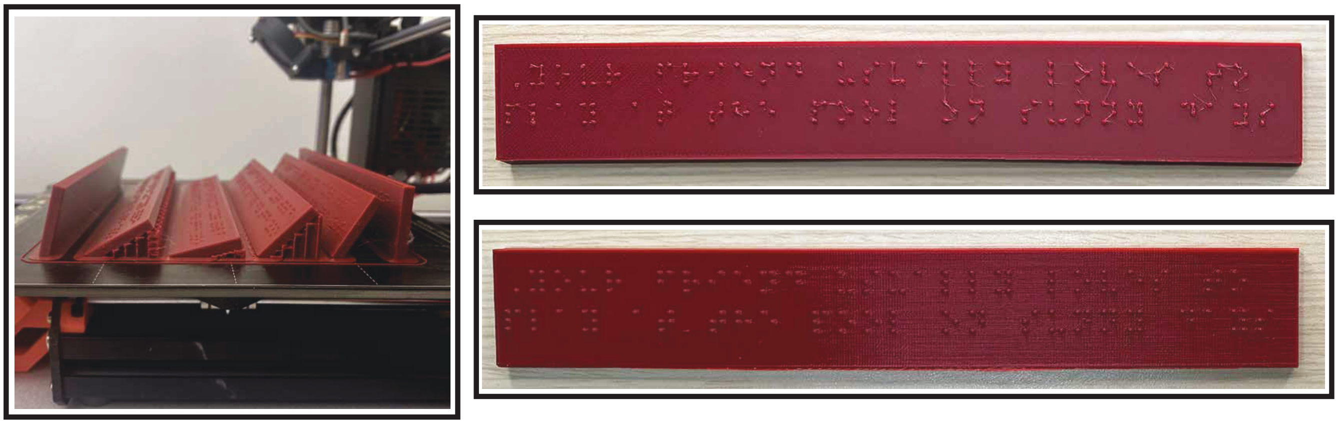
Part	Measurement (in.)
Dot Base Diameter	0.059 (1.5mm)
Distance between two dots in the same cell	0.090 (2.3mm)
Distance between corresponding dots in adjacent cells	0.241 (6.1mm)
Dot height	0.025 (0.6mm)
Distance between corresponding dots from one cell directly below	0.395 (10.0mm)

Table 1: Dimensions of braille for signage used to create the stimuli. From [43].

3.2.1 Technology. Three Original Prusa Mk3S+ printers were used to print all the stimuli from a Polylactic Acid (PLA) filament. Given the randomization we used, all 64 angle-sentence combinations were printed twice, once for the *sanded* and another time for the *unsanded* experiment. The specific print parameters and rationales are included in the supplemental materials, which can be found at https://osf.io/t2rbq/.

3.2.2 Sentence Selection. To minimize the effect of context among different stimuli, we chose a set of standardized sentences used in braille reading speed assessments [31]. We used an extension of the sentence corpus for the MNREAD acuity charts [35]. While these sentences were originally proposed to measure visual acuity [36], they are often used in the evaluation of braille reading performance [41]. The extension consists of computer-generated sentences from 13 different templates [34]. They all contain the same number of characters, simple vocabulary, and no punctuation. To maintain sentence diversity and minimize the impact of context, we selected sentences made from different templates.

MNREAD sentences also provide a standardized spacial layout, which we slightly adjusted to better fit the dimensions of our printing technology. Instead of having the text in three lines, we found a subset of the sentences that could fit in two lines without cropping words, which allowed us to print four to six plates per printing session. Legge et al. suggested that characters per second was an appropriate metric to measure braille reading speed for these sets of sentences [31]. Hence, to maintain a uniform number of characters and a consistent spatial layout, we decided to use grade 1 (uncontracted) braille, similar to the evaluation by Morash et al. [41].



(a) (b)

Figure 3: On the left (a) is a side view of the printer showing the plates at six printed angles (missing horizontal braille). On the right (b), we show two stimuli printed at different angles, namely 0° and 75°. We note that while some visual differences can be seen in the texture and shape of the dots, the most important differences are tactile.

3.2.3 Randomization. Despite the MNREAD-like sentences providing a standard for uniform reading speed, we wanted to minimize the impact of specific sentences on the evaluation of the angle. Therefore, we randomized sentence and angle combinations so that a unique pair only appears again once every other combination has already been used. Since we had eight conditions including the control, we chose eight sentences to pair them. That means that the first group of eight participants did not share any sentence angle combination between themselves, and neither would the second group among themselves. Finally, we also randomized the order in which these were presented to minimize ordering effects and the impact of reading fatigue. Note that we do not randomize which plates are *sanded*, since the goal is not to measure the effect of sanding. The specifics and randomization code are provided in the preregistration and supplemental materials found in https://osf.io/t2rbq/.

3.2.4 Sanding. For the first experiment, we evaluated the plates after being sanded and we measured the reading speed of participants. Sanding is considered one of the best ways to improve the surface quality of 3D-printed objects [58]. This consisted of passing a 320 grit sandpaper over the stimuli back and forth five times.

3.3 Procedures

3.3.1 Sanded Evaluation. For the first experiment, participants were prompted with the same tutorial plate to get them adjusted to the medium and the uncontracted braille. The angle for this plate was 45° as it was the median angle in our set. After briefing the experiment and receiving consent, we recorded the audio of the participants reading out loud. We presented the plates one by one and asked participants to withhold from reading once they had found the stimuli. Then we instructed them to begin reading after a countdown. In between trials, participants were asked to provide a rating on the discernment and comfort of these plates on a Likert scale from one to seven. We also asked open-ended questions for qualitative feedback. This served to extend the time between trials to minimize reading fatigue. We looked at the recordings' audio waveforms to measure reading time as the difference in seconds between the completion and instruction timestamps.

3.3.2 Unsanded Evaluation. This experiment was conducted immediately after the *sanded* evaluation. Participants were told to read the sentences as much as they were comfortable. We presented the stimuli like in the *sanded* experiment. The Likert scale consisted of two questions with seven response options each (1- strongly disagree, 2-disagree, 3-somewhat disagree, 4- neutral, 5-somewhat agree, 6-agree, 7-strongly agree). The Likert questions we used were the following:

- It was easy to discern the individual braille characters.
- The braille characters were comfortable.

3.3.3 Trial count. Each participant saw a total of 16 plates, two for each angle, once for the *sanded* experiment and once for the *unsanded*. Hence there were 192 total trials across all participants and the two experiments. They also saw a tutorial plate for which data was not recorded.

3.4 Analysis

We conducted non-parametric repeated measures analyses for the reading time and the Likert data since the normality and sphericity assumptions were unmet. We used Friedman's test to determine whether the angle significantly impacted the metrics we evaluated. If so, we ran pairwise Wilcoxon Signed Rank tests. Specifically, we ran one tailed tests to determine if the higher angles performed better than the lower angles. We adjusted p-values with the Benjamini-Hochberg False Discovery Rate [3] and used a 0.05 significance level. Finally, we used the Pratt method [46] to account for ties in the Wilcoxon tests. All analysis code was preregistered before conducting the experiment, except for the Pratt tie-breaking method as we did not anticipate ties in our results. The preregistered analysis code can be viewed on OSF at https://osf.io/mcyv5.

For the qualitative analyses, we transcribed, compiled, and cleaned the audio recordings of each session. We then encoded responses into general themes using an inductive thematic analysis approach [4]. Finally, we also separated participant's comments about plates for specific angles to further highlight the impact of angles on results.

3.4.1 *Hypotheses.*

- (**H1**) **Participants are faster at reading braille printed at higher angles, except for braille printed horizontally.** As per the study conducted at the DIAGRAM center, we expect vertical braille, to perform better than horizontal braille [10].
- **H2Participants rate braille to be more comfortable at higher angles.** We also expect higher angles to perform better.
- **H3 Participants rate braille to be more discernable at lower angles.** While comfort is a factor of readability, we foresaw a possible inverse relationship between comfort and discernment. For example, Prusa Research suggested printing half spheres horizontally for greater dimensional accuracy, as this minimizes overhangs.
- **H4 Participants are faster at reading the control print over the 3D-printed plates.** Other explorations of 3D-printed braille determined that FDM printing can produce lower quality braille than achievable with traditional embossers or high-grade professional printers [33, 39].

4 RESULTS

In the following section, we report the reading time, comfort, and discernment results for both experiments as outlined by our hypotheses.

4.1 *H1*: Reading time

Table 2 shows the distribution of reading times grouped by angle, including the control, and a total for all angles. We found print angle significantly affected reading time ($p = 0.011$). Figure 4 shows the distributions of median reading times by angle and the 68% and 95% bootstrapped confidence intervals. All angles tested above 45°, namely 60° (median = 10.30*s*), 75° (median = 9.15*s*), and 90° (median = 9.75*s*), were read faster than both 0° (median = 12.95*s*) and 45° (median = 10.70*s*). Vertical braille was also determined to be read significantly faster than 15° (median = 13.90*s*, $p = 0.014$), and 30° (median = 10.25*s*, $p = 0.033$). However, the test was not able to determine if there was a significant difference between vertical braille and braille printed at 60° ($p = 0.329$) and 75° ($p = 0.662$).

4.2 *H2*: Comfort & Discernment

4.2.1 *Sanded Evaluation.*

Fig. 5 shows the distribution of Likert scores across angles for comfort and discernment ratings obtained in the sanded evaluation. The results suggest that angles above 45° were significantly rated as more comfortable than their lower counterparts. Specifically, 60° (median = 6), 75° (median = 7), and 90° (median = 7), were significantly rated to be more comfortable than angles 0° (median = 4), 15° (median = 4), 30° (median = 4), and 45° (median = 5). We also found 75° and 90° to be significantly more comfortable than 60°, with $p = 0.030$ for both. The evaluation

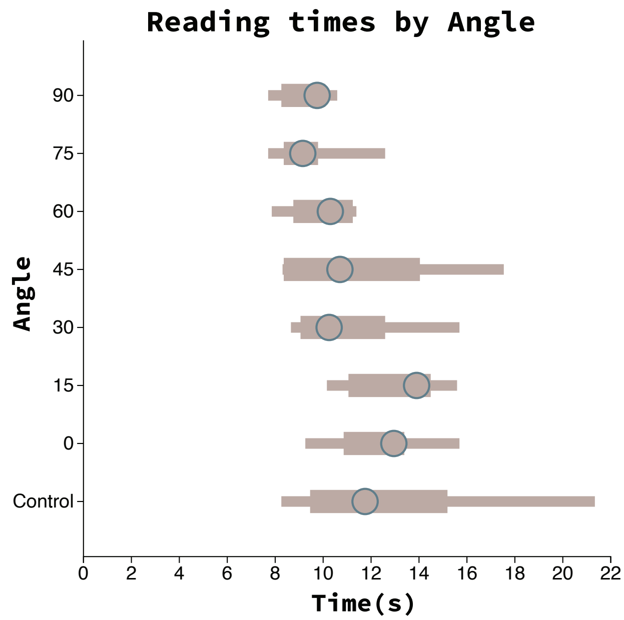


Figure 4: Results of the median reading times (x-axis) of participants grouped by angle (y-axis). The thick error bars represent 68% bootstrap confidence intervals for the median while the thin bars represent 95%.

of discernment ratings shows similar trends. For discernment, the control (median= 7), the 60° (median = 7), 75° (median = 7), and 90° (median = 7) plates performed significantly better than the 45° and lower counterparts. We note that the medians for discernment were generally higher than those for comfort.

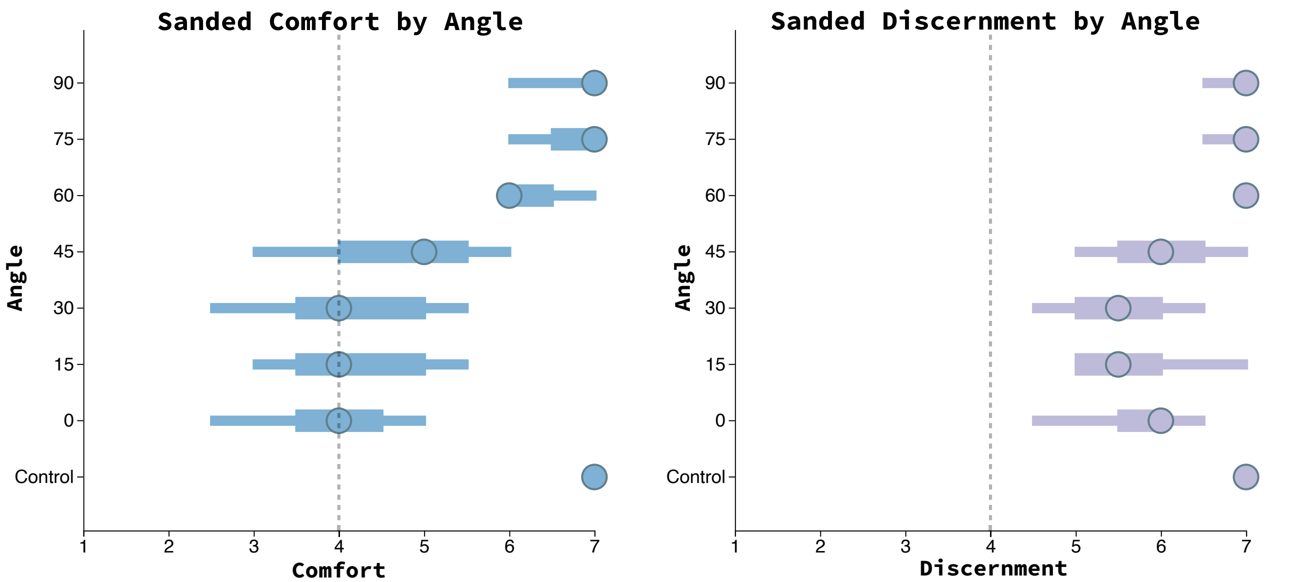
4.2.2 *Unsanded Evaluation.*

Fig. 6 shows the distribution of Likert ratings for the unsanded experiment separated by angle for comfort and discernment. For the comfort ratings, we found that for each pair of angles, the higher one was most often significantly better than the lower one. We note a few exceptions, 15° (median = 1.5) and 30° (median = 2) were not found to be significantly better than 0° (median=2). On the other hand 90° (median= 7) was not found to be better than 75° (median = 7, $p = 0.56$). Note that 4 is the *neutral* response in the Likert questionnaire. For the comfort ratings, the medians of all angles under 45° are lower than the neutral response.

The evaluation of discernment ratings shows similar trends. For discernment, the control (median = 7), the 60° (median = 7), 75° (median = 7), and 90° (median = 7) plates performed significantly better than the 45° and lower counterparts. We also highlight how 45° (median =4.5) is rated more discernible than 30° (median =3.5, $p = 0.014$).

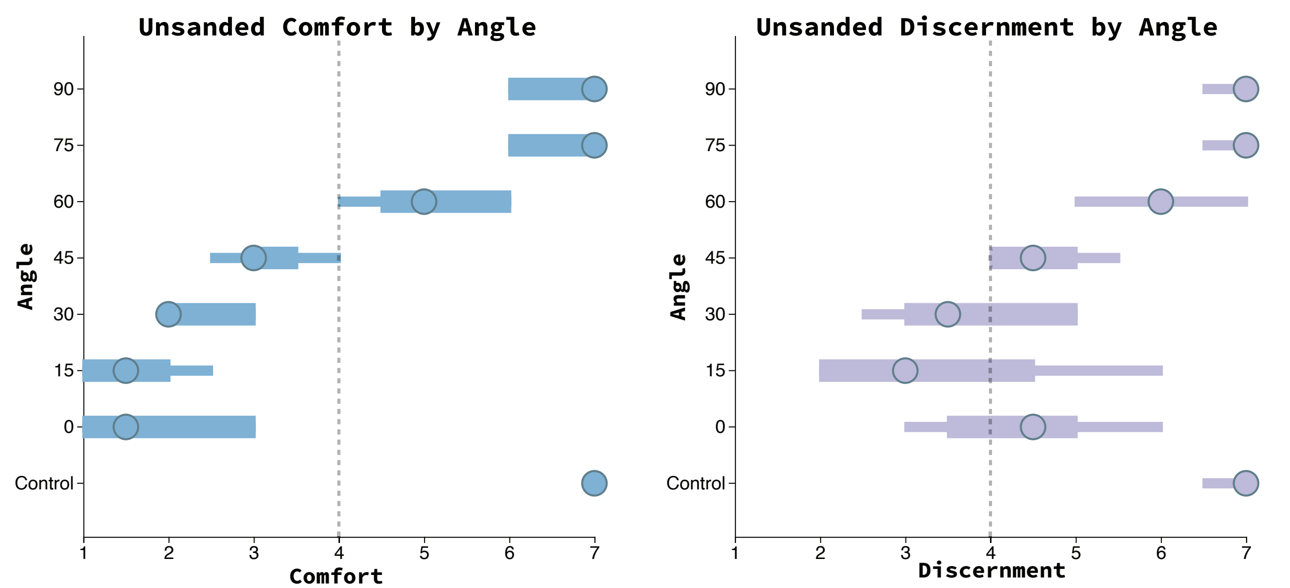
4.3 H4: Control

We used the same tests to determine if the reading time for the control (median = 11.75*s*) was lower than the other angles as proposed in H4. We found no statistical significance that this was the case for any of the angles. Conversely, the control was determined to be significantly rated as more comfortable than 0° ($p = 0.013$), 15°



(a) (b)

Figure 5: The median Likert scores, per angle, for comfort on the left and discernment on the right for *sanded* plates. Note that a one on the x-axis means the plate was deemed very uncomfortable, and a seven means that the plate was considered very comfortable. Finally, the dashed line at four on the x-axis represents the neutral response (neither comfortable nor uncomfortable).The thick error bars represent 68% bootstrap confidence intervals while the thin ones represent 95%.



(a) (b)

Figure 6: The median Likert scores for comfort on the left and discernment on the right for *unsanded* plates. The thick error bars represent 68% bootstrap confidence intervals while the thin ones represent 95%.

Angle (degrees)	Median Reading Time (s)	1st Quartile	3rd Quartile	Min	Max
control	11.8	8.3	20.2	6.7	94.6
0	13.0	9.3	14.9	7.8	127.2
15	14.0	10.4	15.0	7.4	95.2
30	10.3	8.9	15.1	7.2	69.5
45	10.7	8.4	16.9	7.6	104.8
60	10.3	8.1	11.3	7.0	92.1
75	9.2	7.9	11.2	6.8	105.1
90	9.8	7.9	10.2	7.1	67.4
total	10.30	8.30	14.95	6.70	127.20

Table 2: Statistical distribution summary of reading times for the *Sanded* experiment.

Angle	Themes	Codes	Example Quotes
control	Texture, Dimension, Finger motion, Durability	No problem with smoothness/smoothest, rounder, fingers could glide over, could get smooshed down, comfortable	"And then this looks like it's more just printed on conventional paper. I mean, like it could get smooshed down over time, or if, you know, I guess, if water got on it or something happened"(P3)
0°	Legibility, Texture	Easy to read, rough, sticking up, fingers catching	"It is fine, like it's readable. It's not something that would hurt my hands, sliding them across, but I just on that key right here, a little sharper" (P4) " Feel horrible horrible. The dots are taller but they're rough. They're not well formed. "(P12)
15°	Texture, Finger Motion, Dimensions	Rough, not uniform, finger snagging, jagged	"That dragging effect I was talking about earlier, seems to be more prominent. That dot three, it was almost a ghost dot three. " (P7)
30°	Texture, Finger Motion, Legibility	Readable, raised, jagged, stops smooth gliding, roughest	"Don't like it, it's way too rough, and it stops me from smoothly gliding across the lines." (P5)
45°	Texture, Finger Motion	Really rough, different forward and backward, stagger	"Interesting problem with this particular braille, very easy to go forward, hard to go back."(P10)
60°	Texture, Legibility	Kind of uncomfortable, easy to read, little more jagged, fatter and smoother	"This one is less rough and more comfortable. Not quite as rough like sandy, like not sandy, but all the dots were a little bit flatter and smoother to touch. I like this texture better." (P5)
75°	Texture, Duration, Experience	Could be sanded more, pleasant, smooth, could read a page, easy to glide, first line is softer than second	"I think this is the best one so far, I feel like the dot height is good. The spacing is good. The texture is good. Like reading is comfortable." (P1)
90°	Texture, Dimensions	Comfortable, not raised enough, a lot less rough	"So I like this one a lot. It's smooth and comfortable to read, but I do feel like it was a little bit difficult to discern, because some of the dots looked a little bit too sanded. Yeah, maybe just like not raised enough." (P1)

Table 3: Qualitative evaluation for the *sanded* Experiment. Noticeable themes separated by angle.

($p = 0.013$), 30° ($p = 0.014$), 45° ($p = 0.014$), and 60° ($p = 0.0163$) in the sanded experiment. The unsanded experiment mirrored this pattern with the control being rated significantly more comfortable than every other angle including vertical braille ($p = 0.037$) but not 75° braille ($p = 0.061$) although the later was close to the threshold.

5 DISCUSSION

In the following section we discuss how our experimental analysis answered the research questions presented in section 1.

5.1 RQ1: Impact of Angle on Reading Speed

We found a significant impact of angle on reading speed. We hypothesized that this relationship would be strictly increasing; however, the pattern seemed to revolve around two groups of different angles. We found that angles printed above 45° performed better than their lower counterparts, with little differences within them. The reading time analysis did not detect significant differences between 75° and 90° .

These quantitative results were supported by participant responses regarding how they interacted with the different plates. Participants described the importance of their finger movements, namely “gliding”, and how some plates impeded that in various ways. P1 mentioned their “fingers were just snagging” on the 15° plate. Other participants, like P11, discussed the importance of “not catching on my [their] fingers in the rough corners”. P11 described the 30° plates as having “a little drag coming back”. Similarly, P0 mentioned this effect only when going backward for the 15° plate. They said: ‘I noticed that I’m picking up my fingers .” P6 shared this sentiment by expressing how “if I go this way, it’s rougher, but if I’m reading from left to right, then it’s not the same” for the 30° plate. Similarly, participants also talked positively about how some plates were more consistent in both directions. P10 described the dimensions of the 60° plate as: “dot height was fine, spacing excellent, braille much easier to move both directions.”

We also note the differences in the variance of the data across angles as seen in the confidence intervals of fig. 4. This variability is common in different people’s reading speeds [37]. However, we call attention to how the group of 60°, 75°, and 90° printed plates were more consistent at affording faster braille reading.

In section 2.1 on FDM 3D Printing, we mentioned the significance of 45° from a printing perspective. Namely, we explained how angles lower than 45° may lead to overhangs that affect printing quality. Similarly, the *staircase* effect for these angles is more pronounced, as the printer takes longer steps between layers for low angles. We propose these are reasons some of the braille affect participants’ motions across the braille.

5.1.1 *Performance of the control.*

H4 tested the relative performance of participants between the 3D-printed braille and a paper-printed control. Our reading time analysis indicated that participants were not faster at reading paper braille than the 3D-printed one. However, the qualitative and Likert scale evaluations indicated that participants had a notable preference for the paper braille. Therefore, we hypothesize that since the braille types were different, participants might have lost time adjusting to the different dimensions and textures of the paper braille.

5.2 RQ2 and RQ3: Impact of Angle on Participant Responses

In accordance with the results from the DIAGRAM center, we found vertical braille to be preferred over horizontal braille [10]. Participant responses for both comfort and discernment mirror the trends seen in the reading speed evaluation.

5.2.1 *Comfort.*

For comfort, we generally found increasingly higher angles to perform better than lower ones across both experiments. However, we also found there to be a jump between the angles lower than 45° and those higher. The sanded and unsanded experiments show similar trends, with them being more pronounced in the unsanded experiment. We do highlight that across both experiments the 75° plate is rated to be as good as vertical braille. This is supported by participant responses that characterize lower angles as “rougher” and “sharp”, and higher angles as generally smoother. Comparatively the lack of roughness was considered a positive, P12 described the 75° unsanded plate as: “not rough, looks gorgeous”. While it was less common, a couple of participants also noted on the texture of the plate itself. P5 described the backdrop of a 75° plate as “shiny” and P6 described the backdrop of the the 15° plate like “curdoroy”.

In relation to smoothness, P0 characterized the importance of matching the expectations of users as demonstrated by them saying “If you’re expecting smooth Braille, but you get like hard braille, that sure is not ideal”. On the other hand, P7 mentioned being familiar with rough displays: “I’d say it’s about the consistency of a hard braille display”. This sentiment even applied with the study itself, with how P11 described the unsanded version of 75° as “smooth, I was expecting to get, you know, Mr. Scratchy right off the bat…this is nice.”

We propose that plastic defects and deposits in the layer’s start and end points are major contributors to the roughness of this braille. For *horizontal* braille, the starting point of a braille cell will always be to the side of the cell, which is where participants run their fingers. On vertical braille, the starting and ending points of a braille cell are always against the plate, which is more hidden from the fingers. This could explain why participants felt more roughness on some sides than on others, as they could have been bumping on starting points.

5.2.2 *Discernment.*

We hypothesized that there could be an inverse relationship between discernment and comfort. Some comments from the participants alluded to this idea, namely with some lower angles described as “proud” and having “good height”. Similarly, some made comments about the texture inconsistency of some higher angles, alluding to them having less dimensional accuracy which aligns with the expectations of layered printing. For the 90° plate, a P1 mentioned "So I like this one a lot. It’s smooth and comfortable to read, but I do feel like it was a little bit difficult to discern, because some of the dots looked a little bit too sanded, maybe like not raised enough". Nevertheless, it generally seemed that these effects were not as noticeable to most participants. Conversely, other factors like surface roughness were a bigger determinant of reading time.

We found that a few participants described many of the plates as being rough but not unclear. For example, P0 described a plate

Angle	Themes	Codes	Example Quotes
0°	Texture, Dimensions, Duration, Safety	Very rough/sharp, careful/injure, not unclear, like dot height, wouldn't like multiple lines	"Um, I really like the dot height. I think that's really helpful. Okay. Um, but the roughness is not pleasant."(P1)
15°	Texture, Finger Movement, Safety	Too rough/sharp, careful, almost hurt, injure, nothing redeeming, stuttered	"I literally had to take my fingers off the surface to, to kind of give them a little, I could not glide at all. Okay. And it was almost like, like, my movement was so stuttered. I knew what the words were, but I couldn't, I couldn't do more than one word at a time." (P5)
30°	Texture, Duration, Dimensions	Rough, sharp, not for long, inconsistent	"The only issue is just that it's particularly rough. It's one of the roughest" (P0)
45°	Texture, Dimensions	Sharp, not as bad/jagged but not as good, consistent	"It's a little bit sharper, but not as bad as some of the other ones, but not as good as, you know, some of the other ones either." (P1)
60°	Texture, Duration, Finger Motion	A little better, different forward and backward, a little jagged/rough, not for long	"It's almost as good as that last one (75), but a little more jagged." (P3)
75°	Texture, Preference	Favorite, not as rough, shiny, comfortable	"This one's my favorite so far. Um, I think out of all of them actually, it's really comfortable reading. and I think the dot height is a good one too, where like, it's legible, you can read it, it's comfortable." (P1)
90°	Texture	Smooth, rounded, odd sizing, easy, not sharp	"I think this was better than some of the sanded ones. That one seemed pretty smooth. That one didn't, didn't make me nervous reading it." (P0) "Yay, I like how round the dots are, like, they just make it nicer to read. Um, but again, like the spacing and size of the dots might be a little bit off."(P1)

Table 4: Qualitative evaluation for the *unsanded* experiment. Noticeable themes separated by angle.

as having "some roughness to it, but the letters are all clear." A few participants also described instances of what they called *ghost* dots as mentioned by P5. They described this a a dots that were hard to tell if they were there. Another participant described it as "almost missing the dot three … it's almost not there'‘. A similar sentiment was described by P6 who mentioned that the dots seemed to recede for the tutorial. Finally, a couple participants described braille dots as "proud". P11 defined this term as "the word we tend to use for like the height of the dots." Similarly, P1 described the braille as "crispy" and defined it as "when we say crispy braille, it's just a, you know, really defined and really clear and you can read it really well". However, dot height was also described negatively. P12 mentioned that the feel of the 45° plate was "horrible horrible... The dots are taller but they're they're rough."

While not the emphasis of the work, we note that the trends for both the *sanded* and *unsanded* experiments are similar, hinting at these structural differences of the braille. The trends for both comfort and discernment across experiments are very consistent with each other, the main difference being the *sanded* plates having higher medians, which is a reasonable expectation.

5.3 Limitations and Future Work

Below we discuss some of the limitations, exploratory analysis, and future work for this project.

5.3.1 Reading Time. First, we note how the method for measuring reading speed also accounted for reaction time and other cognitive processes. Other evaluations utilize more precise ways of measuring reading time, such as following finger paths with trackers strapped to participant's hands [41]. We believe the trade-off provided participants with more movement and comfort. However, other finger-tracking systems might make the time measures more accurate.

5.3.2 Text length. These results may only generalize to shorter texts due to reading fatigue. Some participants explicitly mentioned the concern for reading plastic braille for extended periods. For example, P5 described how they " wouldn't want to read a whole page of signage with this" when talking about the 0° plate. P9 echoed this sentiment when describing the 60° plate as "not uncomfortable, but it is not something I would read for a long time either". Conversely, P1 mentioned their preference for the 75° plate in the context of museum plaques. Specifically, they mentioned, "If you put these in museums or something, sometimes it's usually a lot of information. I would not wanna read it for more than a couple sentences, but this one, I would feel like I would be able to read it for like a page or something". 3D printing to produce general braille has many limitations, including storage space and long printing times. However, the results of these experiments should be applicable for the use of labels and short texts, which is where we believe their applications mainly lie.

5.3.3 Experiment Separation. We believe that separating the experiment by *sanded* and *unsanded* let us gain valuable information from each of the experiments. This sentiment was reiterated by P7 when talking about the roughness of the 15° plate: "glad you don't time this, the only reason I can read it, and I'm gonna completely honest, that I can read it accurately is because I had the last one [referring to the corresponding sanded plate]." While we believe sanding the plates was adequate to remove some of the larger protrusions from the braille, we also recognize how it affects the stimuli. In an evaluation of surface quality for the adhesion of a spray, Hanton et al. found that sanding seemed to make large surface defects smaller, but also increased the number of imperfections of the surface [21]. We consider performing exploratory analysis to determine the impact of sanding on surface quality.

5.3.4 Other Considerations. While 3D printing is described as an affordable manufacturing method, this notion of low cost is relative. For example, Gupta et al. emphasize 3D printing's potential as low cost in India [20]. However, Zuniga-Zabala and Guerra-Gomez mention how the prices to access this technology remain unfeasible for some populations, especially in countries with lower minimum wages [57]. The Prusa M3KS evaluated by Chen et al. in their cost and printing time comparison of printers was priced at around one thousand USD, which may not be an accessible cost for individuals and many institutions [12]. Cheaper printers exist for around 200-300 dollars but are less user-friendly and require effort to get good-quality prints. This was also brought up by P0, who mentioned the durability of braille but their perceived cost: "I don't think that smooshes, I don't think that gets damaged very much, but it's probably much more expensive to do."

5.3.5 Exploratory Analysis. In a study to determine what factors impact braille reading performance, Martinello et al. found age when learning braille to be a significant factor [37]. We believe this is one of the many demographic factors that could affect people's experience with 3D-printed braille. Namely, we propose to do some exploratory analysis on demographic correlates to see if there are noticeable differences in experiences. This could inform further studies to better target people's specific needs or preferences. Reading angle also has an impact in braille reading [22], something which was also brought up by a couple of participants.

5.4 Recommendations

First, we reiterate that there are many guidelines about the production and use of braille for tactile graphics and 3D models [10, 25, 45]. We found that 75° and 90° printed stimuli performed best in both the reading speed and subjective analyses for the 3D-printed plates. The performance of *vertical*, or 90°, braille is consistent with the recommendations of the DIAGRAM Center. Printing vertically has many design implications, as any other structures that rise from the surface will have overhangs. This can have negative effects on the printing quality of those areas of the model. Nevertheless, printing at 75° can help minimize some of those sloped overhangs which means that designers have more wiggle room to make better models without sacrificing braille quality.

(1) **Identify beforehand when adding braille into a model is reasonable.** Models that require different scales or that do not have flat parts might benefit from different tagging systems.
(2) **Braille should be printed at angles above 45°, but ideally as close to 90° as possible.** Namely, we recommend 75° as an option, especially if this minimizes overhangs from other parts of the model.
(3) **Consider post-processing like sanding** if other restrictions do not allow printing braille labels at good angles.

6 CONCLUSION

In this paper, we present two mixed-method user studies to evaluate the impact of printing angle on the usability of FDM 3D-printed braille. We found that participants read 60°, 75°, and 90° printed braille more consistently faster than braille printed at lower angles. We also found 75° and 90° braille to be rated as more comfortable and discernable than the other angles. Participants' qualitative responses complemented this analysis and highlighted how the plates for these two angles were smoother. While paper braille was not found to be better than 3D-printed braille in the reading time evaluations, participants showed a clear preference for it in the subjective evaluations. Nonetheless, many praised the potential applications of 3D-printed signage, mentioning applications like museum plaques, elevators, and hiking trails. Some also suggested the potential durability of 3D-printed braille over paper. These findings present actionable advice for makers who incorporate braille in their designs, as there are more angle options to print without sacrificing user comfort.

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A STATISTICAL SUMMARIES

The following section contains the results of the pairwise tests conducted in our experiments.

	Angle 15	Angle 30	Angle 45	Angle 60	Angle 75	Angle 90
Angle 0	0.89446	0.96509	0.23079	0.00803	0.00217	0.00197
Angle 15		0.34753	0.07839	0.00197	0.00271	0.00197
Angle 30			0.01363	0.00197	0.00197	0.00197
Angle 45				0.00983	0.00197	0.00197
Angle 60					0.00847	0.00301
Angle 75						0.77444

Table 5: Unsanded Discernment. Blue indicates statistically significant values.

	Angle 15	Angle 30	Angle 45	Angle 60	Angle 75	Angle 90
Angle 0	0.89126	0.25602	0.00528	0.00197	0.00068	0.00068
Angle 15		0.03510	0.02666	0.00068	0.00057	0.00057
Angle 30			0.06097	0.00197	0.00057	0.00057
Angle 45				0.00197	0.00093	0.00197
Angle 60					0.01688	0.00241
Angle 75						0.56095

Table 6: Unsanded comfort. Blue indicates statistically significant values.

	Angle 15	Angle 30	Angle 45	Angle 60	Angle 75	Angle 90
Angle 0	0.60000	0.61152	0.23595	0.02160	0.01629	0.01629
Angle 15		0.78760	0.33312	0.02639	0.01629	0.01629
Angle 30			0.15145	0.02115	0.01453	0.01453
Angle 45				0.03160	0.01629	0.02137
Angle 60					0.61193	0.78760
Angle 75						0.89255

Table 7: Sanded Discernment. Blue indicates statistically significant values.

	Angle 15	Angle 30	Angle 45	Angle 60	Angle 75	Angle 90
Angle 0	0.25568	0.14695	0.07401	0.01329	0.01329	0.01329
Angle 15		0.31933	0.17010	0.01329	0.01329	0.01329
Angle 30			0.39391	0.01453	0.01453	0.01329
Angle 45				0.01629	0.01453	0.01329
Angle 60					0.02994	0.02994
Angle 75						0.78760

Table 8: Sanded Comfort. Blue indicates statistically significant values.

	Angle 15	Angle 30	Angle 45	Angle 60	Angle 75	Angle 90
Angle 0	0.71888	0.35128	0.38422	0.02160	0.02115	0.02115
Angle 15		0.09613	0.35331	0.01453	0.04637	0.01329
Angle 30			0.89183	0.32881	0.09964	0.03324
Angle 45				0.04055	0.02892	0.01629
Angle 60					0.69558	0.32421
Angle 75						0.77164

Table 9: Sanded runtimes. Blue indicates statistically significant values.