Understanding (Non-)Visual Needs for the Design of Laser-Cut Models

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ABSTRACT

Laser-cutting is a promising fabrication method that empowers makers, including blind or visually-impaired (BVI) creators, to create technologies that fit their needs. Existing work on laser-cut accessibility has facilitated easier assembly as a workaround for existing models. However, laser-cut models are still not designed to accommodate the needs of BVI users. Integrating BVI needs can enrich the greater maker community by enabling cross-group discourse on laser-cut making. To investigate how laser-cut model design can be more accessible overall, we study laser-cut assembly as a process deeply intertwined with the fundamental design of laser-cut models. We present a study with seven sighted and seven BVI participants to compare their usage of laser-cut model affordances during assembly. Data for the BVI participants in this study originate from a previous work [13]. We identify assembly cues common or unique to sighted and BVI users, and discuss implications to improve general accessibility in laser-cut design.

CCS CONCEPTS

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

KEYWORDS

Laser cutting; Accessibility; Making; Prototyping; Assembling; Haptic Exploration; Laser-cut Model Design

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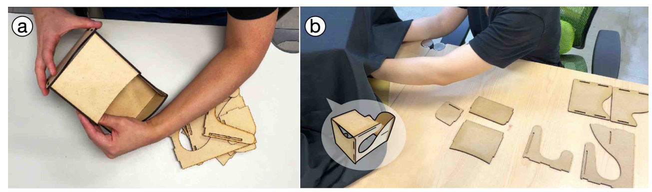

Figure 1: Screenshots of study apparatus. Both BVI (left) and sighted (right) participants were initially presented with stacked pieces and the reference model to their side. The reference model is hidden by a black cloth for sighted participants. When assembling laser-cut pieces with mortise and tenon joints, (a) BVI participants explored the reference model first instead of the stacked pieces, while (b) sighted participants accessed the reference model after first spreading out and sorting the stacked pieces.

1 INTRODUCTION

In recent years, making activities have become increasingly more accessible and affordable for not only engineers, but also non-experts due to low-cost and downsized rapid prototyping machines (e.g., 3D printers, laser cutters), which enhance the creation, modification, or augmentation of personal instruments. People with disabilities have been enabled by such Do-It-Yourself Assistive Technology (DIY-AT) to make artifacts that not only fulfill their own needs, [39, 40, 56], but also help others, create job skills, and gain recognition for their expertise in the greater community [59, 66].

Laser-cutting is one of the most commonly-used techniques for rapid prototyping, as it facilitates fast design iteration by generating lower-fidelity objects (compared to 3D-printing). Prior research on laser-cutting mostly revolved around general design problems, such as facilitating efficient conversion to 2D plates from a 3D model [22, 72, 73, 87] or improving laser-cut objects' functionalities and structural integrity [2, 6, 50, 51]. Laser-cutting has also spread to online communities due to machine-varied precision errors, namely 'kerf', being addressed [69, 71]. This made vector files (e.g., SVG) adaptable to different laser-cutting machines and expanded laser-cutting adoption to larger online platforms (e.g., Thingiverse[1]) [11].

However, little work has targeted the accessibility issues in laser-cut modeling, which, in comparison to 3D printing, involves an additional complex step to assemble laser-cut parts into the full

[1]https://www.thingiverse.com/

model. The design of laser-cut parts historically has not taken blind or visually-impaired (BVI) needs into account. Such parts are designed with the assumption that users have normal vision with which to make sense of the complex structural and spatial relationships necessary for assembly. This assumption is not applicable for BVI populations. Recent work to address this includes Daedalus [13], a system which facilitates the design and integration of laser-cut assembly cues to make laser-cuts more accessible to BVI users. Despite successfully mitigating many issues in non-visual assembly of pre-existing laser-cuts, Daedalus nevertheless focuses on accommodating existing laser-cut models — current laser-cut models themselves not being designed to accommodate or fill the needs of BVI users is still an open problem.

BVI accessibility in the larger laser-cut making community can be improved by understanding commonalities in the fundamental design needs of both BVI and sighted laser-cut users. Integrating BVI needs at the model design level can provide value to both BVI and sighted users by creating an intersection between these communities in the context of laser-cut making to facilitate inspiration and discourse. BVI creators have been known to bring valuable perspectives to design in the general maker community [77], and have invented artifacts which benefit both blind and sighted users [26, 41]. Movements for democratization in the maker community also encourage inclusive integration of accessibility into the greater community [8, 80].

Realizing this vision requires understanding both differences and commonalities in how sighted and BVI users' regard laser-cut model functionality. The current study investigates this question by developing insights from the laser-cut assembly stage, even though our implications target characteristics of the laser-cut design, an earlier stage. Knowledge of how laser-cut parts function in creating the larger structure is a prerequisite for being able to design or create laser-cut models themselves, which is why exploring how sighted and BVI users make sense of laser-cuts at this basic stage can lead to more insight on critical design characteristics of the laser-cut model.

Hence, our research questions (RQs) are as follows:

- **RQ1:** What are the strategies that both sighted and BVI people have in common when assembling laser-cut models?
- **RQ2:** What are the strategies that sighted and BVI people *do not* have in common when assembling laser-cut models?
- **RQ3:** What tactile design properties of laser-cut components have positive or negative influences on assembly?

In this paper, we designed a mixed-methods controlled study in order to compare the assembly strategies and experiences of sighted users and BVI users. The data representing the BVI users in our study was obtained from the formative study conducted in the work of Chang et al. (the authors of Daedalus) [13] on seven BVI participants. There are two studies in Chang et al. — the first study is a formative study done with the goal of identifying BVI accessibility barriers in common types of laser-cut models, prior to the design of the Daedalus system presented in the paper. The second study is a specific evaluation of the Daedalus system in that work. Data from the second study was not used in the current work. Because the formative study was an open-ended exploration of the BVI laser-cut assembly experience, its procedure provided data that could be analyzed in multiple ways and therefore can be used for the purposes of the current study. The goal of the current work is to comparatively analyze the laser-cut assembly strategies of sighted and BVI individuals, and inform future considerations for the design of laser-cut models; hence, it differs from the formative study in Chang et al. which targeted accessibility barriers for BVI individuals without a focus on assembly strategies or comparison with sighted users of laser-cut models.

In order to produce the complete data necessary for our study, we replicated the study procedure in the abovementioned formative study with seven sighted participants to complete the conditions required for comparing BVI and sighted individuals. All participants were asked to assemble five laser-cut models of the same common object type (a chair), which embodied the three most common laser-cut joint types and combinations (e.g., slot, finger, mortise and tenon (MT), slot-MT, and finger-MT). We found that sighted people utilized many visual affordances which, in contrast, were hard to be perceived by touch, but that BVI and sighted groups still shared common conceptual strategies. We also pointed out the underlying differences in assembly approach and proposed several design implications for future reference. In the next section, we detail our motivation from prior work.

2 RELATED WORK

Our work is motivated by the promising qualities of the laser-cutting method, and prior research on manipulation behavior of BVI and sighted people. We discuss them in the following sections.

2.1 Why Use Laser-Cuts?

The privilege of "making" is no longer limited to manufacturers or professionals, but more accessible to BVI people [9, 79], which improves BVI people's access to assistive technologies (AT) which fulfill their ability and custom needs. The domain of DIY assistive technologies (DIY-AT), where BVI people can create ATs that fulfill their custom needs [7, 59, 66] is a thriving area of making that helps to mitigate the high abandonment rate of traditional ATs, which cannot accommodate more diverse needs [39, 40, 56]. Efforts made towards this area of making include understanding the difficulties of physical tasks encountered by BVI people [13, 14, 28], engaging BVI people into the design process [4, 24, 75], designing accessible tools for makers with disabilities [14, 16, 54, 76–78], facilitating BVI expression through creative weaving [15, 25], and creating accessible curriculum to educate makers[64, 65]. The above works promote the vision that BVI individuals will be no longer be only receivers of ATs or help from others, but take a more active role as creators of ATs and members of the greater maker community. Our goal towards accessibility in the core design of laser-cut models themselves is also contextualized within this broader movement towards inclusive making.

Laser-cutting is one of the most common fabrication techniques, being fast and widely used in rapid prototyping. Previous research on the design of laser-cut models focused on unleashing the limitation of 2D characteristics into more complex 3D forms in order to achieve higher fidelity and functionalities [6, 22, 36, 50, 51, 57, 72, 73, 84, 87]. More recently, laser-cut models have become more accessible and end-user friendly [3, 6, 70, 71, 74], as they can now be deployed without the concerns of machine-specific precision issues [71] and can be more durable and interactable as real furniture [3]. From the above, we can see that laser-cutting is becoming more accessible to end-users, and also bears promise for fabricating usable and functional laser-cut ATs, which will move beyond the past 2D uses [18, 30, 43, 44, 52, 53, 58]. However, it is still under-studied how a laser-cut model can be designed to be easily-assembled by both BVI people and sighted people, which is a step required to obtain the final model.

In prior work, Roadkill [1], presented a nesting technique to facilitate fast assembly, but this method is still limited to laser-cut models formed only by finger joints. On the other hand, Daedalus [13] explored the behaviors and difficulties of how BVI people assembled different laser-cut models and presented algorithms to generate tactile aids in the negative space of the laser-cut plate; however, Daedalus did not consider the needs and practices of sighted people, making the applicability of its generated designs to sighted people questionable. Moreover, Daedalus accommodated existing laser-cut models instead of making the laser-cut component design accessible from the ground. In response, we aim to explore more nuanced accessibility considerations for laser-cuts, in order to facilitate design inspiration and discourse between the BVI and sighted maker communities.

2.2 Component Understanding in Visual and Haptic Systems

The haptic sensory domain is an essential channel for BVI people to retrieve knowledge from the physical world. The link between haptic sensing and cognitive processing is also important for BVI users when making sense of components during assembly. The majority of past work on supporting manual spatial exploration for BVI has focused on the 2D domain. However, laser-cut components or assembly process integrates both 2D and 3D spatial sensemaking, which has been under-studied in the haptic domains. 2D tactile graphic design comprises a major body of past work that aims to support spatial understanding for BVI individuals. The recognizability of the tactile images can be affected by different factors, such as image symmetry [12, 27] and size [27, 81, 86], viewpoint [27, 32, 34, 35], and tactile line intricacy [17, 29, 42, 83, 85]. Besides the configurations of tactile images, subject-relevant factors (e.g., visual history) also contribute to the performance of recognition. Some studies show that sighted or late-blind individuals outperformed congenitally blind individuals [33, 49, 82], while others found no association between recognition performance and visual history [5, 31, 62], but rather task-dependent performance [5].

Different from 2D tactile graphics, which remain on a flat surface, laser-cut components are manipulable objects in 3D space as a result of the assembled joints. Prior works revealed that 3D shape understanding in both visual and haptic systems share many similarities and are analogous [45, 60], but not totally equivalent [60]. "Recognition by Component" is a well-known theory describing how human vision recognizes an object by its divided components called "geons", and their spatial arrangement. The way the haptic system recognizes objects is similar [19]. Norman et al. [60] has also found that both visual and haptic systems are more sensitive to global shape differences and less so to very local surface properties (e.g., depth and curvature). However, a major distinction of the haptic system from the visual system is that it cannot inspect the many aspects of an object as rapidly and simultaneously as the visual system does, and weighs more priority on local features [47]. Hence, comparing how the visual and haptic systems of sighted and BVI users impact their cognitive strategies of sensemaking in the laser-cut assembly process may lead us to insights on balancing the benefits and trade-offs of laser-cut plate and model design.

2.3 Cognitive Mechanisms of Assembly

Assembling is a spatial problem-solving task which demands specific cognitive functions for processing spatial information and manual skills for manipulating the assemblies in space [63]. During assembly, people construct 3D mental representations of parts and their combinations in order to comprehend and plan for assemblies, which involves many cognitive resources. Several inherent characteristics of assembly configuration, such as symmetry and number of components, were found to contribute to cognitive load during the assembly task problem-solving, such as figuring out which parts to assemble and how to assemble them [20, 67, 68].

However, without hand-eye coordination, BVI people may experience additional cognitive load and require effort to gather and encode such spatial information. For example, multiple sequences of haptic exploration may be required instead of a visual sweep [48]. Other spatial processes, such as spatial updating (updating one's mental representation of a spatial object due to dynamic changes that may result from object manipulation or the object itself changing shape), may also be more error-prone without vision due to distorted memory of the object locations in the assembly area [37]).

Acquiring the complex manipulation skills required to make sense of assembly parts in the first place is also cognitively demanding by nature for BVI individuals. Development of fine-motor functions during the childhood of BVI individuals, such as grasping and handling small objects, is much slower and more varied than that in sighted children, due to vision being a primary channel for object recognition [10]. Because the core development of fine motor skills runs in parallel with neurodevelopment and physical growth, fine motor developmental delays that still exist by the age of six will result in lasting burdens on ability development that are carried to adulthood [23]. Hence, BVI individuals may experience barriers to assembly not only in planning the mental representation of parts but also in their physical manipulation and assembly.

The work of Chang et al. [13] has studied assistance in this domain through its user-evaluation study (the second study in the paper), which documents some heuristics that a laser-cut model design should follow to achieve accessible assembly for BVI people. But these heuristics do not account for integration with the general maker community, leaving the generalizability of such design questionable. In this paper, we synthesized data from the formative (first) study of Chang et al. [13] with newly replicated procedures on a set of sighted participants in order to explore opportunities for more inclusive, accessible, and universal laser-cut plate design.

3 METHOD

Moving forward from prior research, we designed a study that utilizes data from the formative study of Chang et al. [13] in order to compare and contrast the strategies and tactile-visual properties used by sighted and BVI participants. In this section, we will describe the overarching design of the mixed-methods controlled study, and specify which portions of data from this study were obtained from the work done in Chang et al. [13]. Only data from Chang et al.'s [13] formative study and the study design from this formative study (including the joint type survey in Section 3.1 and the basic apparatus in Section 3.4) became part of the current study. We will first describe the process and rationale for selecting the laser-cut models used to study participants' assembly experience, then explain details of the experiment design and procedure.

3.1 Determining Laser-cut Joints and Models

Our study determines representative joint types in the same manner as the survey conducted in Chang et al. [13], the prior work from which we obtained the data for the BVI participants in this work. In this survey, the joint types for over 600+ of the latest projects tagged with "laser-cut" on Thingverse were labeled. Based on the statistical data from this survey (please find details in [13]), a model was chosen for each most commonly-occurring single joint type or combination: finger, slot, and mortise and tenon (MT) joints, and their pairwise combinations: finger+MT and slot+MT joints. For each of the five categories, a laser-cut model of the type "chair" was chosen as something that could be easily recognized as a frequently-encountered object by both BVI and sighted individuals, such that participants had an idea of what they were to assemble even without seeing the final product. The size of each model was scaled to accommodate standard-thickness wood plates (3mm).

3.2 Threshold for Dependent Measures

Given the tangible nature of assembling, spending too much time on physical manipulation would fatigue our participants. To avoid this, we used the same protocol adopted by prior work which used the time spent by sighted [55] or experienced [14] users as basis to determine time threshold for each task. The thresholds used were the same as those in the formative study of Chang et al. [13], which were determined through pilot studies (Table 2). Within the time threshold, we measured the completion accuracy for each task, which was calculated based on the number of piece pairs which were correctly assembled into a joint over the total number of joints.

3.3 Participants

Because the BVI data in this study was obtained from the work done in Chang et al.'s formative study [13], the BVI participants used in this work are the exact ones who participated in that study. The same methods were used to recruit the seven sighted participants in this current study as those used in the abovementioned formative study [13]. In total, seven BVI participants (5 M and 2 F, median age: 31) and seven sighted participants (4 M and 3 F, median age: 23) were recruited. The recruitment methods were the same for both groups; all were recruited through public announcements on social media. Five of the BVI participants were congenitally blind and two were adventitiously blind. All sighted and BVI participants had some naturally-occurring prior experience in assembling everyday objects (e.g., furniture), but none in assembling laser-cut architecture, and all participants possessed and used both functioning hands during the study.

3.4 Apparatus

In order to explore participants' assembly behavior, we asked participants to assemble the five chairs separately, which were presented in a randomized order. During each assembly, participants were offered a completed reference model to their side and manipulated the corresponding laser-cut pieces directly in front of them (Figure 1). The provision of the reference model as a basic guiding cue stemmed from finding that all BVI participants in Chang et al.'s pilot studies were not able to proceed with assembly upon presentation of only the laser-cut pieces [13].

In the portion of the current study that was run on sighted participants, we decided to occlude the reference model in a box covered by a black cloth (Figure 1b) so that sighted participants could only access the reference model through touch. At the reference level, this equates the sensory access channels of the BVI/sighted participants but does not impact their pre-existing capacity to actually assemble the laser-cut pieces. We made this decision in order to control the laser-cut assembly task such that both BVI and sighted users would think critically about how to assemble the individual pieces. The information from being able to see a completed reference model in addition to touching enables sighted users to see the final location of all laser-cut pieces, which enables sighted users to perform visual matching of the piece locations and eliminates the problem-solving aspect of assembling individual pieces, which is the task we aim to measure in this study. Therefore, we still enable model referencing for sighted users in order to equate the resources provided to both sighted and BVI users, but limit it to touch, equating the condition for BVI to enable controlled comparisons.

A camera-enabled device was placed face-down above the table to video record hand activities on the table. Participants' faces were out of view to maintain anonymity.

3.5 Procedure

After being welcomed and instructed about our study, participants were asked to fill out their basic demographic information, vision ability, and assembling experience. Our study began by introducing participants to the three major joint categories (finger, slot, and MT joints). They practiced examples of each in a learning session and were allowed to move on once they felt sufficiently familiar with the joints. The learning session lasted up to 30 minutes for BVI participants and 10 minutes for sighted participants. The rest of the procedure follows exactly the format of the formative study conducted in Chang et al. [13].

Next, to explore participants' assembly behavior, we asked participants to assemble the five chairs separately, which were presented in a randomized order. Participants were informed that all models belong to the categories of chair or table [61]. During each task, participants were encouraged to think aloud and assemble as much as they could but were permitted to quit and move on at any time if desired. Participants were also allowed an up to 5-minute break between tasks if needed.

After each task, we conducted a post-task interview with participants in a semi-structured manner, where we inquired about their strategies for assembling and their self-assessed score on the difficulty of assembling (scale of 1-7). They were allowed to modify their scores after exploring all presented models and having a better understanding of the full range of difficulty. This testing session lasted about 60 minutes for sighted participants and 100 minutes for BVI participants.

After the testing session, BVI participants were guided step-by-step to the answers from their incomplete assembled models, which helped depict the whole assembly process and allowed them to elaborate on any underlying difficulties in more detail. All participants were compensated with a rate of $14/hr for their efforts.

3.6 Analysis

We transcribed and coded all qualitative interview feedback received in all sessions for further analysis via affinity diagramming. We also analyzed the recorded video footage of the experiment by labeling the time series of each task for each participant with types of assembly behavior. The video footage and interview recordings for BVI participants were obtained from Chang et al.'s formative study [13], but the analysis described below was conducted separately for both BVI and sighted participants in the current comparative study, and is completely different from any data analysis performed in Chang et al. [13].

To address our research questions of identifying behavioral strategies in the laser-cut assembly process, we decided to develop video codes at the granularity of *low-level behavioral actions* (i.e., touching or manipulating pieces in certain ways). By coding for low-level behavioral actions, patterns in these actions that are discovered can be identified as specific strategies reported in our findings. We followed the process of inductive open coding as a form of conventional content analysis [38]. Our open coding resulted in 10 high-level categories (see below) which emerged from the data and were then used as a codebook to label the rest of the video clips once the categories from our open coding process reached saturation (when no more new types of low-level behavioral actions emerged).

The coding process started with two of the authors incrementally examining and labeling video clips with low-level behavioral actions (e.g., touch piece, hold piece, etc). Then, four of the authors (including the above two) discussed the coding patterns and merged each code into the current high-level categories applicable to all footage. All video clips were then labeled using the codebook with these high-level categories by two of the four members. To ensure the inter-rater reliability of video labels, we computed Krippendorff's Alpha-Reliability using the method applicable to nominal data with two observers [46]. Each second was taken as a unit and the label as its nominal item. Two authors labeled all of the data from one of our participants for our calculation, which yielded $\alpha = 0.7533$. The instructions for labeling the videos consisted of the following video label definitions and the rule that all label categories are mutually exclusive (there are no overlapping labels at the same time in a video). The video labels are defined as following:

(1) ***Spread out Pieces***: This label marks the time from when the participant spreads out the pieces that are overlapped at the start of the task (all pieces are initially provided in a stack) to the time when they initiate to a different activity. "Spread out" is differentiated from organizing by displaying no intent other than to separate overlapped pieces.
(2) ***Organize Similar Pieces***: This label marks the time from when the participant starts to organize and group similar/symmetrical pieces to the time when they initiate a different activity.
(3) ***Touch Model***: This label marks the time from when the participant starts to touch the reference model to the time when they initiate a different activity.
(4) ***Explore Haptically***: This label is exclusive to BVI participants. It marks the time from when a participant starts to touch laser-cut pieces or parts of assembled models in detail (e.g. slowly and thoroughly feeling the edges or surface of a piece) to the time when they initiate a different activity. Sighted participants did not exhibit this behavior.
(5) ***Examine Pieces/Assembled***: This label is exclusive to sighted participants. It marks the time from when the participant remains static in video while looking at a piece or moves their hands around without manipulating any objects, to the time when they initiate a different activity.
(6) ***Mid-air Compare/Simulate***: This event is exclusive to sighted participants. This label marks the time from when a participant holds one piece in one hand and another piece or assembled model in the other hand, then places the pieces mid-air in relative positions to one another, to the time when they initiate a different activity.
(7) ***Fit Correct Joint***: This label marks the time from when the participant explicitly attempts to assemble two pieces that form a correct joint to the time when they initiate a different activity. The joint is not necessarily completed at the end of this label.
(8) ***Fit Incorrect Joint***: This label marks the time when the participant explicitly attempts to assemble two pieces that do not form a correct joint to the time when they initiate a different activity.
(9) ***Stabilize Assembled***: This label marks the time from when the participant tries to firm a joint or stabilize an already-assembled part of the model to the time when they initiate a different activity.
(10) ***Remove Assembled***: This label marks the time when participants explicitly attempt to remove parts of model that had already been assembled, including correct/incorrect joints, assembled model, or incorrectly connected pieces.

4 QUANTITATIVE RESULTS

In this section, we report the quantitative results of completion accuracy and self-reported difficulty for each task in this study. The breakdown of these results is visualized in Figure 2.

4.1 Completion Time and Accuracy

All sighted participants were able to complete Finger, MT, and FingerMT tasks with 100% accuracy within the specified time thresholds (Figure 16). In the Slot task, four of the seven sighted participants successfully assembled the model within the time limit. Two

ⓐ Tables of Individual Completion Accuracy

Top: BVI Participants

	Finger	Slot	MT	FingerMT	SlotMT
P1	0%	0%	0%	0%	0%
P2	30%	100%	100%	100%	100%
P3	50%	0%	87.50%	63.64%	71.43%
P4	80%	100%	75%	100%	100%
P5	20%	40%	75%	100%	92.86%
P6	30%	0%	75%	81.82%	28.57%
P7	70%	0%	62.50%	45.45%	0%
Avg.	**40%**	**34.29%**	**67.86%**	**70.13%**	**56.12%**
SD	**28.28%**	**47.21%**	**32.16%**	**37.38%**	**45.63%**

Bottom: Sighted Participants

	Finger	Slot	MT	FingerMT	SlotMT
P1	100%	100%	100%	100%	85.71%
P2	100%	60%	100%	100%	85.71%
P3	100%	40%	100%	100%	85.71%
P4	100%	100%	100%	100%	100%
P5	100%	100%	100%	100%	100%
P6	100%	80%	100%	100%	100%
P7	100%	100%	100%	100%	85.71%
Avg.	**100%**	**82.86%**	**100.00%**	**100.00%**	**91.83%**
SD	**0.00%**	**24.30%**	**0.00%**	**0.00%**	**7.64%**

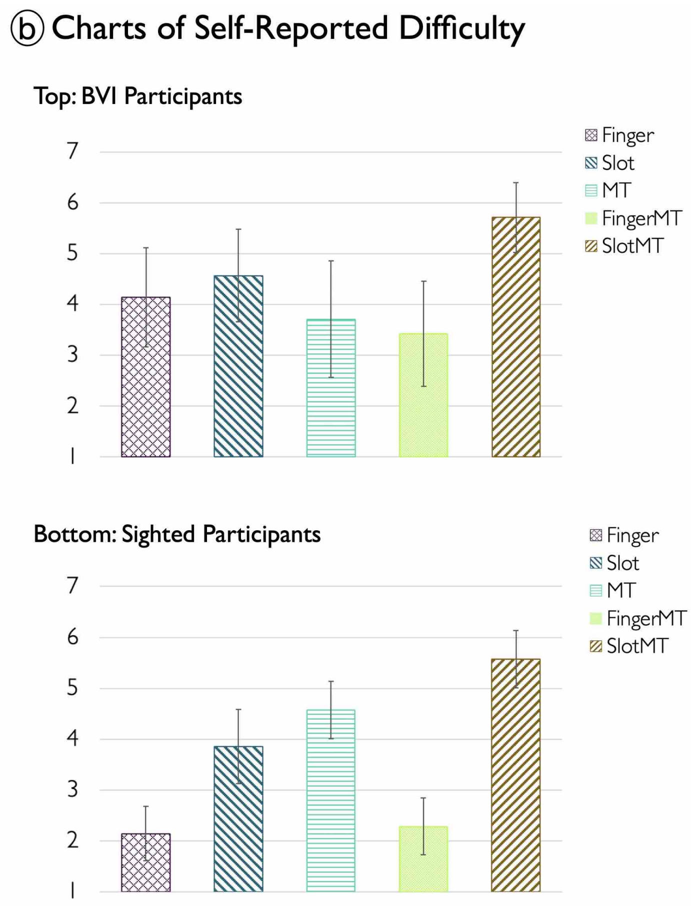

Figure 2: Study results from sighted and BVI participants. The data of BVI participants were retrieved from Chang et al. [13]. (a) Table of individual completion accuracy. Tasks completed before the time threshold are marked yellow while ones participants quit are marked blue. (b) Averages of self-reported difficulty (1-7) with error bars showing 95% confidence intervals.

of the sighted participants (S2,S6) reported completion of the Slot model but had assembled joints in an incorrect orientation. The remaining participant (S3) performed with 40% accuracy on this task and struggled throughout the assembly; however, they were reluctant to use the reference model until the very end of the allotted task time. In the SlotMT task, all sighted participants were able to confirm completion in advance of the time threshold. However, four of them (S1,S2,S3,S7) assembled two pieces in opposite orientations (Figure 7d), and thus yielded 85.71% accuracy in the end.

On the other hand, BVI participants on average experienced more difficulty in each assembly task. The completion accuracy averages for each task were: Finger = 40% (SD = 28%), Slot = 34.29% (SD = 47%), MT = 67.86% (SD = 32%), FingerMT = 70.13% (SD = 37%) and SlotMT = 56.12% (SD = 45%). Most participants worked on all tasks until the end, where B2 and B4 completed four and all five tasks in advance, respectively. However, B1 quit during the MT and SlotMT tasks because he felt that he knew what barriers were hindering him and that he could not resolve them in time, and B7 quit the SlotMT task due to perceiving the complex model to be extremely difficult. Both of these users decided to quit halfway into the tasks, perceiving other better use of their time. Though our data here shows particularly high standard deviations, this is not unusual given the high diversity in physical and cognitive ability across different BVI individuals.

4.2 Self-reported Difficulty

Independent-samples t-tests were conducted for each task to compare the difficulty ratings from sighted and BVI people. In the Finger task, there was an almost-significant difference between sighted ($M = 2.14$, $SD = 1.07$) and BVI participants ($M = 4.14$, $SD = 1.95$); $t(12) = -2.378$, $p = 0.055$. In the MT task, there was also a close to significant difference between the ratings of sighted ($M = 4.57$, $SD = 1.13$) and BVI participants ($M = 3.71$. $SD = 2.29$); $t(12) = 0.888$, $p = 0.054$. However, no significant difference was found in other tasks. In the Slot task, the ratings were: sighted ($M = 3.86$, $SD = 1.46$) and BVI ($M = 4.57$, $SD = 1.81$); $t(12) = -0.811$, $p = 0.508$. In the FingerMT task, scores were: sighted ($M = 2.29$, $SD = 1.11$) and BVI ($M = 3.43$, $SD = 2.07$); $t(12) = -1.287$, $p = 0.135$. In the SlotMT task, the scores were: sighted ($M = 5.57$, $SD = 1.13$) and BVI ($M = 5.71$, $SD = 1.38$); $t(12) = -0.212$, $p = 0.354$. In the sections below, we continue to discuss other qualitative findings together with these statistics.

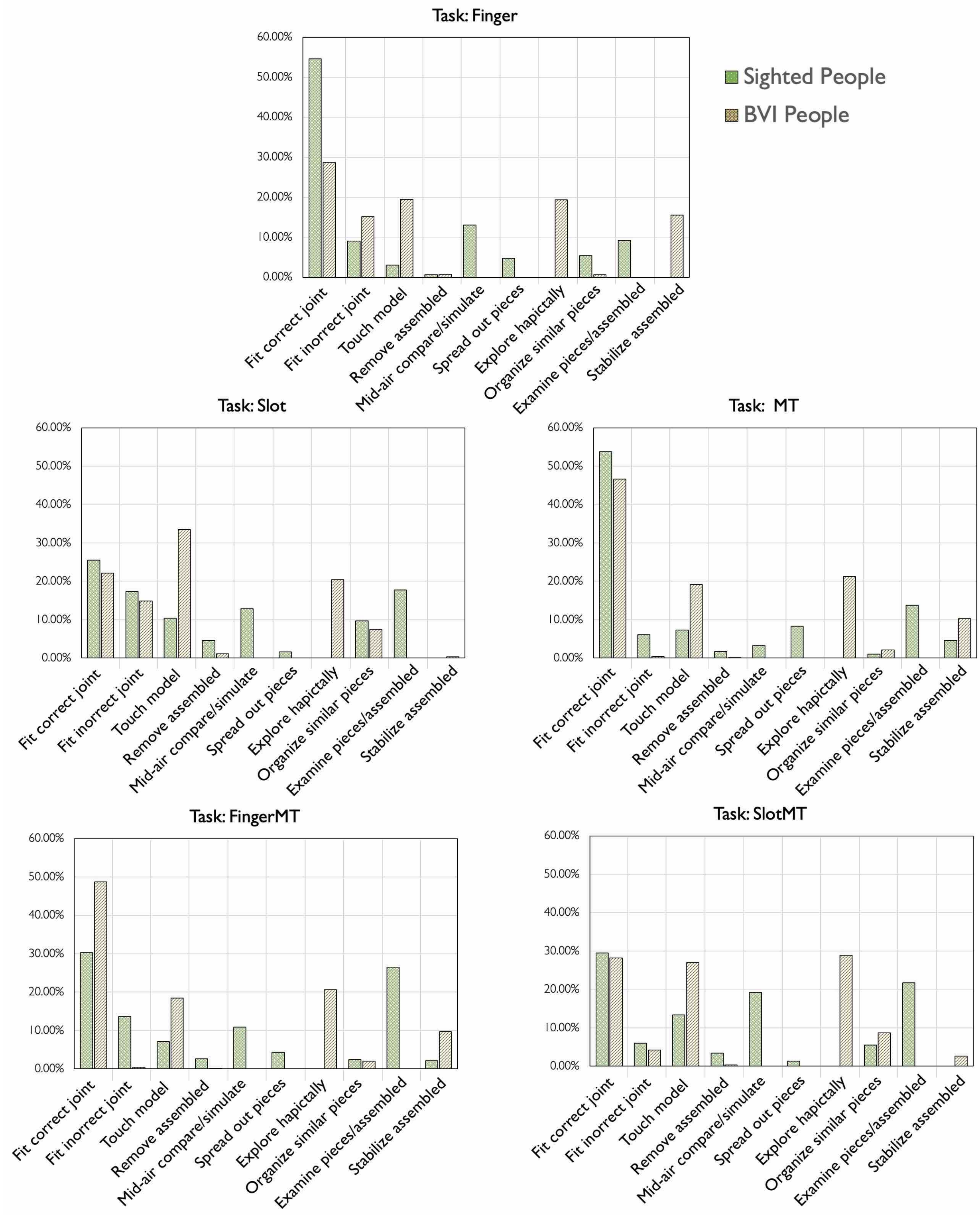

Figure 3: Average activity portions of each task for sighted and BVI participants. Y-axis percentages represent the average ratio of time participants spent on each activity, out of the total time they took to complete each task.

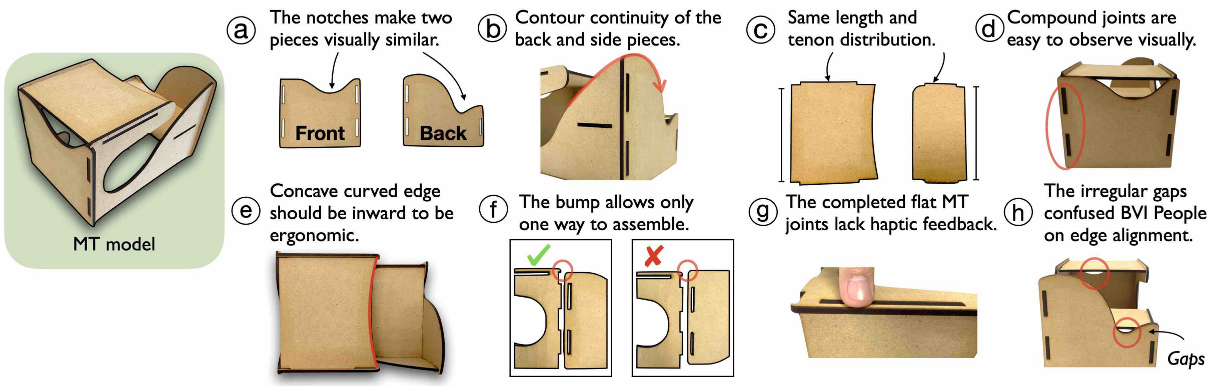

Figure 4: Findings from MT chair task. (a) The front and back wall pieces were seen as similar or matching by sighted participants due to the notches/dips in the middle of the shape. (b) The contour continuity from the back to side pieces provided global visual cues. (c) The table and seat pieces had the same length and similar tenon distribution, which were visually-salient cues of how they would fit between the other pieces in the model. (d) Compound joints are another visually salient cue for inferring joint pairs across pieces. (e) The concave curved edge of the table was inferred to be oriented inward based on ergonomics as a form of sighted participants' semantic knowledge. (f) Slight bump/notch on the left piece corner restricted the joint pairing to be one-directional, which was easily observed by vision but not touch. (g) A completed MT joint forms a flat surface without any protrusion, making the joint completion difficult to perceive by touch for BVI people. (h) The irregular gaps in how the (circled in red) pieces fit confused BVI participants with seemingly-misaligned edges.

5 FINDINGS

In this section, we discuss our findings synthesized from participants' labeled activity distributions, the post-task interviews, and video observation analysis on each task. Both common and differing trends were found across BVI and sighted participants, with some unique challenges in physical manipulation for BVI.

5.1 Assembly Strategies and Clues

This section addresses **RQ1** and **RQ2** by demonstrating which clues from the laser-cut pieces and models were commonly-used by both BVI and sighted participants, as well as strategies that differed between them. These clues and strategies were deeply related to the nature of the laser-cut model's tactile properties (**RQ3**).

5.1.1 Commonly-Used Assembly Clues. The majority of assembly cues consistently used in the same way by both sighted and BVI participants tended to be inherent features of individual pieces. There was more variation in how BVI and sighted users interpreted patterns across the selection of pieces for a model (e.g., symmetry, similarity, or uniqueness) which could be utilized as assembly clues.

Inherent piece features. To determine whether the right pieces and orientations were being assembled, both sighted and BVI participants used two edge-based strategies: aligning the cleanness of an edge or corner based on a joint matching, and aligning edge length/shape between pieces.

The creation of clean edges or corners when assembling pieces was a clue consistently used by both BVI and sighted users. *Within-joint edge alignment* of a joint between two pieces forms a clean-cut junction or corners without any obtrusive bump or gap. For instance, completed finger joints will form an exact 90° corner, and in completed MT joints the mortise will be filled in by the tenon to form a flat surface without any protrusion (Figure 4g). Both BVI and sighted users were able to use the 90° corner alignment as a helpful assembly clue. B1 described fitting the joint of the chair leg in the Finger task: *"I was trying to align their fingers to form a clean corner edge that would match the reference model"*. S2 also stated in the Finger task that *"There will be a protrusion if (finger joints) are paired or assembled wrong."* Sighted users also visually measured edge alignment when assembling slot joints, but BVI users were not able to easily assess slot joints by touch (Figure 7c), and the completeness of MT joints was hard to perceive. During the Slot task, S4 stated: *"You can tell if the joint is correct by observing if any unreasonable protrusion appears,"* whilst B6 described slot joints as: *"Their connected junction was so hard to make sense by touch."* The activity distribution in Figure 3 shows that BVI users spent the most time touching the reference model for the Slot and SlotMT tasks, because Slot joints were so difficult to recognize by touch. B3 demonstrated knowledge of the assembly strategy but lack of affordance to use it when she stated, *"I knew how the MT joint worked, but it needs to protrude a little bit more at least so that I can confirm it is pushed in all the way by touching it."* BVI users knew how to use this strategy but were unable to apply it for joints which were difficult to perceive by touch, such as slot and MT.

Both sighted and BVI participants recognized that matching edge length and shape was an indicator of whether two pieces were meant to be assembled at a certain configuration. Although both types of users were able to notice this, mostly sighted users benefited from this clue due to its limited salience when perceived haptically. For instance, in the SlotMT task, there are four similarly-shaped connectors, two meant for the seat, and two for the chair back. However, they only differed by a slight curve on the piece edge (Figure 7a). The gaps from lack of alignment between the edge of the connector and the seat/back can be observed visually if the wrong connectors are assembled to the seat/back, and many sighted participants benefited from this clue. However, BVI users were not able to clearly perceive the other possible joining locations if they joined this connector to the wrong spot, even when they had recognized the piece was not a correct fit. Sighted users were

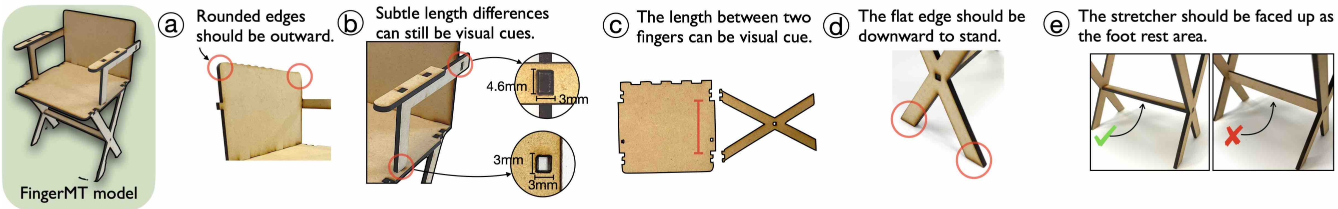

Figure 5: Findings from FingerMT chair task. (a) Sighted participants assumed the rounded edges were "outward" parts of the model based on semantic knowledge pertaining to object design. (b) Subtle differences in mortise length were visually but not haptically observable, and used as assembly cues by sighted participants. (c) The length between two finger joints served as visual cues for which pieces fit together. (d) The flat edges (circled) were inferred to orient downward to stand the model on a surface (sighted participants' semantic knowledge). (e) The cross-stretcher was assembled with its surface facing up, identified by sighted participants as a foot rest area based on their semantic knowledge.

able to observe at once the multiple places where this piece could be joined. From the activity distribution (Figure 3), we can also see how in the SlotMT task, sighted users made significant use of visually-examining the piece assortment and simulation/piece comparison to assist in their assembly. But because BVI users could only perceive the lack of fit itself in a given moment, there could be multiple reasons for it which they would have to haptically explore one by one without the ability for immediate comparison to other clues, hence SlotMT having the largest ratio of haptic exploration among all tasks (Figure 3). Reflecting on MT joint assembly, B5 requested: *"I hope there can be a supporting tool for me to align the edges more confidently, due to the many irregular shapes and gaps in this task (Figure 4h)."*

Shape patterns across multiple pieces. Both sighted and BVI users recognized patterns such as symmetry, general piece shape similarity, and distinctively unique piece shapes. However, sighted and BVI users responded to unique vs. similar piece shapes in a starkly contrasting manner.

Symmetrical pieces were quite easy and quick to recognize for both BVI and sighted users (this result for BVI users is also presented robustly in Chang et al. [13]). Both users tended to sort pieces starting from the symmetrical ones, even for models with different joint types. More interestingly, BVI users benefited the most from unique piece shapes as a clue, while sighted users were more comfortable assembling similar pieces. Unique pieces made the assembly process fluid for BVI people as they recognized each different piece more easily, as commended by B2 in the MT task: *"Every piece having distinguished features will easier for me since I can identify them without hesitation."* In contrast, S3 stated, *"There were no symmetrical pieces, so I just tried to put together whatever looked joinable."* This was also reflected in the BVI participants' lower ($t(12) = 0.888$, $p = 0.054$) self-reported difficulty of MT task (compared to sighted group) and comparatively less time being trapped in wrong pairings (0.431% vs. 13.7% by sighted people) as Figure 3 indicated. Sighted users would sort pieces by similarity, even when assembling asymmetrical models; sighted users still exhibited similarity-based sorting behaviors (S1,S7) for the MT model (Figure 4a), where they put similar pieces together (Figure 1b). The similarity of pieces (e.g., length and shape) was used to indicate their spatial relationship. However, the similarity of pieces could also generate confusion. Many sighted participants (N=3) reported seeing multiple U-shapes (there were four in Slot task as Figure 16 listed) confused them. S7 stated, *"So many ambiguous situations in the task. There are too many similar joints, and the piece shapes are almost all U-shaped.* Figure 3 also shows the highest percentage of time spent assembling the wrong joints (17.4%) for the Slot task among sighted participants, which is also reflected in the completion accuracy (Figure 2). This problem was serious for BVI participants, who all reported that the tasks involving many similar pieces were the most difficult, such as the Slot model (U-shapes) and SlotMT model (small rectangles) as reported by B7: *"There are too many similar pieces in this model that I did not know where to start even though I had a reference model. I was afraid of messing it up by selecting the wrong one."* The time spent correctly assembling joints (22.1%) in the Slot task is the lowest among all five tasks for BVI users Figure 3. BVI users benefited exceptionally from uniquely-shaped pieces, and similar pieces can confuse sighted and BVI users.

5.1.2 Sighted-Only Assembly Strategies. This section describes vision-specific strategies that sighted people were observed to frequently use, but which were not used by BVI participants during assembly.

Global observation and inference. Vision provides the ability to be aware of global information, which helps sighted people observe many cues for planning assembly. Below, we describe how sighted participants used global information to infer assembly strategies, such as combined assessment of multiple piece features and the utilization of prior furniture knowledge to infer the final laser-cut model.

Piece features or features across multiple pieces can be easily observed and combined together as cues for sighted people to easily infer and restrict the joining possibilities. For instance, S4 stated in Finger task *"I tried to figure its [a piece] orientation out by imagining the piece assembled either upwards or downwards, and then evaluated a few joining possibilities along with the number of fingers".* Moreover, some designs of our selected models set inherent physical constraints that restricted the possible orientations in which they could be assembled. This requires the combined assessment of inherent and cross-piece features such as the piece orientation, joint length, and the compatibility of intersected pieces. For instance, there are protrusions in the junction between the side and front pieces in MT model (Figure 4f) that forced them to be assembled in only one orientation, which benefited many sighted participants (N=5). Another example appeared in SlotMT task, in which the seat was divided into three pieces, and the outside ones could only be assembled in one orientation due to the joint constraints (Figure 7b).

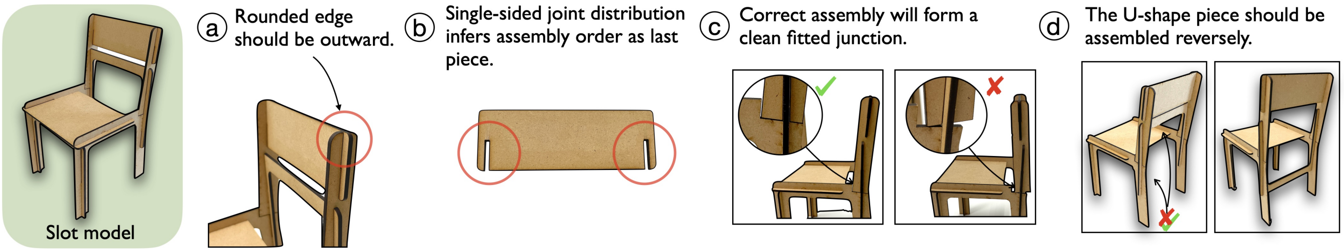

Figure 6: Findings from Slot chair task. (a) The rounded edge was thought to be oriented outward based on sighted people's semantic knowledge. (b) Participants ranked the top rail last to assemble based on the single-side joint distribution of slots on the top rail. (c) Sighted participants used semantic knowledge to infer the chair back would be angled backward with a fitted junction and no irregular gaps if correctly assembled. (d) The U-shape piece was assembled upside-down by some users during the task (right) but corrected afterward (left) by sighted users based on their semantic understandings.

Another global cue for determining orientation is to observe the continuity of contours across pieces, which was useful for determining the orientation of several pieces. This was reported by three sighted participants (S4,S5,S6) when assembling the back of SlotMT chair, which is divided into three separated pieces with very subtle shape differences (Figure 7d). Another example was found in MT task, where S1 noticed and utilized the contour continuity of the back and side pieces to connect them (Figure 4b). The significance of these strategies for sighted users can also be seen in the large portions of time spent visually examining the pieces without any touch or manipulation (the 'examine pieces/assembled' label in Figure 3).

Use of semantic knowledge. Sighted participants can also leverage their prior knowledge or intuition about furniture design to reason and interpret how a piece should be assembled. For instance, in the SlotMT task, S6 assembled the table onto the side of the chair seat (Figure 7e): *"It made sense to assemble this way since school desk chairs tend to have a table on the side folded."*. Also, sighted participants were able to problem-solve any assembly errors or ambiguity using this prior knowledge, such as when assembling the cross-shaped chair legs in the FingerMT task, S7 first assembled in the wrong orientation (Figure 5e) but fixed it after he thought the leg to be the place people rest their legs. He stated *"I first assembled it with the side of the piece facing up, but it seemed wrong as this should be the place people rest their legs, so it should be faced up."* Similarly, in the Slot task, S5 initially assembled the U-shape connector of the chair back upside-down (incorrect) but decided to flip it (correct) (Figure 6d) using his understanding of the piece function: *"I flipped it back since I found this connector has no chair function in that position."*. The use of such a strategy was only possible because sighted users were able to view the global appearance of the half-assembled model and make judgments based on this; BVI users did not have this information constantly available for evaluation.

Linking subtle nuances of the piece edges and corners to specific furniture features also guided the assembly process for sighted users. In the MT task, the table piece can be assembled in two orientations. However, the difference of edge contour (Figure 4e) made its orientation clear for all sighted participants, as S6 stated that *"The curved edge should be oriented inward toward to where the user sit in because such design seems more ergonomic and typical for a desk."* Also, in the Slot and FingerMT tasks, the sides of pieces with rounded edges were recognized as orienting outward (Figure 6a & 5a), while the sides with flat edges were seen as the inner connection with others that will form a clean-cut junction (Figure 6c), or placed flat on the table (Figure 5c). Many sighted participants (N=3) leveraged these nuances, such as S2 in Slot task: *"The rounded edge or corner should be in outward to meet aesthetics (Figure 6a)"*, and S3 in FingerMT task *"The flat edges without any joint should be placed downward to stand on the floor (Figure 5d)."* This can also help clarify the piece orientation as in the Slot model, S7 remarked *"Chair back should be angled backward. This way, people can lean on it" (Figure 6c).*

However, the influence of prior visual knowledge is double-edged. Unable to map with visual experience made the task harder for sighted people, as stated by S5 in MT task *"I need to know what parts the pieces take in the chair or table. All models were reasonable to my knowledge except for MT, which I did not see before. And that's why I rated MT five and SlotMT four, despite the higher complexity of SlotMT."* This may also explain why MT model is relatively harder for sighted people (Figure 2). Figure 3 also shows that sighted users spent the most time (26.5%) examining and making sense pieces in the MT task compared to the other tasks. Another example was found in the Slot task, where S3 persisted in positioning the U-shape one as the chair back *"I thought it was definitely the chair back due to the U-shape, so I ordered its assembly to be last"*. This was a situation where S3 got stuck due to an assumption about the chair semantics and did not complete the task in time.

Visually-distinct piece features. The piece features visually-salient enough to be used by sighted participants for deducing assembly strategies were all overarching joint features, such as the number of fingers in a finger joint, and joint distribution/spacing across all pieces. These features are haptically-inaccessible due not only to their global nature but also the smaller size of joints which make them less haptically distinguishable.

For instance, the number of fingers of finger joints is an exclusive shape characteristic, which was often used by sighted participants to infer pairing of finger joints, as pointed out by S6 in Finger task *"I knew which pieces were paired because I took a glance of the pieces and found many finger joints. Due to their complementary nature, the one with four fingers is obviously to be complementary to the ones with three fingers (Figure 8d left)"*. Another example was also found in Finger task but the number of fingers was used to distinguish the position of the two similar U-shapes (Figure 8d). The size of the two halves of a joint was another notable assembly guide for sighted

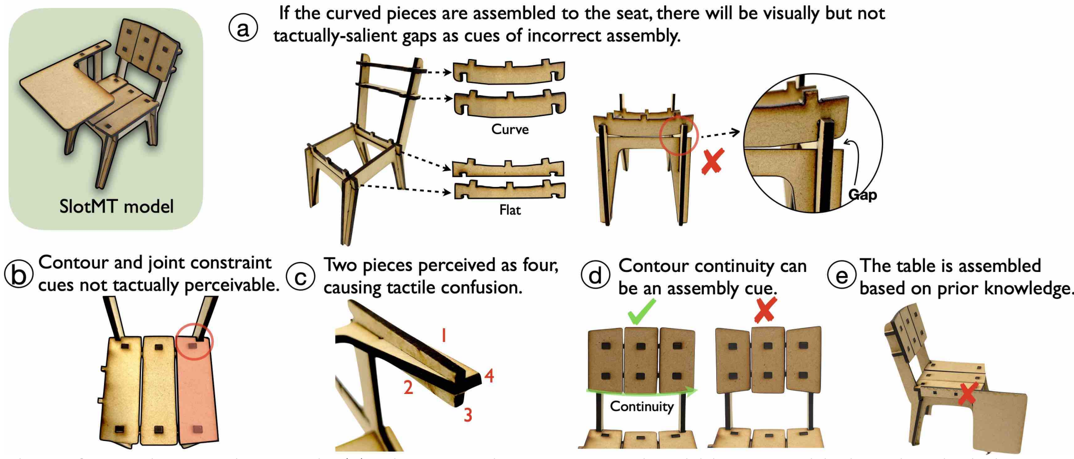

Figure 7: Findings from SlotMT chair task. (a) The curved connectors should be assembled to the slightly-curved chair back, while the flat ones should be assembled onto the seat. If the curved connectors are assembled to the seat, there is a visually- but not tactually-salient gap. (b) The outer seat pieces can only be assembled in one orientation due to the joint constraint (circled), which is more easily observable through combined visual assessment across pieces. (c) These two interlocked pieces were often perceived as four haptically-separate pieces by BVI participants. (d) Some sighted participants (N=4) used contour continuity to determine the orientation of pieces (left), while others assembled them "wrong" (right). (e) The table was assembled incorrectly to the side of the seat by S6 based on prior visual experience.

people (N=6), which was especially found in tasks involving slot and MT joints. Take MT task for example. Sighted participants (S2, S3, S7) reported that they gauged the length of the mortises visually and then estimated which tenon can be matched with it; even more subtle length differences of MT can be observed (Figure 5b), as well as the seat piece difference in Finger task to deduce the orientation (Figure 8a). Such features of length difference may seem accessible to BVI people by touch; however, all BVI participants reported that the concave indentations like slots or mortises were less obvious to perceive by touch (Figure 4g) compared to the joint protrusions. B7 reported this issue in SlotMT task: *"When I was about to assemble the two chair leg pieces (Figure 7c), I did not know they had slots."*

Joint distribution was a clue frequently used by sighted users to deduce which pieces to assemble and how to assemble them. Apart from one-to-one mappings, some joints are aligned or distributed systematically in the same piece, which form a unique affordance helpful to be observed visually. For instance, some joints are 'compound joints' where a single joint pair may consist of more than one joint (Figure 4d). This provides more visual matching clues which largely benefited sighted participants in the MT task. S5 commented that *"This piece comprises two parallel mortises on both sides, which inspired me to look for another piece that has two Tenons in parallel."* Aside from joint pairing, joint distribution also provided clues for positioning pieces. For instance, S7 in Slot task reported his interpretation on the joint distribution of the top rail (Figure 6b) *"I found this long piece having two slots only on one side, which mean it is a rear-end piece that only have one connection with another. So I assembled it last."* Also in the MT chair, the two tenons on both sides of the table and chair distinguished their relative positions, as interpreted by S1: *"You can tell these two flat pieces have two raised edges (Tenons) on both sides so that I conclude that both of them are sandwiched by other pieces. (Figure 4c)"*

5.2 Physical Manipulation

Independent of the above factors which affected the logical process of assembly, both global and piece-wise attributes of the laser-cut models also fundamentally influenced the tactile accessibility of physical assembly (**RQ3**). Fitting a joint requires aligning the two parts of a joint accurately, and applying appropriate force according to the joint orientation. Vision appears to be a major cue for confirming whether finer spaces between joint parts have been filled or misaligned, as well as coordinating co-dependent assembly of multiple pieces and joints. Hence, sighted people were generally able to fit single or multiple joints more easily. Below, we describe how the relationships existing laser-cut model and joint structures have with visual/haptic affordances affected the assembly experiences of our sighted and BVI participants.

5.2.1 Inaccessible Global Features of the Laser-Cut Model. This section describes physical manipulation challenges imposed upon BVI users by global features of the model, such as how pieces interlock with each other or the fixed order in which some models must be assembled.

BVI reliance on stability vs. visual mid-air assembly. We define *mid-air assembly* as fitting a joint with both joint pieces not in contact with the desk or working surface. This can be done when assembling a joint or a piece onto a mid-assembled model. From our observation, mid-air assembly was performed exclusively (Figure 3) by sighted people, who would visually-capture subtle changes in the piece's movement and structure of the whole model during assembly, then dynamically adjust their manipulation to fit the joint stably, such as assembly angle or application of force. They were also observed to infer the joining correctness by placing the pieces in mid-air (Figure 9e). For example, sighted users used the mid-air comparison strategy to determine the orientation of chair back in the Finger task, while two BVI participants (B2,B4) who finished assembling the Finger model with the trapezoid back assembled

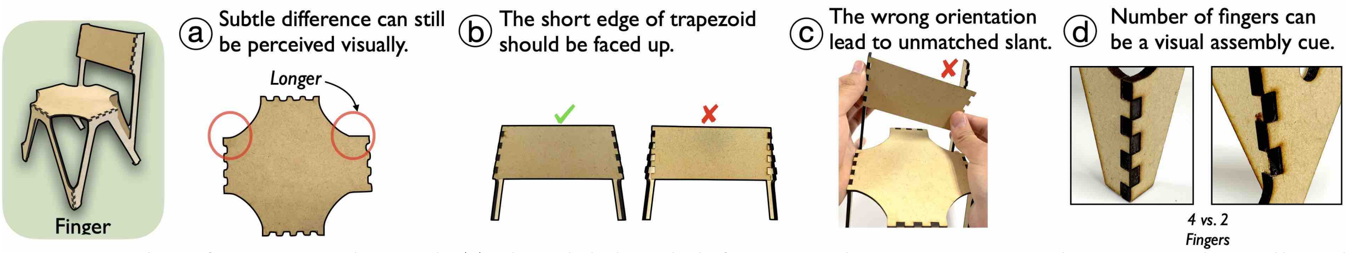

Figure 8: Findings from Finger chair task. (a) The subtle length difference in the seat contour can be recognized visually and used to deduce orientation. (b) The trapezoid piece should be assembled with a short edge facing up, which was not perceived, and then assembled wrong by some BVI participants (B2, B4). In contrast, (c) the incorrect orientation of the trapezoid piece can be salient to observe visually through the unmatched slant pair. (d) Number of fingers was used as a visual assembly cue for joint pairing.

upside-down (Figure 8b), believing the piece was correctly mounted. S7 stated, *"I was not aware of the trapezoid (two slanted sides), but after comparing it to my assembled model, I found the orientation by matching the slant(Figure 8c)."* Mid-air comparison and assembly provided an advantage to sighted users that was not accessible to BVI as a result of the differences in visual and haptic modality.

In comparison, stabilization of the model was a major task for BVI participants, who relied heavily on the desk surface to achieve this. Constant consideration of stability during assembly generated a multitasking burden and restricted BVI users' ability to use their hands for other assembling tasks. BVI participants (N=6) frequently experienced the accidental collapse of partially-assembled models when haptically exploring or adding pieces onto them, and spent a large portion of time stabilizing their own assembly (Figure 3). Stability was thus perceived as a priority for BVI participants, as reflected in (Figure 3) showing that BVI people spent more time stabilizing the assembled model than sighted people. B1 reported this general difficulty: *"When assembling, I need to ensure stabilization of the model with one hand, and assemble with the remaining hand. It's very hard for me to do such multitasking."* An example of this issue can be found in the Finger task, where the seat, N-shape, and U-shape piece were interconnected (Figure 9d). The first two pieces were easier to assemble; but when assembling the third, the just-completed joint would detach easily if force was not properly applied in multiple places at the same time to keep the three joints in place, as B3 explained: *"It seems like I need to assemble three of them at once because the completed joint kept slipping away when I assembled the other one"*. This may also explain why BVI people took much more time on stabilizing model in Finger task (15.6% in Figure 3). The stability issue was also featured in Chang et al. [13].

Difficulties in applying fixed-order assembly. Laser-cut pieces can be designed in a restricted assembling order for the sake of interlocking or stabilizing the entire model without additional equipment. In our study, the MT chair has a similar feature in which smooth assembly can be achieved only when the seat is assembled before a side wall. S2 described the process of discovering this: *"The difficult part was assembling the seat pieces, as I tried a few different orders but all failed. It seems to have an fixed order."* Order is also not obvious to BVI people who cannot infer the order from global assessment before beginning assembly. BVI participants (N=3) were aware of this, as one of them said *"It is hard to assemble the chair seat since you need to decide which one comes first. I did it wrong because I assembled the outer frame first instead of the seat which should be assembled first."* The difficulty in observing order was shared across sighted and BVI people, but may pose much more physical effort for BVI people in disassembling and reassembling, which may lead to the collapse of model as in the above-mentioned struggle with stability.

5.2.2 Haptic Accessibility of Individual Laser-Cut Joints. Inherent haptic properties of laser-cut pieces also imposed several challenges for physical manipulation, such as the required precision of the joining angle, and irregular haptic feedback during assembly caused by tightly-fitting parts confusing BVI participants.

Required precision of joint assembly angle. Due to the perpendicular formation of a laser-cut joint, the joint must be assembled at a very precise angle to ensure fitting. Take an MT joint in the FingerMT task, for example. The ideal case is to find the mortise and insert the tenon vertically into it at a precise 90° angle, which is more easily achieved with vision. Without vision, there are more barriers to joint assembly. The first is difficulty in locating the small mortises (Figure 9a). Second, it is also hard to adopt such a precise joining angle and maintain it during the entirety of the insertion period without visual feedback. More specifically, this difficulty was observed in the form of the joint often being joined at a diagonal angle by BVI participants, which would jam the tenon in the inside wall of mortise and prevent full assembly of the joint (Figure 9b). B7 described this problem: *"You need to manipulate [the joint] very precisely, including aligning the position and adjusting to a good angle. It is so easy to fail if you cannot achieve both of them at the same time."* Alignment and application of directional force were also required for finger joints, which were also difficult for BVI people to manipulate. B1 stated, *"I think the finger joints can be first complemented with each other in 180° on the table. In this case (when fitting the joint in FingerMT in Figure 9c), it's hard for me to align the fingers together properly."* Observed from the post-video analysis, multiple BVI participants (N=3) exhibited the tendency to first match fingers in parallel on a surface in similar fashion to how one might for puzzle pieces, then bend them into a perpendicular corner to form the joint (Figure 9c).

Irregular haptic feedback during joint assembly. The lack of accessible feedback on joint completeness was frequently remarked on by BVI participants, especially for slot and MT joints; this was also a prominent result in Chang et al. [13]. Here we provide more detailed insight on what contributed to this inaccessibility. The

Figure 9: Assembly manipulation. (a) Small mortises are hard to find and locate by touch. (b) A diagonal joining angle can cause the tenon to jam the inside wall of the mortise and the outside surface. This small angle was hard to adjust without vision. (c) BVI people assembled finger joints by matching two pieces on a surface, then bending the joint to form 90° angle. (d) When assembling the second joint in a multi-piece component, just-completed joints was prone to detachment. (e) Sighted people deduce the feasibility of joining pieces through mid-air comparison without having to actually attempt the assembly.

motion of joining pieces during joint insertion was often unsmooth due to the friction-prone material and surface edge of the laser-cut piece, as well as the design for a tight fit. This raised doubts on the correctness of assembly for BVI users, such as when a joint part sometimes became momentarily stuck or displayed uneven movement during the insertion motion, which without visual cues could be interpreted as having a variety of possible causes. B7 in Slot task recalled, *"I started doubting if I was doing it wrong when the joint got stuck halfway. I was not sure if it was due to the wrong piece pairing or just the wrong inserting angle."* B6 also commented in the post-interview, *"Even though I knew this is the right pair, I would take longer time assembling if the angle slightly deviates, and the uneven feedback caused me to doubt whether I'm doing it correctly."* The limitations of the laser-cut piece design, fit, and material made the fundamental process of joining pieces difficult for BVI users in a way that went unnoticed by sighted users.

6 DISCUSSION

We first summarize our findings and contributions in response to our RQs and prior work, then propose design implications for laser-cut models and generalizability to other domains of physical artifact creation.

6.1 Sighted and BVI Usage of Laser-Cut Models

In response to our first two research questions **RQ1 & RQ2**, the presented findings identified both common and unique strategies and struggles across sighted and BVI participants during their assembly of laser-cut models. We saw that both sighted and BVI users would align edges of pieces as a clue to assemble laser-cut pieces (section 5.1.1), but only sighted users were able to access clues at the level of joints (section 5.1.2), due to the small size and tactile inaccessibility of most joints. In answering **RQ3**, we found that BVI users were able to access most edge-based tactile clues because of their larger and more distinguishable scope, compared to joint patterns which were more visually-observable but not accessible by touch. Commonly-used strategies included patterns in individual edge shape (e.g., symmetry and shape uniqueness), as well as aligning edges of interlocking pieces.

The consistency of sighted and BVI participants in their usage of symmetry patterns and commonly-perceived spatial features of the laser-cut pieces corroborates prior work showing that spatial recognition in the visual and haptic systems is similar [45, 60]. BVIs' lack of using joint-related cues, as well as difficulties in physically manipulating the assembled pieces (section 5.2) also reflect known challenges in BVI recognition and handling of small objects, compared to the ability of visual sweeps which can instantaneously process a wide scope of spatial information [10, 48].

An interesting contribution of our study is the finding that the uniqueness of piece shapes was an important design feature which provided haptic cues to make BVI assembly significantly easier – but made sensemaking slightly harder for sighted users, who relied heavily on visually-informed semantic inference during assembly (section 5.1.1). Our study also demonstrated that sighted and BVI users shared a surprising amount of similar struggles in their usage (assembly) of laser-cut models, in addition to the similarity in strategies described above. For example, both sighted and BVI users struggled in assembling fixed-order parts of the model (section 5.2.1). BVI and sighted users were also both confused by similar piece shapes (section 5.1.1), which gave the appearance of being related or equivalent without actually being so. These are opportunities for design changes which can benefit both user groups.

Our results build on the findings of broader prior work comparing spatial manipulation in BVI and sighted individuals, while providing specific design implications for laser-cut pieces and models. Some of our findings also inform principles which are more widely applicable to the overall design of physical artifacts.

6.2 Implications for Laser-Cut Model Design

We discuss design implications for more accessible laser-cut model design in the future and in the process, build on concepts from prior research that may assist with addressing these design issues. Some of the design implications in this section can appear more specific or imaginative than generalized design guidelines. However, many of our findings were relatively fine-grained (e.g., perception of laser-cut joints, friction-induced difficulties in manipulation, etc.) and directly informed the implications presented here. These recommendations pend validation, and we hope that future designers can continue the process of elucidating the best ways to design inclusive laser-cut models.

6.2.1 Joint haptic accessibility. In our study, we observed that the dominance of vision allowed more diversified strategies for sighted people while using only the sense of touch hindered BVI people from successful assembly due to several nuanced problems.

The similar strategies we observed in BVI and sighted users (section 5.1.1), such as perceiving edge corner, joint length, and shape patterns, can be less effective for BVI people when applied to joints due to the lower haptic sensory resolution compared to vision. As described in section 5.1.1, BVI users benefited from the distinct

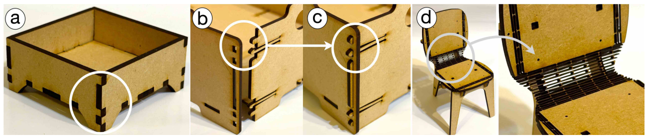

Figure 10: Implementations of potentially accessible joint designs. (a) Fingers with distinct widths (Modified from thing:2250238). (b) SpringFit [71] joints allow more manipulation room to snap-fit the joint (c) and generate a haptic click once connected (thing:333047). (d) Living hinges can bend to form a corner without effortful assembly (Link to model).

shape patterns in the MT task, while the many similar pieces could be confusing. Also, in section 5.1.2, the visually-distinct features, such as length nuances or concave indentations, are conversely inaccessible by touch. We thus suggest that future designs of individual laser-cut joints make the shape more haptically-distinct. For instance, the size of a joint could be made as large as possible to be perceived by touch. BVI users benefited from unique shapes – the patterns of a joint can have more distinctive shapes, such as creating fingers with different instead of uniform widths in a finger joint or tactile engraving patterns (e.g., zigzags or waves) on the joint edges to make them more distinguishable from the rest of the piece (Figure 10a). Another perspective to promote BVI accessibility within designers is to reduce characteristics that rely on the use of visual affordances (section 5.1.2), such as the use of compound joints that require global visual awareness, or the use of the joints with concave shapes, such as slot joints and mortises, which may not be noticeable by touch for BVI people. Solutions external to the model design, such as tactile or audio instructions, should be designed and attached if the above-mentioned visual affordances are necessary for the particular model.

Also, according to section 5.2.2, another reason the haptic properties of individual joints are not accessible to BVI people is due to the required precision of joining angle and the friction-induced irregular haptic feedback when joining two pieces. A joint design proposed by SpringFit [71] could be a potential solution as its proposed "cantilever-based" mounts and joints could lower the friction when joining two pieces, and allow room to accommodate slight deviation joining angle (Figure 10b). Another advantage of "cantilever-based" joints is the easily-distinguished haptic feedback provided by the spring tip locking in place when a joint is completed (Figure 10c), which could serve as confirmation feedback for joint completion. Aside from modifying the joint design, another solution could be to "avoid joints". This can be done by reducing the inherent number of joints in the design, or adopting a design that does not need joints. For instance, the design of living hinges (Figure 10d), a cutting method that makes parts of a laser-cut piece flexible using a lattice-based cutting pattern, is a promising way to form 3D polyhedron models without joints. T-pattern joints proposed by Fang et al. [21] could also be another potential option, as the joints are cut-in-place and require no effort to determine piece connection for assembly. However, more work is needed to understand how BVI users could manipulate these novel forms of joints. Model designers can trade off carefully between the essential joints, the usage of living hinges, and the intended functionalities of laser-cut models to minimize the portion of required assemblies.

6.2.2 Shape design across multiple pieces. In light of section 5.1.1, both sighted and BVI people were able to recognize and strategize assembly for symmetrical pieces. However, sighted people displayed a preference for similarity-based strategies, while BVI people largely benefited from the piece uniqueness. In this regard, we encourage the laser-cut models to be designed leaning toward unique pieces for promoting BVI accessibility. Though this may cause minor confusion for sighted people due to their gravitation toward semantic cues or visual memory, we believe their overall visual ability can still help them to comprehend and respond using global and several nuanced assembly cues. For example, sighted users in our study were still able to assemble the MT model (with many unique pieces) in a relatively fast time despite rating it as more difficult. Considering the context of practical use, pieces can also be classified and pre-arranged into three categories: symmetrical, unique and similar pieces. This may benefit both groups to plan their assembly early on, as both groups exhibited these three categorizing behaviors in our study.

6.2.3 Accessible understanding of fixed order assembly. Drawing from section 5.2.1, the difficulty in observing global fixed-order was imposed on both sighted and BVI people, and required several bouts of trial and error, which can be a particularly heavy penalty for BVI people due to the barriers in physical manipulation (section 5.2). We suggest that pieces requiring fixed order should be specially conveyed earlier in the assembly stage to fit into both user groups' assembly plans. Integration of this into the laser-cut model itself can possibly be achieved by making the joints meant to be assembled first haptically- and visually-salient, such as longer joint lengths or distinct shapes, to clearly indicate their higher priority. There are also options for solutions external to the model considering the end-user context. Fixed-order pieces can be nested in the same vicinity as in Roadkill [1], and presented to the user earlier when being unboxed. Or like what was done in Daedalus [13], a new heuristic for fixed order is defined that asks users to assemble starting from the closest pieces to those that are further.

On the other hand, post-hoc measures should also be adopted for mid-assembled wrongly-ordered models in order to minimize the cost of disassembling and reassembling. This might involve interventions both internal and external to the joint, such as designing removable joints or enabling other methods (e.g., adhesive or bolt) to connect the piece if the intended joint was blocked or unable to join due to the fixed order. Designers in the future should evaluate the necessity of fixed order or interlocking mechanisms and provide remedies for wrongly-assembled models rather than forcing the user to restart.

6.3 General Concepts for Accessibility in Physical Artifacts

Some of our findings point to more general principles which can be applied to make the design of physical artifacts outside of laser-cutting also more accessible to both BVI and sighted users. This applies to the design of other objects within the DIY space (e.g., 3D printing or paper craft), as well as those outside of it, such as commercially-designed products. These principles mainly revolve around high-level assumptions common to sighted users, which must be defamiliarized to promote accessibility.

Our findings demonstrated that sighted users tended to heavily use semantic concepts which were not physically-encoded in the material in order to make sense of the novel artifact(s) in front of them; in this case, the laser-cut pieces. They used vision to assess the chair pieces globally and guess which elements were which parts of a chair before touching anything. This situation can also be analogized to other interfaces or artifacts which are new to a user the first time. When designing artifacts for both BVI and sighted users, making sure that key features of the artifact do not rely on global assessments which have a scope larger than what can be perceived with a hand or covered by a set of fingers can ensure that the scope of information assumed to be perceived by the user is common across both user groups.

Similarly, when designing physical artifacts, one should not assume that the user has knowledge of the spatial relationships between any elements which are not physically connected. In our findings, sighted participants utilized joint distribution across all pieces as a significant clue for assembly, but this clue was inaccessible to BVI users in part due to the disconnectedness and wide spread of the joints across all pieces. This provided a clear example of how design for sighted individuals builds on the ability to observe physically-encoded spatial patterns that are, yet, physically-disconnected. To make physical interfaces accessible to BVI users, physical connection must be manifested through a link that can be perceivable by touch. Auditory cues are supplementary to touch in this context, which provides more grounded contiguous information for physically-oriented interaction.

6.4 Limitations and Future Work

The sample of BVI participants we accessed may not have had even representation of prior visual experience and education level; for instance, B2 and B4, who displayed relatively better performances for the tasks, reported that they could form a graphical representation in their brain when tasking due to their prior visual experiences. Also, many of our BVI participants possessed higher education degrees due to a national policy where the study was conducted. Though we did not intend to recruit people with specific backgrounds, it is worth exploring how differences in education and their corresponding training could lead to certain motor skill acquisitions. Additionally, the results of our study may appear to reveal more overall information about visually-based strategies of sighted users despite our goal to compare BVI and sighted sensemaking of laser-cut models. Though we would like to observe more about the specific assembly strategies of BVI users, this is not unusual because laser-cut models have traditionally been designed for the use of sighted and not BVI individuals. Sighted users possess higher sensory resolution for observing assembly details than tactile-only, providing more information to work with. Hence, it is important to research how to transform these visually-oriented laser-cut model characteristics into more accessible non-visual counterparts (e.g., tactile or audio cues) to promote overall accessibility.

Considering our goal to understand the design characteristics of laser-cut models that influence BVI and sighted users, the current study's focus on the assembly phase covers a fundamental but limited part of laser-cut model design. To fully support non-visual needs in this domain, whether the final assembled model itself fulfills the needs of BVI users needs to be explored in future work. In the process of completing the current work, we have also learned that using a qualitative coding process to develop customized labels for analyzing detailed behavior can be extremely useful in studying unique experiences, particularly in cases where the behavior of interest may be difficult to measure using other means (e.g., self-report, interviews, or pre-defined quantitative measures). In our case, this took the form of hand manipulation strategies and habits that participants may not have even noticed they were doing. Future researchers interested in studying assembly-based experiences are welcome to engage in reuse and validation of our codebook for contexts outside of laser-cut assembly. We also encourage use of the open coding method cited in this work to develop labels that meet the needs of more specific research contexts.

7 CONCLUSION

In this paper, we presented a mixed-methods study with seven sighted and seven BVI individuals who completed assembly of five laser-cut models. We retrieved the detailed data of BVI participants from the formative work in Chang et al. [13] to compare with sighted people on the same assembly task procedures. By analyzing completion accuracy, qualitative feedback, and labeled activities in video footage, we found strategies and struggles both shared by and unique to either BVI or sighted groups. For example, BVI and sighted shared similar cognitive strategies, such as the alignment of connected pieces and piece shape patterns (e.g., symmetry, uniqueness), but sighted users were more easily fazed by pieces that could not be clearly identified as part of a known object, and BVI users struggled significantly more with identifying spatially-distributed piece features and physical manipulation of the pieces themselves. Based on our findings, we proposed design implications for non-visual accessible laser-cut design and general principles for accessible physical artifact design.

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A SUPPLEMENTARY FIGURES AND TABLES

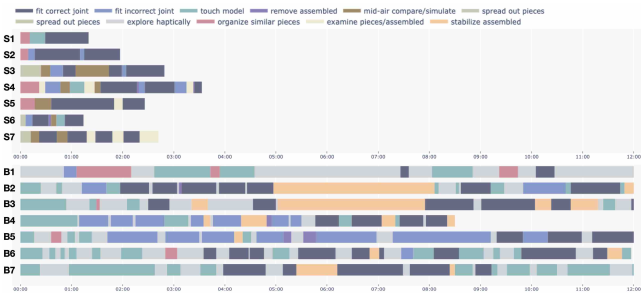

Figure 11: Labeled time series data of Finger task of sighted (top) and BVI (bottom) participants.

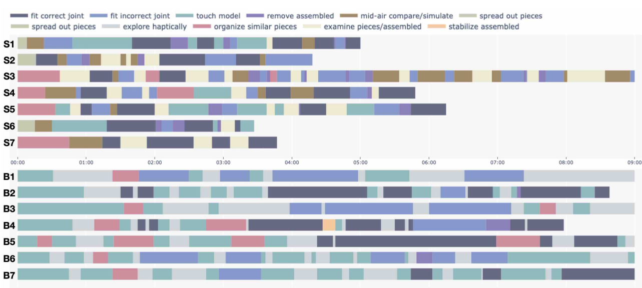

Figure 12: Labeled time series data of Slot task of sighted (top) and BVI (bottom) participants.

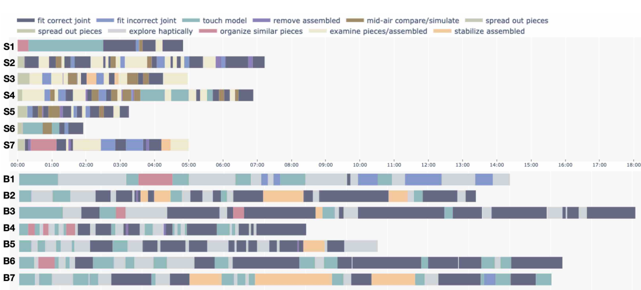

Figure 13: Labeled time series data of MT task of sighted (top) and BVI (bottom) participants.

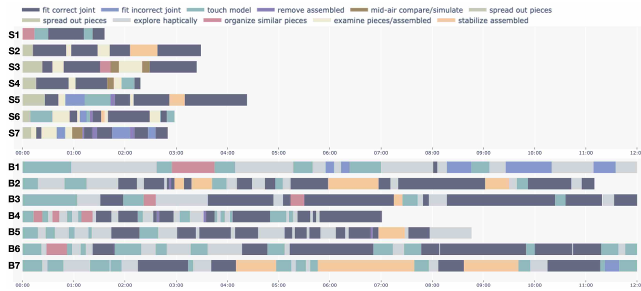

Figure 14: Labeled time series data of FingerMT task of sighted (top) and BVI (bottom) participants.

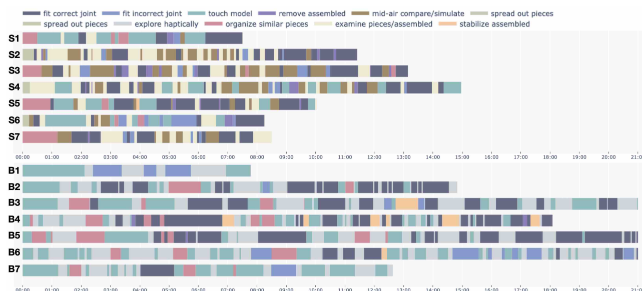

Figure 15: Labeled time series data of SlotMT task of sighted (top) and BVI (bottom) participants.

Table 1: Participant Demographic Information.

ID	Age	Gender	Vision Level	Education	Major	Experience in Crafting/Assembling
B1	31	Male	Born blind	Undergraduate	Psychology	LEGO, Rubik Cube, Computer, Fan
B2	31	Male	Born with light perception only, lost at age 21	Master	Law	LEGO, 3D puzzle, IKEA shelf
B3	18	Female	Born blind	High School	None	Toy revolver and music box in the class
B4	32	Female	Left: born blind, Right: light perception only	Undergraduate	Japanese	IKEA bedframe and shelf
B5	17	Male	Born blind	High School	None	LEGO and origami
B6	48	Male	Born blind	Undergraduate	History	LEGO, faucet, shelf and fan
B7	33	Male	Born blind	Undergraduate	Early Childhood Education	None
S1	30	Female	Full Vision Sensory	Doctoral	Computer Science	Life experiences occurred naturally such as assembling furniture, DIY class at school, etc
S2	22	Female		Undergraduate	Foreign Languages	
S3	27	Female		Master	Anatomy	
S4	26	Male		Undergraduate	Electrical Engineering	
S5	23	Male		Undergraduate	Information Management	
S6	22	Male		Undergraduate	Design and Electrical Engineering	
S7	23	Male		Undergraduate	Computer Science	

Table 2: Completion time (in seconds) of 5 sighted people used for determining time threshold for the study.

Participant ID	Finger	Slot	MT	FingerMT	SlotMT
1	531	253	250	208	897
2	113	207	636	331	232
3	151	189	148	249	457
4	224	115	421	134	322
5	190	90	234	213	220

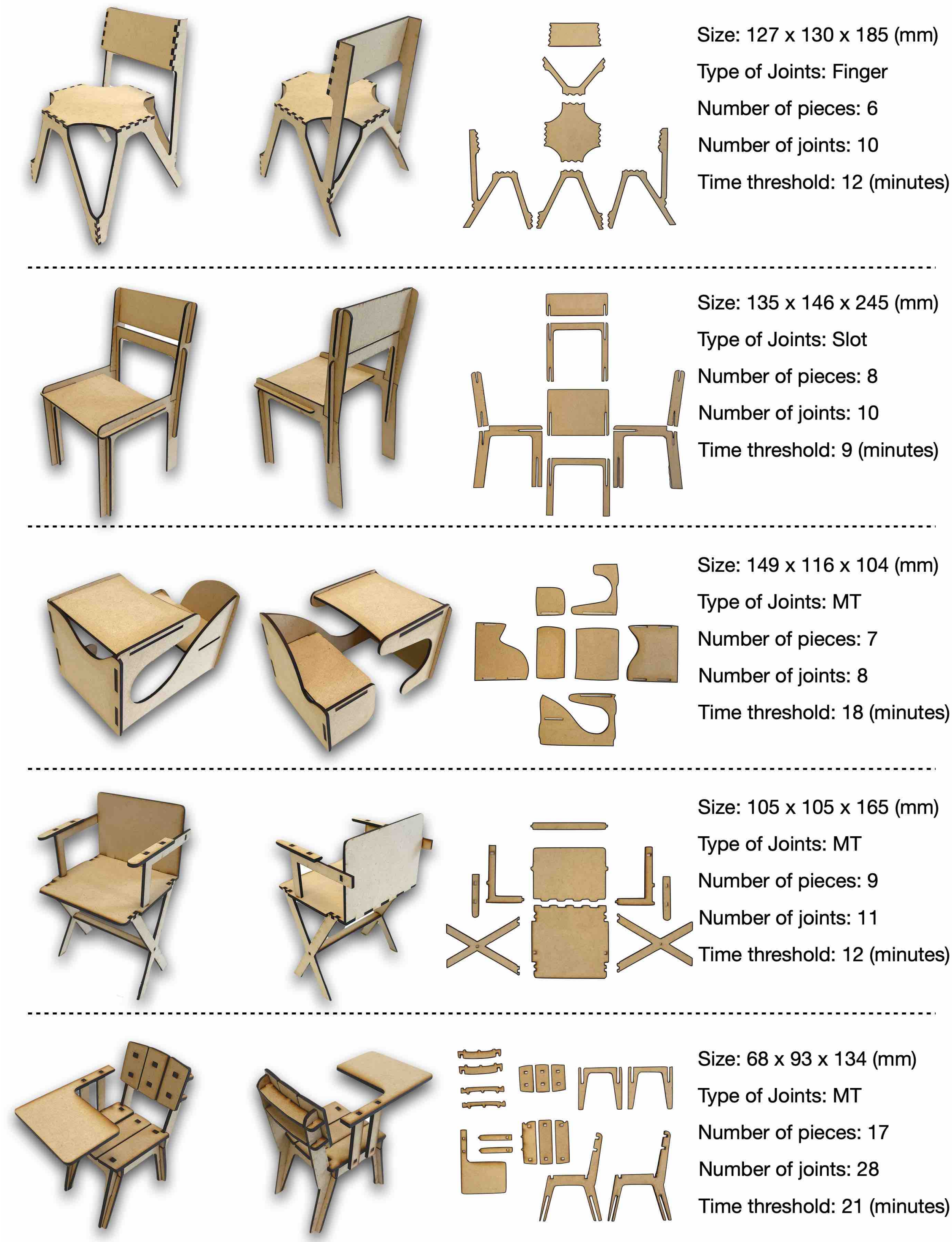

Figure 16: Details of each chair used as our representative laser-cut architecture examples. In a top-down order, the chairs were named based on the types of joint:, Finger, Slot, MT, FingerMT and SlotMT in this paper.