Daedalus in the Dark: Designing for Non-Visual Accessible Construction of Laser-Cut Architecture

Ruei-Che Chang
National Taiwan University
rueichechang@gmail.com

Chih-An Tsao
National Taiwan University
hl6540@gmail.com

Fang-Ying Liao
National Taiwan University
fyjh21317@gmail.com

Seraphina Yong
National Taiwan University
seraphinayong@ntu.edu.tw

Tom Yeh
University of Colorado
tom.yeh@colorado.edu

Bing-Yu Chen
National Taiwan University
robin@ntu.edu.tw

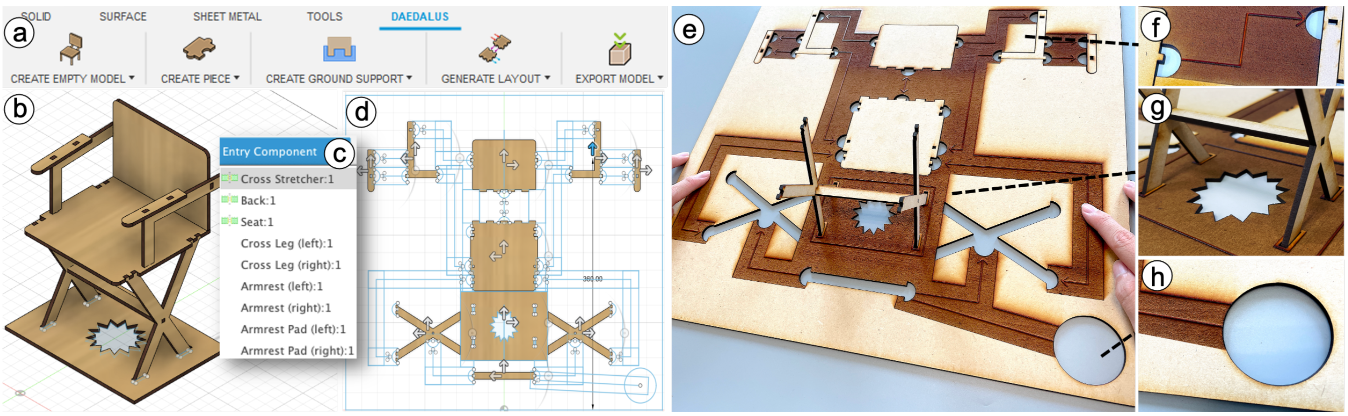

Figure 1: *Daedalus*: generator of BLV-friendly tactile aids for laser-cut assembly. (a) *Daedalus* software interface elements. (b) The user builds a laser-cut model via built-in function *Joint Assembly* in Fusion 360. (c) Upon receiving the input of joints, *Daedalus* can provide entry component candidates to generate BLV-accessible layout (d). (e) A BLV user assembles a laser-cut chair (bottom-left) using a *Daedalus*-produced layout, in which: (f) Tactile arrows guide joint connections; (g) Slots act as stabilizers; (h) A hollowed circle linked to a component marks the assembly entry point.

ABSTRACT

Design tools and research regarding laser-cut architectures have been widely explored in the past decade. However, such discussion has mostly revolved around technical and structural design questions instead of another essential element of laser-cut models — *assembly* — a process that relies heavily on components' visual affordance, therefore less accessible to blind or low vision (BLV) people. To narrow the gap in this area, we co-designed with 7 BLV people to examine their assembly experience with different laser-cut architectures. From their feedback, we proposed several design heuristics and guidelines for *Daedalus*, a generative design tool that can produce tactile aids for laser-cut assembly given a few high-level manual inputs. We validate the proposed aids in a user study with 8 new BLV participants. Our results revealed that BLV users can manage laser-cut assembly more efficiently with *Daedalus*. Going forth from this design iteration, we discuss implications for future research on accessible laser-cut assembly.

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CCS CONCEPTS

• **Human-centered computing → Accessibility systems and tools**.

KEYWORDS

Fabrication; Prototyping; Laser Cutting; Accessibility; Assistive Technology; User-centered Design; Assembly

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1 INTRODUCTION

Among fabrication methods, laser-cutting is faster (compared to 3D printing) and produces sturdier objects (compared to paper-prototyping). Constructing an object using laser-cutting typically involves two stages: designing individual pieces and assembling these pieces into a complete object. Past research primarily addressed the first stage — design. Design tools were proposed for tasks ranging from facilitating efficient conversion to 2D plates from drawn models [22, 45, 46, 52, 55], promoting the complexity of laser-cut object functionality [29, 30], to strengthening objects' structural integrity [1, 4, 42, 44]. However, these design tools seldom address the second stage — assembly. The lack of research on tools to support the assembly process may stem from the assumption that users have normal sight which allows them to see individual pieces as well as how these pieces are put together. However, for users who are blind or low-vision (BLV), such assumption is false. The over-reliance on visual perception and representation renders the assembly process inaccessible to them. Therefore, there is a need for research on a new tool to support BLV people to make sense of individual laser-cut components during assembly [3].

Accessibility of DIY prototypes is important for BLV empowerment, as it allows them more control over their needs for unique assistive technologies [34]. Making laser-cut architecture assembly more accessible to BLV people can also not only allow them to access the convenience of laser-cut objects, but also facilitate dexterity and spatial skill training. For instance, non-visual acquisition of spatial skills can benefit from sensory feedback of motor signals, which can take the form of manual familiarization with object components and whole-structure relationship by construction iterations [21]. Additionally, methodical construction iteration of 2D-to-3D object models is also used by visual impairment specialists in the teaching of mathematical concepts [11]. Hence, making laser-cut assembly accessible to BLV users can facilitate their well-being on multiple dimensions.

To make the first attempt on developing accessible aids for laser-cut construction, we took a user-centered design approach. We first performed a formative study with 7 BLV individuals to investigate how they experience the current format of laser-cut DIY objects during the assembly process, and through a co-design process identified certain accessibility design features. Our results suggested that in order to facilitate the assembly process, BLV people required informational hints about entry components, stabilization, joint pairing, joining directions, symmetry and assembly order by spatial placements, etc. We co-designed several tactile and spatial representations of the hints (Figure 1 abcd), categorized by several heuristics and guidelines, while considering information moderation and model aesthetics.

Inspired by these findings, we implemented *Daedalus*, an add-in compatible with a commonly-used design system (Autodesk Fusion 360[1]), which automatically generates tactile cues to better guide the laser-cut assembly process for BLV people. After basic initiation (e.g., import and extrude sketch, assemble joints), the designer chooses whether to add the support area (Figure 1 g, 6). Based the proposed heuristic 3.5 and guidelines 3.6, *Daedalus* then recommends potential entry components to the designer (Figure 1 c), and finally generates an auto-arranged spatial layout with tactile aids that is printable by a laser cutter. Via a follow-up evaluation with BLV users (n=8), we demonstrated that the generated tactile aids could significantly address the accessibility barriers for laser-cut assembly. We end by discussing more design implications and future work.

The main contributions of this work are: (1) A formative study with 7 BLV participants identifying accessibility barriers and design heuristics that address them. (2) *Daedalus*, a design add-in compatible to a commercial design system while considering proposed design heuristics. (3) An evaluation with 8 BLV participants showing the effectiveness of proposed tactile aids and revealing design implications for future research.

[1]https://www.autodesk.com/products/fusion-360/overview?term=1-YEAR

2 RELATED WORK

The creation of *Daedalus* was inspired by the shift in maker movements towards accessible fabrication, and the high expressivity of laser-cutting machines which has not yet been harnessed to benefit the BLV population.

2.1 Accessible Fabrication and the Maker Movement

The rise of maker culture has promoted affordable and accessible prototyping tools (e.g., 3D printer, laser cutter, etc) [7, 50] as well as online platforms for sharing knowledge about design and fabrication (Instructable[2], Thingiverse[3], Pinterest[4], etc.) [9], which offer opportunities for end-users to recreate, augment and customize existing or new appliances on their own [15, 16, 24, 25, 41, 51]. This movement has also made Do-It-Yourself Assistive Technology (DIY-AT) more accessible to BLV people, extending the power of non-expert individuals with disabilities to create devices that meet their own needs, in contrast to ready-made AT which poorly accommodates high variability in disabilities' manifestation [24, 25, 34]. Accessible tools and techniques are needed to increase the involvement of BLV users, who know best what they need [5]. Observations of maker spaces and workshops revealed that users with disabilities want to make in order to fulfill their own needs, help others, and gain recognition for their ability; they also revealed that DIY-AT promotes greater adaptation and adoption of AT [37, 40]. Below, we detail research in this area that has focused on both creating specific fabricated tools for BLV, as well as tools that enable BLV to do the designing and creation themselves.

2.1.1 Fabricating assistive tools for BLV. Providing non-visual access to everyday interfaces that may be digital or intangible is essential for BLV individuals. Multiple fabrication-based solutions have been explored. For instance, fabricated tactilizations of visual information include not only data-oriented visualizations that improve data sensemaking and design education [8, 36] by creating geometric coordinates or graphic design layouts, but also more creative content such as imagery in children's books that convey dynamic spatial concepts in story imagery to promote interactive reading experience for children [28]. Fabricated objects can also more actively facilitate direct interaction with computing devices. For instance, TangibleCircuits [17] and Interactiles [54] render 3D-printed models to improve BLV interactions with capacitive touchscreens. Facade [23] also uses 3D-printing to create tactile

[2]https://www.instructables.com/
[3]https://www.thingiverse.com/
[4]https://www.pinterest.com/

buttons that make flat interface panels more accessible. Touchplates [26] uses a flexible method of integrating tactile feedback onto flat surfaces that can be laser-cut, 3D-printed, or made by hand.

2.1.2 Design tools to facilitate BLV making. To address the need for BLV user involvement in the fabrication of their own tools, recent works have made the effort to empower BLV people in the making and designing process. TangibleCircuits made online circuit tutorials accessible to BLV people by parsing digital circuit diagrams into 2.5D tactile ones. ShapeCAD [49] addressed usually-visual 3D-modeling by creating an interface for BLV users with 2.5D shape display interaction. Molder [48], supported design of tactile aids by adding multimodal audio and high-contrast visual feedback for BLV designers. Flat, tactile templates have also supported BLV editing of spatial screen layouts [32].

As seen above, most of the BLV-oriented fabrication technologies we have seen support 3D-printing with the exception of flat (tactile-oriented) fabricated objects, which can use laser-cutting or 3D-printing. However, laser-cutting is still often used to prototype more complex 3D objects that require assembly. Below, we review the state of laser-cutting fabrication in HCI and the opportunities it creates for improving accessibility.

2.2 Technology for Usable Laser-cutting

Laser-cutters are a rapid prototyping tool that has become increasingly more low-cost and miniaturized. It is also ideal for making tactile text and graphics [27, 32, 36], labeling Braille [20], or aiding everyday tasks, such as typing [26].

However, our survey below shows that laser cutting, despite its high versatility, has received less attention from the accessibility perspective, compared to 3D printing. Laser-cutting is recognized as an important method for fast design iteration, which is needed in most cases of creating more complex fabricated objects [6].

Current tools for laser-cutting focus on the structure and function of the assembled laser-cut object, as well as facilitating laser-cut design for novice users. Various algorithms and design interfaces focus on simplifying the conversion of 3D models or drawings into planar-assembly format [4, 22, 35, 45, 46]. Other systems work to enhance the functionality of laser-cut architecture. Platener [6] combines laser-cutting with 3D-printed fine parts to expedite low-fidelity prototyping, LamiFold [29] embeds advanced rotary, linear, and chained mechanisms in the plate design for more mechanically-functional laser-cut objects, and Bend-a-rule [53] designs bendable laser-cut parts for 3D contouring. Others automatically generate suitable joint combinations for laser-cut assembly [44, 55].

2.3 Object Manipulation in the BLV Population

A significant difference between laser-cut and 3D-printed objects, is the requirement of planar assembly. BLV people's processing of haptic object input in the absence of a global visual representation creates a need for designing laser-cuts that better facilitate sense-making of pieces during component assembly [3]. Blindness leads to compensated mental imagery representation and haptic recognition skills, which are important for the spatial problem solving required during object assembly [18, 19].

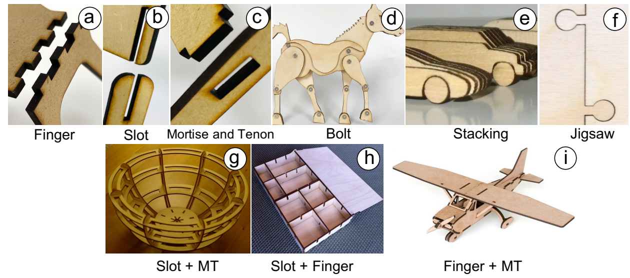


Figure 2: Joint categories sampled from the 600+ latest examples on Thingiverse. (a,b,c) Parts of selected chairs in our study. (d) Thing:3511749. (e) Thing:23586. (f) Thing:26277. (g) Thing:38766. (h) Thing:77657. (i) Thing:361789.

Accordingly, facilitating the activity of laser-cut assembly for BLV users not only extends their ability to fabricate, but also contributes to education and spatial training for daily life skills. Deconstructable haptic models are used to teach algorithmic thinking for BLV students [11], and tactile/haptic familiarization with changing model configurations is used to train and improve BLV individuals' peripersonal spatial skills [13, 31].

3 FORMATIVE STUDY: CO-DESIGN ACCESSIBLE LASER-CUT CONSTRUCTION

In order to identify accessibility barriers and design heuristics (first contribution), we conducted a formative study, taking a participatory design approach by positioning BLV people as co-designers. Since most participants were unfamiliar with laser-cut structures, prior to the co-design session, they received five chair/table laser-cut models to practice. They were instructed to assemble the models independently to the best of their ability. In the co-design session, participants and researchers discussed the encountered barriers and the potential ways to address them. More details about the formative study and findings are presented next.

3.1 Determining Target Laser-cut Joints and Models

To ensure that our study introduced BLV people to a comprehensive sample of current laser-cut architectures, we reviewed and labeled over 600 most recent projects tagged with "lasercut" on Thingiverse. We labeled each model's joint types, and the categorization of joint types was determined by referral to prior research [55] and online sources[5]. We also noted that a single model may involve multiple joint types, and our categorization accounted for common joint type combinations.

Our review in Figure 2 revealed that slot (37.7%), finger (33.7%) and Mortise and Tenon (MT, 43.7%) joints were the most significantly-occurring joints compared to bolt (13.6%), stacking (12.9%), and jigsaw (2.6%). We also found that some of them did not appear independently but in combination with other joints (37.38%). Upon examining pairwise combinations of these three most commonly-used joints, 58.3% were finger and MT joints, 33.5% were slot and

[5]https://www.instructables.com/Laser-Cutting-Basics/

Table 1: Participants demographic information in study1.

ID	Age	Gender	Vision Level	Education	Major	Experience in Crafting/Assembling
P1	31	Male	Born blind	Undergraduate	Psychology	LEGO, Rubik Cube, Computer, Fan
P2	31	Male	Born with light perception only, lost at age 21	Master	Law	LEGO, 3D puzzle, IKEA shelf
P3	18	Female	Born blind	High School	None	Toy revolver and music box in the class
P4	32	Female	Left: born blind, Right: light perception only	Undergraduate	Japanese	IKEA bedframe and shelf
P5	17	Male	Born blind	High School	None	LEGO and origami
P6	48	Male	Born blind	Undergraduate	History	LEGO, faucet, shelf and fan
P7	33	Male	Born blind	Undergraduate	Early Childhood Education	None

MT joints and the remaining 8.2% were finger and slot joints. We found that slot and finger joints frequently form the model exterior, with MT joints supporting internal structure. Hence, slot and finger joint combinations were rare.

In accordance with the above results, we decided to introduce finger[6], slot[7] and MT joints[8], and the combinations of finger+MT[9] and slot+MT[10] joints, respectively to our participants as key example models of laser-cut architecture. We chose chair/table models for each joint set as a frequently encountered daily object (Table 2). In the study, we scaled models' original sizes to be printable with respect to standard-thickness wood plates (3mm).

3.2 Participants

Seven participants (5 M and 2 F), aged from 17 to 48 (median: 31), were recruited through public recruitment posts on social media. 5 are congenitally blind while 2 are adventitiously blind (Table 1). All had some prior experience in assembling everyday objects, but none in assembling laser-cut architectures. All possessed and used both functioning hands during the study.

3.3 Apparatus, Procedure and Analysis

Prior to the formative study, we conducted a series of pilot studies that informed the exact design of our apparatus and procedure, such as the task setup and the time threshold. Our study began by introducing participants to the three major joint categories. They practiced on examples of each in a learning session, which lasted up to 30 minutes.

Next, 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 left and manipulated the corresponding laser-cut components to their right (Figure 3 a). Our decision to provide a reference model as a basic guiding cue stemmed from all BLV participants in our pilot studies not being able to proceed with assembly upon presentation of only the laser-cut components.

We specified a time threshold for each assembly, determined based on integrating considerations from our pilot studies. Our observed factors included number of components, sizes, difficulty, etc. We adopted completion accuracy as our evaluation metric, which was calculated based on the number of component pairs that were correctly assembled into a joint within the time threshold divided by the total number of joints. The reason for using the time threshold was to avoid participant fatigue and maintain a reasonable study duration. The same technique has been used by prior research on disabled groups [14, 33].

After exploring all models, participants were guided to correctly assemble each of the five chairs in a co-design session, where participants and experimenters discussed and commented on how to address the barriers encountered by participants. We enabled participants to describe more abstract concepts by providing tactile aids in the form of crafting materials (Figure 3 b), such as putty, toothpicks and tactile stickers.

We analyzed the recorded video footage of the experiment by transcribing and coding all qualitative feedback and our observations in all sessions for analysis of affinity diagramming.

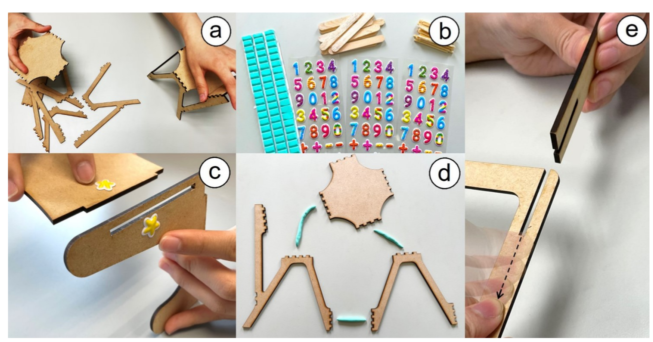
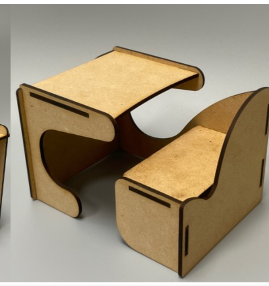


Figure 3: Study 1 apparatus. (a) Participants assemble scattered pieces with a completed reference provided to their left. (b) Crafting materials used for BLV co-design session. (c) A participant suggests labeling joint parts. (d) A participant suggests using tactile lines to indicate joint pairs. (e) A participant suggests adding a groove extended from the slot opening as a hint of joining completeness.

[6]https://www.dezin.info/chair-cadeira-free-dxf-file/
[7]Modified from: https://filecnc.com/home/11446-Opensource-Laser-Cut-Chair-DXF-File.html
[8]https://www.dezin.info/kids-desk-with-chair-study-desk-laser-cut-cnc-router-plans-cdr-file/
[9]Designed by an occupational designer outside the research team
[10]Modified from: https://www.dezin.info/baby-table-and-chair-free-cdr-vectors-art/

Table 2: Details of each chair used as our representative laser-cut architecture examples in Study 1 and 2.

Chair/table models					
Size (L x W x H) (mm)	127 x 130 x 185	135 x 146 x 245	149 x 116 x 104	105 x 105 x 165	68 x 93 x 134
Type of joints	Finger joint	Slot joint	MT Joint	Finger and MT joint	Slot and MT joint
Number of pieces	6	8	7	9	17
Number of joints	10	10	8	11	28
Time Threshold (minutes)	12	9	18	12	21

3.4 Result: Completion Accuracy

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%) (Figure 11). Most participants worked on all tasks until the end, where P4 and P2 completed four and all five tasks in advance, respectively. However, P1 quit during the MT and SlotMT tasks because he knew what barriers were hindering him and stated *"I already knew I wouldn't be able to finish the tasks after several tries (on previous tasks), but I can walk through each task to tell you how to improve."* P7 who quit only the SlotMT task made similar remarks due to perceived difficulty of the presented model. They thus decided to quit for the sake of time.

3.5 Result: Co-Designed Heuristics

We discuss design concepts and solutions elicited from our participants. We then identify and categorize several heuristics on making laser-cut construction more accessible.

H1. Defining the entry component by stability of the model. All participants expressed the desire to be offered an entry component of the assembly model due to spending much time on initial exploration (on average 17% of time of all tasks). However, the defining features of a desirable entry component varied across participants and models. Some participants preferred the component which was largest or had the most number of joints as the entry. For example, when talking about the Finger chair, P2 stated that *"I would start from the [chair's] core to form the main structure that make it stand, which I think is usually characterized by largest size, most number of joints or most distinct shape,"* while another group of participants felt starting from the bottom of model was more intuitive (e.g., chair legs), as described by P6 in the task4: *"My logic is to start from the bottom. In other words, I would like to stabilize the chair as soon as possible, similar to building a house."* In sum, despite the different preferences, their shared goal of entry component was one that if started with, could form a stable structure the earliest.

H2. Informing pairs and joining directions. Given that participants spent much time struggling with difficulties in making sense of and pairing components, some suggested to label two parts of joint with the same sign as a pairing hint (Figure 3c), which was mentioned by P2: *"It's good to add the same sign on the parts of a joint if they were supposed to be connected,"* while others recommended generating tactile lines on the remaining parts of the wood plate that houses the assembly parts to indicate their pairing relationships (Figure 3d), or even tactile arrows to bring out joining directions.

H3. Informing similar-contour or symmetrical pieces, and assembly order. Participants desired to be informed of special contour, order or symmetry since these features took them much time and effort to manage. For symmetrical pieces, participants proposed to symmetrically project and arrange 3D symmetrical components in 2D plate, as stated by P7: *"Symmetrical pair can be placed at left and right to form a symmetrical spatial arrangement."* For other components that were semantically- related (e.g., placing chair seat components together) or had similar contour, participants preferred to have them arranged in close proximity, as suggested by P5: *"The ones that are similar should be placed close to each other, while others that have no relationship to each other should be distinctly separated."* For determining assembly order, some participants suggested numbering. However, others preferred to have this information manifest by placing the components that should be assembled last as far away from them as possible. P2 described: *"The ones that should be assembled first can be placed closer to me."*

H4. Feedback on completeness of slot joints. Different from the cases that finger and MT joints allow shallow joining of component edges and surface, slot joints require users to interlock edges in a way that makes components overlap, which made the assembly structure less intuitive and the completeness uncertain to our participants (P1, P4, P7). To address this, P1 proposed using a groove extended from the slot as the hint (Figure 3e): *"I think the lines should be extended all the way of slots so that I can know where to be match in the end."*

H5. Information moderation and model aesthetics. After discussing all barriers and potential designs, some participants raised the concern that too much information may cause them confusion. P7 reported that *"I think everyone has different preferences for labeling, and too much information can interfere with our comprehension. I therefore think it is better to provide us with just the big picture. Other tiny clues can be explored by ourselves."* Moreover, most participants (n = 5) were concerned about model aesthetics, especially regarding on-model cues. P3 described: *"I felt that the engraved labels will make the completed model unattractive. It would be better if they can be implicit or detachable, like stickers."* Hence, we should trade-off between providing desired labels that do not affect model appearance, and keeping them as salient and uncrowded as possible to avoid confusion.

3.6 Design Guidelines

We identified and categorized the types of assembly processes on which participants expressed the most feedback, and synthesize the key design guidelines for our system below:

- **G1 — (Assembly Initiation)**. Define an entry component that considers structural support, component size and number of joints. (by **H1**)
- **G2 — (Assembly Mechanics)**. Generate abstract and tactile multimodal labels for component pairs, orientation, symmetry, and order to guide users during assembly. (by **H2,H3**)
- **G3 — (Assembly State)**. Provide non-visual feedback for users to check whether a joint or model has been completely or accurately assembled. (by **H4**)

And we should keep **H5** in mind when realizing **G1, G2, G3**.

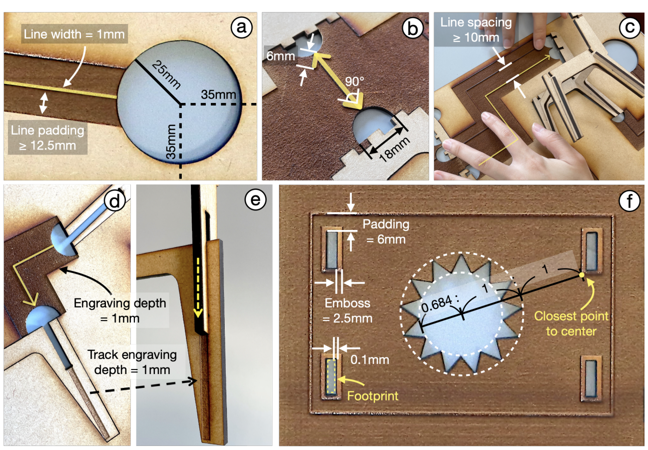


Figure 4: *Daedalus* assembly cues and their configurations. (a) Hollowed circle in the bottom-right of the plate that links to the entry component. (b) Double-headed arrow indicates finger joint pair. (c) Participants place half-assembled models back into the plate to access pairing cues. (d) Single-headed arrow marks the joining direction of slot joints. (e) Rastered guide track showing join completeness for slot joints. (f) Ground support for FingerMT chair.

4 IMPLEMENTATION OF DAEDALUS

Based on our formative study findings, we created *Daedalus*, a design tool plug-in built into and compatible with a popular modeling tool (Autodesk Fusion 360). *Daedalus* comprises of a library of BLV-accessible features for laser-cut patterns and an accessibility-aware editing environment. We illustrate them in the following sections.

4.1 Accessible features produced by Daedalus

We first detail our proposed accessible features in accordance with accessibility problems found in our formative study.

4.1.1 Entry component. To assist with assembly initiation (**H1, G1**), we provide an identifiable large hollowed circle with a line linking to the entry component on the wood sheet (Figure 1 h and 4 a). The hollowed circle is always placed at the bottom right of the wood sheet uniformly for all patterns.

4.1.2 Tactile lines and arrows. On the laser-cut plates, we engraved single and double-ended arrows (Figure 4b) to represent pairing hints and their joining directions **(H2, G2)**. For instance, pointing from the Tenon to Mortise joint part with a single arrow represents the direction of the plug-in assembly action (Figure 1f); for slot joints, the component lined up to an arrow's tail should be inserted into what is pointed by the arrow's head (Figure 4d, underlying rationale is detailed in section 4.2). Double arrows were only used for finger joints since they can be joined from either direction. Tactile lines were used as our initial design due to the common usage of tactile graphics for BLV people (e.g., contouring objects), and we adopted a basic rectilinear style to possible confusion from custom angles and multiple turns. The line spacing was defaulted to 10mm (Figure 4 c). The engraved padding was set on both sides to 12.5mm (Figure 4a).

4.1.3 Hollowed half circles along the joints. The hollowed half-circle cut along the joint has two purposes. First, it informs BLV users of the presence of the joint and its type when they follow the tactile lines. Second, it makes the assembly component easily detachable by pull with a single finger.

4.1.4 Rastered guide tracks. To support **H4, G3**, we extended *guide tracks* from slot joints to indicate attached joints' ends of completion (Figure 4e). They were implemented exclusively for insertable slots (pointed to by arrow heads) to provide completion hints while being considerate of model aesthetics (**H5**).

4.1.5 Structural support. To alleviate stabilization problems **H1**, we hollowed out footprints to stand-up the model in (Figure 1 g and 4 f). The footprint area was bounded by embossed rectangles, and marked with a hollowed star in the center for perceivability. All of the above is bounded by a rectangular frame.

4.1.6 Spatial layout. The layout generation holistically considers entry component (**H1**), support footprint (**H1**) and assembly order from bottom-up (**H3**). First, the hollowed circle linking to entry component is placed at the bottom right of the board. Second, components of the model are arranged from bottom-up, and layered based on their proximity to the entry component. Third, symmetrical components are divided and take left- and right-mirroring positions in their corresponding layer.

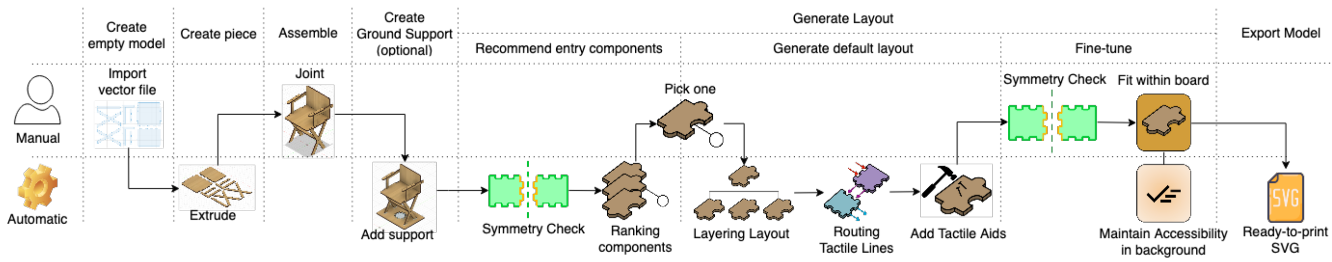


Figure 5: System Diagram. (Top row) Required and optional manual inputs. (Bottom row) Automatic functions in Daedalus.

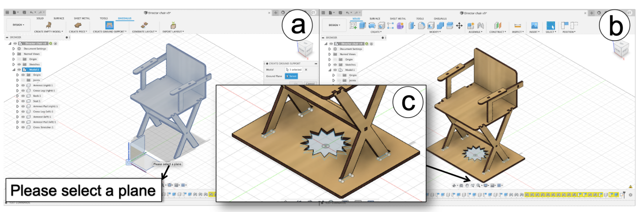


Figure 6: Workflow for adding support area. (a) *Daedalus* asks the user to specify the plane for locating the support to be placed. (b,c) *Daedalus* captures the footprint of the chair automatically, and adds the ground support area with a hollowed star to the authoring space.

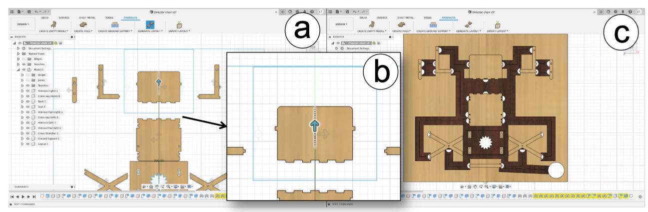


Figure 7: Sketch editing environment. (a,b) *Daedalus* set moving constraints for each component (blue frames) in order to maintain spatial arrangement. (c) The preview of generated layout in *Daedalus*.

4.2 Daedalus: Design add-in

Daedalus is an accessibility-aware system for laser-cut modeling considering the above-mentioned heuristics and guidelines. The above tactile aids can be automatically generated by *Daedalus* given just a few manual inputs. We first illustrate a user-walkthrough scenario, then underlying technical details in the following sections.

4.2.1 User Walkthrough. To illustrate a typical use case of *Daedalus*, we describe a scenario where a designer would like to make their design of a FingerMT chair accessible to wider audiences.

- *Initialization.* The user begins with *create empty model* (Figure 1a) and imports the completed sketch to the authoring space (Figure 5). Users can then specify the desired wood plate thickness (by *create piece* in Figure 1a), and assemble the pieces using built-in function *Joint Assembly* in Fusion 360.

- *Generating accessible layout.* After finishing the initial steps above, the user can choose how to add the support area for the assembled model by *create ground support* (Figure 1a, 6). The user can then proceed to *generate layout* with a click (Figure 1a). *Daedalus* will recommend a list of entry component candidates (detail in section 4.2.2). The user is asked to pick one from the list (Figure 1 c). This step also requires the user to judge whether this will result in the layout having a near-global vertically symmetrical configuration, which has universal benefits for spatial sensemaking across people with differing visual ability [12].

- *Editing.* After the above, *Daedalus* generates a BLV-accessible layout template that requires users to fine-tune component placement to be within the board's printable area. During editing, *Daedalus* is aware of the accessibility of the edits in real-time (e.g., keep spacing of lines and components, maintain symmetry and layering relationship, as in Figure 7). The user is encouraged to achieve vertical symmetry if possible, for organized layout. When finished, the user can export a colored SVG file ready-to-print for laser cutting (Figure 9) with *export model* (Figure 1a).

4.2.2 Algorithms of layout generation. Layout generation considers entry component (**H1**), support area (**H1**), pairing hints (**H2**), component symmetry (**H3**), assembly order based on proximity (**H3**), and feedback of completeness of slot joints (**H4**). We describe how *Daedalus* arranges a layout while considering all of these.

- *Recommending entry components. Daedalus* sorts and recommends entry components with the following order: symmetry of the to-be-generated layout, proximity to the bottom of model, size, and number of joints. First, *Daedalus* detects identical components as symmetrical pairs. Second, *Daedalus* generates layout trees by taking each component as root (described in next paragraph), and rates the symmetry of each layout by the number of within-layer symmetrical pairs. Finally, *Daedalus* requires the user to select a layout tree with the most vertically symmetrical configuration, which is easily determined with human effort (Figure 5).

- *Layering components. Daedalus* builds an undirected graph of the model with components as vertices and joints as edges. A breadth-first search with given entry component as root (*R* in Algorithm 1) is then performed to layer components, and generates a layout tree in the end. The ground support is not involved in the search but placed as an individual layer to connect with all components that compose the bottom of the model.

- *Arranging symmetrical within-layer components.* Within-layer components are spatially grouped if they: (1) share a child or (2) are connected. In each group, *Daedalus* will mirror relative placement of symmetrical components, and sort the remaining components in each layer based on their relative positions in 3D space. This method allows *Daedalus* to mirror symmetrical components in left/right on the wood plate while retaining the spatial relationships of components.

- *Identifying joint types and opening directions.* To mark the correct tactile aids, *Daedalus* needs to identify the types of joints and the opening directions. First, *Daedalus* iterates all joining points (each joint has two) specified by the user at initialization, and takes the closest edge to compute further. If an edge is located inside a component, *Daedalus* identifies it as MT joint; otherwise, as slot or finger joint. Each edge (one part of a joint) contributes an opening direction, and each joint has two. By comparing the two opening directions of a joint, it can be classified as a slot joint if the opening directions are parallel, and finger joint if perpendicular. Based on these principles, half hollowed circles, single-head and double-head arrows can be added to the plate (Figure 8).

- *Drawing rastered guide tracks.* The rastered guide tracks can be automatically added to the insertable slots. If the opening directions of a slot joint are vertical, the insertable slot will be below it. If horizontal, *Daedalus* will examine components' ordering relationship in the built tree graph. Child nodes are regarded as insertable by default, considering the ease of inserting a lone piece into a larger half-assembled model.

- *Routing tactile lines.* We implemented A* search as the routing technique, which is computed in an additional bitmap. The routes are rendered starting from the joints of the tree root (entry component), and subsequent children. During routing, we minimized the number of turns by regarding each turn as a cost into the cost function. The engraved area width is then set as 12.5mm on both sides of the lines, as mentioned above.

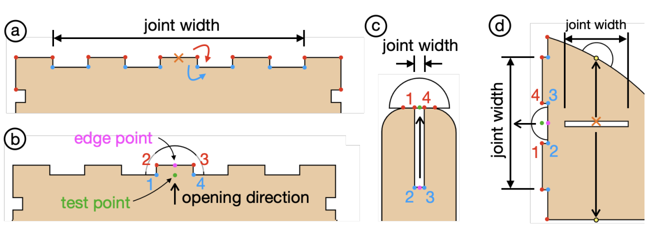


Figure 8: Illustration of identifying joint types and opening directions. (a) Starting from the user-specified joint point (cross), *Daedalus* examines the clockwise (red) and counter-clockwise (blue) turns along the edge, which form two-by-two sequences, and stops when encountering three same successive turns, non-right-angle turns or curved edges. Joint width can thus be defined in this way. (b) By randomly selecting a sequence, the opening vector can be defined as from the test point (green, decided by the middle of point 1 & 4) pointing to the edge point (pink) or reversed if the test point is outside the component. (c) The same concepts are applied to slot and (d) MT joints. The half circle of the mortise is added to its direct projecting points on the shape contour.

Algorithm 1: Layout Generation by *Daedalus*

Input: Components C, root component R, joints J
Output: *layout* in SVG
$G \leftarrow Graph(vertex : C, edges : J)$;
$T \leftarrow BFS(G, R)$;
$T \leftarrow grouping(T)$;
$lowerBound \leftarrow 0$;
for $i = 1 \rightarrow T.treeHeight$ **do**
  foreach $group \in T.layer[i]$ **do**
    $symmetryPairs \leftarrow$ same components in *group*;
    if *symmetryPairs is not empty* **then**
      $principalAxis \leftarrow$ the principal axis of the position distribution of the components in *symmetryPairs*;
    else
      $principalAxis \leftarrow$ the principal axis of the position distribution of the components in *group*;
    end
    sort the components in *group* by its coordinate on the *principalAxis*;
    place the components in *group* horizontally and above *lowerBound* in the *layout*;
    align the components in *group* that connected each other vertically;
    align the components in *group* that connected with the components in $T.layer[i-1]$ horizontally;
    foreach $symmetryPair(c_1, c_2) \in symmetryPairs$ **do**
      mirror arrangement of c_1, c_2 in *group*;
    end
  end
  $lowerBound \leftarrow$ the current height of the *layout*;
end
foreach $joint \in J$ **do**
  $path \leftarrow A^{*}SearchWithMinimalTurns(joint.end1, joint.end2)$;
  if *path exist* **then**
    draw *path* on *layout*;
    $jointType \leftarrow$ jointClassifier(*joint*);
    foreach $end \in joint$ **do**
      if $jointType(end)$==*FINGER or MORTISE* **then**
        draw arrow head at *end* on *layout*;
      end
      if $jointType(end)$ == *SLOT* **then**
        if *slotInsertable(end)* **then**
          draw arrow head at *end* on *layout*;
          draw guide track on *layout*;
        end
      end
    end
  end
  draw half circle at both ends of *joint* on *layout*;
end
draw entry circle and link to the closest joint in *R* on *layout*;

Table 3: Participants demographic information in Study 2.

ID	Age	Gender	Vision Level	Education	Major	Experience in Crafting/Assembling
P1	23	Female	Born blind	Master	Special Education	IKEA Furniture
P2	30	Male	Born blind	Undergraduate	History	IKEA Shelf and chair, Water Filter
P3	33	Female	Born blind	Undergraduate	History	Puzzle
P4	26	Male	Born with light perception only, lost at age 16	Master	Music Engineering	3D puzzle and LEGO
P5	21	Male	Born blind	Undergraduate	Sports Management	LEGO
P6	20	Female	Born blind	Undergraduate	Special Education	Puzzle and Toy Brick
P7	29	Male	Born blind	Undergraduate	Culture and Nature	Toy Brick
P8	30	Male	Blind since 21 due to car accident	Undergraduate	Social work	Remote controls, Furniture, Toy revolver

5 EVALUATION

In Study 2, we evaluated the accessible features created with *Daedalus* (described in Section 4) with BLV participants.

5.1 Participants

Eight participants (5 M and 3 F) different from those in Study 1 were recruited (ages: 21 to 33, average: 26.5, median: 27.5). All except one (adventitious) were congenitally blind (Figure 3), and had few prior experiences in daily assembling activities, none in laser-cut assembly. All had and used both functioning hands during the study.

5.2 Apparatus, Procedure and Analysis

Study 2 used the same five tasks and time thresholds from Study 1. Participants were presented with a Daedalus-generated accessible laser-cut plate in each task (Figure 9). Instead of providing participants with a completed reference along the way as in Study 1, in Study 2 references were only provided for two minutes before participants started assembly. This was to encourage engagement with the proposed plate design.

During the study, participants were first introduced to the three major joint categories and practiced on examples with *Daedalus*'s tactile features. This learning session lasted about 40 minutes. Participants then performed the five chair assembly tasks presented in randomized order during the evaluation session. They were allowed to touch a completed reference for two minutes prior to each task, as mentioned above. The plates were all kept in place to facilitate fluid haptic exploration during the task. At the end of each task, participants were briefly informed of incomplete parts and asked for their thoughts on the tactile features. After all tasks were completed, participants were asked to subjectively rate their experience (Figure 10). The entire study lasted 2.5 hours on average.

We analyzed video footage of the study, and labeled the order in which components were retrieved and assembled for each task (Figure 13). We also transcribed and coded all qualitative feedback and our observations for further analysis via affinity diagramming.

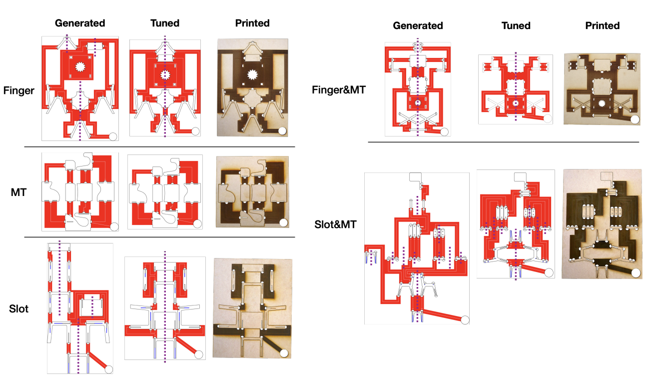


Figure 9: *Daedalus*-generated SVGs (left), tuned SVGs by an occupational designer (center) and printed laser-cut plates with assembly components removed (right). Dotted lines indicate layer-local and within-component lines of symmetry in the *Daedalus*-generated layouts, and global lines of symmetry in the tuned layouts. (Note: the MT layout and the top of the SlotMT layout do not have lines of symmetry, because these model parts are inherently asymmetrical.)

5.3 Results

In this section, we discuss our findings regarding the order in which participants' assembled components, assembly completion accuracy, observed assembly barriers and post-task interview.

The completion accuracy averages for each task were: Finger (93.75%, SD = 17.68%), Slot (75%, SD = 27.77%), MT (68.75%, SD = 34.72%), FingerMT (54.89%, SD = 29.97%) and SlotMT (70.09%, SD = 33.06%), as shown in Figure 11. In contrast to Study 1, no participants in Study 2 quit halfway into any task. Participants' performance on all but one task (FingerMT) was better than in Study 1. From observations and footage analysis we speculate this exception was due to the over-complexity of components' haptic profile for the FingerMT model, causing certain holes to be undetectable by hand (Figure 12e). These results are encouraging, considering that BLV participants in Study 1 had more time to reference the fully completed model in all tasks. Though the data shows particularly high standard deviations, this is not unusual given the high diversity in physical and cognitive ability across different BLV individuals.

5.3.1 Entry component. Most participants found the hollowed circle to be salient and the linked entry component helpful to the task, as reflected by P6 in the FingerMT task: *"The entry component is distinct and suitable to be the first one as it is formed by MT joints*

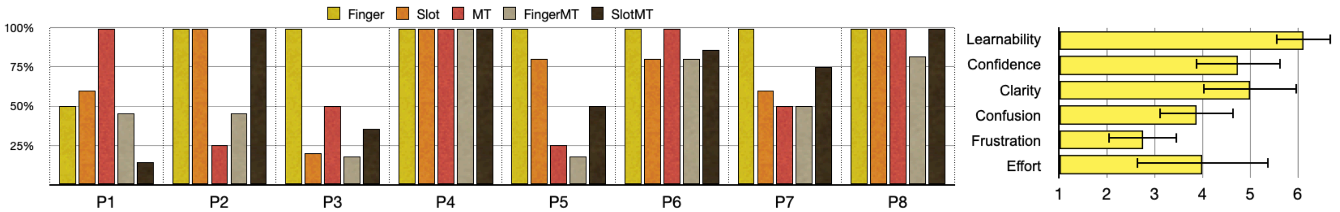
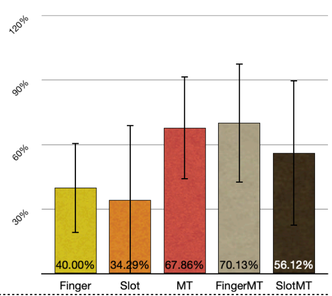


Figure 10: Study 2 results (continued). (Left) Completion accuracy across all participants (n=8) on each task. (Right) Subjective ratings with error bars showing 95% confidence intervals.

Study1

	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%



Study2

	Finger	Slot	MT	FingerMT	SlotMT
P1	50%	60%	100%	45.45%	14.29%
P2	100%	100%	25%	45.45%	100%
P3	100%	20%	50%	18.18%	35.71%
P4	100%	100%	100%	100%	100%
P5	100%	80%	25%	18.18%	50%
P6	100%	80%	100%	80%	85.71%
P7	100%	60%	50%	50%	75%
P8	100%	100%	100%	81.82%	100%
Avg.	93.75%	75%	68.75%	54.88%	70.09%
SD	17.68%	27.77%	34.72%	29.97%	33.06%

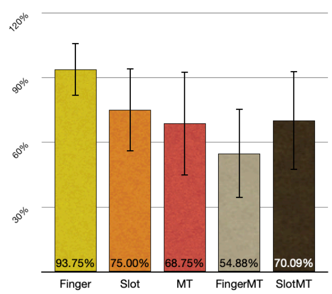


Figure 11: Study 1 (Top) and study 2 (bottom) performance results. (Left) Individual completion accuracy. Tasks completed prior to time threshold are marked green while ones which were quit are marked red. (Right) Bar chart of average completion accuracy of each task with error bars showing 95% confidence intervals.

instead of the finger joints linking to the seat. This way I can stabilize the chair first." Some participants emphasized the quality of entry component connecting with multiple joints - *"The shape of this one is large and unusual, and it connects multiple pieces which helps me to clarify more assembly directions at the start."* However, in the Finger task, half of our participants (P4,P5,P6,P8) suggested to use the seat as entry or at least include it in the first layer. A participant explained that *"I would start from the largest piece [seat] as it can be stabilized into a triangular shape with two other pieces. Otherwise, it was hard to stabilize the three legs."* These findings echoed with **H1**.

5.3.2 Tactile arrows mapped to half-circle hollows. We received much positive feedback on the tactile arrows as guiding cues for pairing and joining directions. For example, in SlotMT task, P2 commented that *"I found the arrows clear and definite. The half-hollows informed me of the joint position while arrows pointed to the next step. It's impossible to accomplish this task with only one of the two."* Regarding joining directions, P4 stated that *"The lines and arrowheads are clear. I carefully followed the arrows which indicated pairing and joining hints after I realized [the joints] were MT joints."* However, arrows also confused some participants (P4, P5) due to their winding routes (Figure 12a). P5 complained about this in the Finger task: *"It was hard to make sense of the guiding line. It just kept making so many sharp turns."* Another drawback is that the spacing between some arrows was too close for them to be easily separated. For instance, P5 reported after assembling the slot chair that *"I think I was hindered by the too-close arrows [Figure 12b]. But I finally figured them out if I touched more carefully."*

5.3.3 Rastered guide tracks on slot joints. For tasks involving slot joints, participants found it useful to confirm whether a slot joint was slid in completely. For example, P7 reported after the Slot task that *"The [guide tracks] were helpful because I could dynamically compare the changing relative length of slot and track when assembling, to check joint completeness and correctness."* However, the guide tracks could also mislead BLV participants if not defined or separated clearly. This was encountered by P6, who kept pushing the n-shape component down when misled by unintentionally-adjoining guiding cues for the chair stiles (Figure 12c).

5.3.4 Structural support. To tasks necessitating more structural support during assembly (Finger and FingerMT), participants found it helpful to stabilize the model mid-assembly, which aligned with our design purpose. A participant told us that *"Because this chair is stable only when the seat is assembled, it'd be good to have support when assembling it [seat]."* - P8 on FingerMT task. An unexpected benefit of this support was that it provided confirmation of completeness *" The support helped me confirm if the bottom of the chair was correctly assembled."* - P3 in FingerMT task.

5.3.5 Components' spatial layout for support, symmetry and order. All participants approved our design of spatial layout regarding ordering. For example, P8 told us that *"The rule about placing components to be assembled at the end far away helped a lot because when I knew when only the armrests were left to complete; I could directly touch the far ends of the plate without using arrows, which saved a lot of time,"* in FingerMT task. P5 commented on symmetrical placement: *"I know there are mirrored parts on the left side if the ones on the right side have been found. [Symmetrical placement] helped me not miss things."* However, the placement of the support footprint

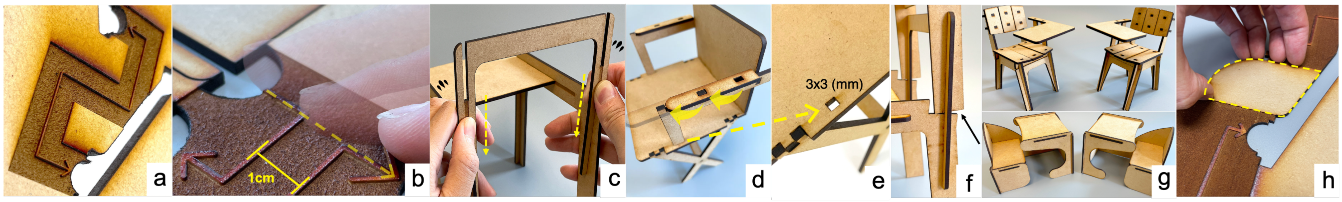


Figure 12: Study 2 diagrams. (a) Winding routes of tactile arrows of Finger chair reported in Study 2. (b) Participant mistook two individual arrows for a single arrow (dotted line) due to their narrow spacing (1cm). (c) A participant mistook the guided track as part of the adjoining cues for chair bottom. (d) The armrest pad of FingerMT chair incorrectly assembled. (e) The square mortises on the seat of the FingerMT chair are too small to find by touch (3x3 mm). (f) The back of Slot chair was assembled in an incorrect orientation. (g) Both MT and SlotMT chairs can be assembled in mirrored orientations. (h) Non-engraved board parts were mistaken for assembly components.

bothered some of our participants when exploring components. For instance, P5 complained that *"The position [of support footprint] was bothersome because I had to detour and prevent my hands from bumping into the assembled model when exploring,"* in the FingerMT task.

5.3.6 Subjective feedback. Overall, participants reported (on scale of 1-7, in Figure 10) all of our tactile aids were easy to *learn* (M=6.13, SD = 0.83), *clear* (M=5.00, SD = 1.41), and *confident* (M=4.75, SD = 1.28) to assemble during the tasks. They noticed the designs to make laser-cut assembly accessible, as encouraged by P2 that *"No one has done this before! If those rules and symbols can be defined as clearly in Braille, this could receive an even wider audience due to its good learnability."* However, our designs were sometimes *confusing* (M=3.88, SD = 1.13) given the above-mentioned reasons, and the assembly tasks took *effort* (M=4.00, SD = 2.00) to catch on, due to the walk-up-and-use experiment design. But this was also the reason that participants felt less *frustrated* (2.75, SD = 1.04); as stated by P3, *"Some things still confused me even during the assembly process, but this is normal when you first explore something new."*

5.4 Discussion and Implications

In comparison to visual resolution, which can capture the state of multiple pieces and perceive subtle differences simultaneously, tactile resolution is much lower, leading to several barriers in assembly. Here we discuss them and propose implications for future research in accessible laser-cut construction.

5.4.1 Errors in absence of model referencing. By conducting two studies, we found several errors or wrong paths made by participants that were exclusive to Study 2 due to the lack of model reference during assembly. First, model nuances were hard to memorize in Study 2. For instance, the tiny mortises on the seat of FingerMT chair were hard to perceive for most participants (Figure 12e), and was the major factor hindering them from proceeding or finishing within the time threshold. Another problem appeared at the same chair - P8 confirmed completeness too early, and with armrest pads assembled incorrectly (Figure 12 d), which was his only error across all tasks - *"I thought they were correct as it seemed to be the only remaining option, and assembled very fluidly."* The orientations of back components of Slot chair were often flipped (Figure 12f) by participants (P1, P5, P6) when assembling. Finally, MT and SlotMT chairs were found assembled in mirrored orientations by several participants (Figure 12g). Hence, providing participants with more tactile cues for such nuances is necessary, especially when developing laser-cut assistive technologies for more sophisticated assembly in the future.

5.4.2 Confusion caused by cut and engraved areas. When presenting laser-cut plates to BLV people, different engraved forms or textures may cause confusion. During the study, participants (P1, P6) mixed up components and non-engraved parts (Figure 12h) due to their similar textures. P1 in the Finger task told us that *"The [remaining non-engraved wood area] felt like components I was supposed to assemble. It would be better if I could distinguish them apart from other textures."* Misleading textures were also found on the junction between engraved and non-engraved parts, which were mistaken as the edge of the plate. This was encountered by P4: *"I did not find the last piece at first because I mistook its border as the end of the plate. I think it would help to define the working area."* The hollowed star of the support area was also confused with removed components, as stated by P4 *"The star can be embossed rather than hollowed out since I first mistook it as the hole for a removed component."* Therefore, such confusion can be avoided when presenting engraved laser-cut hints for BLV individuals by explicitly defining these parts with more diverse, yet salient engraved forms or textures.

5.4.3 Breadth-first vs. depth-first assembly. In Study 2, all joints were made easy to reach by the half-circle hollows, and we taught participants breadth-first ordering for assembly. However, we speculate that touching intuition tends to be "linear" and thus participants gravitated towards "depth-first" assembly in some tasks. This can be observed in MT task (Figure 13c), where participants (P2, P4, P8) in Study 2 followed the arrows consistently and retrieved components in a depth-first manner.

Another implication of this breadth vs. depth-first touching intuition results is dependence on the assembly context. During Study 2, P2 particularly enjoyed the entire experiment as a DIY process and expressed that *"This is DIY! No one needs to tell me if it's incorrect. I like to explore [the aids and joints] by myself; this is the whole point of DIY,"* while other participants argued that our designs left too much room for interpretation. P6 reported, *"There were too many half-circle holes on a component so I did not know which joint*

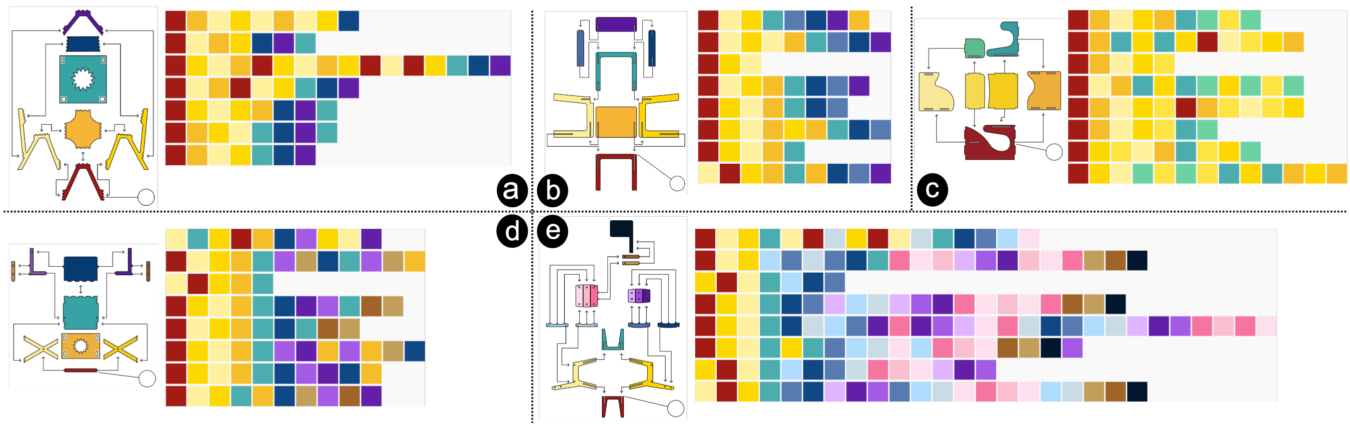


Figure 13: Maps of components' retrieval order organized by color. Participants 1-8 are ordered from top to bottom. Color blocks change when participants switch from assembling one component to another (not necessarily successfully). (a) Finger chair. (P3's corrupted data is not shown) (b) Slot chair. (c) MT chair. (d) FingerMT chair. (e) SlotMT chair.

to assemble next. Leaving only one for each component to indicate next step is enough," in the SlotMT task. For evaluation purposes the task in our study was close-ended, but open-ended DIY tasks may require more breadth-first handling when making decisions about possible next actions. Future work may need to compare and contrast such behavior of BLV people in cases of context-switching between restricted or open-ended scenarios to find best ways to support DIY exploration or accurate assembly.

5.4.4 Benefits and educational applications for BLV people. None of our participants had prior experiences in assembling laser-cut models, but many of them expressed much interest and imagination about benefits in non-fabrication contexts after using our aids. P5 suggested that *"This can be used as teaching aids for blind children to learn about larger structures that cannot be held or orally described, like the structures of railways and buildings."* P6 found laser-cuts useful for hand dexterity training *"I think manipulating such small and detailed joints can be used to train our hand dexterity, as well as our spatial sense."* The work in this study has strong potential to also support education for BLV in more generalized areas [11, 13, 31], such as architecture and spatial training.

6 LIMITATIONS AND FUTURE WORK

We discussed learned lessons and limitations of the current work, and propose topics for future work.

6.0.1 Individual differences. Through our studies, we observed that BLV people's visual and life experiences were influential to the assembly experience. From the results of Study 1 & 2, we see that participants with prior vision ability perform better overall in completion accuracy. These participants also depicted in our interviews that their way of thinking to be more "graphical" when assembling, as stated by adventitiously-blind P2 in Study 1 *"There is an image forming in my brain when I was touching the completed model."* However, congenitally blind participants also have abilities unique to their life experiences. For example, P2 (Study 2) liked to craft and fix things independently, and hence displayed more experience and caution in perceiving chair model details. On the other hand, many of our participants possessing an undergraduate degree is due to a national policy promoting underrepresented groups. We did not intend to recruit participants with overly-rich experiences and exceptional skills. Future research can explore how technical backgrounds or visual history impacts object assembly skill, and how to assist the abilities of BLV people on assembly tasks.

6.0.2 System and User Evaluation. We did not conduct a system evaluation due to a few reasons. First, it is hard to define the proper metrics for such evaluation. The lack of ground truth labels of existing online vector files makes it difficult to evaluate the sensing parts of our system, where joint types and directions are detected in order to add corresponding tactile aids. An acknowledged data set on these or more joint features would be helpful for evaluating our proposed techniques in the future. Second, the effectiveness of tactile aids should be evaluated by BLV people themselves, making such validation difficult at large scale (e.g., on the 600+ samples we examined). This is a limitation of the current work, but we believe our proposed designs can still enlighten future research on the accessibility of laser-cut assembly as the first attempt in this area.

On the other hand, most functionalities offered by *Daedalus* were simple GUI interactions similar to those of state-of-the-art modeling software. Hence, we did not test usability with designers. However, what accessibility-centered systems mean to designers and what trade-offs they should make when considering accessibility is worth exploring in future work.

6.0.3 System Implementation. The system's recommendation of entry components is primarily based on the heuristics (e.g., layout symmetry, stabilization) identified from our formative study. However, to achieve higher accuracy, physical simulations of the laser-cut model can be accounted for promoting better stability when assembling [1]. On the other hand, *Daedalus* requires "user-in-the-loop" to make the generated layout more compact and organized. The relatively intensive manual parts of using *Daedalus* are joint assembly and within-board adjustments (Figure 5). The functionality of semi-automatic assembly proposed by Assembler[3] [43] can helpfully ease the effort of assembling joints manually, while the nesting algorithms [2, 10, 38, 39, 47] can also be integrated to reduce efforts on within-board edits. We consider these as future work to make *Daedalus* more user-friendly and less material wasted.

6.0.4 Distributing hints between model parts and plate. In our implementation, all cues were on the remaining wood plate instead of the components due to aesthetic concerns. This may lead to a disconnect when transferring the hints from 2D plate into the being-assembled 3D model, which caused some difficulty for BLV people in the late-assembly phase, as described by P6 in the SlotMT task: *"I did follow the lines and arrows fluidly at the beginning but I got stuck after assembling the starting layers, and had to depend on my memory to assemble afterwards."* Temporarily detaching assembled parts to place back into the 2D plate may partially address this (Figure 4 c), but is not sustainable. Integrating or partially replacing current engraved hints with detachable tactile or Braille markers (while maintaining model aesthetics) is a potential solution, which may also mitigate the large material consumption of engraved tracks. Future work on design system should address such hint accessibility by examining model configuration, and distributing hints based on assembly stage as suggested by the Study 1 guidelines.

6.0.5 Universal design of tactile symbols. In our current implementation, connection cues are represented by common and salient symbols (e.g., arrows), and connected in rectilinear style by our path-finding technique; however, this may not be sustainable once models or assembly actions become more complex. Though there was not much complaint regarding symbols, future work can explore different symbols that can be both visually and haptically perceived and interpreted more intuitively in the context of assembling laser-cut objects. We also previously mentioned that engraved parts are perceived by BLV people as different textures, and can generate different shades of color that may confuse sighted people. Future work should examine universal design of engraved hints.

6.0.6 Assembling laser-cut model at scale. In this paper, we introduced less-complex (compared to commercial laser-cut products) and graspable-size (with respect to furniture-scale) laser-cut objects as a first attempt on uncovering accessibility problems in laser-cut assembly. Models of varying scale, such as a more complex object (e.g. robot), can be divided into different parts (e.g., head, hands, etc.), printed by Daedalus, and assembled into 3D sub-models by BLV users. However, the next step on assembling these sub-models into a complete 3D object will be a new 3D-3D assembly question. Designing on-model pairing hints might be a potential solution in this stage but more research should be conducted in future work.

Additionally, the fact that we adopted models with only reflectional symmetry or asymmetry leaves some interesting questions unanswered: for instance, how do we design tactile aids for models with radial or spherical symmetry? Or, how do we arrange the layout for laser-cut models with repetitive assembly patterns (e.g., Figure 2g)? Tactile aids for assembling more interesting laser-cut geometries are valuable to explore in the future.

At the same time, one existing area of research focuses on making laser-cut objects sturdy enough to withstand large forces [1, 4], allowing them to be used as real furniture. We believe our high-level principles can be an initial insight into such assembly (e.g., stabilizing mid-assembly, informing pairing, etc.), but we highly encourage exploring other joint types (e.g., bolt) when considering furniture-scale assembly and making assembly tools accessible.

7 CONCLUSION

In this paper, we describe the creation process of BLV-accessible tactile aids for laser-cut assembly that can be achieved by *Daedalus*, a design add-in compatible with commercial modeling software. Our underlying design heuristics and guidelines were informed by a formative study with BLV users, where we identified several assembly obstacles for commonly-used laser-cut joints and our example models. We then designed cues for entry component, structural support, pairing hints by arrows, rastered guide tracks and spatial layout information, that correspond to assembly order and symmetry. We developed *Daedalus*, a generalizable software add-in that can computationally generate all of the proposed aids and output a colored SVG file ready-to-print for laser cutting. In a follow-up user study, we evaluated our proposed aids and found that users completed assembly more successfully in tasks with them. Through this study, we gained more insights and discussed the implications of accessible laser-cut architecture design for the future research.

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