Assembling 3D-Printed Objects Without Vision: Challenges, Strategies, and Opportunities

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Abstract

3D-printing can benefit blind and low-vision (BLV) users by offering tactile access to information typically conveyed visually. Complex printed models often require users to assemble multiple components, a process that relies on visual cues for sighted individuals, while the assembly experiences of BLV users remain poorly understood. In this work, we investigate how BLV users experience and navigate 3D-printed object assembly. We conducted a user study with six BLV participants under three conditions: (1) unassisted, (2) assisted by a sighted mediator, and (3) guided by step-by-step verbal instructions. Verbal instructions helped participants identify, confirm, orient, and fasten components; but challenges locating and distinguishing joints persisted. Co-designing with BLV users identified uses for tactile markers to complement verbal cues and support spatially relevant aspects of the assembly process. Our results highlight the need for assembly instructions tailored to BLV users, and we conclude with recommendations for future research and development.

CCS Concepts

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

Keywords

Accessibility, User-Centered Design, Assembly, Accessible 3D-Printing

ACM Reference Format:
Anna Matsumoto, Danyang Fan, and Sean Follmer. 2025. Assembling 3D-Printed Objects Without Vision: Challenges, Strategies, and Opportunities. In *Extended Abstracts of the CHI Conference on Human Factors in Computing Systems (CHI EA '25), April 26–May 01, 2025, Yokohama, Japan.* ACM, New York, NY, USA, 6 pages. https://doi.org/10.1145/3706599.3720005

1 Introduction

As 3D printing has become more accessible, it has increasingly served diverse populations, including blind and low-vision (BLV) individuals [1]. The flexibility and customizability of 3D-printing enables people with disabilities to produce artifacts tailored to their needs in areas including education, DIY projects, accessibility, and learning [2]. For BLV users, affordable consumer-grade 3D-printers have made it possible to create tactile models that represent concepts otherwise difficult to convey through natural language alone [3, 4].

Many complex models, such as those with moving pieces [3], size constraints [24], and complex geometry [3], often require printing individual components that need to be assembled. Additionally, assembly can also serve as an interactive way to understand systems and processes [5]. However, current research and practices on assembly aids assume visual abilities by relying on diagrams and visual cues [8, 13], while assembly experiences of BLV users who often cannot rely on these cues are not well understood. Without visual aids, communicating spatial information through verbal instruction alone is a known challenge [6].

In this study, we investigate the experiences of unassisted BLV individuals assembling 3D-printed models and identify the challenges they encounter. We then provide instructions based on prior guidelines, such as using sighted mediators [3] and step-by-step instructions [12], to understand how these methods may help and challenges that persist. Additionally, we engage in co-design with BLV participants to develop their own aids to support the assembly process. This work contributes to a deeper understanding of the challenges BLV individuals face during the 3D-printed object assembly process. It also provides insights into how audio feedback and instructions might assist—or not—in improving the assembly experience. Finally, the study highlights ideas from BLV users regarding instructional aids that could enhance and make the assembly process more accessible.

2 Related work

Our research builds on current 3D-printing model design and guidelines for BLV users [3] and existing assembly instruction principles for sighted individuals.

2.1 Accessible 3D-Printing

As 3D-printing technology has become increasingly valuable for BLV individuals, numerous accessible 3D-printed resources have become available on platforms such as 3D Opal[1], tactiles.eu[2], Thingiverse[3], and TinkerCAD[4]. These 3D-resources allow BLV individuals to access spatial information through touch. 3D-printed tactile materials have been used to support inclusive learning across a variety of fields, including programming [14, 15], chemistry [6], biology [5], graphic design [16], mathematics [17], and literature [19, 20].

[1]http://sahyun.net/projects/3Dprint/objects.php
[2]http://tactiles.eu
[3]https://www.thingiverse.com/
[4]https://www.tinkercad.com/

CHI EA '25, Yokohama, Japan

ACM ISBN 979-8-4007-1395-8/2025/04
https://doi.org/10.1145/3706599.3720005

By further incorporating movable or removable parts, 3D-printing can promote active learning and interactive exploration [3], such as understanding complex biological processes [5]. For movable parts, additional aids such as detailed descriptions and in-print features such as Braille or 3D symbols are recommended as accompaniments to support independent exploration [3, 6]. With emerging interest in 3D-printing resources for BLV users, Guidelines for Producing Accessible 3D Prints (2024) have been created to communicate why, when, and how to use 3D printing to create inclusive 3D models [3].

2.2 Assembly Instruction Principles

Assembly instructions are important for facilitating self-assembly [10], with extensive research focusing on sighted users. In assembly instructions, diagrammatic visualizations that guide users through step-by-step instructions can play crucial roles that help users break down complex tasks and build mental models of spatial and functional relationships among components [8–13]. For BLV users who cannot rely on these diagrams, however, assembly instructions pose significant challenges. Text-only instructions are often error-prone for complex objects, as users must rely solely on descriptions to form a mental model [11, 12]. While adding spatial or relational descriptions to verbal instructions can aid comprehension, conveying layout and orientation without visual references remains difficult [6]. Previous studies co-designed tactile aids for laser-cut DIY furniture, but the added dimensional complexity of 3D-printed objects makes creating accessible assembly instructions a unique challenge [18].

3 METHODOLOGY

To investigate the challenges and strategies associated with non-visual assembly, we conducted three different assembly tasks under three distinct conditions: (1) Unassisted Assembly, (2) Mediated Assembly in which participants can make requests to a sighted mediator, and (3) Step-by-Step Assembly to explore how well best-practice instructions for sighted individuals may aid BLV users. Following the assembly tasks, we co-designed with participants potential ways to improve the assembly process. In the co-design, we asked participants to construct their own assembly instructions. We provided participants with craft materials, including a 3D pen, stickers, and clay, to help them communicate their ideas.

3.1 Participants

Six participants (3 with low vision [LV1-3] and 3 who are legally [B1-3], including 3 males and 3 females aged between 20 and 80) were recruited through public announcements on local BLV mailing lists. Gift cards worth 70 USD were provided as compensation for participation in the 2-hour study.

3.2 Procedure

Participants were seated at a table and invited to assemble different models under each condition without time constraints. Before each task, they were verbally provided with the model's name and the number of components. For each assembly, participants were instructed to think aloud their strategies. The study was approved by our institution's IRB board.

3.3 Conditions and Materials

3D models used in this study were downloaded from open-source websites[5] [6] and printed in PLA using a Bambu Lab X1C printer with a 0.4 mm nozzle. We conducted a pilot study with six blindfolded sighted participants to evaluate six candidate 3D models, aiming to identify which posed distinct challenges relevant to BLV assembly. Each participant assembled three randomly assigned models under the constraint that each model would be tested an equal number of times. We gathered feedback on challenges such as joint complexity, component selection, and surface detection. Based on these observations, we selected three final models that represent major challenges: varied joint mechanisms (Helicopter model), repeated identical joints with multiple fastening options (Skeleton model), and complex organic geometry featuring small joint elements (Ankle model), as shown in Table 1. We then counterbalanced these models across conditions in the main study.

3.3.1 Condition 1: Unassisted Assembly. The objective of Condition 1 was to investigate the challenges and strategies inherent to the assembly of 3D-printed parts. Participants were instructed to assemble the 3D models independently and not ask questions. However, if requested, they could use a pen or stick to assist with the perception of small features.

3.3.2 Condition 2: Mediated Assembly. The goal of Condition 2 was to explore what types of additional information participants might request and ways verbal feedback may help. Participants were instructed to assemble the 3D models and ask for additional information or hints as needed.

3.3.3 Condition 3: Step-by-Step Assembly. The objective of Condition 3 was to explore how existing verbal step-by-step assembly instructions might help participants assemble the models and identify remaining challenges. Assembly instructions used were based on the step-by-step framework from Novick and Morse [12]. Each step consists of three sentences consisting of:

Geometric Descriptions (e.g., First, we will start with the base. It is a square component with 2 rectangles on its top. The two rectangular protrusions on top should be parallel to your body).

Instructions Mapped to Actions (e.g., Attach the main body, the largest part, to the base).

Feedback Mechanisms (e.g., If assembled right, you can feel 4 holes on the side of the main body).

Step-by-step instructions were read aloud by the study facilitator and progressed upon request. In addition to the step-by-step instructions, participants, like in the Mediated Assembly condition, could request any additional information to be verbally provided for us to probe additional needs.

3.4 Analysis

Two researchers conducted open coding of video footage and think-aloud comments from the assembly process. These sources were triangulated using latent and constructionist approaches to identify unit tasks, along with their associated challenges and strategies.

[5] https://www.tinkercad.com/
[6] https://www.thingiverse.com/

Table 1: Models used in this study

Model	Component Number	Joint Type	Properties
A: Toy Helicopter [21]	7	6 Distinct	Different fastening styles
B: Body (Skeleton) [22]	15	15 Identical	Many identical joints
C: Human Foot [23]	5	1 Distinct, 3 Identical	Complicated shape

For Model B, as there were no significant criteria to be used to differentiate legs and arms, we judged any combination to be correct. For Model C, we only used the first 5 components to equalize assembly time based on the results of a pilot study. In addition, we modified the original model with joints to enable assembly without the need for non-printable parts.

Table 2: Assembly Results and Error Stage under each Condition

	LV1	LV2	LV3	B1	B2	B3
Unassisted Assembly	Success	Error (4)	Error (3)	Success	Success	Error (4)
Mediated Assembly	Success	Success	Success	Success	Error (4)	Error (4)
Step-by-Step Assembly	Success	Error (4)	Success	Success	Success	Success

(#) denotes the unit task number in which the error occurred, as introduced in Section 3.4 LV3 gave up the task in Unassisted Assembly after facing challenges in Unit Task (3)

These unit tasks were then deductively reviewed, refined, and ultimately synthesized into five Unit Tasks based on hierarchical task analyses from prior research [7, 10], which are: (1) Identifying and Sorting Components, (2) Selecting Connectable Components, (3) Finding Joints (added specifically for BLV users), (4) Orienting Components, and (5) Fastening Components. Coding and task synthesis were iterative processes involving multiple meetings among the researchers, which included peer review, constant comparisons of new codes with existing data, peer debriefings with colleagues, and repeated triangulation with study footage to promote accuracy and minimize researcher biases. With the goal of gaining a broad understanding of the largely unexplored space of non-visual 3D assembly, the procedure and analysis prioritized qualitative insights over assembly time, as participants were encouraged to explore, request information (for Condition 2 and Condition 3), and reflect in real time.

4 RESULTS

Here, we describe participants' experiences across the study conditions, highlighting the challenges they encountered and strategies they used. We then share the ideas participants proposed during the co-design task to address some of the challenges they experienced and assist with the assembly process. While all participants could infer the final appearance of Models A and B from their names, none were able to do so for Model C. Table 2 shows successes and errors across the conditions.

4.1 Unassisted Assembly

Five of six participants finished the unassisted assembly task. LV3 gave up after he could not find the holes that make up joints in the model:

"I think at this point I need to call someone who is not visually impaired to help me how to do it."

LV2 assembled one component in the wrong orientation. The following subsections decompose participants' experiences into the unit tasks that make up their assembly process (Figure 1).

4.1.1 Unit Task 1: Identifying and Sorting Components. All participants first haptically explored the components they were provided to understand their shape [B1, B2, B3] and confirm the total number of components [B1-B3]. Based on their exploration and prior mental image of the represented object, participants sought to identify components by semantically meaningful names [LV1-3, B1-3].

Next, participants sorted the components to facilitate finding and making comparisons between these components in future unit tasks. For components they could identify, they spatially arranged these components according to the components' relative positions in their mental image of the object [LV1, LV3, B2, B3]:

"[I] already know what a helicopter looks like, I could tell this was bottom, propeller goes to top" [LV1].

However, for similar components that were difficult to distinguish or identify, participants sorted them by size and length [LV1, B1, B2, LV3, B3], by joint type [LV3], or by symmetry [B1, B3].

4.1.2 Unit Task 2: Selecting Connectable Components. After sorting components, participants needed to select components that connect. Most preferred a bottom-up approach [LV1, LV2, B1, B2, B3], but if the bottom part was not the largest, some opted to start with the larger component [LV1, B1, B2]:

"Find the biggest pieces first and figure out the others" [LV1].

Participants with prior mental images of the represented object often utilized the spatial arrangement they created to assist in component selection [LV1, LV3, B1-3]. Participants without that prior mental image, however, often struggled to find components that connect [LV3, B3]. For them, distinct joints offered another method to identify connecting joints, but for models without distinct joints, participants could only evaluate connectivity by colliding pairs of components based on shape [LV1, LV3, B1, B3], which was often ineffective [LV3, B3].

Figure 1: Participants' assembly process. (a) Unit Task 1: Identifying and sorting components. (b) Unit Task 2: Selecting Components. (c) Unit Task 3: Identifying Joints. (d) Unit Task 4: Orienting Components. (e) Unit Task 5: Fastening Components.

4.1.3 Unit Task 3: Identifying Joints. Having selected connectable components, participants needed to find joints that connect. However, participants faced several challenges in locating and identifying the joints. First, joints with small holes on the surface were difficult to haptically detect [LV1-3, B1-3]. Several participants recommended using thin sticks to locate holes [B1, B2, LV3]:

"Without [a] stick, I couldn't find the hole because my finger was too flush with the object" [LV3].

Participants found protruding features easier to detect than concave ones.

Second, participants often had difficulty distinguishing joints from the geometric features of the model. This included mistaking natural model features, such as concave areas [LV3, B1, B3] and thin parts [LV3, B1, B3], for joints [LV3, B1, B3]. These misinterpretations frequently led to incorrect insertion attempts:

"Whenever I see some small depression or holes in it, I think something needs to go that side" [B3].

Third, some participants had trouble distinguishing joint features. This includes mistaking two separated pins as a single pin [B1, B3], or miscounting four holes as two or three [B2, LV3]. Difficulty identifying joints was compounded by not knowing how many and what types of joints to expect:

"It would be nice if the instruction says, how many and where the holes are...I spent a lot of time looking for which piece just has one peg versus two" [LV3].

4.1.4 Unit Task 4: Orienting Components. Once participants identified the correct components or joint pairs, they needed to orient the parts so that connecting faces align. In cases where only one orientation was possible, participants successfully assembled the pieces through the process of elimination [LV1, B1, B2]:

"I don't know what this is but hole sizes are different, so even if I tried one way, I would try another way and figure out the orientation" [B2].

However, some joints allowed multiple orientations which complicates the process and makes trial and error insufficient for proper alignment. Particularly for joints that could be connected in many directions, participants again had to rely on mental images or shape recognition to determine the correct orientation. Reversing front and back was still a common error [LV2, B2, B3].

Participants also lost track of holes when components contained multiple joints, forcing them to re-identify joints multiple times. Some participants kept a finger in a hole to prevent losing the correct joint position [LV1, B1-3].

4.1.5 Unit Task 5: Fastening Components. After completing the previous unit tasks, participants secured the components together. This often involved applying force in various configurations to identify how the pieces fastened (e.g., slide-in vs. snap-fit). Obvious haptic feedback, such as snap, confirmed success. However, without tactile feedback, participants frequently separated and reattached parts to ensure they were properly fastened [LV2, B1, B2, B3].

4.2 Mediated Assembly

With a sighted mediator who could provide verbal information about the model, all participants finished the assembly. Two participants [B3, B3] assembled one component in the wrong orientation. In this condition, participants asked a variety of identifying and confirming questions.

4.2.1 Identifying Questions. When participants did not have a prior mental image of the represented object, participants asked the mediator to provide an overview of the model and the assembly process. The mediator, through a bottom-up approach, explained how each component connects while referring to components by physical features (long, small, etc.). However, these instructions alone were not sufficient for B3 to figure out the assembly process (Unit Task 1).

Several participants additionally asked the mediator to identify the presence of small joints [B3], the total number of joints [B3], what the joints should feel like [B3, LV3], and the positioning of joints [B3], but continued to rely on the trial and error process of colliding components to find matching joints [B3, LV3] (Unit Task 3).

When several participants could not figure out the correct orientation for fastening, they requested further information about insertion angles for the joints [B3]. B3 used this information to correctly fasten the corresponding joints (Unit Task 5).

4.2.2 Confirming Questions. Participants also asked various questions to confirm their actions and understanding of the model throughout several unit tasks. When sorting models, B1 and B2 asked the mediator to confirm their identification of individual components (Unit Task 1):

"Is this the head?" [B2].

After selecting two components to connect, participants [B1-B3] asked whether the components should connect, which B2 and B3 described to help (Unit Task 2):

"Do I have the head on the right body part?" [B2].

Finally, participants [LV3, B1, B3] asked the mediator if they were fastening correctly (Unit Task 5).

4.2.3 Persistent Challenges. Several challenges persisted. In addition to challenges finding and selecting matching joints when provided with information about the joints as discussed above, B2 also had difficulty properly orienting two components along the proper connection face (Unit Task 4).

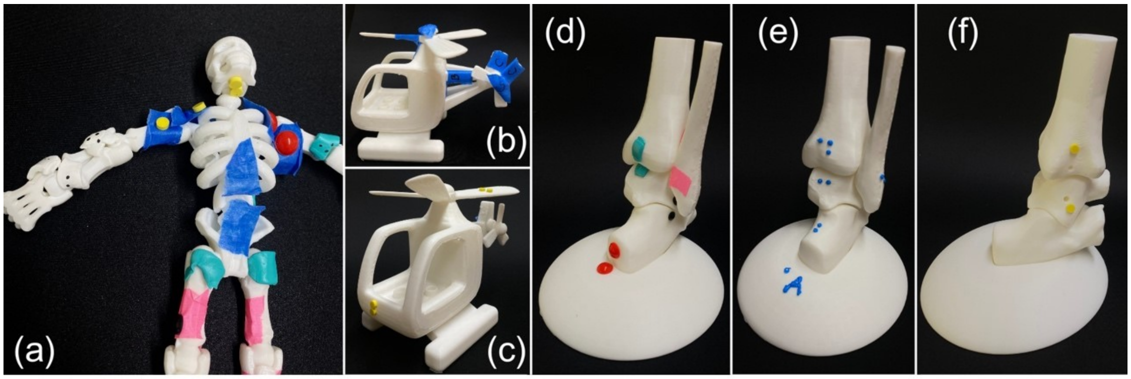

Figure 2: Results of the co-design. (a) Participants suggested color/texture coding, (b) using an alphabetical coding system, (c), (e) number coding with Braille, (d) color/texture matching, (f) and adding protruding small features.

4.3 Step-by-Step Assembly

With step-by-step instructions, all participants finished the assembly, but one participant [LV2] assembled one component in the wrong orientation. All participants responded positively to the step-by-step instructions.

4.3.1 Addressed Challenges. Provided geometric descriptions of components helped all participants select components to be connected (Unit Task 2). Action-based instructions helped participants [LV1-3, B2] orient and fasten components smoothly (Unit Tasks 4 and 5). Participants appreciated how the assembly instructions concluded each step with feedback about what to expect if that step was performed correctly [LV1, LV3, B1, B3].

4.3.2 Persistent Challenges. Detecting small joints was a persistent challenge [LV3, B2]. LV3 also requested further assistance identifying and confirming components (Unit Task 1):

"These are the feet (instructed component) is that correct?" [LV3].

4.3.3 New Challenges. Since each step consisted of 2-3 sentences, several participants had difficulty remembering all parts of the instructions, leading to incomplete steps [B1, B3]. B3 forgot details about the features of an attaching component and resorted to trial and error to locate the attaching components. B2 and B3 requested that the instructions be repeated. Additionally, B3 found the bottom-up assembly order confusing and suggested organizing the components by joint type.

4.4 Co-Design Session

When co-designing assembly aids, two recommended modifying joints [LV1, LV3] and five participants [LV1-3, B1, B3] proposed augmenting the model with tactile aids.

4.4.1 Modifying Joints. Two participants proposed modifying the joints to snap-fits to provide more salient confirmation of fastening (Unit Task 5). LV3 added that making these joints separate shapes would additionally confirm proper joint pairing:

"*If all joints had different shapes, triangle, square, and circles, that would be a good idea"* [LV3].

4.4.2 Tactile Aids. Participants proposed several tactile aid schemes corresponding to challenges across multiple unit tasks.

Aids that follow a numbering (Figure 2c, Figure 2e), lettering (Figure 2b, Figure 2e), or a shape-based system were recommended [LV1-3, B1] to help users find, order, and match components when integrated with verbal instructions (Unit Task 2). The location of aids was recommended [LV1, LV2, B1, B3] to be placed near joints to help users find and distinguish between joints (Figure 2f) (Unit Task 3) and assist with alignment (Figure 2a, Figure 2d, Figure 2e) (Unit Task 4). Aids paired by color and texture were recommended [LV2] to help match symmetric components or attachment points (Figure 2d).

5 CONCLUSION AND FUTURE WORK

Our study identified several challenges BLV users face when assembling 3D-printed models unassisted. Participants encountered difficulties in understanding the role of individual components when identifying and selecting connecting pieces, particularly when they were unable to form a mental image of the object from its name alone. When working with a sighted mediator, participants frequently sought confirmation of component relationships, especially during initial assembly stages or when encountering complex joints. However, a structured, step-by-step verbal instruction set significantly reduced errors and reliance on trial-and-error by breaking down the process into manageable steps. These findings highlight the importance of robust mental imagery, real-time confirmation, and clear, systematic instructions to ease cognitive load and improve assembly success.

Despite these benefits, challenges remain. For certain models, locating and distinguishing joints from other features proved particularly difficult, as it often required exploring complex surface geometries that are hard to describe verbally. Participants exhibited a limited capacity to retain verbal instructions, emphasizing the importance of breaking them into digestible chunks and allowing users to explore at their own pace. Contrasting prior work on laser-cut assembly for BLV individuals [18], our work also highlights challenges associated with component orientation due to the 3D-nature of 3D-printed objects. This increased spatial complexity led to persistent orientation errors across all conditions, as shown in Table 2. The findings suggest that 3D-printed object assembly requires additional strategies for guiding orientation.

During the co-design, five out of six participants suggested augmenting models with tactile markers as spatial complements to verbal instructions. They proposed using markers with varying properties—such as shape, texture, and location—to encode critical information for assembly, including component identity and orientation, matching pairs of components and joints, and joint locations. Participants also recommended incorporating snap-fit joints with unique shapes to distinguish connectable joints and validate correct assembly. Further investigation into the implementation and effectiveness of these ideas are promising avenues for future work. Furthermore, the challenges and insights uncovered may inform other assembly applications, such as DIY consumer products including furniture. However, additional research is needed to confirm the generalizability of our results beyond 3D-printed contexts.

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