Augmented Reality Assisting the Assembly of Do-It-Yourself Furniture

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ABSTRACT
Furniture assembly is often perceived as a confusing and demotivating task, especially when relying on traditional manuals and/or online videos, which can be mis. Do It Yourself (DIY) furniture manufacturing can be even more challenging, as it requires not only assembly steps but also material fabrication stages, often demanding access to advanced technologies. This research introduces a set of DIY furniture designs and evaluates the use of WebXR to assist the assembly process. This study aims to assess the potential of AR in supporting the assembly of DIY furniture, identifying its benefits and challenges. The chosen research method was a proof-of-concept exploratory trial, which in turn was divided into three stages: (i) design of DIY furniture, (ii) development of AR tutorials to support furniture assembly, and (iii) user evaluation. These stages were integrated into undergraduate and graduate courses within teaching, research, and community outreach activities, thus fostering interdisciplinary collaboration, with undergraduates contributing to furniture design and assembly, while graduates focused on AR tutorial development. The data analysis was based on the participants' responses to the questionnaires following the furniture assembly. None of the participants had prior experience with AR tutorials. Nevertheless, all participants successfully assembled the proposed furniture: a table, a stool, and a chair. The assembly process, however, was hindered by the instability of the webXR system in keeping virtual objects fixed in space, the excessive grouping of tasks within each step, and the difficulty participants faced in identifying the furniture components. It was observed that the average assembly time was directly related to the level of complexity previously assigned to each piece of furniture. These findings highlight the need for improvements in the proposed experience. By leveraging AR technology, this project has the potential to improve accessibility to DIY furniture by providing autonomy in assembly tasks.
Keywords: Extended Reality, Tutorial, Mounting, User experience.

1 Introduction
Furniture assembly frequently presents significant challenges for users, mostly due to conventional assembly guides, frequently criticized for their confusing structure, poor-quality visuals, and lack of clarity in step-by-step instructions (Dixon; Terton; Greenaway, 2018; Huang et al., 2018). To make the process easier, many companies provide printed instruction manuals, usually including illustrations and step-by-step guidance (Donkor, 2010). However, such manuals may lack essential information for the proper development of the assembly process, which can compromise the user experience, making it frustrating and challenging, even for individuals with prior experience (ReclameAqui, 2025c, 2025b, 2025a).

The Do-It-Yourself (DIY) movement represents a growing tendency, especially in the furniture business, due to several factors such as the search for more economic options (Vyas, 2020), the customization of the housing environment (Wolf; McQuitty, 2013) and the pleasure of doing something handmade (Birau, 2025). DIY is a philosophy of life that encourages the design of objects needed in everyday life, allowing a reduction in consumption and generating greater savings in the development of these products (Wolf; McQuitty, 2011). Nowadays, there are several options for self-assembly furniture, from simple bookcases (Kirchmer, 2023) to complex structures (Usukhbayar; Jiang; Tanaka, 2023).

DIY activities are characterized by self-driven efforts in which individuals undertake tasks, such as assembling furniture using provided instructions and tools, without professional assistance (Spinillo; Fujita, 2012; Watson, 2012). People are motivated to engage in DIY activities, including furniture assembly, due to economic benefits and the lack of product availability (Wolf; McQuitty, 2011). This approach democratizes the access to furnishings, making it more financially viable and adaptable to individual needs (Mettler et al., 2023).

DIY furniture projects can range from simple repairs and modifications to entirely custom-built pieces, often reflecting individual style, sustainability values, and cost-effectiveness (Buechley et al., 2009; Fox, 2014). Customary characteristics of DIY furniture include creativy and customization (Buechley et al., 2009; Fox, 2014), use of modular designs of (Altehenger, 2022), and sustainability (Ankarberg; Terzioğlu; Sundin, 2023).

The pandemic years had great collaboration in the development of this movement, because of the general isolation and lockdown all over the world, which encouraged people to handcraft abilities and to become independent of outsourced services (Mantz, 2021). Moreover, technology and social media helped spread the mindset of the DIY movement, encouraging people through Youtube tutorials, TikTok "how to…" videos and Facebook groups (Pišl, 2023).

The assembly process typically involves using tools and following step-by-step pictorial instructions to guide the construction (Spinillo; Fujita, 2012). In order to assist these assembly tasks, Augmented Reality (AR) systems allow people to view virtual instructions and technical information overlaid on the physical world, in real time (Dargan et al., 2023).This is particularly useful in this context, where visualization of assembly steps and interaction with three-dimensional models can facilitate the understanding and execution of complex tasks (Chytas et al., 2020). Studies show that AR not only improves knowledge retention but also reduces the time needed to reach proficiency (Raj et al., 2024).

The immersive technologies have great potential as support to assembly tasks (Di Pasquale et al., 2024), especially with the possibility of developing applications in Web Extended Reality (WebXR) Application Programming Interface (API). This API enables the creation and deployment of XR applications (such as Virtual Reality and AR) directly from the browser of different mobile devices, regardless of platform and independent of installed apps (Yang et al., 2021). It is noteworthy that one of the lead researchers in the current study has applied the AR experience in assembly of wood frame panels (Cuperschmid; Grachet; Fabrício, 2016), verifying the expansion potential to DIY furniture, this having even more execution ease in comparison to wood frame panels that have the weight and dimension difficulties.

Hence, the main objective of this research is to introduce a set of DIY furniture designs and presents a prototypical study that evaluates the use of webXR to assist the assembly process. This study aims to assess an initial overview of the potential of AR in supporting the assembly of DIY furniture, identifying its benefits and challenges. In order to attain this purpose, this study shall collect data related to: I) assembly process, II) user experience with AR, and III) participant well-being during experiments. This endeavour seeks to democratize access to self-assembly furniture, facilitating the process by overcoming the limitations of traditional manuals and enhancing the user experience. The results of this research have the potential to contribute to the continuous improvement of AR-based assembly support systems.

2 Theoretical Background

2.1 DIY movement

The DIY movement emerged in the 1910's in the United States, gaining strength with post-war scenario of home improvement, and its essence lies in encouraging people to manufacture and repair products such as furniture objects in an artisanal way, with easily available tools and raw materials, normally found at home, without the help of professionals, "doing it yourself" (Atkinson, 2006).

The production processes of materials and consumer goods have undergone significant changes over time. In the 1960s, a gap was observed between the quality parameters of manufactured products and the high expectations of customers. Efforts to improve product quality to meet these expectations led to increased final costs, which affected the cost-benefit balance of products (Matuszek & Seneta, 2020). This phenomenon spurred a pursuit of efficiency in production processes, involving the elimination of unnecessary components and the reduction of manufacturing time, which led to the development of the "Design for Assembly" (DFA) method (Moultrie; Maier, 2014). Once tested and adopted by large corporations, DFA proved highly valuable, making production processes considerably more economical (Boothroyd; Dewhurst; Knight, 2002).

Design for Assembly (DFA) is a design and evaluation approach focused on simplifying product assembly, reducing costs, and improving efficiency and quality. DFA seeks to minimize components and steps in the assembly process, delivering quantifiable benefits such as enhanced efficiency and cost savings (Boothroyd; Dewhurst; Knight, 2002). DFA principles can be applied across various industries, including furniture manufacturing and construction. These principles include design simplification, standardization, modularity, accessibility, minimization of fasteners, symmetrical design, reduction of adjustments, and fewer assembly steps. The correlation between assembly efficiency and the Assembly Efficiency Index (AEI) is crucial for validating DFA's effectiveness in specific projects (Zhai et al., 2023).

In addition to advancements in production processes, cultural changes in consumer preferences have influenced product design (Mohammed Yousif; Ramirez, 2024). The demand for environmentally friendly products, longer lifespans, and socially responsible corporate policies are just some of the challenges the industry has faced in recent years to meet market demands. Among these cultural shifts, the DIY movement stands out, gaining widespread adoption, particularly in developed countries like Germany, the UK, and the USA, where labor costs are high (Spinillo; Fujita, 2012). For DIY-oriented products, assembly is performed by end-users rather than specialized labor. This unique aspect impacts both the design process and the way assembly instructions are communicated to users.

Replicability is essential in DIY, depending on the replicator's personal skills and the availability of specific tools to define the complexity and difficulty of the task. In their research, revealed that around 8% of YouTube tutorials do not work and that a potential replicator would waste time and resources if they replicated it.

According to (Richardson, 2004a), some perceptions also alter the user's notion of difficulty, such as the number of components in the set and the step in question in a visual way. An alternative would be to separate the parts into packages according to the assembly phase. Avoiding repeating instructions for the same steps in different phases also helps to reduce the perception of difficulty, given the reduction in the volume of instructions. In parts with three-dimensional orientations, spatial confusion is very common, so ensuring that the fixing points are distinct in order to avoid positioning inaccuracy minimizes the possibility of error and the perception of difficulty, as well as the use of symmetrical components in order to reduce the mental load in the correct positioning of the fittings.

It is relevant to mention some guidelines to support the creation of DIY tutorials (Lahaye et al., 2023a), among them the use of a concise, clear and explanatory title; a thumbnail image (presentation) with a complete and well-lit view of the final object; a complete list of necessary materials and estimated completion time; photos of the tools in order to simplify their identification; describe the uniqueness and purpose of the project; pay attention to risks to the health of the user and the assembler; guide the necessary precautions and good practices; provide an index and the structure of the tutorial chronologically; detail the steps; list all the tools to be used in the step at the beginning of the explanation of the phase in question; inform about common errors and viable alternatives; merge videos and texts; provide references; link to other tutorials when necessary, considering that many external links can intellectually overload the user and provide supplementary files whenever necessary.

When comparing the instructional article and the instructional video, it was observed that videos and instructional articles practically do not differ in content, but rather in the presentation of information. According to (Behnke et al., 2019), the main characteristic of good instruction should be perceptive simplicity regardless of the level of personal skill. Visualizing the process, more than just writing it down, helps the person being instructed to imagine and compare their results, but the trend of videos on the web is towards short guides rather than complete tutorials . In their research, (Grom; Bytsan, 2022)revealed that around 8% of YouTube tutorials do not work and that a potential replicator would waste time and resources if they replicated it. As a growing concept, the DIY movement and its developments, like tutorials and furniture, can benefit from immersive experiences, bringing novelty and improvement to this field.

2.2 AR for furniture assembly

Extended Reality (XR) encompasses immersive technologies such as Virtual Reality (VR), AR and Mixed Reality (MR) (Khan, 2022). XR technologies have grown exponentially, offering versatile applications across industries like healthcare, entertainment, and manufacturing (Delaney, 2023; Stacchio et al., 2023; Choi; Lee, 2024). Interaction with XR is enabled through devices like head-mounted displays (HMDs), locators, and hand controllers (Li et al., 2020).

AR builds on VR by blending virtual objects into the real world, allowing real-time interaction (Liu; Zhang, 2013) This is adequate in this research with the object furniture that are being assembly in the real world. WebXR combines the use of XR with the flexibility of a web browser, enabling the rapid and creative development of immersive experiences (SIGGRAPH, 2021). This means that there is accessibility to use XR technologies directly from web pages, without the need to install additional applications or plugins. With this, users can access XR content through devices such as smartphones, tablets, computers and VR/AR headsets, using browsers such as Google Chrome or Mozilla Firefox. This makes these experiences more accessible and democratizes access to immersive technology (Li et al., 2020).

AR has been applied to assembly tasks to enhance visualization and instructional processes. For instance, the AR-oriented Information Planning System (ARIPS) and the AR-based Assembly Instruction System (ARAIS) are notable examples, where ARIPS helps process engineers generate assembly files, and ARAIS provides shop floor workers with augmented visualization for precise execution of assembly operations (Li et al., 2018). Similarly, the Allview framework explores the integration of XR, including AR, in Vocational Education and Training (VET) for the Woodworking and Furniture (W&F) sector. This research focuses on developing immersive training environments, combining tools like VR, MR, and 360° videos, to enhance digital and sustainable assembly practices (Leal-Enríquez; Gutiérrez-Antúnez, 2024). These applications demonstrate AR's potential to optimize assembly instructions and foster transformative training methodologies.

The interactivity and visualization can enrich the process in furniture assembly with the potential of reducing cognitive workload by offering intuitive visual cues and step-by-step instructions, making the assembly process more manageable for first-time users (Deshpande; Kim, 2018a). Techniques that parse assembly instructions and reconstruct 3D models of furniture components can animate the assembly process and helps users visualize each step and understand the sequence of actions required, thereby reducing errors and assembly time (Shao et al., 2016b).

The use of AR provides engineering simulations with a smaller margin of error, increasing the accuracy and efficiency of planning and execution processes (Zhao et al., 2023). Furthermore, AR can be used to train workers and construction teams, providing a better understanding of construction processes and procedures, thereby contributing to shorter construction time and less waste (Xu; Moreu, 2021). It has also been explored in the context of furniture, enhancing user experience. IKEA's mobile application allows customers to seamlessly integrate virtual furniture into their physical environments, highlighting the significant impact of interactivity and novelty in the shopping process (Ozturkcan, 2021).

Similarly, AR-based assembly instruction systems, such as the interactive application proposed by (Chikaraddi et al., 2022), provide scalable and sustainable solutions for guiding furniture assembly, leveraging evolving technologies for diverse deployment scenarios. Moreover, AR technology has been employed to replicate furniture arrangements, enabling users to customize interiors and explore layouts interactively without physical objects, thus addressing time-intensive processes associated with traditional furniture purchases (Mohan et al., 2022).

Closer to the aim of this work, particularly for Ready-to-Assemble (RTA) furniture, an experimental study using an AR application demonstrated its benefits for first-time users, especially when assembling more complex furniture highlighting the need for well-designed visual features and interaction modes in AR applications and providing insights to guide the development of performance-driven tools for spatially demanding assembly tasks (Deshpande; Kim, 2018a). These advancements demonstrate AR's potential role in furniture-related applications, from design visualization to assembly guidance.

3 Materials and Methods

This study was designed as a proof-of-concept exploratory trial, involving three main stages: i) design of the furniture pieces (table, stool and chair) during an undergraduate course; ii) creation of an AR system for assembly and; iii) user evaluation.

3.1 Furniture design

To develop the furniture, a community outreach course was offered in the second semester of 2023 for undergraduate students of Civil Engineering and Architecture. In this discipline, reference research was carried out and furniture designs were developed for indoor common areas. The use of accessible furniture assembly materials and equipment, such as pine boards, and cutting services commonly offered by home centers similar to circular and jig saws in order to disseminate furniture assembly in all economic and geographic layers of Brazil.
The initial resulting design proposals from the course were prototyped on a reduced scale using additive FDM 3D printing techniques and subsequently evaluated for their stability, ease of assembly and overall design. t was observed that many of the resulting designs included complex cuts and fittings, in addition to large dimensions.

This would be discouraging for carrying out assembly tasks considering the execution time and amount of material required, as well as requiring extensive previous experience of the user, contrary to the observed DIY principles observed in the literature (Collier; Wayment, 2018).

Hence, a set of tables, chairs and stools were chosen among the furniture designs developed in the course (Figure 1). The selected designs presented an interesting set for evaluation purposes for the current research, as they had progressive levels of assembly complexity, the stool being the simplest, followed by the table and chair (Figure 2). This is due to the parts' weight, difficulty of assembly, number of assembly steps, dimensions of the resulting furniture design, as well as the dimensions of its parts and its quantity. Those characteristics were observed to be desirable in DIY (Podskarbi et al., 2017).

Figure 1: Set of furniture designed by undergraduate students.

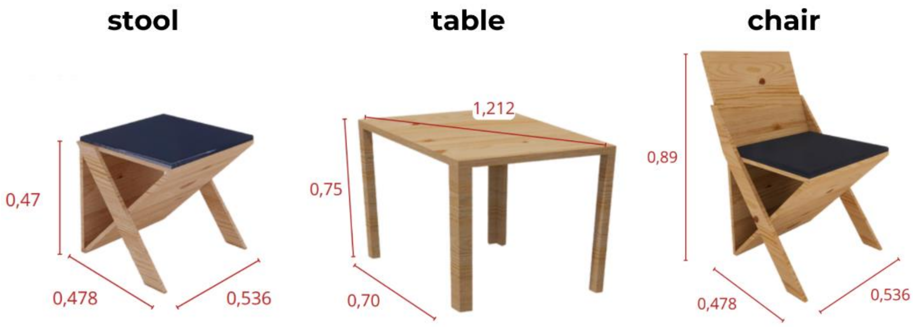


Figure 2: Pieces of furniture with their dimensions.

3.2 Creation of the AR application

The development of the aforementioned AR application came to pass in a course "AR in Architecture" offered to postgraduate students of the UNICAMP's "Arquitecture, Tecnology and City"program in the first semester of 2024, in a course that discussed the implications of AR within the realm of architecture. Therefore, masters' and doctoral students enrolled in the course discussed and reflected upon the theme, ultimately coming up with possible manners of elaborating AR applications for furniture design assembly (Figure 3).

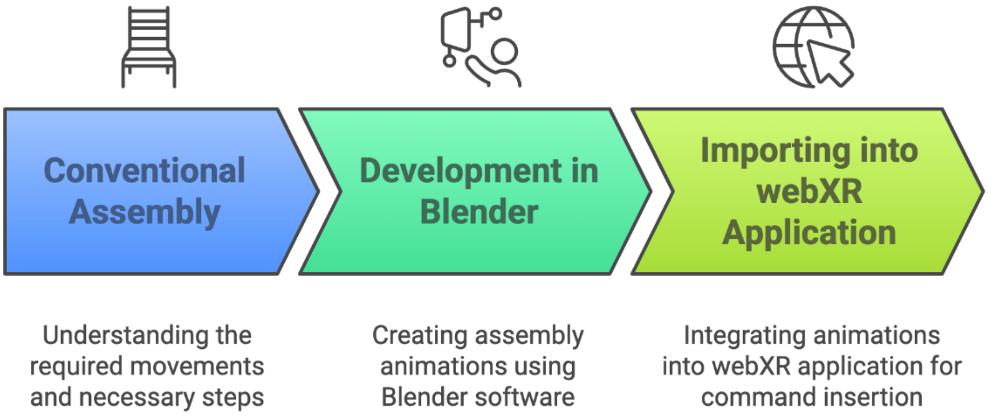


Figure 3: Creation of AR application workflow.

There, the applications and user evaluation protocol were developed as an initiative involving the creation of animations and applications in WebXR. The development of the AR tutorial was structured as an iterative process, prioritizing application performance based on the planned assembly steps. The initial phase involved analyzing the physical assembly of the furniture to understand the required movements and steps, such as the correct placement of screws and fittings. This analysis was crucial to ensure that the instructions conveyed in the AR tutorial were accurate and aligned with real-world assembly processes.

The animations for the tutorial were created using Blender, an open-source 3D software selected for its advanced animation capabilities and compatibility with AR platforms. Furthermore, its support for the .glb file format, a widely recognized standard for AR applications, ensured seamless integration with WebXR no code applications. The furniture models, initially designed in SketchUp during the Atelier course, were imported into Blender for the animation development.

The animation creation process within Blender involved several key steps. First, the 3D models were imported and organized into layers, with components grouped logically to facilitate efficient animation workflows. Each assembly step was animated using keyframes to ensure smooth transitions, including actions like aligning parts, inserting screws, and fitting joints. Camera angles and lighting within Blender were adjusted to highlight critical actions, enhancing the instructional clarity of the animations. Once completed, the animations were exported in the .glb format, maintaining compatibility with the AR platforms used for tutorial deployment (Figure 4).

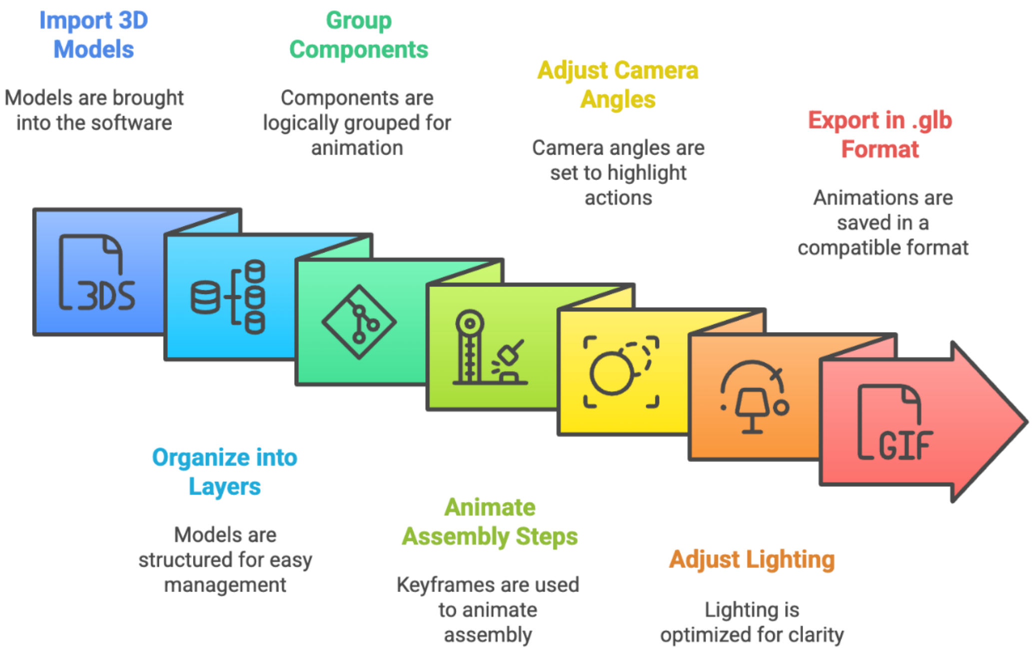


Figure 4: Animation creation workflow.

To choose an application, a survey of no-code applications for smartphones (Table 1) was carried out. Based on this data, tests were carried out on apps that offered a free version with no time limit. Among them, XR+ was chosen (XR+, 2024), which offered different types of tracking, the possibility of a mobile simulator and the availability of all the features in the free version. However, it is worth noting that there was a limit of 5 scenes per project.

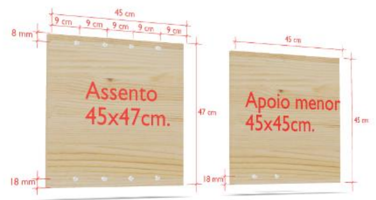
Table 1: Survey of webXR applications

APP	3D format	File size limits	Trial version	Pricing	Tracking
8th Wall[1]	.glb	100 MB	Basic plan free	Pro: US$ 99/month	Image Face Hand Real-world location
Awe[2]	.OBJ; .FBX; .GLB	20 MB	Basic plan free	Plus: US$ 12/month Lite branded: US$ 89/month Custom branded: US$ 149/month	Image Face AR Real-world location
Easy AR[3]	.MB; .MA; .MAX; .JAS; .C4D; .BLEND; .LXO; .FBX; .DAE; .XSI; .SKP; .3DS; .OBJ; .DXF	--	Personal Edition free	Professional: $39,00/month Classic: $1399/month	Image 3D object Surface Sparse Spatial map
Hololink[4]	.GLB; GLTF; .USDZ	10MB	30 days	Personal: US$ US$ 9 /month Basic: US$ 29 /month Pro: US$ 99 /month Business: US$ 159 /month	Image Simple Surface
MyWeb AR[5]	.GLB	15MB	14 days	Pro: US$ 25/month Ultimate: US$ 399/month Ultimate Plus: US$ 990/month Phygital Marketing: US$ 1200/month	Image QR Code Curved Image Real-world location
Onirix[6]	.FBX; .OBJ; .GLB	Polygons: 200.000; Vertex: 500.000; Nodes: 100; Texture Size: 1.000	15 days	Starter: EU$ 45/month Profissional: EU$ 299/month Get Scale: EU$ 1499/month	Image Rotation Real-world location Spatial
Web AR Studio[7]	.GLB; .GLTF	25MB	Non-commercial version free	Standard: US$ 8/month Business: US$ 24/month Unlimited: US$ 110/month	Photo QR Code Surface Real-world location
XR+[8]	.OBJ; .FBX; .GLB	20MB (free version); 50MB (paid version)	Non-commercial version free	Advanced: US$ 109,00/month Super: US$ 439,00/month	SLAM Image Face Body (paid version)

[1] Available at <https://www.8thwall.com> . Accessed on 17 april 2024.
[2] Available at <https://awe.media/> . Accessed on 17 april 2024.
[3] Available at <https://www.easyar.com/> . Accessed on 17 april 2024.
[4] Available at <https://www.hololink.io/> . Accessed on 17 april 2024.
[5] Available at <https://mywebar.com/> . Accessed on 17 april 2024.
[6] Available at <https://www.onirix.com/> . Accessed on 17 april 2024.
[7] Available at <https://web-ar.studio/pt/> . Accessed on 17 april 2024.
[8] Available at <https://xr.plus/> . Accessed on 17 april 2024.

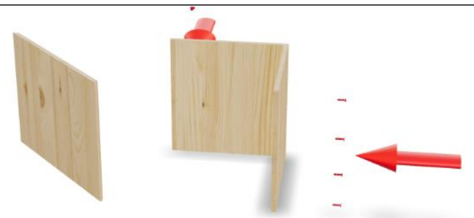
The animations were then imported into the chosen WebXR application. The XR+ provided the environment for integrating the animations with additional instructional elements, such as written and audio commands, to enhance user understanding and interaction. The tutorials contained 5 scenes in the case of the stool (Figure 5) and 4 scenes in the case of the table (Figure 6) and the chair (Figure 7).

1- **Organize the parts** (smaller support, larger support, legs, seat, and cushion).



2- Mark and drill 4 holes on two sides of the seat and 4 holes on one side of the smaller support.

3- Attach the seat to the smaller support using 4 screws.



4- Attach the larger support to the smaller support and then to the seat using 8 screws.

5- Attach the pair of legs with 4 screws on each leg, and place the cushion on top of the seat.

Figure 5: Stool Assembly.

1- Organize the parts (boards, legs, angle brackets, and screws).

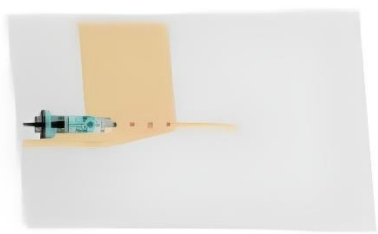
2- Attach the legs to the tabletop using the large screws.

3- Secure two angle brackets to each of the table legs.

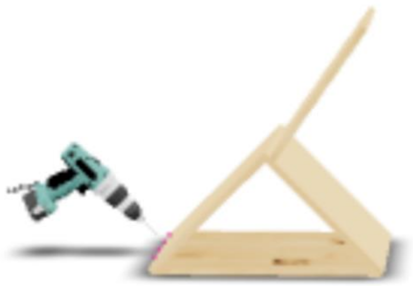
4- **Align and attach** the finishing top to the tabletop using the small screws.

Figure 6. Table Assembly.

1- With the pre-drilled pieces, position the seat at a 90-degree angle to the support and attach the seat to the rear support using 4 screws.



2- Attach the backrest to the seat + rear support assembly using 4 screws.



3- Secure the front support to the backrest + seat + rear support assembly using 4 screws (connecting the front support to the rear support) and 4 screws (connecting the front support to the seat).

Attach the legs to the assembled structure using 6 screws on each side of the chair (2 connecting the leg to the front support, 2 connecting the leg to the seat, and 2 connecting the leg to the backrest).

Figure 7. Chair Assembly.

3.3 User Evaluation

The target group selected for this experiment consisted of undergraduate students in Civil Engineering and Architecture, enrolled in elective university extension course at Unicamp, a public Brazilian university, during the second semester of 2024. According to enrollment records, their average age ranged from 19 to 23 years. These students have academic backgrounds aligned with the topics addressed in the study—such as assembly, design, and spatial reasoning—although most had limited prior experience with DIY furniture assembly. This lack of experience enabled a clearer evaluation of the impact of using an AR-based tutorial. Furthermore, the group is representative of the broader Brazilian population, with many students coming from less privileged socioeconomic backgrounds, which highlights both the democratizing potential of the DIY movement and the social relevance of this research.

The thirty-four enrolled students were first- and second-year students from the Civil Engineering and Architecture and Urbanism programs of UNICAMP. None of them had significant prior experience with DIY furniture assembly; only a small portion of the students had assembled simple furniture sold in retail stores with the aid of paper and/or pdf manuals. Thus, a woodworking activity was conducted involving the use of a drill, belt sander and jigsaw, customary DIY furniture assembly tools.

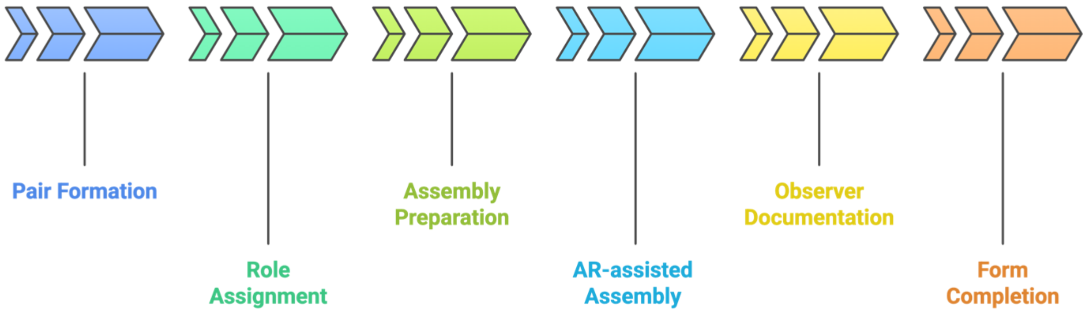


Figure 7: User Experience Process.

To this end, the user evaluation process was submitted to Plataforma Brasil and the UNICAMP Research Ethics Committee and authorization for human research was obtained in July 2024 (Certificate of Presentation of Ethical Appreciation, CAAE: 80547924.0 .0000.8142; CEP: 6.958.238), thus obtaining the necessary ethical aproval parameters for analogous researches as according to Brazilian law. The consent forms were signed by the students who voluntarily wanted to participate.

Followingly, the individual furniture assembly istelf began on the physical model laboratory within the university campus, supervised by a lab technician and monitored by researchers. Previously cut wooden pieces, screws, glue, a tape measure, and a screwdriver were placed on a table for each participant. A total of thirty (30) people participated in the experiment, with fifteen (15) assembling stools, seven (7) assembling chairs, and eight (8) assembling tables.

It is worth mentioning that none of the students had any previous experience with AR tutorials or similar geared towards furniture design. The beginning and finishing times of the assembly process were marked and observed throughout the assembly. Difficulties, errors, spontaneous comments, repetitive gestures, and challenges encountered during the assembly or in using the AR application were documented as well as suggestions and participant feedback. Additionally, photographs were taken of the results and specific moments during the assembly for later evaluation. Each student assembled only one piece of furniture (no one repeated the assembly process with different items).

4 Results

After completing the furniture assembly using the AR-assisted process, users were asked to fill out an evaluation form. The form used a Likert scale ranging from 0 to 5 divided into three sections: I) Assembly process (10 questions), II) User experience with AR (6 questions), and III) User well-being during experiments (4 questions). The emphasis on user-centered design aimed to provide vital insights into the system's practical and ergonomic impact.

4.1 Assembly process

Based on the forms' answers it was observed varying levels of satisfaction and ease across the three types of furniture. The initial explanations (Q1) were perceived positively, especially for the table (85.7% strongly agreed or agreed) and stool (71.4%), while the chair had more neutral or disagree responses, suggesting some users had difficulty understanding the tutorial's dynamics for this item. Identifying assembly parts (Q2) was easy for users, particularly for the table, with 85.7% strongly agreeing or agreeing, while the chair showed a lower percentage of ease in identifying parts, reflecting some difficulty in this task. Users generally felt confident in following the tutorial steps (Q3) and performing the assembly (Q4), with most agreeing that the steps were clear and manageable, particularly for the table and stool. The chair, however, had more mixed results, with a higher proportion of users finding the assembly steps and process less intuitive (Table 2).

User satisfaction and confidence were generally high across the furniture types. Most participants felt satisfied with their performance (Q5) in the assembly process, particularly with the stool, where 92.9% of users strongly agreed or agreed with their satisfaction. The safety of the assembled furniture (Q8) was also a strong point, with the majority of users feeling confident in the stability of their furniture, particularly for the stool and table. As for future use of AR tutorials (Q9 and Q10), there was a notable increase in confidence and comfort, particularly for the stool and table, with most users agreeing they would be able to assemble similar items without the tutorial.

However, the chair still saw lower comfort levels, indicating that while the AR system was effective, users felt less confident about replicating the task without further assistance (Figure 8).

Table 2: Collected data from users about assembly process statements.

Stool	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10
Strongly agree (5)	6,25%	18,75%	0,00%	6,25%	43,75%	25,00%	43,75%	50,00%	43,75%	12,50 %
Agree (4)	31,25%	18,75%	37,50%	37,50%	43,75%	25,00%	25,00%	43,75%	37,50%	25,00 %
Neutral (3)	50,00%	25,00%	37,50%	31,25%	6,25%	6,25%	18,75%	6,25%	0,00%	31,25 %
Disagree (2)	12,50%	25,00%	18,75%	25,00%	0,00%	37,50%	12,50%	0,00%	12,50%	18,75 %
Strongly disagree (1)	0,00%	12,50%	6,25%	0,00%	6,25%	6,25%	0,00%	0,00%	6,25%	12,50 %
Table	**Q1**	**Q2**	**Q3**	**Q4**	**Q5**	**Q6**	**Q7**	**Q8**	**Q9**	**Q10**
Strongly agree (5)	57,14%	85,71%	71,43%	14,29%	28,57%	42,86%	14,29%	42,86%	71,43%	57,14 %
Agree (4)	28,57%	0,00%	14,29%	57,14%	42,86%	14,29%	57,14%	28,57%	14,29%	14,29 %
Neutral (3)	14,29%	14,29%	0,00%	28,57%	14,29%	28,57%	28,57%	0,00%	0,00%	0,00%
Disagree (2)	0,00%	0,00%	14,29%	0,00%	14,29%	14,29%	0,00%	28,57%	0,00%	14,29 %
Strongly disagree (1)	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	0,00%	14,29%	14,29 %
Chair	**Q1**	**Q2**	**Q3**	**Q4**	**Q5**	**Q6**	**Q7**	**Q8**	**Q9**	**Q10**
Strongly agree (5)	0,00%	0,00%	12,50%	0,00%	12,50%	0,00%	0,00%	37,50%	12,50%	12,50 %
Agree (4)	25,00%	0,00%	62,50%	0,00%	12,50%	12,50%	25,00%	37,50%	0,00%	12,50 %
Neutral (3)	25,00%	25,00%	25,00%	50,00%	25,00%	50,00%	25,00%	12,50%	62,50%	12,50 %
Disagree (2)	50,00%	25,00%	0,00%	37,50%	37,50%	37,50%	37,50%	12,50%	12,50%	37,50 %
Strongly disagree (1)	0,00%	50,00%	0,00%	12,50%	12,50%	0,00%	12,50%	0,00%	12,50%	25,00 %

Q1: The initial explanations were sufficient to understand the dynamics of the AR tutorial
Q2: I found it easy to identify the parts for assembly
Q3: The tutorial showed exactly the steps I should take
Q4: I found it easy to carry out all the assembly steps
Q5: I felt satisfied with how well I performed and completed the task using AR
Q6: I did not have any physical difficulties during the assembly process (parts that were too heavy, handling the tools)
Q7: I feel that I assembled the furniture quickly
Q8: Would you feel safe using the furniture you assembled?
Q9: After assembly with the AR tutorial, would it be possible to assemble the same piece of furniture again without the tutorial?
Q10: I feel comfortable assembling another piece of furniture using an AR tutorial?

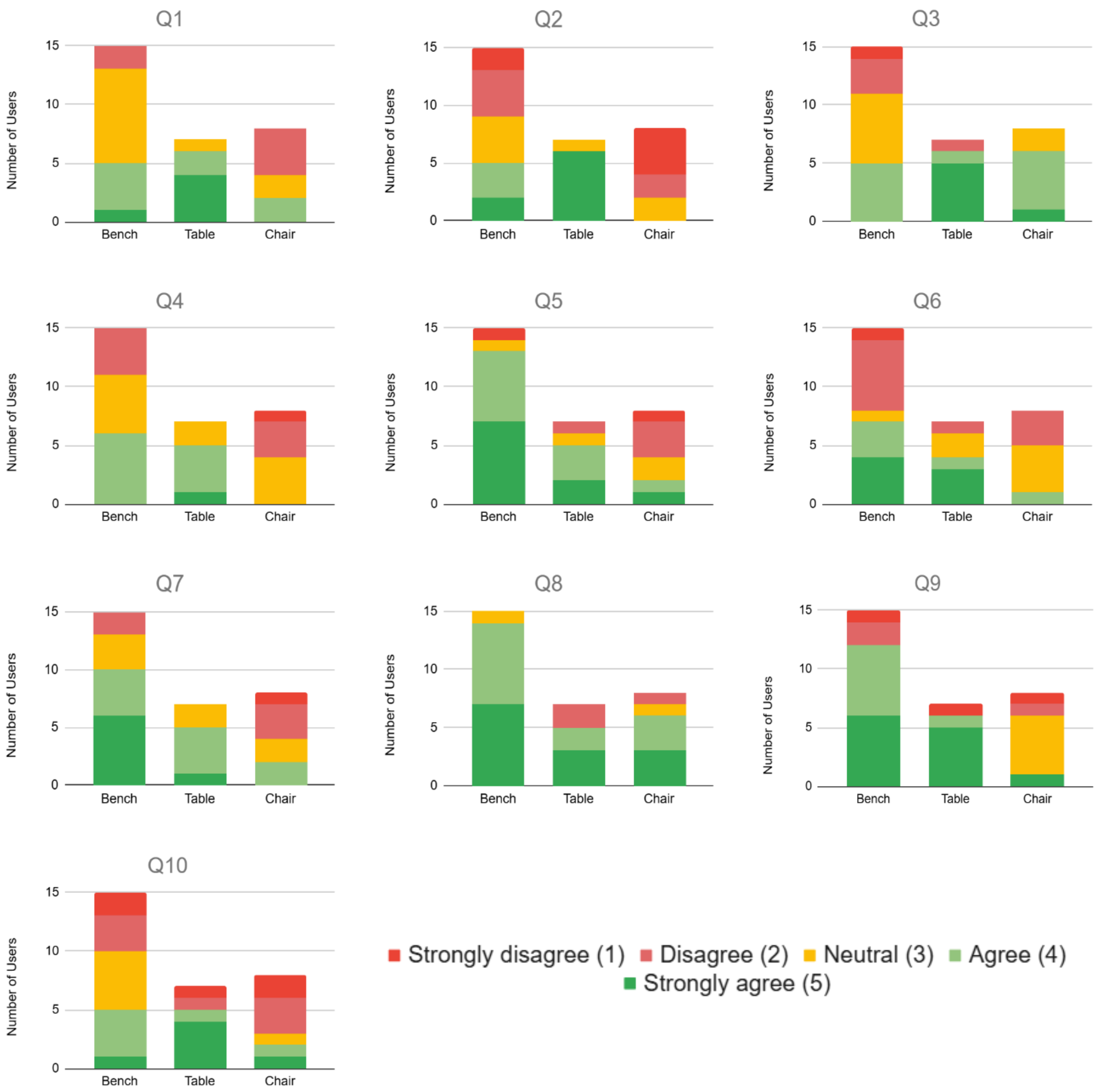


Figure 8: Visual scale of the furniture pieces for the assembly process statements.

4.2 User experience with AR

Approaching the AR application itself, the collected data reveals distinct user experiences across the stool, table, and chair assembly processes using AR. The table consistently outperformed the other furniture items in terms of usability and effectiveness. For instance, navigation between assembly steps (Q11) was easiest for the table, which achieved relatively better feedback regarding the naturalness of digital object overlays (Q12) and technical reliability (Q15), with fewer users reporting significant issues like crashes or slowdowns. However, even for the table, there were notable challenges, as evidenced by mixed responses about immersion (Q14) and novelty (Q16), where only a small portion of users found the experience extraordinary (Table 3).

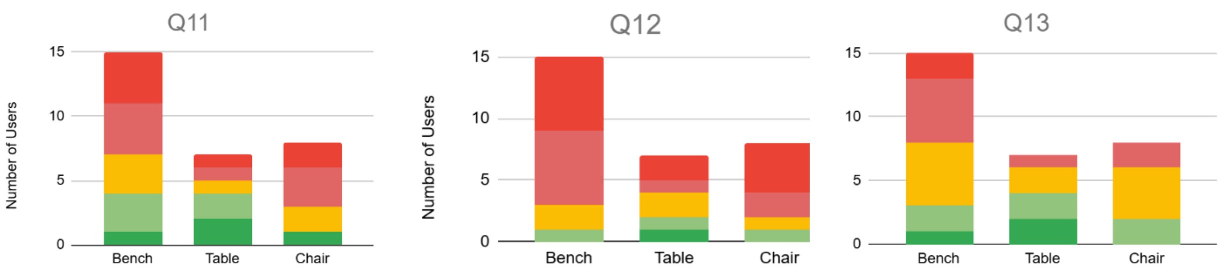
In contrast, the stool and chair assemblies encountered more pronounced issues with the majority of negative feedback. For the stool, responses highlighted difficulties navigating steps (Q11) and a lack of smooth digital overlays (Q12), with six participants strongly disagreeing about the naturalness of AR integration. The chair faced similar struggles, particularly with immersion (Q14) and technical reliability (Q15), where the majority of users disagreed or strongly disagreed about the seamlessness of the experience.

Across all items, the perceived novelty and engagement of the AR system (Q16) were modest, indicating a need for enhanced features to better captivate users. These findings suggest the AR system is more effective for simpler assemblies (like the table) but requires significant refinement to improve its intuitiveness, immersion, and overall user satisfaction for more complex tasks (Figure 9).

Table 3: Collected data from users about experience with AR statements.

Stool	Q11	Q12	Q13	Q14	Q15	Q16
Strongly agree (5)	6,25%	0,00%	6,25%	0,00%	12,50%	0,00%
Agree (4)	18,75%	6,25%	12,50%	0,00%	0,00%	31,25%
Neutral (3)	18,75%	12,50%	37,50%	31,25%	0,00%	37,50%
Disagree (2)	31,25%	43,75%	31,25%	31,25%	25,00%	25,00%
Strongly disagree (1)	25,00%	37,50%	12,50%	37,50%	62,50%	6,25%
Table	Q11	Q12	Q13	Q14	Q15	Q16
Strongly agree (5)	28,57%	14,29%	28,57%	14,29%	28,57%	14,29%
Agree (4)	28,57%	14,29%	28,57%	14,29%	0,00%	14,29%
Neutral (3)	14,29%	28,57%	28,57%	28,57%	14,29%	28,57%
Disagree (2)	14,29%	14,29%	14,29%	0,00%	14,29%	42,86%
Strongly disagree (1)	14,29%	28,57%	0,00%	42,86%	42,86%	0,00%
Chair	Q11	Q12	Q13	Q14	Q15	Q16
Strongly agree (5)	12,50%	0,00%	0,00%	0,00%	0,00%	0,00%
Agree (4)	0,00%	12,50%	25,00%	0,00%	12,50%	12,50%
Neutral (3)	25,00%	12,50%	50,00%	12,50%	25,00%	25,00%
Disagree (2)	37,50%	25,00%	25,00%	37,50%	25,00%	37,50%
Strongly disagree (1)	25,00%	50,00%	0,00%	50,00%	37,50%	25,00%

Q11: Was it possible to easily navigate between the different stages of assembly using the tutorial?
Q12: The superposition of digital elements in the real environment was natural and intuitive?
Q13: The colors and texts made it easier to understand the tutorial?
Q14: I felt completely immersed in the digital environment created by AR during the assembly process?
Q15: There were no technical problems, such as slowness, crashes or loss of tracking of digital objects?
Q16: When using this AR system, I felt involved in something extraordinary, was it a novelty?



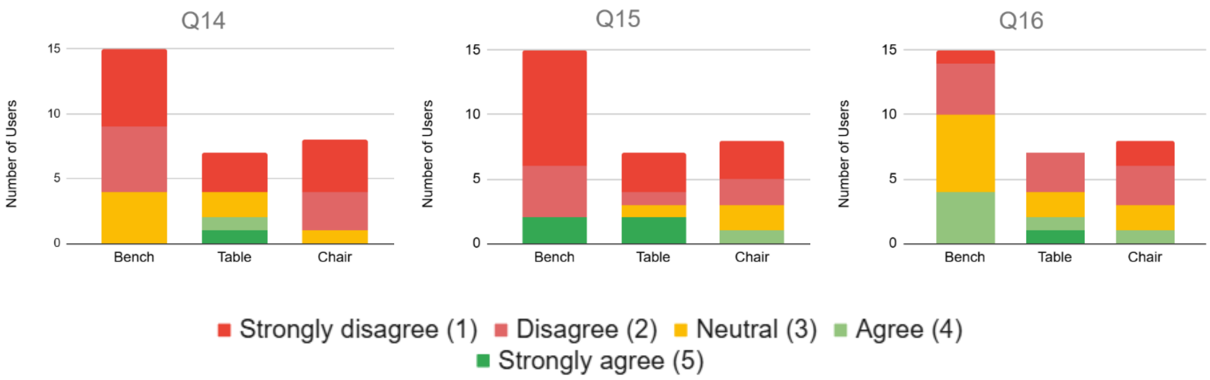


Figure 9: Questionary about the experience with AR.

4.3 User well-being

The users' responses about their well being during the experience with AR suggests that user well-being during furniture assembly varied depending on the furniture type. Most users did not find the assembly process tiring (Q18), particularly for the stool and table, where 78.6% and 85.7% of respondents, respectively, either strongly agreed or agreed. However, this percentage does not coincide in the case of the chair, where only 50% felt the same, confirming the initial knowledge that the chair assembly process required more effort. Similarly, when evaluating the comfort of using a smartphone during assembly (Q17), opinions were mixed. While some users agreed about its comfort (21.4% for the stool, 14.3% for the table, and 21.4% for the chair), a substantial proportion found it neutral or disagreed, with the stool and chair receiving the most negative responses, highlighting potential ergonomic issues or the strain of prolonged smartphone use (Table 4).

Regarding motivation and task performance, the AR system received moderate ratings. Users generally felt encouraged and motivated to complete the task (Q19), especially for the table and stool, where 50% and 42.9% agreed or strongly agreed. In contrast, the chair had a higher percentage of neutral responses (35.7%), indicating that users felt less motivated while assembling it. The AR system was effective in ensuring error-free assembly on the first attempt (Q20) for most tasks, particularly for the table, where 71.4% of users agreed or strongly agreed. The stool and chair also showed satisfactory results, with 50% and 35.7% of users agreeing, respectively. Overall, while AR positively impacts users' well-being for simpler tasks like the stool and table, improvements in ergonomics, user motivation, and fatigue management are necessary, especially for more complex tasks like the chair assembly (Figure 10).

Table 4: Collected data from users about well-being statements.

Stool	Q17	Q18	Q19	Q20
Strongly agree (5)	6,25%	50,00%	6,25%	25,00%
Agree (4)	12,50%	25,00%	37,50%	25,00%
Neutral (3)	31,25%	0,00%	25,00%	18,75%
Disagree (2)	37,50%	18,75%	25,00%	18,75%
Strongly disagree (1)	12,50%	6,25%	6,25%	12,50%
Table	Q17	Q18	Q19	Q20
Strongly agree (5)	14,29%	57,14%	14,29%	28,57%
Agree (4)	14,29%	28,57%	42,86%	42,86%
Neutral (3)	57,14%	0,00%	14,29%	14,29%
Disagree (2)	0,00%	14,29%	28,57%	14,29%
Strongly disagree (1)	14,29%	0,00%	0,00%	0,00%
Chair	Q17	Q18	Q19	Q20
Strongly agree (5)	12,50%	25,00%	12,50%	12,50%
Agree (4)	25,00%	37,50%	12,50%	50,00%
Neutral (3)	25,00%	25,00%	62,50%	0,00%

Disagree (2)	25,00%	12,50%	0,00%	12,50%
Strongly disagree (1)	12,50%	0,00%	12,50%	25,00%

Q17: Using the smartphone for AR during assembly was comfortable?
Q18: I did not feel tired during assembly?
Q19: When I was using the AR system, I felt encouraged and motivated to complete the task?
Q20: Using the AR system I was able to complete the task without errors, on the first attempt

Figure 10: Results obtained from the questionnaire on user well-being.

4.4 Observations

During the assembly process observations were made about the general assembly, especially regarding the problems observed in the experience highlighting several recurring issues that impacted the assembly experience and were not approached in the Likert scale objective questions. A significant number of observations (Figure 11) approached challenges related to furniture and parts handling indicating that the physical interaction with the components was a considerable concern. This was closely followed by issues with parts identification, confirmed by the assemblers' comments, suggesting that users may have struggled to visually or contextually match the components during the assembly(Figure 12). It was also noted the existance of problems with the holes previously made, since they were misaligned with other parts of the furniture, resulting in errors during the assembly and, consequently, instability of the furniture itself (Figure 13).

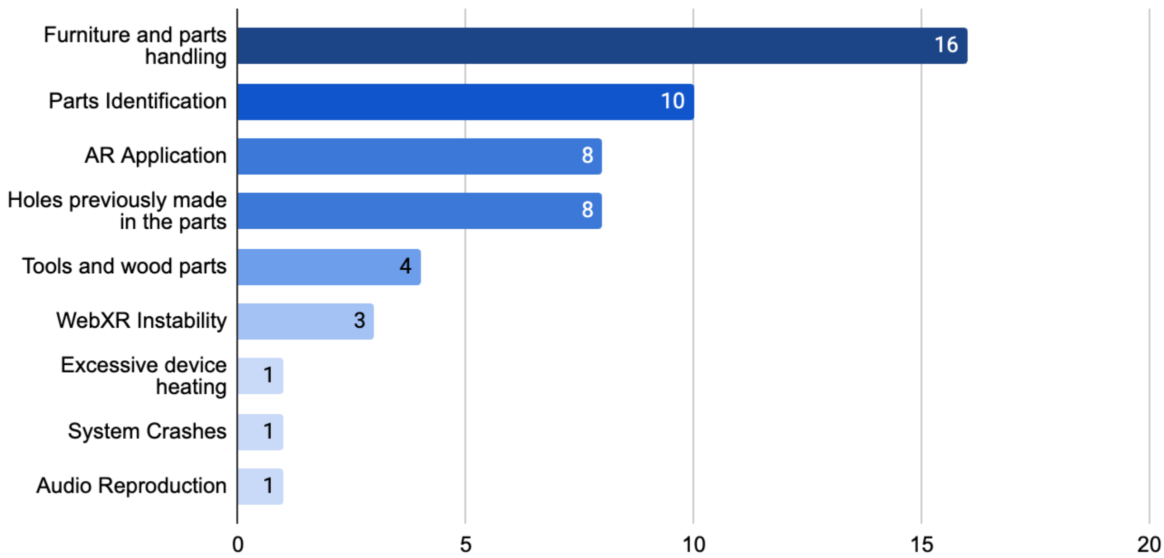


Figure 11: Observations about the assembly process.

Figure 12: Difficulties in handling the furniture during the screwing process.

Figure 13: Wood piece with misaligned holes and unstable furniture.

Additionally, WebXR instability and AR application issues were identified as potential barriers, pointing to technical limitations in the AR system, which could have caused confusion or disrupted the assembly flow. Excessive device heating and system crashes also appeared as isolated problems, indicating potential device performance limitations, which might affect the user experience.

From the assemblers' perspective, the most frequently reported issue was parts identification, which may indicate a need for clearer visual cues or better labeling within the AR interface (Figure 14). WebXR instability was also a major concern, as 6 assemblers pointed out this issue, further underscoring the need for a more stable connection and interaction between the AR system and the user's environment. AR application-related issues were similarly mentioned, which could involve difficulties in navigation or understanding the AR overlays, highlighting room for improvement in user interface design. Moreover, audio reproduction was a point of contention, suggesting that audio instructions or cues may not have been clear enough or appropriately timed for all users.

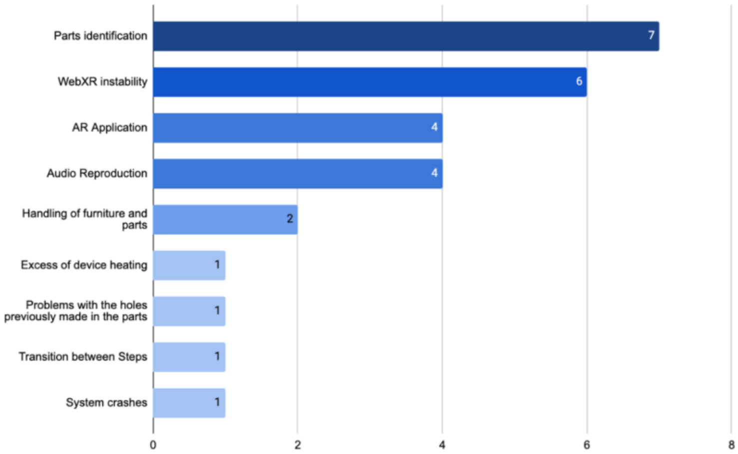


Figure 14: Observations from the assemblers about the experience.

The start and finish times were recorded in order to obtain the average assembly time for each piece of furniture (Figure 15). The average assembly time indicate that the table took the least time at 45.9 minutes, followed closely by the stool at 47.1 minutes, while the chair required significantly more time at 62.5 minutes. These variations may be attributed to differences in the complexity of the designs, the number of components, or the level of difficulty in following the assembly instructions. The observed times suggest that the chair assembly might present more challenges, potentially highlighting areas for improvement in either the furniture design or the assembly guidance provided through the AR system.

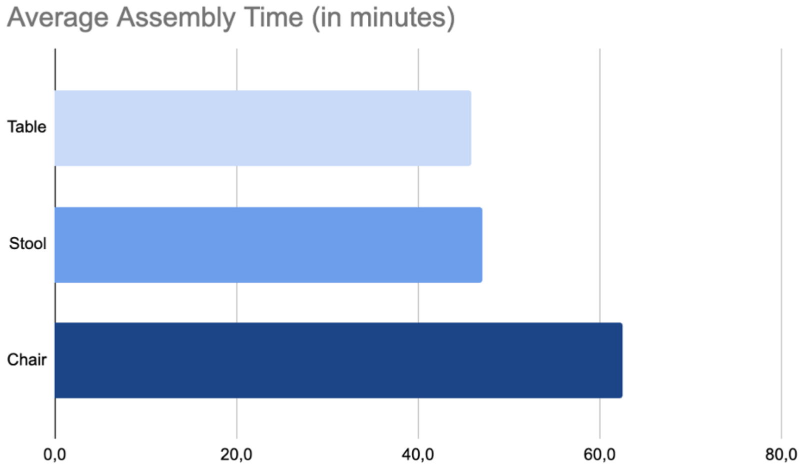


Figure 15: Average Assembly time.

5 Discussion and Conclusions

This proof-of-concept exploratory study aimed to introduce a set of DIY furniture designs and evaluate the potential of AR as a supportive tool in the assembly process. It sought to identify initial challenges and opportunities that could guide the development of a more robust and scalable AR-based workflow for DIY furniture assembly. The findings offer preliminary evidence that AR can help bridge the gap between traditional assembly practices and innovative digital solutions enabled by technologies such as WebXR.

The results obtained in the user evaluation revealed that all participants, despite having no prior experience with AR, successfully assembled the proposed furniture (table, stool and chair) (Figure 16). This demonstrates the general effectiveness of AR in simplifying complex tasks, consistent with other studies (Shao et al., 2016b; Deshpande; Kim, 2018b). However, technical challenges such as instability in the WebXR platform, difficulty in fixing virtual objects, and issues in identifying physical components were identified, echoing the concerns raised by (Zhao et al., 2023) about the importance of precision and stability in AR applications.

Figure 16: Furniture assembled by the students in the user evaluation.

The assembly times varied according to the complexity of the furniture, with the chair requiring the most time and a large quantity of negative feedback, compared to the table and stool. This aligns with the principles of Design for Assembly , which emphasize the importance of design simplification to improve assembly efficiency. User feedback also highlighted varying satisfaction levels, with simpler furniture like the table and stool being more intuitive and easier to assemble. These findings support on the need for perceptive simplicity in instructional design.

Despite its potential, the research faced limitations. The use of the free version of the chosen WebXR application, XR+, was limited to a maximum of 5 scenes. This meant that tasks had to be grouped together, overloading the mental workload required to carry out the steps. There were also challenges with tracker stability, along with device performance issues such as overheating and crashes, as well as difficulties in parts identification, all of which highlighted areas for improvement. It is worth noting that AR tutorials for DIY have not yet been extensively explored, and for this reason, the guidelines proposed by (Richardson, 2004b; Wakkary et al., 2015; Lahaye et al., 2023b) had to be adapted to this new medium. This work is still evolving and requires further studies to refine the proposal so that new AR tutorials can achieve greater efficiency.

The volatility of WebXR platforms was also noted, as the XR+ application used in this study is no longer available, alongside with Awe (identified in section 3.2), emphasizing that this is an emerging area that has not yet been consolidated. Results will help develop, in the future, a more robust process involving the development of AR for the assembly of DIY furniture.

By demonstrating the feasibility of AR for assembly tasks, this work lays the groundwork for further applications in education, professional training, and other DIY sectors. For instance, AR could enhance technical courses by providing immersive, step-by-step instructions, or serve as an alternative to traditional manuals in the furniture industry.

Future research should focus on optimizing WebXR technologies for stability and usability, exploring ergonomic interfaces to enhance user comfort, and expanding the study to include diverse demographics and furniture types. Addressing the mentioned challenges could involve integrating AI to automate component identification, refining user interfaces, and optimizing the platform for broader device compatibility, ensuring AR's role as a robust solution for complex assembly tasks.

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