

SafetyBuilder: An AR-based Framework for In-situ AI-assisted Creation of Child Safety Protection

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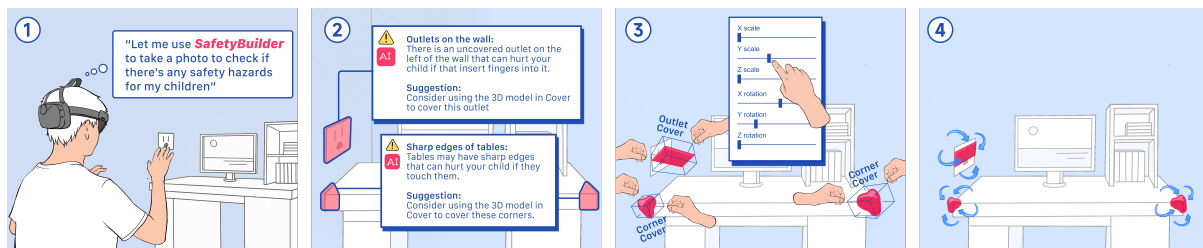


Fig. 1. With the framework, the childcare provider can (1) quest to detect the potential child safety hazard in the target environment, (2) obtain detailed information about the detected hazards and suggested protective solutions, (3) create and customize the 3D designs of the protective devices in situ, and (4) install the 3D-printed ready-to-use devices.

Children often encounter safety hazards, such as sharp table corners or exposed electrical outlets, which are out of their radar. Childcare providers may lack awareness of these hazards and the technical expertise required to design effective protective solutions. To address this, we propose SafetyBuilder, an AR-based framework that enables childcare providers to detect safety hazards in the environment and create customized protective devices for 3D printing. The framework comprises three core components: real-time environmental hazard detection, AI-assisted suggestions for protective measures, and in-situ customization of 3D printable protective devices. We then evaluated SafetyBuilder via design workshops involving 10 participants and user testing of a proof-of-concept prototype system with nine participants. The results showed that the

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ACM 2474-9567/2026/3-ART8

<https://doi.org/10.1145/3789690>

framework effectively supports users in identifying potential hazards, creating customized protective devices, and improving their confidence in managing child safety risks.

CCS Concepts: • **Human-centered computing** → **Interactive systems and tools**; *Mixed / augmented reality*.

Additional Key Words and Phrases: Child Safety Hazards, Framework Design, VLM, AR, AI-assisted, 3D Printing, Co-design, Protective Device

ACM Reference Format:

Jiawei Li, Zisu Li, Siyu Chen, Ziyang Wang, Yukai Zhang, Mingming Fan, and Liang He. 2026. SafetyBuilder: An AR-based Framework for In-situ AI-assisted Creation of Child Safety Protection. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 10, 1, Article 8 (March 2026), 29 pages. <https://doi.org/10.1145/3789690>

1 INTRODUCTION

Child safety hazards, such as sharp corners, exposed electrical outlets, and unsecured furniture, and common yet often overlooked due to childcare providers' limited hazard awareness and technical expertise [26, 63]. To identify these hazards in indoor environments, previous research has developed tools for hazard detection, including vision-based monitoring systems [85], multi-sensor alert systems [10, 17, 39], and mobile applications [30]. However, these approaches primarily focus on object detection or rely on fixed sensor installations, thus inadequately capturing the contextual factors contributing to the hazards within environments. Safety risks often emerge not merely from isolated objects but from their interactions with the surrounding environment. For example, a heavy book placed on a tall shelf poses a significant risk if the shelf is unstable or positioned near areas frequently accessed by children.

In addition to detecting child safety hazards, developing protective solutions to mitigate environmental hazards is challenging due to diverse situational constraints, such as furniture geometry, appliance placement, and space limitations. Common approaches rely on installing standardized assistive devices or temporary hazard modifications, such as corner protectors for tables or baby gates for staircases [1, 52]. However, these one-size-fits-all solutions offer limited customization, frequently resulting in mismatches between protective devices and specific environmental contexts. For example, to protect children from scalding risks posed by exposed hot water pipes, finding an appropriate insulation sleeve for the pipe may be tedious and error-prone, requiring careful measurement of pipe dimensions and selection of compatible materials from numerous candidate products. Meanwhile, emerging 3D printing technologies have enabled rapid creation of custom physical shapes across various fields, such as do-it-yourself (DIY) assistive devices for accessibility [3, 40, 84], custom wearables [36, 46], and interactive devices for prototyping [14, 29]. However, leveraging 3D printing to produce tailored protective solutions for child safety remains underexplored. To lower the barrier for creating protective devices and to situate the design in everyday contexts, we explored an AR-based approach that allows in-situ editing of the protective design. Users can preview designs in real time, minimizing iteration cycles and ensuring the 3D printability of the target protective device.

In this work, we aim to provide a comprehensive pipeline to empower non-expert childcare providers to detect, design, and fabricate safety protection for children through in-situ AR with AI support, following the research question: *How can emerging technologies—such as AI, AR, and digital fabrication—support the creation of protective devices tailored to specific child safety hazards in everyday environments?*

To answer this question, we propose *SafetyBuilder*, an AR-based framework for in-situ, AI-assisted creation of protective devices for child safety. The framework supports three tasks: detecting environmental hazards, suggesting protective solutions, and customizing 3D printable solutions within the context of the environment. This framework was informed by a three-part formative study. First, we conducted semi-structured interviews with 12 childcare providers to examine the challenges and current practices in identifying and addressing child safety hazards. Participants reported the need for clearer identification of safety hazards, the difficulty

of developing functional protective solutions, and the lack of support for customizing the protective devices for specific scenarios. To understand what existing 3D-printed protective devices are made for customization, we conducted a survey of 3D creations on Thingiverse, one of the largest online repositories for 3D printing, by analyzing protective devices designed for injury prevention and childproofing purposes through keyword searching. As a result, we collected a database that contains models suited for addressing child safety hazards. Finally, we held five co-design workshops with 10 experts—including product designers, UX professionals, 3D printing specialists, and AR/VR researchers—to co-develop guidelines for designing custom protective devices with the assistance of AI through AR-based interactions.

Drawing insights from the formative study, we developed SafetyBuilder by integrating three key components: 1) automatic identification of child safety risks in indoor environments, 2) context-aware guidance that explains each hazard and recommends mitigation options, and 3) in-situ editing of 3D printable protective devices with installation guidance (Figure 1). We evaluated the framework through two user studies. In the first study, we conducted one-on-one design workshops with 10 childcare providers. Participants used SafetyBuilder to design safety solutions for two realistic indoor scenes and provided feedback on their experience. In the second study, we developed a proof-of-concept prototype based on the previous design workshop results and conducted end-user study with nine participants, followed by post-test interviews. As a result, participants successfully identified 44 safety hazards and created 13 protective devices, all of which could be 3D printed and installed without assistance. Our qualitative analysis of the usability testing suggests that the prototype system was effective, user-friendly, and enjoyable to use. The findings validated the core concepts of the framework and demonstrated its potential for supporting childcare providers in creating tailored safety solutions.

To summarize, our work contributes:

- A three-part formative study—including semi-structured interviews with targeted stakeholders, a survey on existing 3D-printed child safety solutions, and co-design workshops with experts—to examine the challenges, current practices, and available solutions in child safety protection.
- An AR-based framework that supports childcare providers to detect child safety hazards in the environment and create custom protective devices in situ for 3D printing.
- TWO evaluations including framework concept probing through 10 individual design workshops and usability testing of a proof-of-concept prototype with nine users, validating the feasibility and usability of the core components in the framework SafetyBuilder for identifying potential safety hazards, understanding the risks caused by various hazards, and creating customized protective devices for 3D printing.

2 RELATED WORK

2.1 Child Safety Hazards Detection and Interpretation

Child safety hazards are a critical and widespread global health issue that affects the well-being and development of children [58]. Prior works showed that childcare providers who understand common hazards are more likely to take preventive action [51, 65]. To help childcare providers be more aware of potential child safety risks, some researchers have introduced tools for hazard detection, including vision-based tools, multi-sensor reminders, and mobile applications [17, 30, 39, 85]. For example, Zhu et al. [85] introduced a vision-based framework for detecting in-crib hazards like blanket occlusions and hazardous toys to improve infant sleep safety. Ahmad et al. [2] proposed a model to enhance child safety by monitoring a child’s movements through video data and alerting parents about potential risks. However, these methods of hazard detection typically rely on object detection and fixed sensors, they fail to recognize hazards and their relationships within the environment. Many safety hazards arise not just from single objects, but from how they interact with the surrounding space. Therefore, in addition to detecting the potential hazards by organizing single objects, our work also explores how to interpret contextual environment for child safety risk prevention.

The use of AI to interpret contextual information offers significant potential for enhancing the detection of child hazards, making it more situationally aware. Traditional approaches to understanding semantic information have focused on geometric representations [60] and 3D scene graphs [4, 37]. For example, Hughes et al. [31] presented a scene graph with a metric-semantic 3D mesh layer, including obstacle-free locations, rooms, and buildings. Su et al. [70, 71] developed systems to automatically identify accessibility features and barriers (e.g., stairs, elevators, doors) and create detailed indoor accessibility maps. Such approaches are limited by fixed-class models, which struggle to generalize in unfamiliar environments. This limitation is particularly relevant and even exaggerated in the context of child safety, where hazards may be unpredictable or change rapidly depending on the indoor environment.

Our system is inspired by other recent works exploiting VLM for interpreting contextual information from images. VLM-based systems provide not only object recognition but also an understanding of the broader scene, allowing them to describe key elements (e.g., objects, people, text, scenery) in relation to their context [50, 61, 62]. These efforts have been particularly successful in helping blind and low-vision (BLV) audiences understand visual scenarios by providing descriptions of the predominant content and its spatial relationships [33]. Inspired by these works, we utilize VLM to enhance contextual awareness in hazard detection, which has yet to be fully explored.

2.2 AR-based System Supporting In-situ Design

Building upon the prior literature on AR-based interfaces for supporting in-situ design, our approach enhances the capabilities of users to create customized solutions for child safety in real-world environments. In-situ design has emerged as a potential component of lower-effort design tools for custom fabrication [68]. Augmented reality (AR) has been both a tool and a target domain for custom design, it offers a way to bridge the gap between digital design and physical usage environments by enabling in-situ design [27, 32, 47]. Prior works in AR-enabled design have explored spatial interactions and the ability to preview artifacts in their intended context in two main aspects, including immersive design (e.g., Remixed reality[47], BlendMR[28] and RefAR[81]), and authoring AR experiences (e.g., ProcessAR[16], InteRecon[44], Protoar[56], and SpatialProto[54]). These works highlight the conceptual similarity of “design-for-virtual environment” and “design-for-personal fabrication” [21]. Therefore, inspired by these research studies, this work enables direct in-position digital design to accommodate the contextual needs of the situation through the AR-based interface.

2.3 Custom Parametric Design for Personalized Devices

Designing functional objects from scratch in 3D modeling software such as Blender [73] and AutoCAD [83] requires significant expertise in geometry and engineering, resulting in a high barrier for non-expert users to convert their abstract idea and intent into physical, functional devices [8]. To address this, various parametric design tools were developed to enable users without sufficient expertise to manipulate predefined parameters to generate functional designs [23, 41, 66, 75]. For instance, Shugrina et al. [66] introduced a method that enables non-expert users to customize parametric models while ensuring they remain valid and manufacturable for 3D printing, by pre-design geometry regions. Veuskens et al. [75] developed an interactive tool that assists non-expert users in creating well-constrained parametric 2D and 3D computer-aided design (CAD) models by visualizing the effects of constraints. Building on these approaches, our system provides pre-designed 3D models for protective devices, enabling child childcare providers to create functional, customized safety solutions. By allowing users to manipulate parameters such as size and shape, our system ensures that the devices can be tailored to the specific hazards and situational needs in their environments.

In summary, our work builds upon three key research threads: hazard detection and contextual interpretation (Section 2.1), in-situ AR-based customization (Section 2.2), and parametric design for personalized fabrication

Table 1. Position of SafetyBuilder compared against the closest prior works.

	AttentionAR [59]	RASSAR [72]	AccessLens [40]	CustomizAR [45]	TinkerXR [5]	SafetyBuilder (ours)
Indoor safety detection	✓	✓	✓	✗	✗	✓
In-situ interaction	✓	✗	✗	✗	✓	✓
Adapatations for safety issues	✓	✓	✓	✗	✗	✓
Customizable protection devices	✗	✗	✗	✓	✓	✓
User-driven creation for protection devices	✗	✗	✗	✓	✓	✓

(Section 2.3). Unlike existing works that either (1) focus on general safety or accessibility in static images or controlled environments, or (2) require expert-level interaction for protection device fabrication, our work introduces SafetyBuilder that uniquely integrates context-aware VLM reasoning, intuitive AR interfaces, and custom parametric models into a unified framework. SafetyBuilder is specifically designed for non-expert childcare providers, enabling them to detect, understand, and fabricate tailored protective devices for situational child safety hazards in real-world indoor environments. A comparison between SafetyBuilder and the closest prior systems across auto detection, in-situ interaction, customization for 3D devices, and fabrication for physical safety is presented in Table 1.

3 FORMATIVE STUDY

We conducted a three-part formative study, including semi-structured interviews to understand the current practices and challenges for child safety protection, a survey on existing 3D-printed protective solutions to explore customization for child safety protector designs, and co-design workshops to develop guidelines for designing custom protective devices with the assistance of AI through AR-based interactions.

3.1 Part I: Semi-structured Interviews with Childcare Providers

3.1.1 Participants and Procedure. To examine the challenges and current practices in addressing child safety hazards and understand users' perspective on custom 3D-printed safety devices, we screened and invited 12 participants (four males and eight females) who had experience parenting children aged 3-6 (e.g., five parent-child, five older siblings, and two kindergarten teachers) to participate in our IRB-approved remote semi-structured interview. The interview consists of a retrospective of the participant's past experiences in identifying and addressing potential indoor child safety hazards with any challenges they encountered, an introduction to how 3D printing works through a demonstration video, and an ideation session on how 3D-printed devices can potentially assist in creating protective solutions to child safety hazards. The interview lasted approximately 60 minutes, and the participant's consent for recording their responses was obtained before the study began.

3.1.2 Analysis and Findings. The recorded interview sessions were transcribed and analyzed following the reflexive thematic analysis method [11]. We enumerate the key findings below.

Finding #1: Challenges of identifying the potential indoor child safety hazards. Nine participants expressed that it is imperative to know what safety risks may exist with furniture, yet they are often overlooked due to the lack of experience and knowledge. For example, children like to climb and explore furniture, increasing

the risk of accidents, such as “fall” (P6) and “collisions” (P1). While specialized furniture suitable for children is available, children’s childcare providers often overlook the safety hazards caused by other furniture designed for adults already in the room. For example, “*It wasn’t until my child was knocked by a doorknob that I realized I should have fitted protectors to my room’s doorknobs*” (P4). Additionally, childcare providers may struggle to recognize hazards from a child’s perspective, as children often interact with household objects in ways that adults do not anticipate. For example, “*Adults don’t think of sticking their hands into electrical outlet holes, but children will do it driven by curiosity*” (P1). This highlights the importance of identifying potential safety risks embedded in everyday furniture and household setups.

Another concern raised by the majority of participants ($N=10$) is that the safety risks increase greatly when multiple children play together. For instance, children might push or tussle over toys, leading to falls or injuries, e.g., “*I will be aware of any dangerous objects when the two children are playing together, such as sharp objects like scissors*” (P11). Participants were concerned that they could not pay careful attention to possible safety hazards when the children were together. For example, “*I often need to take care of two children while making phone calls with my clients*” (P12). This implies the need to consider the safety hazards when multiple children play indoors.

Finding #2: Approaches of mitigating child safety hazards Most participants ($N=11$) noticed the limited variety of commercially available protective products for child safety and reported that existing solutions often fail in specific scenarios. They often expressed difficulty in selecting appropriate tools to address unpredictable or situational hazards. For example, “*A child in the nursery was once injured by a curtain, but we still haven’t found the right product to wrap it in*” (P2). Even for similar types of hazards, the solution often depends on contextual factors such as the object’s size or location, increasing both time and financial costs. As P3 explained, “*Two different sizes of cups require the purchase of two different sizes of cup cover*”. Participants emphasized the need for an extensive and diverse library of protective solutions—including items like “*corner protectors*” (P1), “*anti-tip straps*” (P5), “*safety gates*” (P8), and “*locking mechanisms for cabinets and drawers*” (P10)—to meet a wide range of child safety needs across different indoor environments.

Finding #3: Characteristics of indoor child safety protection To effectively protect children from safety hazards, participants ($N=10$) emphasized the importance of quickly identifying potential risks in various indoor environments. First, they expressed a desire not only to detect hazards but also to understand their implications. For example, “*if a sharp edge on a piece of furniture is detected, I would like to learn more details about the potential injuries caused by this hazardous object*” (P4). Second, participants valued portability and ease of use, noting the benefit of a lightweight device that enables users to move through a space and detect hazards effortlessly. For example, P5 said, “*I wish I could have a lightweight and portable device with me so I can walk around and easily capture the potential hazards in the house*”. Lastly, participants highlighted the lack of knowledge about appropriate protective responses, pointing to the need for accessible resources that can suggest relevant solutions. For example, P4 suggested using rubber covers to hide sharp corners, e.g., a rubber corner cover, while P5 wanted drawer locks suitable for all cabinets in the home.

These comments suggest that hazard detection should be fast, intuitive, and deployable across multiple locations—not limited to a fixed site—and that solution recommendations should support users with little prior experience in safety design. Regarding 3D printing, participants were enthusiastic about its potential for producing tailored safety devices. P2 said, e.g., “*If it is possible to make a protective cover for the curtains that smashed the kids that fits its size, that’s really great*”. However, several also noted the steep learning curve of 3D modeling. As P12 stated, “*I have no experience with 3D modeling, if it is a simple process, I would be willing to use it*”. Despite these concerns, all participants viewed 3D printing as a promising and accessible technology for creating custom protective devices to address diverse child safety challenges.

Based on the results, we identified the following three components that were essential to support childcare providers in detecting potential safety hazards and creating protective solutions: 1) easy identification of safety

hazards with sufficient background information, 2) easy access to create functional protective solutions, and 3) support for customizing the protective devices for specific scenarios.

3.2 Part II: Survey on the Hazard Scenarios and 3D Printable Protective Devices

Following the interviews, we taxonomized scenarios where safety risks may potentially exist based on the literature, and examined 3D printable protective devices made by enthusiastic hobbyists through an analysis of 3D creations posted on Thingiverse.

First, to identify fundamental categories of child safety hazards, we identified five major child safety hazards from the literature focusing on common causes of domestic child injuries [13, 22, 38]. From this synthesis and our interview findings in Section 3.1, five high-level hazard types were identified: *bumping*, *burn*, *pinching*, *tipping*, and *electrical injuries*. *Bumping injuries* occur when children accidentally collide with sharp furniture edges or corners. *Burn injuries* occur when children come into contact with hot surfaces such as tableware or hot water bottles. *Pinching injuries* occur when children get their fingers caught in door hinges, drawers, or cabinet doors. *Tipping injuries* occur when unstable furniture or appliances—such as bookshelves or televisions—tip over as children climb or pull on them. *Electrical injuries* occur when children insert fingers into power outlets or touch exposed wires. Based on these five categories, we further decomposed each into plausible hazardous scenarios that may occur in typical indoor environments. To identify concrete scenarios, we synthesized three sources of data: descriptions and examples provided by participants in Section 3.1 (e.g., “*children pulling curtains*”, “*pinching risk*”), safety-incident examples documented in prior studies [13, 22, 38, 74], and iterative discussions with two domain experts—an early-childhood educator and a child-safety researcher. Through three rounds of refinement, we derived a final set of 16 scenarios spanning the five hazard categories (e.g., sharp table corner, hot tableware, and power outlets), as shown in Figure 2. Finally, to ensure the taxonomy emphasized high-impact hazards, we validated and prioritized scenarios based on the frequency in which the hazard was mentioned across interviews and the literature.

To explore possible custom protective solutions to the identified safety hazards in the above hazards and scenarios, we collected 300 3D models tagged with at least one of child safety-relevant labels, such as *safety*, *child safety*, and *child assist*. Then, we synthesized these models to find five emergent functions essential to protective devices: *lock*, *cover*, *stopper*, *guard*, and *clip*. *Lock* prevents children from accessing dangerous areas or objects by restricting movement. For example, cabinet locks can stop children from opening cabinets that may cause tipping injuries. Similarly, switch locks can keep children away from turning on appliances or lights. *Cover* is used to shield potentially dangerous areas or objects from direct contact with children. For example, socket covers prevent children from inserting their fingers into electrical outlets, while corner covers can soften the sharp edges of furniture to reduce the risk of bumping. *Stopper* blocks or stops the movements of objects to prevent injuries. For instance, door stoppers can prevent doors from slamming on children’s heads, and window stoppers can prevent windows from being opened too far, reducing the risk of falls. *Guard* acts as a physical barriers that prevent children from coming into contact with hazardous areas. For example, a knob guard can stop children from adjusting stove knobs, reducing their risks of burn injuries. *Clip* is used to secure objects in place, making them less accessible to children. For example, wire clips can bundle wires and keep them away from curious children who might pull on them. Based on these functions, we categorized all the models into 16 types of protective devices, as shown in Figure 2.

Lastly, two researchers manually labeled all the found 3D models using the protective function they afford and the applicable scenarios they can support to address specific safety hazards. A third researcher verified the labeling results to ensure consistency and accuracy. As a result, we created a database that contains models with specialized functions suited for addressing potential child safety hazards in five categorized scenarios (Figure 2).

These models are used to provide the 3D model templates for childcare providers to build upon for desired 3D printable protective devices.

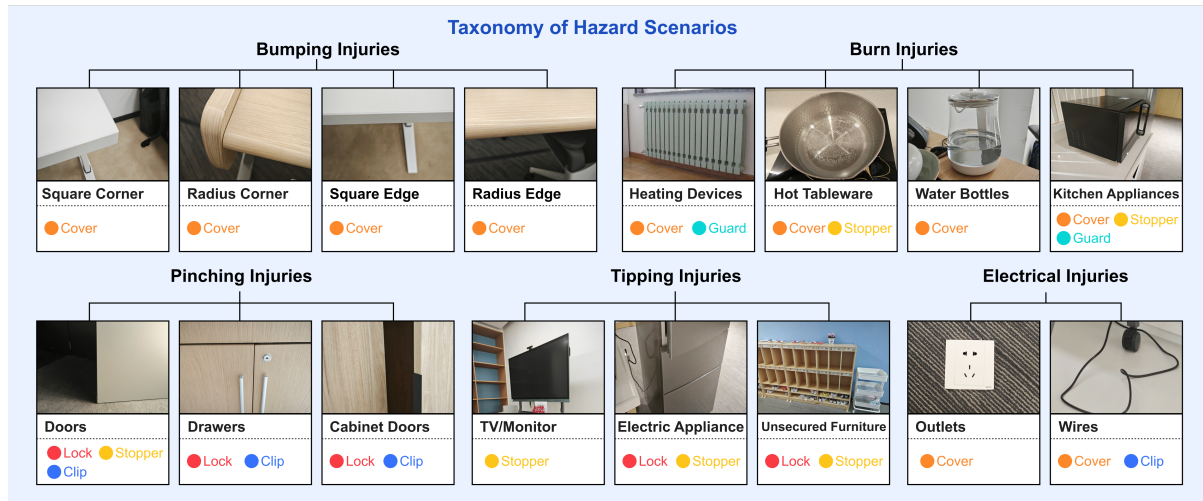
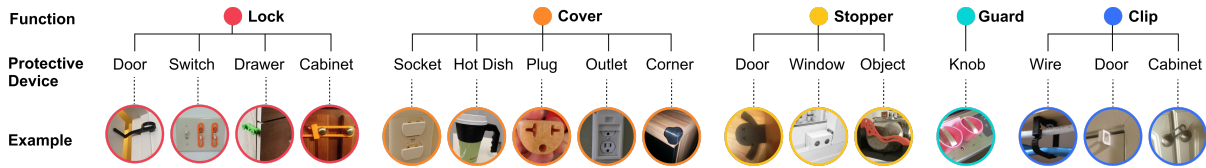


Fig. 2. Taxonomy of hazard scenarios and protective devices, including five main functions with 16 types of protective devices, and five hazards with the taxonomy of 16 hazard scenarios and possible functions of protective devices to address them.

3.3 Part III: Co-design Workshops with Experts

3.3.1 Participants and Procedure. Finally, to develop guidelines for designing AI-assisted custom protective devices using AR-based interactions, we conducted co-design workshops with 10 experts (three male, seven female; aged 23–30) from diverse backgrounds, including two product designers, three UX professionals, two 3D printing specialists, and three AR/VR researchers. All participants were familiar with AI and AR and had basic knowledge of digital fabrication. They were randomly assigned into five interdisciplinary groups to encourage cross-domain discussion. Each workshop lasted approximately 60 minutes and was video-recorded for subsequent analysis. During the session, each group was first presented with two realistic indoor scenarios featuring potential child safety hazards—the kitchen and the living room—to ground their ideation in concrete contexts. Participants were then asked to envision how AI and AR technologies could jointly support in-situ hazard detection, the design and customization of protective devices, and their deployment within the two real-world child safety scenarios. Building on the three core components identified in formative study 3.1, participants were encouraged to ideate freely and represent their concepts visually using annotated sketches or scenario storyboards, without constraints from current technologies or existing solutions. These artifacts captured proposals for user–system interactions, including how childcare providers might receive hazard alerts, select recommended solutions, and adjust device dimensions directly in AR through gestures or contextual cues.

After each workshop, we conducted a thematic analysis [11] of participants' suggestions, ideas, and sketches. All focus groups were recorded and automatically transcribed using the built-in transcribing tool in the meeting software. Two researchers then independently coded the transcripts and performed an inductive thematic analysis using the affinity diagramming approach [49]. The coders regularly discussed their codes and resolved disagreements to produce a consolidated codebook. Subsequent meetings with all co-authors ensured consensus on the preliminary coding results. The example artifacts produced by participants were shown in Figure 8 and we summarize the key findings from the co-design sessions below.

3.3.2 Analysis and Findings.

Suggestion #1: Overall functions of the AR system. In general, experts suggested that the AR system should combine functions including hazard detection, protective device selection, and adjustment of protective device size.

Suggestion #2: Providing detailed hazard information and tailored protective solutions. For hazards detection, they pointed out that the system should provide detailed information about the identified hazards, such as “*where is the hazard*” (P4, P7, P9), “*why is it necessary to resolve these hazards promptly*” (P2, P3, P5, P10) and “*under what circumstances could these hazards become dangerous*” (P1, P7). Additionally, most of the participants ($N=8$) found providing protective custom solutions was important.

Suggestion #3: Providing printable and categorized 3D templates for protective devices. For protective devices, the system should prepare a series of pre-designed and categorized printable 3D model templates. Participants suggested that the system should curate its template library around different devices for common hazards (e.g., sharp-edge guards, socket covers, door-finger pinch stoppers, and furniture-tip-over brackets), so that childcare providers can quickly locate an appropriate solution without design expertise.

Suggestion #4: In-situ adjustment of protective devices by bare hands. Finally, to support childcare providers in adjusting key dimensions for printable protective devices to fit the specific object they are securing, participants suggested that the system should allow users to adjust the model through bare hands. Two 3D printing experts claimed that the customization and printing of 3D models demand professional expertise and effort. Therefore, it is essential to reduce the cognitive and technical burden on childcare providers by offering an intuitive and hand-driven editing workflow in AR environment.

4 SAFETYBUILDER FRAMEWORK

Built on the formative study's results (**findings 1-3** in Section 3.1, **taxonomy of hazards scenarios & protective devices** in Section 3.2 and **suggestions 1-4** in Section 3.3), we introduce the SafetyBuilder framework, an integrated framework designed for the in-situ, AI-assisted creation of child safety protection. SafetyBuilder consolidates hazard detection, detailed hazard-oriented feedback, and interactive in-situ customization of protective devices via an AR environment. In general, as shown in Figure 1, SafetyBuilder contains four key tasks: (1) in-situ capture of the target environment, (2) hazard detection and hazard-oriented feedback, (3) create and customize the 3D designs of the protective devices in situ, and (4) install the 3D-printed ready-to-use devices.

Task #1: In-situ capture of the target environment. As shown in Figure 1.1, the first step of SafetyBuilder involves the in-situ capture of the target environment, a fundamental task required for contextual hazard analysis. The user initiates the process using an AR headset equipped with an integrated camera. Users activate the camera function to scan and photograph the environment.

Task #2: Hazard detection and hazard-oriented feedback. As shown in Figure 1.2, upon capturing the environment, SafetyBuilder employs AI to detect and classify child safety hazards present in the captured environment and provide hazard-oriented protective feedback. Firstly, the system detects the hazard by recognizing hazard scenarios mentioned in Section 3.2. The system then generates hazard-oriented feedback, providing

childcare providers with detailed descriptions of identified hazards. The description includes identification of hazard location, explanation of potential danger, and suggestions on custom protective solutions.

Task #3: Create and customize the 3D designs of the protective devices in situ. As shown in Figure 1.3, once the system identifies the hazards present in the environment, childcare providers proceed to select from pre-designed, categorized, and printable 3D model templates. These templates encompass various protective devices (e.g., corner covers, socket covers, door stoppers, and anti-tip brackets) organized according to common hazard scenarios established in Section 3.2. Additionally, users can instantiate these protective devices directly within the AR environment, placing digital protective devices onto their corresponding physical counterparts. At this stage, users perform initial sizing adjustments using intuitive AR interactions such as hand gestures (e.g., pinching and grabbing) to ensure the protective device preliminarily aligns with the actual object requiring protection. Then, SafetyBuilder allows for detailed fine-tuning and precise parametric adjustments of protective device dimensions to ensure a practical fit. SafetyBuilder also supports fine-grained control through intuitive AR interactions, enabling childcare providers without specialized technical expertise to effortlessly adjust critical dimensions (e.g., length, width, and height).

Task #4: Install the 3D-printed ready-to-use devices. As shown in Figure 1.4, the final element of SafetyBuilder is to print the digital devices and install the devices in the corresponding place. After completing the fine-tuning step, the adjusted device parameters are confirmed, generating a final printable model ready for 3D printing.

5 FRAMEWORK CONCEPT EVALUATION

We conducted one-on-one design workshops with childcare providers to investigate whether the framework could support the creation of child safety protection, inspire them to achieve effective custom creation of safety devices, and identify new design opportunities.

5.1 Participants

We recruited 10 participants who had experience with parenting children (four males, six females; aged 21-33). Among the participants, five were from a local kindergarten, and the rest were from a graduate school with different backgrounds (two designers, two AR/VR researchers, and one 3D printing expert).

5.2 Procedure

Firstly, we prepared two scenarios from real-life indoor environments for participants, both related to different types of child safety hazards. **Scenario #1: Electronic & Burn injuries.** In this scenario, the exposed hot water tap poses a risk of burning injuries, and the sharp edges of the table pose a potential hazard for bumping injuries; **Scenario #2: Tipping injuries.** In this scenario, the table's insecure feet pose a hidden risk of tipping injuries if pressure or weight is unevenly applied. Additionally, before the workshops, we utilized our framework to design the process for creating protective solutions specifically tailored to each scenario.

During the experiment, participants first proposed the protective solution design in AR for the two scenarios independently through text and simple sketches based on their understanding without any initial guidance. Then, after the framework and our pre-designed examples were introduced, participants were invited to iterate and enhance their initial designs using the functionalities provided by our framework, resulting in a new version of the design. Finally, we conducted semi-structured interviews with each participant for detailed feedback regarding their experience with our framework and the usability of the framework in supporting their creation of custom child safety protection. The entire workshop lasted approximately 60 minutes. After each workshop, we followed thematic analysis to analyze participants' design and feedback.

5.3 Results

5.3.1 Design Results. After showing SafetyBuilder, all the participants preferred our framework design and iterated on their initial design. As a result, we found the final version of participants' designs was consistent with our framework. For example, as shown in Figure 3, in P1's design. Similarly, the second example is P3's design, its in-situ detection, suggestions on protective solutions, and the model editing steps (bare-hand editing and fine-tuning) were the same as our framework. Meanwhile, we also found new designs from our participants. For example, the third example is P7's design, he provided advice that hazard information should incorporate risk ratings.



Fig. 3. The final design examples (P1, P3, P7) in design workshops.

5.3.2 Feedback Result. Overall, participants provided positive feedback on the framework. Participants claimed that SafetyBuilder is a novel and useful framework, and they agreed that the system implemented based on this framework will be easy to learn. Additionally, they also found SafetyBuilder can be extended to more safety scenarios beyond the provided cases.

The framework is novel and useful in child safety protection. Most of our participants ($N=9$) claimed that SafetyBuilder was both a novel and useful framework. For example, “I find the implementation of child safety hazard protective solutions in AR to be innovative and meaningful” (P3) and “After engaging in deeper design using the framework, I believe it facilitates the integration of hazard detection, size measurement, and protective device selection into a streamlined workflow” (P6). The framework also helped participants to check and iterate on their designs.

The framework is easy to learn. One of SafetyBuilder's goals is to lower the barrier for childcare providers to create custom solutions for child safety protection. After showing the framework, a majority of our participants

($N=8$) agreed that the system implemented based on this framework will be easy to learn and also simplify the process for creating custom solutions. For example, “*What impressed me most about this framework is its attempt to make the process of creating custom practical devices accessible*” (P10). Moreover, P8 also suggested that the editing step in our framework should ensure that the models are functional and printable.

The framework has the potential for further expansion. More than half of the participants ($N=6$) recognized the framework’s extensibility, finding that it could easily adapt to a broader range of safety scenarios and protective solutions beyond the provided use cases. For example, “*This framework is capable of addressing a broader range of safety issues and providing more solutions, thereby increasing its value*” (P1).

6 PROTOTYPE SYSTEM AND USABILITY TESTING

To demonstrate SafetyBuilder’s effectiveness in supporting childcare providers in detecting hazards and creating customized child safety protection, we implement a system based on our framework and the results of workshops. We then evaluated the system’s usability through an end-user study with nine participants.

6.1 Prototype Implementation

We designed the workflow of our prototype for detecting child safety hazards and providing suggestions on custom 3D printable protective solutions through the AR-based interface. The usage of prototype contains five key steps: (1) take a photo of the indoor space, (2) detect safety hazards, (3) select protective solutions to address child safety hazards, (4) place the selected 3D model template of the protective device at the location of the safety hazard, and (5) adjust the protective device’s parameters for custom design.

Step #1: Taking a photo of the indoor space. In this step, the child childcare provider launches SafetyBuilder and takes a picture of the target scene using the built-in AR helmet’s camera. The user can adjust the position and angle to take the photo for an ideal view. For example, as shown in Step #1 (Figure 4), to ensure that a room is safe, a child childcare provider activates SafetyBuilder and takes a picture of the room by pressing the “Photo taking” button.

Step #2: Detecting safety hazards. After taking the photo, the user uploads it, and the system detects the potential safety hazards existing in the captured scene. Upon the detection of safety hazards, the system provides suggestions on protective solutions. Two types of accurate and high-quality responses based on the uploaded photo are generated with the pre-prompted VLM: (i) safety hazards with their detailed information, and (ii) recommendations on the protective devices suited to address the detected safety hazard. For example, as shown in Step #2 (Figure 4), the child childcare provider updated the image to SafetyBuilder by pressing the “Uploading” button, then SafetyBuilder analyzes the room and identifies several potential safety hazards: sharp edges of the table and an exposed electrical outlet near the desk. Along with identifying these hazards, SafetyBuilder also provides the childcare provider with specific suggestions for protective solutions, such as for the sharp corners of the desk, SafetyBuilder suggested corner covers. The prompt engineering details of the VLM are discussed in Section 6.1.1.

Step #3: Selecting protective devices to address child safety hazards. After receiving the protective solutions, the child childcare provider then selects a 3D model template of the protective device from a list of recommended protective devices associated with the function described in the textual suggestion, which is provided in the previous step. For example, as shown in Step #3 (Figure 4), to cover dangerous desk edges, the childcare provider turns to the “Model Selection” interface, then selects the “Corner Cover” device in the “Cover” function.

Step #4: Placing the selected protective device at the target location of the safety hazard. After selecting the 3D model template, the childcare provider uses their bare hands by a pinching or grabbing gesture to move the selected protective device to the location where the safety hazard exists. For example, as shown in

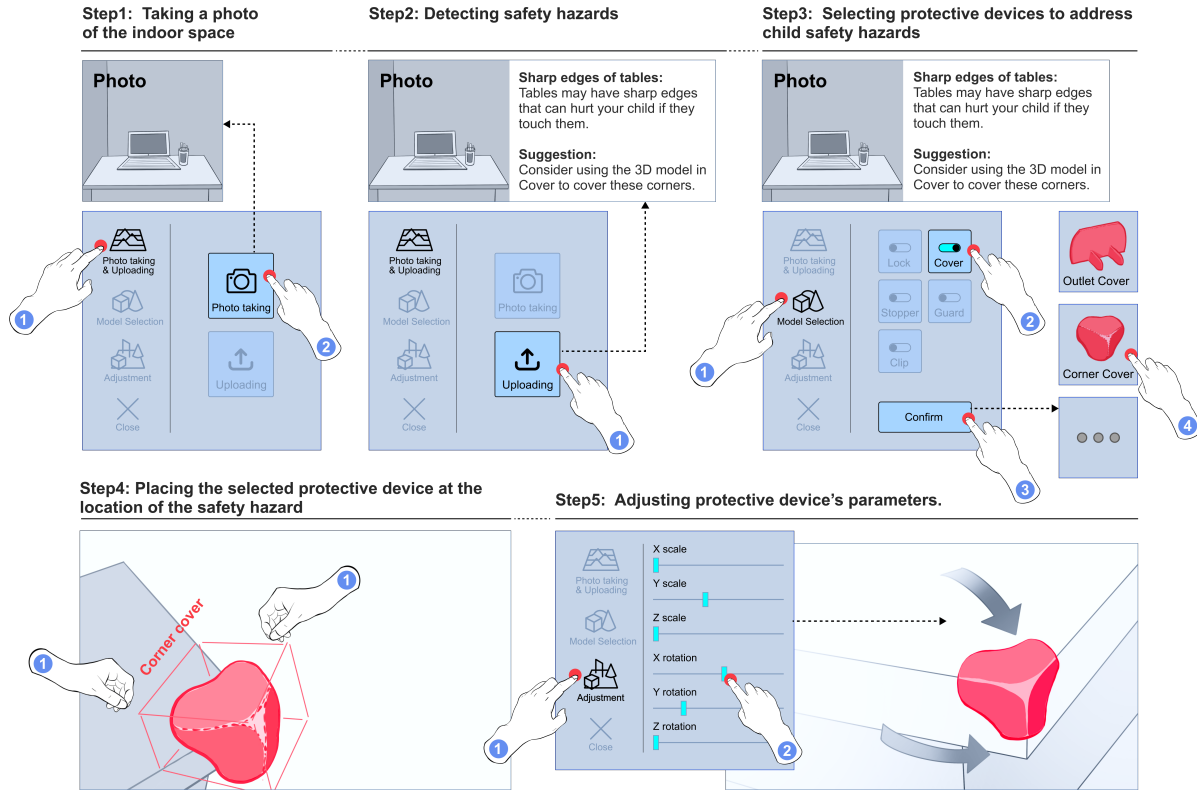


Fig. 4. Prototype workflow: (1) taking a photo of the indoor space, (2) detecting safety hazards and providing protective solutions, (3) selecting protective devices at the location of the safety hazard, (4) placing the selected protective devices at the location of the safety hazard, and (5) parametric adjustment of the protective devices.

Figure 4, to cover the desk edges, the childcare provider placed the digital corner covers on each sharp edge of the desk.

Step #5: Parameterizing the design of the selected protective device. Finally, with the sliders provided in the AR interface of SafetyBuilder (shown in Figure 4-Step #5), the childcare provider adjusts the protective device's parameters by modifying its size and orientation to accommodate the contextual needs of the hazardous situation. To ensure the functionality of the protective devices from the parameter changes (e.g., the position of holes in a socket cover), the user can only modify a portion of the parameters associated with the protective device model while others are sustained to accommodate the physical constraints, such as structural integrity. For example, as shown in Step #5 (Figure 4), the childcare provider adjusts the size and shape of the corner cover to fit the edges of the desk. Section 6.1.2 details this model editing process.

6.1.1 VLM-based Detecting and Suggesting. We choose GPT-4o as our target VLM. The core part of SafetyBuilder is to assist GPT-4o in learning the knowledge embedded within the child safety hazards in Section 3.2, enabling more precise detection of child safety hazards and generating high-quality, personalized solutions. The details of the prompt are shown in Section A.

To ensure that GPT-4o fully understands the taxonomy of hazard scenarios and protective devices, as well as producing structured responses, we drew on the prompt optimization practices from previous works [78, 80], implementing a series of prompt designs aimed at improving response generation. Specifically, the first author conducted a set of preliminary prompt designs and tested them with GPT-4o. Then, another three authors acted as quality checkers, providing feedback on the generated content. This iterative process continued through multiple rounds until all authors were satisfied with the generated content. Finally, we integrated the design space with five key prompt input factors, and we then combined each part to form a complete prompt, as illustrated in Figure 5. **(1) Setup.** This part provides GPT-4o with global instructions to help it understand the background of the child safety hazards to be addressed. **(2) Hazards Information.** This part integrates child safety knowledge into GPT-4o, enhancing its systematic understanding of child safety hazards. This enhanced understanding enables GPT-4o to detect finer details and acquire prior knowledge, which in turn supports users in customizing hazard solutions. This part includes two modules: the *Hazards & Scenarios* module that outlines potential child safety hazards and scenarios, and the *Custom Solution* module that incorporates different functions of protective devices to address the possible hazards in the scenarios. The information about hazard scenarios and protective solutions presented in these two modules was gathered from our taxonomy, as detailed in Section 3.2; **(3) Task Description.** After GPT-4o developed a systematic understanding of child safety hazards, we outlined the tasks that GPT-4o needed to accomplish within the SafetyBuilder in this stage; **(4) Output Structure.** This part serves to ensure that the output of GPT-4o is in the correct format and makes the outputs more contextually relevant. **(5) Photo Input and Optimization.** To optimize the VLM’s response to the child childcare providers, this part is designed to improve the quality of each response generated by GPT-4o. For each input photo. We employed Chain-of-Thought (CoT) prompts to enhance GPT-4o’s reasoning skills [79]. For each detecting session, (1) - (4) are only used at the beginning of the generation, while (5) is added in the prompt across all detection rounds.

6.1.2 Parametric Adjustment Design. Our system enables customization of the protective device, allowing users to control and design a personalized solution tailored to child safety hazards. By providing the in-situ modeling of the parametric model through an AR-based interface, the user can measure, edit, and evaluate the 3D model of the protective device in reference to the real-world context for 3D printing. To support customization, SafetyBuilder differentiates between adjustable and non-adjustable parameters in the 3D models.

Adjustable parameters include elements such as length, width, and orientation, which users can modify to fit specific situational needs. For example, users can adjust the height of an outlet cover to accommodate different types of outlets. They may also customize the thickness of the cover to ensure it sits flush with the wall or to enhance durability based on the type of outlet and its surroundings. This flexibility enables users to create customized safety solutions tailored to their physical environment, ensuring that the printed protective device fits precisely where needed.

Non-adjustable parameters are fixed in their design to maintain critical safety features or dimensions essential for the item’s intended purpose. For example, the spacing between holes in an electrical power outlet cover is standardized to meet safety regulations and cannot be changed. These fixed parameters ensure user modifications do not compromise critical design features and safety standards, preserving the device’s functionality.

By distinguishing between adjustable and non-adjustable parameters, SafetyBuilder allows users the freedom to customize protective devices while ensuring that the core safety features remain intact.

6.1.3 System Implementation. To maintain a balance between generation speed and reasoning quality, we compared both GPT-4¹ and GPT-4o² as the VLM for contextual hazard detection and guidance. We ultimately selected GPT-4o for its faster multimodal inference and higher consistency in structured output. The AR environment of

¹<https://openai.com/index/gpt-4/>

²<https://openai.com/index/hello-gpt-4o/>

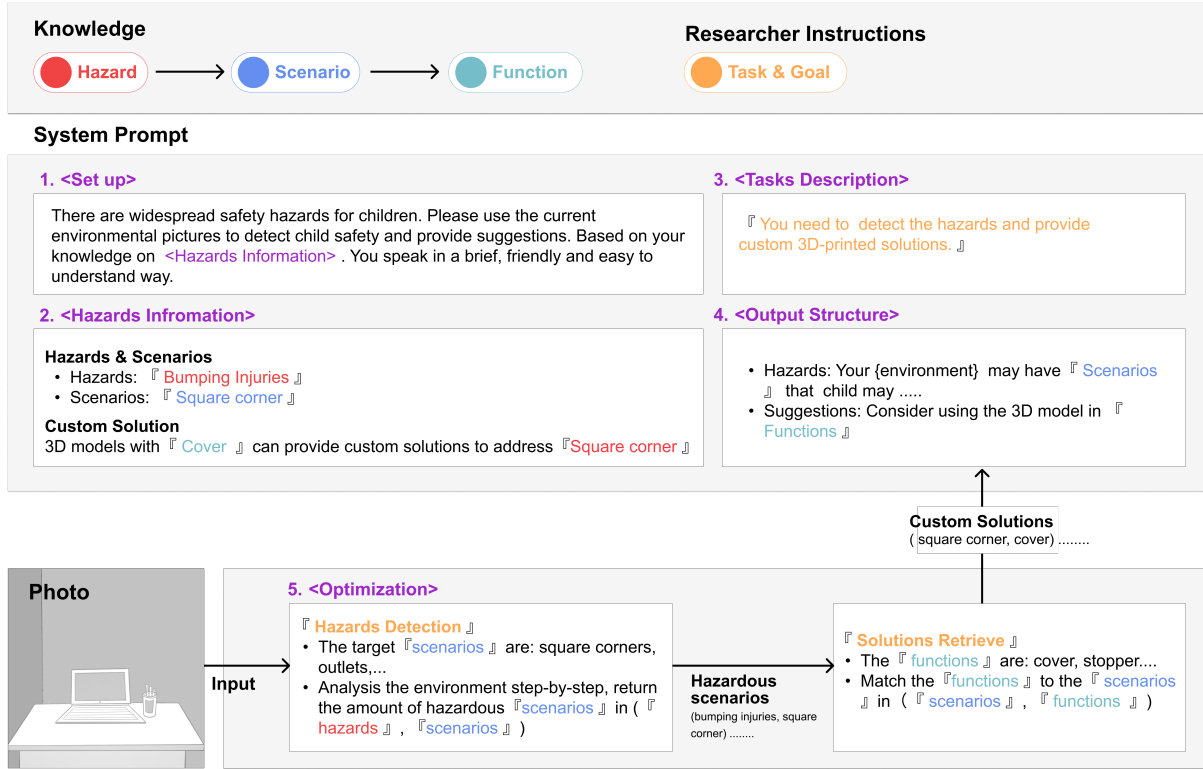


Fig. 5. Prompt design of high-quality hazard detection and custom protective solutions. The input prompt consists of five parts: (1) set up, (2) hazards information, (3) tasks description, (4) output structure, and (5) photo input and optimization.

SafetyBuilder was developed using Unreal Engine Version 4.26³ and is displayed through a HoloLens 2 headset. Additionally, we integrated the Mixed Reality Tool Kit (MRTK 5⁴) to manage hand interactions and UI elements such as buttons and sliders, ensuring seamless user interaction within the AR interface.

6.2 Technical Evaluation on System Performance

To assess the technical performance of SafetyBuilder’s VLM-based hazard detection module, we conducted a quantitative evaluation using 200 indoor images from the SUN-RGBD dataset [67]. The images covered five common child-safety contexts: living room, kitchen, bedroom, and bathroom. Two researchers annotated the images according to the taxonomy introduced in Section 3.1, resolving any discrepancies through discussion. In total, 467 hazards were identified, and approximately 75% of the images contained multiple hazards, allowing evaluation of multi-label reasoning. The evaluation measured SafetyBuilder’s accuracy in detecting potential hazards, particularly multiple concurrent hazards, as well as its end-to-end latency during hazard analysis and AR rendering.

³<https://www.unrealengine.com/en-US/blog/unreal-engine-4-26-released>

⁴<https://github.com/microsoft/MixedReality-UXTools-Unreal>

6.2.1 Metrics. We used the following metrics in our evaluation. First, we measured detection performance using standard multi-label classification metrics, including precision, recall, and F1-score. To assess model reliability, we analyzed the hallucination rate of hazards predicted by the model but absent from the ground-truth annotations. Finally, to evaluate system efficiency, we measured end-to-end latency, defined as the time from image capture to the completion of hazard visualization in HoloLens.

6.2.2 Results. Overall, SafetyBuilder achieved high accuracy in detecting potential hazards (*precision* = 0.98, *recall* = 0.93, *F1* = 0.95) across the five hazard categories. Detection was especially strong for visually salient risks such as bumping and electrical hazards, while performance was slightly lower for pinching and tipping cases that required finer spatial reasoning. The average hallucination rate was 0.05, primarily due to ambiguous reflections or cluttered scenes. End-to-end latency averaged 6.2 seconds over a standard Wi-Fi connection using GPT-4o, which remained acceptable for real-time AR feedback in SafetyBuilder.

6.2.3 Failure Cases and Hallucination Risks. False negatives typically occurred when hazards were partially occluded, such as thin cables or small metal edges. False positives arose mainly under visually ambiguous conditions. In several cases, the system misinterpreted lighting artifacts or shadow gradients as physical hazards, and occasionally treated reflections in mirrors as real-world risks. For example, mistaking window reflections on glossy cabinet doors as an exposed electrical outlet and detecting the lighting artifacts reflected in the window as one hazard. Over-detection also appeared in cluttered environments with repetitive objects, such as interpreting bundled charging cables or headphone cords as exposed electrical wiring. These hallucinations reflect the model's sensitivity to visual ambiguity rather than conceptual misunderstanding. Overall, while the current model's accuracy supports practical deployment, future improvements could include multi-view validation and low-confidence filtering to reduce such errors.

6.3 User Evaluation

We conducted an IRB-based user study to understand how SafetyBuilder improves child hazard recognition and how SafetyBuilder can be used to modify these dangerous environments by creating printable protective solutions. Nine participants (five male and four female; aged 23 - 33) were recruited from a local kindergarten. All participants had experience parenting children and prior experience using AR or VR devices. Seven (P1-7) had no prior experience in 3D printing, while P8 and P9 had basic knowledge of 3D printing. The hardware configurations and AR deployment employed in the study were consistent with those detailed in Section 6.1.3.

6.4 Study Design and Procedure

The study lasted approximately 45 minutes. Before the study, participants filled in a questionnaire to collect their demographic information. In the study, participants were first introduced to the experiment setup and signed a consent form. Then, participants walked through the HoloLens 2 official tutorial to learn how to navigate the user interface with basic hand gestures under the experimenters' assistance. Subsequently, we introduced the participants to the basic information about SafetyBuilder, including how to activate SafetyBuilder and how to use SafetyBuilder to detect and resolve child safety hazards. Participants were encouraged to identify child safety hazards in their everyday environments and address 1-2 hazards. Upon arrival at the participant's kindergarten or home, the researcher and participant collaboratively selected a room for the experiment. After the experiment, the participants were asked to complete a questionnaire with Likert-type (scaled 1-7) questions on evaluating the usability of SafetyBuilder. We then printed the protective devices they selected and modified in the experiments. Participants were then asked to take photos, install the printed model, and share their thoughts. In the end, we held interviews (30-40 minutes) with our participants regarding their qualitative feedback. The entire session was recorded on video by the experimenter.

6.5 Results

In this section, we present the results collected from our user study, including subjective ratings of our system and qualitative feedback from participants. The questionnaire utilized a 7-point Likert scale to gather user subjective ratings of SafetyBuilder. Additionally, we collected qualitative feedback during interviews. Figure 7 illustrates examples of the protective devices and how they addressed the hazardous environment created by our participants. They submitted a total of 13 protective devices for seven different scenarios. We conducted a thematic analysis of the qualitative feedback from nine participants. We report the subjective rating results in Section 6.5.1 to assess the system’s usability of SafetyBuilder to address child safety hazards and further report the qualitative results in the following subsections.

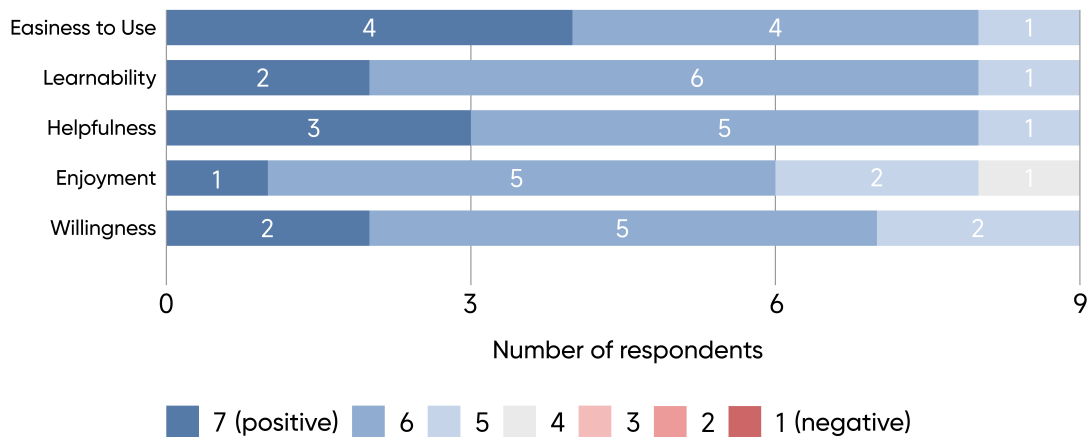


Fig. 6. Subjective rating scores for SafetyBuilder. 1 - strongly disagree, 7 - strongly agree. The average rating scores for each metric range from 5.67 and 6.33, with a standard deviation between 0.60 and 0.87. These findings indicate that the majority of our users provided high ratings for the metrics and found SafetyBuilder is effective, helpful, and user-friendly for handling child safety hazards.

6.5.1 Overall Experience of SafetyBuilder. All the participants indicated that the SafetyBuilder system was helpful in detecting and addressing child safety hazards. Participants were asked to provide their ratings to evaluate the usability and performance of the system in our questionnaire, containing five questions on a 7-point Likert scale, with 1 representing *Strongly Disagree* and 7 representing *Strongly Agree*, as illustrated in Fig. 6. We employed five metrics: ease of use, learnability, helpfulness, enjoyment, and willingness.

Participants rated the ease of use of SafetyBuilder with a high score of 6.33 ($AVG=6.33$, $STD=0.70$). This reflects the system’s intuitive interface and straightforward interaction process. For example, “*The user interface was simple and intuitive, with no burden on the user. Additionally, the button functions were well-designed, allowing each step to be completed with just a single click*” (P1). The learnability of SafetyBuilder also received a strong average score ($avg = 6.11$, $std = 0.60$), underscoring the system’s potential for rapid adoption by users, regardless of their technical background. The scores of helpfulness were also well received ($AVG=6.22$, $SD=0.67$), as P2 said, reflecting participants’ agreement that SafetyBuilder significantly helps them in identifying and mitigating child safety hazards. Moreover, participants expressed the willingness to use SafetyBuilder, giving it a high score ($AVG=6$, $SD=0.70$). This indicates that participants see SafetyBuilder as an essential tool for maintaining child safety in

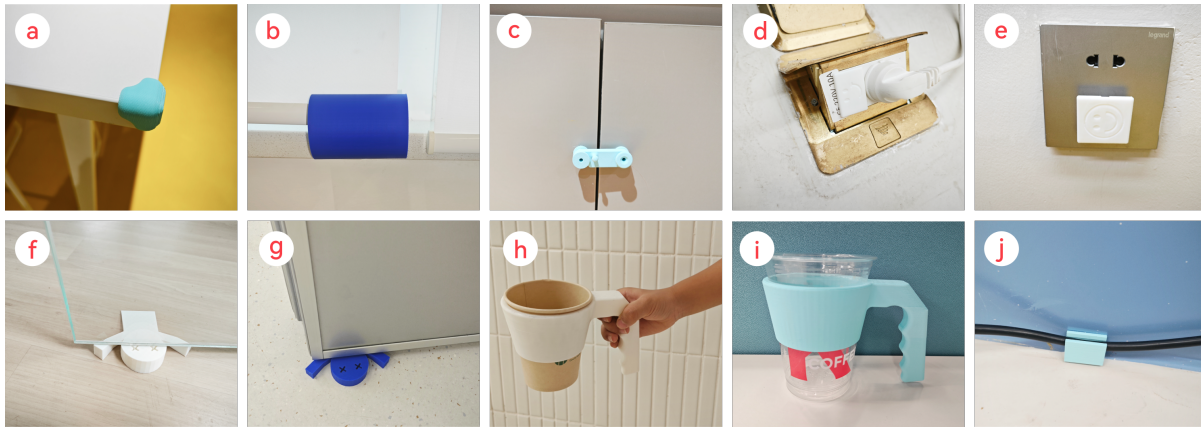


Fig. 7. Example 3D-printed protective devices created by participants. (a-b) corner cover, (c) cabinet door lock, (d-e) outlets cover, (f-g) door stop, (h-i) cup cover, and (j) wires clip.

various environments. Moreover, they found using SafetyBuilder to be an engaging and positive experience, as shown by the rating for enjoyment ($AVG= 5.67$, $SD= 0.87$). For example, “*I have a strong interest in AR and 3D printing, and using SafetyBuilder to address potential hazards for children is particularly meaningful to me when I need to focus on my work*” (P4).

These results show that SafetyBuilder is an effective, user-friendly, and enjoyable tool for addressing child safety hazards, with its robust hazard detection capabilities and intuitive design receiving positive feedback from participants.

6.5.2 Immersive Interactions in AR Enhance Parametric Adjustment. Participants highlighted that the immersive interactions facilitated by the AR environment in SafetyBuilder enhanced their experience, particularly during the parametric adjustment of protective devices. The ability to engage directly with the virtual models in an AR space enabled intuitive comparisons with real-world objects. For example, “*I didn’t need to measure the table with a ruler to create a functional corner guard*” (P5). Participants reported that this in-position interaction not only allowed them to adjust model parameters without expertise in 3D modeling but also created a more natural and engaging experience, as P8 stated: “*When editing items, I sometimes forget that I am in a virtual environment.*”, further emphasizing the integration of the virtual and physical realms that SafetyBuilder offers.

6.5.3 3D Printing Enables Practical and Low-cost Protective Solutions. Our results demonstrate that integrating SafetyBuilder with 3D printing enables users to easily create practical and customized protective devices. Participants described the printed items as functional and effective in mitigating child safety hazards. For instance, “*The outlet cover securely concealed the outlet, making it very useful for safety when children were playing nearby*” (P3). However, participants expressed difficulties and dissatisfaction with the parametric adjustment process for protective devices that require precise physical constraints, such as cup covers (as shown in Figure 7, h-i). P8 thought integrating auto-measurement [45] would be helpful.

It’s noticeable that all participants successfully installed the printed models without step-by-step instructions, and they also encountered no significant challenges during the installation process. They found that standalone protective devices (e.g., corner cover, wire clips) were easy to utilize. For example, P4 and P5 each designed two door stoppers of different sizes and found that they fit the specific dimensions of their doors. For protective

devices that need to be assembled, such as cabinet door locks, P2 thought a brief installation guide would be helpful.

6.5.4 Change in Habitual Perception of Child Safety Hazards. In general, our results show that SafetyBuilder serves not just as a detection tool but also as an ongoing educational resource, enhancing users' awareness and understanding of safety risks in real time. Participants strongly agreed with the solutions recommended by SafetyBuilder for the identified hazards. For example, *"SafetyBuilder provided many common solutions that I often find hard to think of myself, making it very practical"* (P3, P6). What's more, SafetyBuilder's ability to continuously provide hazard information and knowledge was particularly appreciated. Participants reported that their understanding of child safety hazards significantly improved after using SafetyBuilder. For example, *"As the system identifies safety hazards, the accompanying prompts continuously provide me with additional relevant knowledge"* (P2).

We also observed that some participants who previously did not pay much attention to child safety hazards are now more focused on this issue. For example, *"I used to be rather casual about protecting my child, but after using SafetyBuilder, I've noticed that even after taking off the headset, I instinctively check whether the room is safe"* (P5). The feedback reflects a change in habitual perception, where the user has developed a more proactive approach to child safety, extending beyond the use of the system itself. While these observations highlight the short-term change in habitual perception of safety hazards, further study would be needed to determine whether these changes persist over the long term.

6.5.5 Potential of Applying SafetyBuilder to Wider Scenarios. Participants praised SafetyBuilder for its generality in detecting and addressing child safety hazards and suggested new application scenarios, functionalities, and solutions to further enrich SafetyBuilder's design space. In addition to indoor environments, outdoor scenarios could be incorporated into SafetyBuilder. Participants believed that this expansion would enable the system to address a broader range of hazards that children may encounter outside the home, such as playground equipment, parks, and traffic-related safety risks. For example, *"Some playground equipment, such as swings and climbing frames, may become worn or damaged due to prolonged use. These issues can result in sudden equipment failure, potentially causing injury to children"* (P1). Moreover, age-specific customization could be another valuable enhancement to SafetyBuilder. P1 noted that *"A child's physical condition changes dynamically over time"* and P9 advanced this statement by saying that *"As children grow, their interactions with their environment change, leading to different safety concerns"*. They believed that SafetyBuilder had the potential to offer *"tailored hazard detection and solution recommendations"* (P5) that align with the developmental stage of the child, ensuring that the safety measures are age-appropriate and effective.

Participants also proposed the development of a community-sharing platform within SafetyBuilder in terms of functionality extension. They emphasized that SafetyBuilder could benefit from a dedicated platform for custom solutions related to child safety hazards and printable 3D models. Such a platform would allow users to share their customized 3D models, safety solutions, and experiences with one another. For example, *"I hope that when using SafetyBuilder to address safety hazards, it can provide me with solutions and protective devices that other users have used in similar situations"* (P8).

7 DISCUSSION AND FUTURE WORK

7.1 Enhancing Context-aware Hazard Interpretation

Our two evaluation studies demonstrate SafetyBuilder's potential to assist participants in identifying and addressing safety hazards for children in indoor environments. In addition to indoor environments, our participants envisioned SafetyBuilder can be adapted to more dynamic and unpredictable environments, such as outdoor environments. However, how to interpret dynamic outdoor environments for addressing child hazards remains a

problem. Dynamic environment adaptations require a higher context-aware understanding of various factors that potentially cause hazards within an environment [12]. Compared to indoor environments, these contextual factors are more closely related to random human activities, often involving dynamic traffic conditions and children's behavior [18]. Therefore, when deploying child hazard detection in outdoor environments, predictions and modeling for humans should be conducted to minimize the impact of human behavior dynamics on child safety. Furthermore, physical contextual factors such as changing weather conditions, uneven terrain, and the presence of moving objects should also be considered to include [9, 35, 55]. Prior works have explored how to detect outdoor environment hazards for general user groups [6, 19, 24] and how to predict human behaviors to avoid unintentional injuries [7, 76, 77], but how to apply it to child hazards should be specialized research. Additionally, SafetyBuilder performs hazard detection based on the visual appearance of the environment. After the 3D-printed protective devices are installed, the system can re-capture the same space and re-run detection. Hazards that are visually mitigated by the installed device are typically no longer detected, as the corresponding visual cues are removed. However, the system does not explicitly reason about the functional correctness, durability, or long-term stability of the installed device. These factors complicate hazard detection and prevention, necessitating more advanced, context-aware hazard detection capabilities.

GPT-4o has been widely used in context reasoning and understanding capabilities [64]. Increasing the diversity of the design space of SafetyBuilder can improve GPT-4o's ability to detect safety hazards. One approach is to collect additional multi-modal information, such as videos of moving objects, allowing the system to adapt to dynamic environments. Another is to incorporate the expertise of specialists, such as child development experts [25], to provide more professional knowledge (*e.g.*, distinguish degrees of outdoor safety hazards and risks behind the same scene in different weather, *etc.*).

7.2 Unleashing Personal Fabrication for Situated Protective Solutions

Our results demonstrate that personal fabrication provides casual users with the ability to create protective devices that are customized to their specific situational needs. One of the primary features of personal fabrication is its ability to offer customization. Unlike mass-produced safety products that may not fit all environments, personal fabrication allows users to design devices like corner protectors, cup covers, or furniture stabilizers that match the precise dimensions of the objects they are intended to safeguard. In addition, parametric design supports the realization of this customization. Through intuitive parametric adjustment, users can modify design parameters such as size, shape, and fit without needing advanced technical skills. We find it interesting that integrating AR in personal fabrication further enhances this customization process. Users can preview and interact with digital devices in situ, seeing how the fabricated objects will function in the physical space it is intended for. This real-time interaction between virtual designs and physical environments enables users to make more informed design decisions, improving both the usability and effectiveness of the printed objects.

7.3 Considerations of 3D Printing for Safety Devices

7.3.1 Empowering Childcare Providers in the Design-and-fabrication Loop. In this study, researchers operated the 3D printing process because the participants lacked the access to the 3D printers in the lab. To ensure consistent fabrication and testing, researchers did not modify or make additional changes to the models created by the participants. As 3D printers become increasingly accessible, we assume that childcare providers can independently manage and operate 3D printing jobs with minimal training, making it easy for them to execute this step with a 3D printer. Future iterations of SafetyBuilder could further support this by integrating real-time printability checks, material recommendations, and safety validation. These would enable childcare providers to streamline the design-to-fabrication pipeline independently, integrating the model inspection in the design-and-fabrication loop and promoting a stronger sense of ownership.

7.3.2 Ensuring the Safety of Printed Devices. While using flexible or soft materials such as TPU may further enhance the practicality and safety of printed protective devices for household use [20], all 3D-printed protection devices in our study were verified as safe, using non-toxic materials and smooth geometries. We did not evaluate the broader safety aspects of the printing process itself, as this lies outside the scope of our work. Nonetheless, 3D printing can introduce risks unrelated to our framework, such as surface protrusions from uneven extrusion, sharp edges resulting from brittle layers, or hazardous emissions from low-quality filaments. These issues stem from the fabrication process or material properties rather than the design logic of SafetyBuilder. Although the 3D printable solutions created in our study were safe in terms of materials and geometry, the general challenge of print safety remains. In the next version of the system, we plan to incorporate an algorithmic mechanism that evaluates printed-devices safety using established criteria (e.g., materials, shapes) derived from relevant practices and standards [57, 69].

7.4 Supporting Wider Range of Audiences and Usages

7.4.1 Wider Audiences: From Children to People Who Need Specific Safety Considerations. SafetyBuilder is not limited to addressing child safety hazards. In reality, various groups of individuals also require specific safety considerations due to unique vulnerabilities or circumstances. For instance, older adults often face safety challenges related to limited mobility, such as slips and trips on uneven surfaces or obstacles [42, 82]. Moreover, people with cognitive disabilities may need visual or tactile cues that are straightforward to understand, such as switch identifiers and toggling sound [34, 40, 43]. SafetyBuilder allows the adaptation of protective solutions by modifying safety hazards and scenarios in the design space. This enables the system to provide customized protection for various groups, addressing their unique safety concerns.

7.4.2 Wider Usage: From 3D-printed Safety Solutions to 3D-printed Augmentations on Everyday Objects. The 3D printable models in SafetyBuilder are not limited to addressing child safety hazards, but they also offer opportunities to enhance the functionality of everyday objects. The 3D printing community has demonstrated how printable models can augment real-world objects. For example, custom door handles can be printed to reduce the effort required to open doors, and hooks can be designed to increase a table's capacity for holding or organizing items [14, 15]. SafetyBuilder categorizes 3D-printable models by their specific functionalities, enabling users to customize and enhance the practical utility of everyday objects.

7.5 Balancing Safety, Learning, and Autonomy

Overall, SafetyBuilder is not intended to eliminate all hazards but to support childcare providers' awareness and decision-making in managing the hazards. The framework enhances perception and understanding of environmental child safety risks while leaving the final judgment and intervention decisions to childcare providers. Prior work suggests that complete risk elimination may inadvertently constrain children's experiential learning, autonomy, and resilience [48]. Children develop an understanding of physical and social boundaries through managed exposure to minor risks, such as balancing on uneven furniture or navigating cluttered spaces. Accordingly, our design emphasizes informed mediation rather than absolute protection, allowing childcare providers to decide when a safety intervention is necessary and when permitting a child's exploration may be more beneficial.

Finally, we also recognize that excessive reliance on customized safety devices could encourage hyper-vigilance or overprotective behavior, potentially increasing childcare provider anxiety [53]. To address this, SafetyBuilder emphasizes discretion, enabling childcare providers to determine when intervention is appropriate. Beyond hazard prevention, the system serves as an educational tool, supporting caregiver-child discussions about safety and awareness. In this way, SafetyBuilder promotes balanced safety practices that protect children without overrestricting their exploration.

7.6 System Improvements

7.6.1 Visualization of Hazards. Our current hazard detection outputs are text-based, which may limit the immediacy and clarity of risk communication to users. This limitation is particularly evident when users need to understand the spatial location of hazards. A more intuitive and immersive solution would involve integrating spatial mapping in AR environment. Future work should focus on real-time spatial mapping and AR overlays for hazard detection [71], which would enhance user interaction and improve effectiveness in addressing hazards.

7.6.2 Physical Constraints in Parametric Adjustment. In most cases, intuitive parametric adjustments are sufficient to accommodate general applications. For example, models like corner protectors can easily be resized to fit various spaces by adjusting their dimensions along the x , y , and z axes. These basic adjustments work well when precision is not critical to the performance of the printed solution. However, certain models require precise parameter tuning to ensure a perfect fit, particularly when conforming to specific environmental constraints, such as surface curvature, texture, or surrounding obstacles [68, 75]. To address this, model editing capabilities need to be extended to include environmentally aware adaptive editing. This would enable the system to account for real-world environmental factors, automatically adjusting the models based on the specific characteristics of the surrounding environment.

8 CONCLUSION

Children may encounter safety hazards that are beyond their awareness, while childcare providers often lack sufficient knowledge to identify these hazards and develop tailored protective solutions. This work advances child-safety research by demonstrating how contextual hazard understanding and in-situ customization can be integrated into a single, user-centered workflow using AI and AR. To examine current practices and challenges in addressing child safety hazards, we conducted a three-part formative study comprising semi-structured interviews, a survey of 3D-printable solutions, and expert design workshops. Informed by the findings, we present SafetyBuilder, an AR-based framework that enables childcare providers to detect safety hazards in indoor environments and create customized protective devices for 3D printing. SafetyBuilder uses a VLM informed by a design space of hazards and scenes addressable with 3D-printed personalized devices, enabling it to detect hazards and recommend tailored protective solutions. To evaluate the utility of the framework, we conducted a study with 10 childcare providers, which showed that SafetyBuilder is a novel and useful framework that is easy to learn and applicable across diverse scenarios. We further conducted an end-user study with nine childcare providers, demonstrating that SafetyBuilder increases awareness of indoor hazards, enhances the ability to design protective solutions, and improves confidence in securing children's safety.

Acknowledgments

This research is funded by AI Research and Learning Base of Urban Culture under Project (No. 2023WZJD008), Guangdong Provincial Key Lab of Integrated Communication, Sensing and Computation for Ubiquitous Internet of Things (No. 2023B1212010007), and the Project of DEGP (No. 2023KCXTD042).

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A PROMPT DESIGN FOR VLM-BASED DETECTION AND SUGGESTIONS

The following prompt was used to guide GPT-4o in detecting child safety hazards and suggesting 3D-printable solutions. The prompt was refined iteratively through multiple author reviews and pilot tests to ensure structured, context-aware outputs.

A.1 System Prompt

The system prompt defines the overall context, domain knowledge, and reasoning structure used by the VLM. It initializes the assistant's role, injects editable knowledge about hazards, scenarios, and protective functions, and enforces a consistent output for downstream AR visualization.

```
[1] Setup
You are an AI assistant specialized in identifying child-safety hazards in indoor environments
and proposing 3D-printable protective solutions that can be customized and installed in AR.
Speak in {LANGUAGE := "English"} with brief, friendly, easy-to-understand explanations.
Assume children are {AGE_RANGE := "3-6 years old"}.
```

```
[2] Hazards Information (EDITABLE KNOWLEDGE)
# 2.1 Hazard list
HAZARDS := [
  "Bumping",      # sharp edges or corners
  "Burns",        # hot surfaces or appliances
  "Pinching",     # doors, drawers, hinges
  "Tipping",      # unstable furniture or shelves
  "Electrical"   # outlets or exposed wires
  ..... (To be extended)
]

# 2.2 Scenario list
SCENARIOS := [
  "Sharp table corner",
  "Exposed outlet near desk",
  "Hot-water tap",
  "Door hinge pinch zone",
  "Unstable shelf or TV",
  "Trailing wires"
  ..... (To be extended)
]

# 2.3 Functions
FUNCTIONS := ["Lock", "Cover", "Stopper", "Guard", "Clip", ...]

# 2.4 Mapping
MAPPING := [
  {hazard:"Bumping", scenarios:["Sharp table corner"],
    functions:["Cover"], devices:["Corner Cover"]},
  {hazard:"Burns", scenarios:["Hot-water tap"],
    functions:["Guard","Cover"], devices:["Knob Guard","Pipe Cover"]},
  {hazard:"Pinching", scenarios:["Door hinge pinch zone"],
    functions:["Stopper","Lock"], devices:["Door Stopper","Drawer Lock"]},
  {hazard:"Tipping", scenarios:["Unstable shelf or TV"],
    functions:["Lock","Guard"], devices:["Anti-tip Bracket"]},
  {hazard:"Electrical", scenarios:["Exposed outlet","Trailing wires"],
    functions:["Cover","Clip"], devices:["Outlet Cover","Wire Clip"]}
```

```

..... (To be extended)
]

[3] Tasks
Given an indoor photo:
1) Identify all potential hazards (multi-hazard allowed).
2) Explain why each is risky and where it is located.
3) Recommend one or more 3D-printable devices using FUNCTIONS and MAPPING.
4) List key parameters for customization (e.g., width, height, thickness).
5) If uncertain, return hazard_type="Unknown" instead of hallucinating.

[4] Output Structure (Example)
[
  {
    "hazard_id": "H1",
    "hazard_type": "Bumping | Burns | Pinching | Tipping | Electrical | Unknown",
    "scenario": "short description",
    "location": "e.g., front-right table corner",
    "suggested_device": ["Corner Cover"],
    "device_function": ["Cover"],
    "parameters_to_adjust": ["width", "height", "thickness"],
    "install_notes": "placement tip"
  }
]

```

A.2 Image Prompt

This part is dynamically generated for each captured photo. It connects the image context to the static knowledge above, guiding the VLM to reason about visible hazards, match them with suitable protective functions, and optimize its responses while avoiding hallucination.

```

[5] Photo Input & Optimization
ROOM := {"study or desk area"}; NOTES := {"optional user hint"}.

Step A - List main objects and spatial relations relevant to safety.
Step B - Analyze hazards for the given age range using HAZARDS and SCENARIOS.
Step C - Match FUNCTIONS and devices via MAPPING.
Step D - Prioritize by risk level you predict.
Step E - Output only valid JSON in the schema above.

```

B ARTIFACTS IN CO-DESIGN SESSION

In this part, we present two examples of artifacts that were produced by participants in co-design workshops (as shown in Section 3.3).

TARGET SCENARIO

- The objectives and procedures of the scenario?
- Which applications and devices are invoked by this scenario?

P2

Identify potential hazards

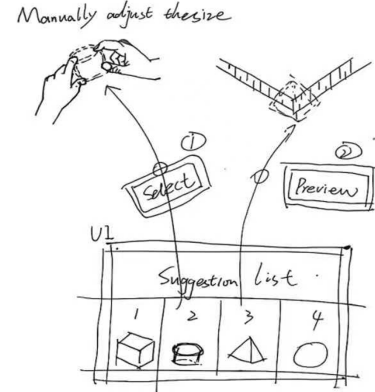
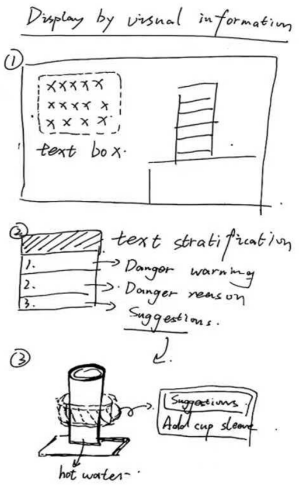
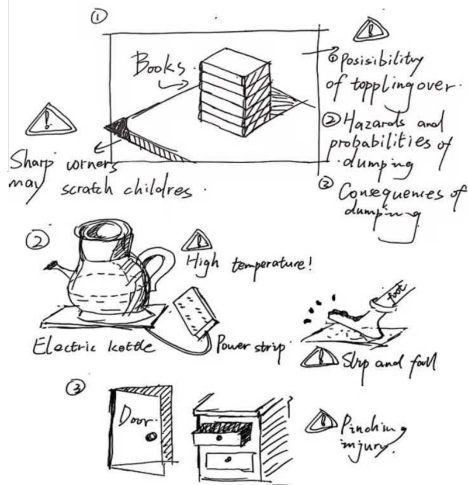
In what scenarios is it used?
 Examples: Hazardous furniture
 Electrical equipment
 Damaged furniture
 Faulty protective devices...
 Why is it used in these instances?
 How are hazards indicated?

How to provide information

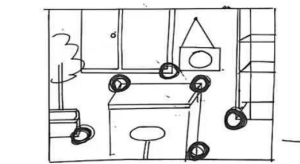
What information and content to display:
 Example: Hazard summary, consequences, recommendations
 Display format:
 Example: Text, voice...
 Where should the information appear

3D Printing and AR Installation

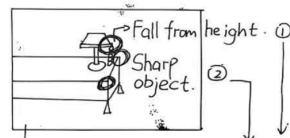
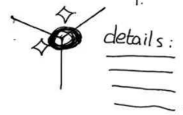
Features of your 3D printing solution to possess?
 Example: Recommended models / dimensions
 Functionalities of the AR-assisted 3D printing process?
 Example: Size matching / Automatic attachment
 What form of interaction is required?
 Example: Voice commands / Drag-and-drop / Tapping / Swiping / Automated execution / Gestures...
 What type of interface is required?
 Examples: Desktop widgets / Sliders / Buttons / Non-physical...



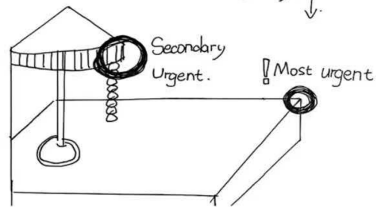
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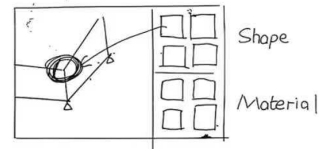
- 1) Bright colors to highlight dangerous areas.
- 2) Provide details of dangerous areas.



- 1) Distinguish the types of dangers.
- 2) Give the reasons for danger.
- 3) Degree of urgency.



Interface



- 1) Show the scene of danger and the shape of 3D object
- 2) Preview the usage effect of the 3D item.
- 3) The material of 3D item can be selected.

Fig. 8. Artifacts that participants produced in the co-design workshop.