designs

MDPI

Article

SAR Miniatures: Physical Scale Models as Immersive Prototypes for Spatially Augmented Environments

Omar Martinez Gasca [1,*], Lucas Van Dorpe [2], Ivo Dewit [1] and Lukas Van Campenhout [1]

[1] Product Development, Faculty of Design Sciences, University of Antwerp, 2000 Antwerp, Belgium; ivo.dewit@uantwerpen.be (I.D.); lukas.vancampenhout@uantwerpen.be (L.V.C.)
[2] Dott Achilles, 2800 Mechelen, Belgium; lucas.vandorpe@achilles.be
* Correspondence: omar.martinezgasca@uantwerpen.be

Abstract: This paper explores the use of physical scale models as immersive prototypes in the design and development of Spatial Augmented Reality (SAR) environments. SAR integrates digital projections with physical spaces, offering benefits for spatial reasoning and coordinated activities. However, designing SAR systems at full scale presents challenges in testing and refinement due to their complex physical–digital properties. To address this, we developed augmented miniature environments for two case studies: an in-store retail navigation system and a manufacturing assembly process. These models effectively materialized SAR's most important experiential qualities at a manageable scale, enabling the exploration of spatial relationships, coordinated user activity, and system functionality in a tangible and accessible way. The miniatures facilitated collaborative design, providing a shared medium for stakeholders to visualize and experiment with SAR applications. This paper presents augmented miniatures as effective tools for SAR design that foster creative exploration and communication, and highlights opportunities for future research in combining these models with digital prototyping technologies.

Keywords: spatial augmented reality; embodied interaction; design for interaction; design research; miniature models; research through design

check for updates

Academic Editor: Wenbin Yu

Received: 21 October 2024
Revised: 3 January 2025
Accepted: 8 January 2025
Published: 10 January 2025

Citation: Martinez Gasca, O.; Van Dorpe, L.; Dewit, I.; Van Campenhout, L. SAR Miniatures: Physical Scale Models as Immersive Prototypes for Spatially Augmented Environments. *Designs* **2025**, *9*, 10. https://doi.org/10.3390/designs9010010

1. Introduction

Spatial Augmented Reality (SAR) is a technology that makes use of video projectors to overlay graphical information directly onto physical surfaces, thereby augmenting real-world environments and objects with digital content. The key difference with other types of Extended Reality (XR) technologies is that SAR does not require the display device to be worn or held by the user [1]. This distinctive experiential characteristic of SAR systems offers several benefits for users. For example, it has been shown to enhance spatial comprehension during complex tasks [2] and facilitate the creation of shared spaces that improve coordination and collaboration in group activities [3]. These qualities make SAR particularly valuable in contexts in which spatial and collaborative engagement is essential, such as museum exhibits [4], manufacturing operations [2], and design activities [5].

However, much of SAR research has traditionally focused on addressing the technical challenges of its implementation, such as projection accuracy and real-time tracking [6–9]. While these issues are undeniably crucial, there is an increasing recognition by XR developers of the need to balance technical advancements with human-centered considerations [10–12]. As such, to fully capitalize on the benefits of SAR, it is essential to consider users' cognitive and social needs in the development of augmented environments.

This entails understanding and addressing the distinctive aesthetic and experiential qualities of SAR environments, which are crucial not only for enhancing user engagement but also for ensuring that SAR systems effectively fulfill their intended purposes. For instance, in their "One reality" framework, Roo and Hachet [13] look into the unique interactive properties of different XR modalities to conceptualize a system that seamlessly transitions between physical and digital experiences. Their approach emphasizes maintaining users' connection with the physical environment and with other users, for which SAR is leveraged for its ability to create shared spaces and allow direct manipulation of augmented objects. Similarly, Bekele and Champion [14] compare the qualities of various XR technologies and evaluate their effectiveness in enhancing cultural learning. Their assessment looks at various interaction methods in XR technology from both an experiential and a technological perspective in order to identify an approach that enables a contextual relationship between users, their physical surroundings, and the virtual environment. These examples underline that SAR's potential is maximized when it moves beyond purely technical concerns to embrace user experience, interactivity, and engagement.

Objectives of This Paper

Building on the outlined perspective, the present paper seeks to contribute to the discussion of the distinctive esthetic and experiential qualities of SAR environments. To do so, we present an exploratory research effort centered around two case studies, each involving the creation of miniature environments onto which digital content was projected. These miniature environments served as platforms for exploring and communicating various scenarios and interaction routines within two distinct SAR contexts. Through this exploration, we aim to deepen our understanding of the qualities that define augmented environments. By focusing on these qualities, we seek to identify design approaches that can more effectively leverage the core properties of SAR technology, ensuring that these are accessible and impactful during the design and development of SAR applications. In doing so, we aim to address the growing need for human-centered considerations in SAR research, particularly in contexts that demand intuitive interaction and collaborative engagement.

2. Methods

Our research effort is centered around the use of miniatures as supporting tools in the design and development of SAR environments. As such, we formulate our initial research question as: how do augmented miniature environments materialize experiential and aesthetic qualities of SAR during the design and development of full-scale applications?

To structure our approach to this question, we follow the design science research framework presented by Peffers et al. [15], since it is structured around the construction of design artifacts, the evaluation of these artifacts, and the refinement of knowledge. The process consists of six activities: (1) problem identification and motivation, (2) define the objectives for a solution, (3) design and development, (4) demonstration, (5) evaluation, and (6) communication. Hence, we present in this introduction the context and relevance of the problem (activity 1), as well as the objectives of our exploration in relation to this research space (activity 2). In what follows, we outline the key theoretical motivations for using augmented miniatures as supporting tools, drawing from relevant literature, after which we describe the physical construction of the miniatures (activity 3) and their implementation (activity 4). This is followed by an analysis process aimed at refining our understanding of the miniatures' qualities through reflection on our implementation of them (activity 5). At this stage we revisit the original insights from the literature on SAR's experiential qualities and build upon them based on these findings. Finally, the last section summarizes our findings and provides an outlook on future steps (activity 6). This approach emphasizes the importance of integrating theoretical foundations with practical application, ensuring that the research contributes to both the advancement of knowledge and the improvement of practice.

It is important to note that this paper does not present a formal evaluation of SAR systems or interaction methods. Instead, it offers an account of our experience developing and implementing augmented miniatures as part of the design and development of SAR environments. Through this descriptive approach, we aim to share insights gained during the process, focusing on how these miniatures facilitated the exploration and communication of design scenarios and interaction routines. Our intent is not to test specific hypotheses but to contribute to the growing body of knowledge surrounding SAR design by reflecting on the practical and aesthetic considerations encountered in our work.

3. Background and Related Work

The related work in this section first reviews the key experiential qualities of SAR environments, highlighting the benefits derived from its distinctive characteristics. It then explores the role of physical models and prototypes in design practice, outlining how these tools help designers frame and investigate design questions. Finally, we present augmented miniatures as a practical and effective tool for exploring and communicating the distinctive experiential qualities of SAR, particularly by bridging the physical and digital dimensions essential for SAR applications.

3.1. The Experiential Qualities of SAR

Arguably, the defining characteristic of SAR is its use of the physical environment itself as a display medium for digital content, which enables a more natural way for users to grasp and manipulate information. By leveraging people's familiarity with physical engagement, SAR resonates with the principles of embodied interaction, which emphasize that cognitive processes are deeply rooted in the body's interactions with the physical world [16,17]. This perspective aims to make interactions with digital systems more intuitive and meaningful through physical engagement [18]. By projecting digital content onto physical surfaces, SAR allows for direct tangible engagement with the system, such as in the Tangible 3D Tabletop [19], in which users manipulate physical markers on a tabletop map to interact with geolocated data, adapting the projections on the map based on the movement and placement of tangibles. This seamless integration of physical and digital elements not only enhances interaction but also supports improved spatial comprehension, as it allows users to rely on familiar environmental cues and natural perceptual processes to navigate the system. The study by Baumeister et al. [20] demonstrated that, compared to head-mounted displays, which require adjusting to a virtual interface, SAR's approach to aligning digital information with the physical world reduces cognitive load and enables users to better understand complex spatial relationships. This aligns with similar findings in which SAR systems demonstrate improved performance in tasks requiring spatial awareness [2,21].

Another important consequence of presenting digital content directly over a physical environment is the materialization of a shared space where multiple users can simultaneously engage in a collective experience. This shared space acts as a common reference point that facilitates discussion and the communication of ideas [5,22] but, given the dynamic and adaptable nature of digital content, it can also serve as a guide for coordinated activity. As opposed to head-mounted displays that isolate the user from its physical surroundings, projected content allows groups of users to coordinate their activity in response to each other's actions and to the augmented environment, collectively interpreting and responding to ongoing changes [23]. Through this interplay of interactions among the digital content, the physical setting and other users, SAR becomes a space for shared exploration and collective understanding. For instance, in the SAR system in [3], participants were tasked with navigating and interacting with a simulated museum exhibit, guided through different scenes by floor-projected arrows and highlights. These visual cues not only directed movement and focus but also facilitated communication and coordination among users, enabling them to negotiate and synchronize their actions more effectively to collectively share better viewing angles.

While the aforementioned advantages of SAR stem from the interactive possibilities of its physical and digital dimensions—which allow for intuitive interactions and dynamic content presentation—the overall experience of an SAR environment depends on the interplay and cohesiveness among these two dimensions. The physical and digital events that comprise an augmented environment have very different sensorial qualities: the former tend to be persistent and static, while the latter are temporal and dynamic. The way in which these two types of events interact with each other is known as coupling [24] and shapes both the usability and aesthetic quality of SAR systems. For instance, in the Tangible 3D Tabletop, placing a tangible over the flat map displays a magnified image of the map section over the tangible, and when the user rotates the tangible, the image zooms in or out accordingly. This interaction routine contains two events with different sensorial qualities, the physical action of rotating the tangible and the immediate transformation of the digital map. When these are brought together cohesively, they are perceived by the user as one seamless and harmonious experience. Previous studies have underlined that well-designed couplings are not only a source of aesthetic satisfaction but also enhance the intuitiveness of interactions [18], as the smooth connection between physical actions and digital responses contributes to a sense of natural engagement. This underlines that well-designed couplings not only improve usability in an SAR environment but also create a visually and sensorially rewarding experience that resonates with users on a deeper level.

Altogether, the experiential qualities described in this section demonstrate how SAR systems can create intuitive, engaging and collaborative environments that enhance both usability and user experience. A summary of these characteristics is presented in Table 1 to illustrate the technology's benefits.

Table 1. Summary of SAR's distinctive experiential qualities.

Technology Characteristics	Experiential Quality	Benefits for Users
Projection directly onto physical surfaces	Use of natural perception processes to engage with the augmented space	Spatial comprehension
No need for head-mounted or handheld displays	Awareness of social and environmental cues	Coordinated activity
Use of digital and physical elements	Coupling between digital and physical events	Natural sense of engagement, aesthetically pleasing experience

3.2. The Role of Physical Models and Prototypes

Physical models and prototypes are widely recognized as fundamental elements of design practice, which positions them in a crucial role in the development of technology. These artifacts are implemented for multiple purposes throughout a design process, such as the creative exploration of ideas, provoking critical reflection, or verifying technical requirements. At their core, physical models enable designers to examine, frame, and inquire into design problems to evaluate potential solutions [25]. Consequently, selecting the qualities of a model or prototype is essential for identifying and addressing the most relevant design questions for a given context. For this important role, different frameworks have been developed aimed at clarifying the way in which these artifacts assist designers in navigating a design space. For instance, Lim, Stolterman, and Tenenberg [26] presented an analysis of the fundamental nature of prototypes, in which they describe two key dimensions that support designers in "traversing a design space". First, prototypes can function as (1) filters, allowing designers to deliberately exclude certain aspects of a design during a given phase to explore variations in other qualities. Second, prototypes are essentially (2) manifestations of ideas, providing tangible means for stakeholders to experience a concept and for designers to engage in a reflective conversation with the design idea, as illustrated in Schön's notion of reflection-in-action: the process of thinking and adjusting while being actively engaged in a task [27].

This underlines the importance of identifying the core experiential elements of a technology in order to implement tools and methods that make these properties accessible during the design process. By doing so, designers can align their exploration with the intended impact of the technology. Hence, awareness of a technology's essential experiential attributes enables designers to gain deeper insights into the aspects of the experience that are most critical to achieving success. Importantly, this does not imply that prototypes need to replicate the exact characteristics of a full implementation to foreground important information. Buchneau and Fulton Suri [28], in their "experience prototyping" approach, contend that even a simple object, such as a brick representing certain weight, can effectively convey experiential aspects. Therefore, when designing interactive technology, careful attention must be paid to how models and prototypes mediate the process of exploration and understanding.

3.3. Augmented Miniatures as an Approach to SAR Development

One of the most significant challenges in the design and implementation of SAR environments is related to the scale of application. As an immersive technology, SAR is often employed in large-scale interventions, which limits opportunities to explore and test its properties ahead of full deployment [29,30]. To approach the design of large spaces, scaled-down representations provide a practical means for designers to visualize, experiment with, and refine concepts before committing to full-scale implementation [29–31]. Furthermore, as the fundamental qualities of an SAR experience depend on achieving a cohesive integration between its physical and digital dimensions, augmenting these physical miniature environments with projected digital content offers a valuable approach to designing SAR applications.

While digital models are often favored due to their cost-efficiency and ease of iteration, the ubiquity of CAD modeling in design processes means that the additional step of 3D printing a physical model is straightforward and provides substantial and distinct benefits, as physical models present unique affordances that complement digital representations. They provide an immediate, tangible sense of scale, materiality, and spatial relationships, which are difficult to convey on a computer screen. Developers working on Augmented Reality (AR) applications frequently cite difficulties in designing for the physical elements of immersive experiences, such as spatial distribution and graspable objects, when relying solely on 2D digital environments [32–34]. As such physical models are particularly valuable for practitioners for exploring and articulating the spatial and tangible aspects of interaction [34]. Research has consistently demonstrated the benefits of physical scale models in helping people better grasp spatial relationships. For example, studies in architectural design and urban planning have shown that physical models enable clearer visualization of spatial layouts, distances, and proportions compared with their digital counterparts [35,36].

Moreover, since an augmented miniature is able to present a complete scene, rather than emphasizing isolated elements, it allows for a more intuitive understanding of the overall dynamics of the system. This is particularly valuable in SAR environments, where awareness of contextual cues—such as physical layout, other user's activities and animated content—influences how users coordinate their actions to engage with the system's features. XR prototyping studies emphasize the importance of preserving contextual information, as it helps maintain the fidelity of the experience, even when fidelity is down-sampled for testing or documentation purposes [34]. As such, augmented miniatures allow designers to experience the interplay between users, physical space, and digital content in a more intuitive and holistic manner, even when abstracting the scale of the system. Hence, unlike 2D digital representations, which may flatten the complexity of these relations, physical models enable collaborative interpretation of system behavior, grounding the design process in a comprehensive, tangible context [33,34].

In summary, augmented miniatures provide a compelling approach for addressing the challenges of SAR development. By bridging the gap between physical and digital dimensions of SAR, they enable the experience and exploration of the distinctive experiential qualities of the technology: its benefits for spatial comprehension and its influence on coordinated activity. This approach ensures that design decisions are informed by a holistic understanding of the interplay between users, physical space, and augmented content, which are critical to the success of SAR environments.

4. Design and Implementation of Augmented Miniatures

This section constitutes the third step of our research process: design and implementation. We present the two augmented miniatures employed in this study, offering background information on the context and objectives that guided the development of each miniature. In addition, we provide detailed descriptions of the scenarios and interaction routines that each miniature is intended to communicate and explore. Following these descriptions, a concise discussion is included for each case, reflecting on key observations about how the miniatures manifested the SAR environment's qualities.

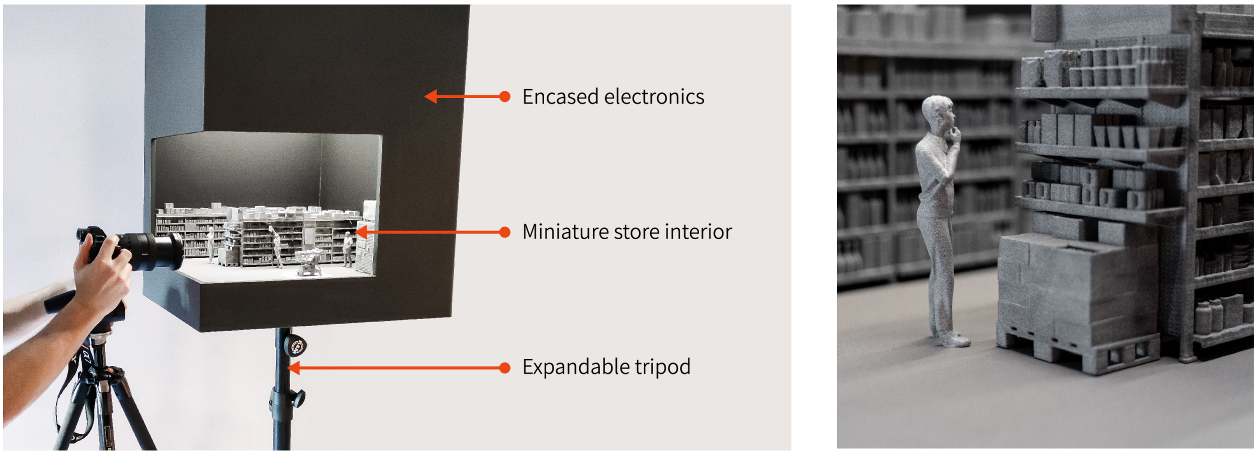
4.1. The Augmented Supermarket Miniature

The video for the functionality and scenarios of this miniature can be found in the Supplementary Material (Case1-supermarket).

4.1.1. Background and Description of Miniature

This augmented miniature environment was developed for a large European supermarket chain. The primary objective was not to test a specific technical application, but rather to create a physical representation of the potential use of SAR within a retail context, serving as a tool to provoke discussions about the digitalization of in-store communication. Thus, the starting point for this SAR miniature was a conceptual future scenario in which a supermarket is outfitted with a projection system that is able to cast imagery onto any floor or shelf. In this context, SAR is considered a medium of interaction between a customer, the store, and the products stored within. Through the use of projected digital content, the miniature depicts various scenarios in which SAR is conceptualized as a tool for dynamic wayfinding, highlighting promotions and as an aid in shopping, in this way presenting it as a technology that has the potential to replace more traditional media such as wayfinding arrows on the floor, printed panels, or displays.

The miniature itself consists of a scaled-down supermarket interior featuring five shelving units, three static customer figures, a retail worker, a shopping cart, and a step stool. Despite the static nature of the figures, movement is implied through projected animations, such as footsteps on the floor, bringing the scene to life. The whole system is enclosed in a wooden box, with the lower half containing the miniature scene while the top half stores all necessary electronics (Figure 1). The box is mounted on an expandable tripod stand, ensuring that the miniature is at eye level when viewed standing, encouraging engagement and close inspection.



(**a**) (**b**)

Figure 1. Augmented supermarket miniature: (**a**) overview of main components; (**b**) detail.

To accurately integrate animated content with the physical miniature, a reverse-perspective rendering method was employed. The entire system was first designed virtually in Blender version 3.5.0 (2023), where the miniature's structure and components were modeled in 3D. Virtual light sources were positioned to simulate the illumination angles required for projection, enabling the precise placement of physical projectors in the final setup. The animated content was designed in this virtual space, including elements like moving shopping carts and transparent labels above shelves. These animations were rendered into video files, one for each projector, and fine-tuned for synchronization and timing. The content was then mapped onto the physical scene, ensuring accurate positioning through a pin-in-hole registration system. Custom 3D-printed holders were used to position the projectors in alignment with the virtual transformations. A final calibration step was conducted to correct the distortions of the projected images, utilizing grid warping techniques to align the projected grid with a physical reference. This calibration ensures that the digital content accurately overlays on the miniature model, for a seamless interaction between the physical and digital elements.

4.1.2. Description of SAR Interaction

The first scenario presented through the miniature is related to in-store promotions and offers. A flat surface located above the product shelves is used as a "display", receiving projected content (Figure 2a). Its position and format resembles a traditional printed sign or a mounted screen used to convey relevant information to customers. However, in this case, through the use of projections, these data extend beyond the limits of the "display". Hence, in this scene the environment is augmented, not only to communicate information about discounts, but also to help customers locate the products in question by mapping the information directly onto their surroundings, highlighting the discounted products with a red projection, linking them to the sign itself (Figure 2b).

(**a**) (**b**)

Figure 2. Scene depicting SAR used for in-store promotions: (**a**) the sign above the shelves communicates an available promotion; (**b**) discounted products on the surrounding shelves are highlighted.

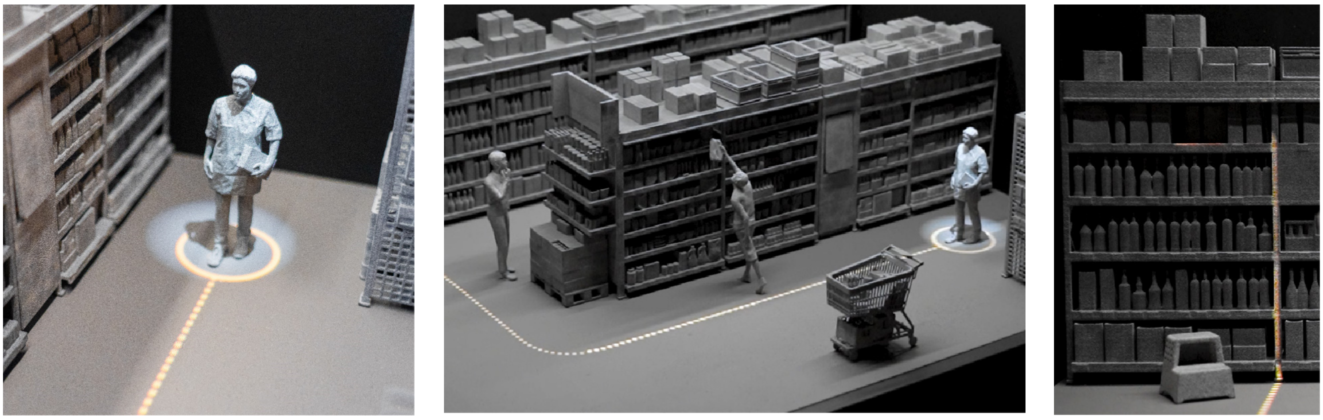
The next scenario further extends the idea of utilizing SAR to locate products on the shelves, presenting the possibilities of a hybrid shopping experience, which combines physical and online shopping. As the store has a limited number of products that are physically present, customers can browse designated displays with products they can find and buy physically there, and with products they can order through an online purchase within the store. In the scenario presented, a customer browses through a selection of wines while the system links the on-screen bottles to their physical presence in the store by using projections to highlight their location in the shelves in real time (Figure 3).

(**a**) (**b**) (**c**)

Figure 3. Hybrid shopping experience: (**a**) a customer uses a display on the shelves to browse available products; (**b**) as they browse through the catalog the highlight on the shelves changes; (**c**) a different product is highlighted.

The next scene presents the SAR system as a wayfinding tool. In this scenario, every customer that has created a list in their smartphone of items to buy is assigned a color within the store. While walking through the aisles, the projections highlight the products that they need (Figure 4). Furthermore, this wayfinding functionality can also be used to support the staff of the store. In a different scenario, the environment is augmented to support in-training supermarket employees, with the projections creating a path for them to find empty spaces in the store's shelves that need to be restocked (Figure 5).

Figure 4. Scene depicting wayfinding for customers.



(**a**) (**b**) (**c**)

Figure 5. Scene depicting wayfinding for employees: (**a**) the projections start from employee location; (**b**) a path is laid on the floor towards the location to restock; (**c**) the path reaches the sought location on the shelf.

4.1.3. Discussion of the Supermarket Miniature

The SAR application depicted in this section integrates digital processes—such as online catalogs and shopping lists—with the physical layout of the store. Through this integration, the SAR system primarily serves as a wayfinding tool, guiding users to specific products and enhancing navigation within the supermarket. For this reason, this application primarily highlights SAR's potential to support spatial awareness.

As part of the communicative role of the miniature, it was important to materialize this quality in order to facilitate understanding to different stakeholders, not only about the system's functionality, but also of the overall dynamics that SAR could introduce into a shopping experience. Hence, by presenting a comprehensive scene that encapsulates the physical structure of the store alongside the dynamic projected content, the miniature makes it possible to observe the interplay between digital services and the physical layout. This approach aligns with the aforementioned findings in XR prototyping research, which emphasize the importance of preserving contextual information to facilitate an intuitive understanding of system behavior [34]. As such, the permanence of the physical miniature proved especially valuable, as it provides a familiar and stable reference point against which the transformative effects of SAR can be demonstrated. The animated digital content—such as projected footsteps—dynamically direct attention without obscuring the broader context of use.

One significant insight gained from observing the SAR system through this medium was the distinction between two types of strategies for presenting information: direct actionable cues and contextual information in the periphery of attention. For instance, the projection of a path to help employees locate empty shelf spaces represents a direct cue for action, which leverages the dynamic qualities of SAR's digital content to guide users intuitively and efficiently within the physical environment. In contrast, static promotions and discounts displayed above the shelves rely on the permanence of the physical space, allowing information to remain accessible without demanding immediate attention. Establishing this differentiation proved essential to effectively harness SAR's unique capabilities and allow a seamless interplay between actionable and contextual information. For example, it became evident that, while promotions are initially static and peripheral, SAR can extend their function by dynamically connecting these signs to the specific locations of discounted products on the shelves. While this functionality can be communicated through other media, the miniature's potential to palpably blend the dynamic behavior of digital content with a permanent physical structure allows for a richer understanding of how SAR transforms this particular context.

Ultimately, as a tangible, shared artifact, the augmented supermarket miniature allowed stakeholders to collectively grasp and discuss the interaction dynamics within the SAR system, fostering a shared understanding of the design's implications. This shared reference point proved invaluable in this particular case, as it allows bridging communication gaps between technical and non-technical stakeholders, ensuring that the experiential qualities of SAR were effectively conveyed and critically examined.

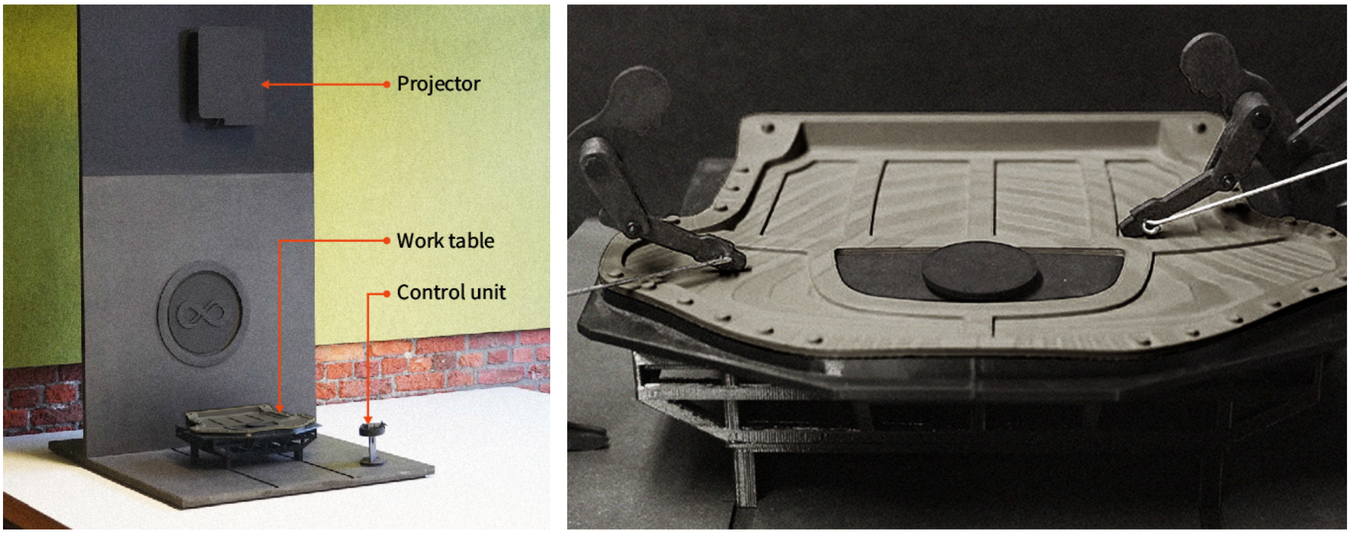
4.2. The Augmented Industrial Workplace Miniature

The video for the functionality and scenarios of this miniature can be found in the Supplementary Material (Case2-workplace).

4.2.1. Background and Description of the Miniature

The context for this demonstrator was provided by a manufacturer of large plastic parts. The SAR implementation in this case was concerned with facilitating the preparation for the assembly process of the body panel of an industrial vehicle. This panel contains two large plastic parts that need to be assembled together in order to form a rigid and stiff piece. Additionally, the two parts need to be prepared simultaneously, by two different operators. Throughout this process, these parts are blown off, cleaned, labeled, and heated; glue is applied on one of them, and both parts are put together, clamped, and welded. For all of this, the manufacturing company developed a designated workstation that included a mobile table, a manipulator, and a clamping caliber.

The miniature was developed with the objective of exploring the possible benefits and contributions of an SAR system for the assembly operations of this specific plastic part. Thus, the demonstrator is a 1/10 scale model of the workplace (Figure 6). It consists of a horizontal surface over which a working table is placed; this table, is not only designed specifically to accommodate the roof parts, it also provides a circular surface over which projections can be received to convey information during different operations. A vertical wall containing a pico projector is located behind the table. Several props were added to the model, like a control unit with different tools (glue gun, blow torch, pen, degreasing spray). Additionally, two operator puppets were built to act out several scenarios, and to make the different possibilities of the system visible and tangible.



(a) (b)

Figure 6. Augmented industrial workplace miniature: (**a**) overview of main components; (**b**) operator puppets interacting with miniature.

4.2.2. Description of SAR Interaction

The first operation supported by the SAR system is the dusting of the piece. The part laid on the worktable is entirely covered by a projected texture of animated waves (Figure 7), which represent the direction in which the operator needs to blow to remove dust. While this is happening, the projection also overlays several arrows that point towards difficult corners where dust might accumulate in the piece. The next operation is the degreasing of the areas on which glue is going to be applied. For this, lines are projected over the areas on which solvent needs to be applied (Figure 8a), in this way providing guides that the operator can follow. In this step of the process, the operator needs to wait for the solvent to dry and, thus, a timer is projected onto the working table while also covering the entire piece with a slowly disappearing texture (Figure 8b–c). This overlaid texture is meant to provide information about the remaining time while staying in the periphery of attention.

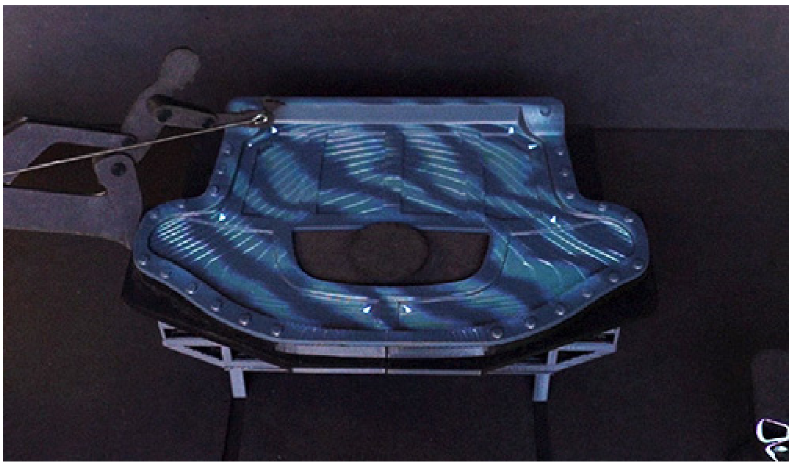
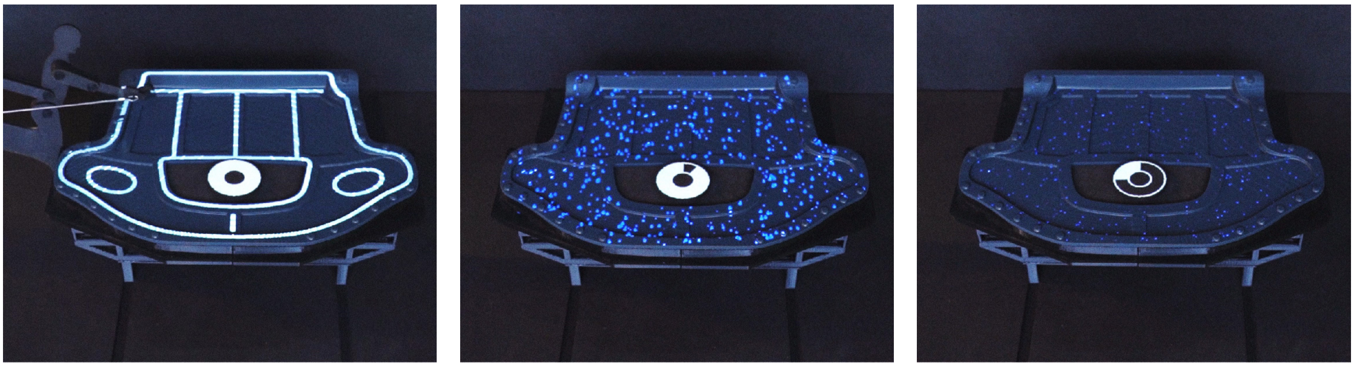


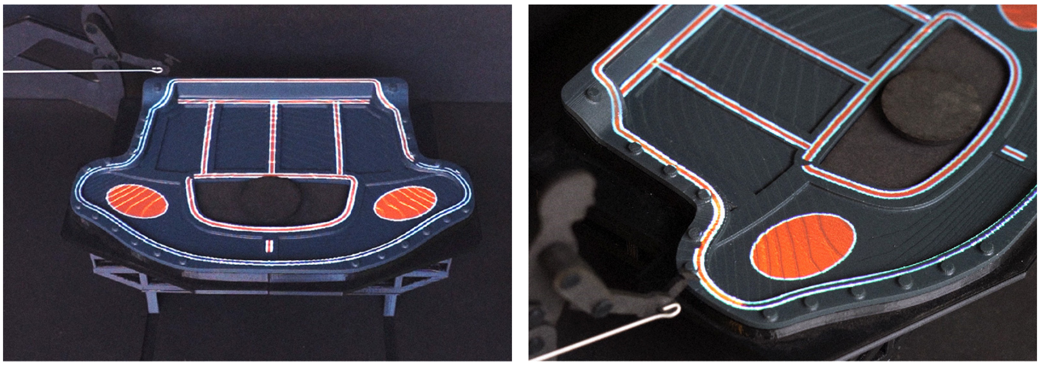
Figure 7. Scene depicting the dusting of the piece.

The next operation in the SAR system is the application of heat to the areas to be glued. In this instance, the projections not only highlight the areas that need to be worked on, but also the correct order and speed at which to apply heat. For this purpose, said areas are shown as an outline that is gradually filled by a red color (Figure 9), thus, providing a frame of reference for the operator about the appropriate speed of their movement. Next, the pieces need to be numbered, for which the projections guide the operators from the tool table towards the correct place where the number needs to be added, indicating position and orientation to standardize the process (Figure 10).



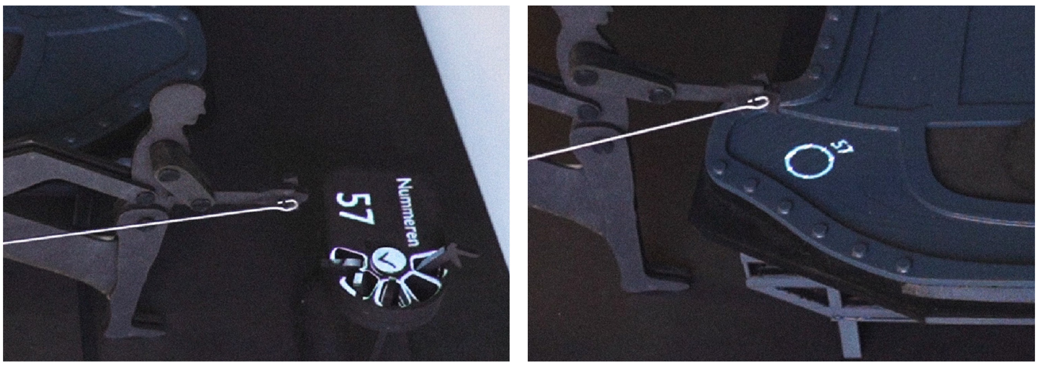
(**a**) (**b**) (**c**)

Figure 8. Scenario for degreasing: (**a**) white guidelines for the application of solvent appear over the piece; (**b**) after application, a blue texture appears to indicate waiting time; (**c**) the texture gradually disappears.



(**a**) (**b**)

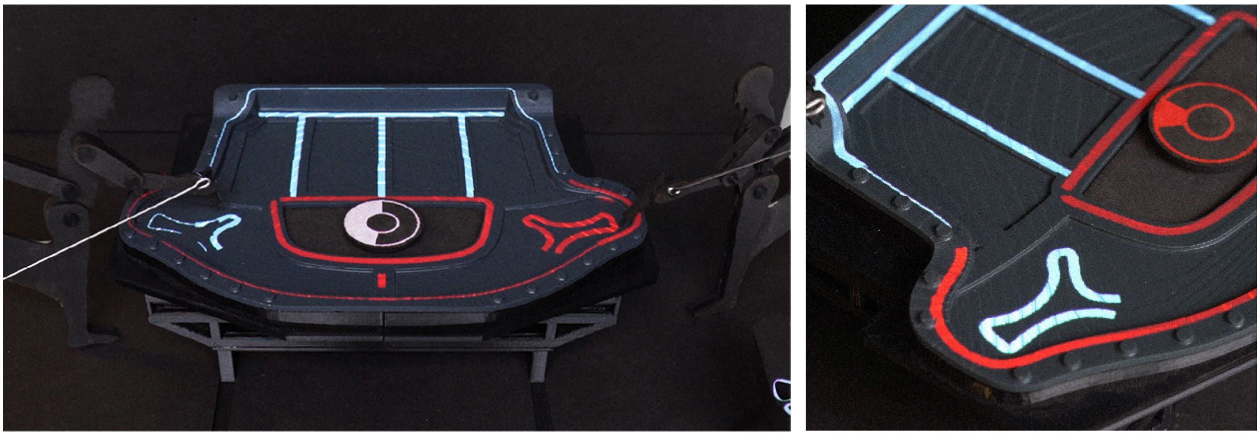
Figure 9. Scene depicting the application of heat: (**a**) overview of guidelines as a white outline presented over the piece; (**b**) the guidelines gradually fill up with a red color to indicate speed and direction.



(**a**) (**b**)

Figure 10. Numbering the pieces: (**a**) the process starts at the work table; (**b**) projections indicate the correct position and orientation of the number.

Finally, for the application of adhesive, the projections once again highlight the areas that need to be worked on. However, in this instance the projections are shown in two different colors to distribute the task between two operators (Figure 11). These projections also convey information about the correct order and speed of the application of adhesive by gradually thickening up the outline of the signaled areas and by projecting a timer. After the two pieces have been glued together, the projections indicate that the piece needs to be moved.



(**a**) (**b**)

Figure 11. Scenario for application of adhesive: (**a**) the guidelines distribute the task between the two operators by being presented in two different colors; (**b**) the correct order and speed for the operation is indicated through the thickening of the guidelines.

4.2.3. Discussion of the Industrial Workplace Miniature

This section described an SAR application that leverages the technology's qualities to overlay digital guidance cues on a physical workspace, assisting operators in completing precise assembly tasks. Similar to previously reported applications in industrial contexts [2,21], this SAR environment aims to make use of the technology's ability to enhance spatial comprehension to assist two operators in completing a series of precise tasks.

Building upon the differentiation established in the supermarket miniature between peripheral information and direct actionable cues, this case study sought to implement two complementary strategies for delivering information to users within the SAR environment. The first strategy relies on the permanence of the physical environment. As such, it involved presenting contextual information in an ambient manner that did not demand immediate or focused attention. This information is mapped directly onto specific areas of the workspace, enabling intuitive access to it without disrupting workflow. For example, during the degreasing task, a projected texture visually indicates the solvent's drying time, replacing the need for an explicit timer. This ambient display conveys temporal information naturally and effortlessly through the gradual disappearance of the texture. As with the supermarket case, the tangible quality of this miniature allows the presentation a complete picture of the physical layout in which this system is implemented, providing a stable reference point that can be experienced through natural perceptual processes. As such, the augmented miniature makes it possible to visualize how ambient information integrates into the overall dynamics of the context, which proved crucial for refining the specific aesthetic qualities of the disappearing texture.

The second strategy focused on cues for action, which guided not only the location but also the sequence and timing of operator movements. Given the dynamic context of this application, it was important that this miniature allowed a direct tangible manipulation of its elements. For this reason, the miniature was developed with an open design (see Figure 6a) that allows the use of two operator puppets for a representation of different positions and movements in relation to the projected digital cues. Unlike the supermarket case, where SAR primarily supports individual engagement with the system's features, this context emphasizes a more collaborative and task-oriented approach to SAR interactions. As such, this hands-on approach proved particularly critical in interactions requiring synchronized effort, such as the application of adhesive, where projected content coordinates two operators simultaneously. By puppeteering the operator figures within the miniature, it became possible to experiment with the timing and order of actions, enabling the exploration of different temporal scenarios by varying the speed of cues or task durations and visualizing how these changes impacted the flow of operations. In this way, the tangible and interactive nature of the miniature provided valuable insights into how the system could potentially accommodate operators with differing skill levels.

Overall, this miniature reinforced the importance of contextual fidelity and tangible manipulation in SAR prototyping. Its flexibility to test ideas and visualize operator interactions further demonstrated the way in which an augmented miniature is able to convey the experiential possibilities of SAR in a manageable way, ensuring that its temporal, spatial, and collaborative affordances were effectively understood and incorporated into the design.

5. Discussion

In this section, we reflect on the work presented and explore how the two miniatures effectively manifested SAR's most important experiential qualities, which was crucial to their complementary roles within the design process.

5.1. Materializing SAR's Qualities Through Augmented Miniatures

The most significant advantage of using augmented miniatures in SAR development lies in their ability to concretely demonstrate the interaction between the physical and digital dimensions of the technology before committing to full-scale implementation. As previously established, this relationship forms the foundation of an SAR experience, with the most significant benefits of SAR emerging from the cohesive integration of these two aspects.

Virtual reality (VR) has also been proposed as tool for addressing SAR implementation challenges when physical testing is impractical, for instance evaluating how projection distortions change under different conditions [37]. However, while VR proves useful for testing these specific technical issues, it cannot fully replicate certain experiential qualities inherent in SAR. For instance, VR applications like TactileVR [38], which integrates physical toys into virtual environments, attempt to add physical engagement—which is lacking in VR—in order to enhance user engagement in educational and play settings. Similarly, work by Piumsomboon et al. [39] aimed to overcome the limitations of head-mounted displays by exploring how virtual awareness cues can provide users with information about their collaborator's attention and actions in a VR environment.

These strategies highlight the importance of selecting the appropriate prototyping method—whether VR or physical miniatures—based on the specific design aspect that needs testing. While VR can be well suited for testing particular technical issues like projection alignment or distortion, miniatures can offer a more direct, tangible representation of how physical and digital elements seamlessly blend in an SAR environment. By preserving the physicality and context of use, augmented miniatures offer unique opportunities to understand how digital content interacts with and transforms physical spaces. For example, the supermarket miniature effectively illustrated how SAR can convey spatial information in two distinct ways, making it easier for stakeholders to understand the unique interactive possibilities of this technology. Moreover, introducing interactivity into the miniature further emphasizes the temporal dynamics inherent in augmented environments. While the supermarket miniature materialized this aspect by simulating the movement of customers with animations, enabling stakeholders to directly simulate movements within the scene—as in the workplace miniature—emphasizes how users must coordinate their actions with multiple contextual factors in real time.

However, the limitations of miniatures must also be considered. The fidelity of miniaturized environments inherently restricts the ability to fully represent certain qualities of SAR. For instance, the notion of couplings—the interaction between physical and digital events—is harder to convey in miniatures. In the supermarket model, while the system's response to user interactions—such as highlighting products in response to browsing—could be demonstrated, the limited interactivity of the miniature prevents users from fully experiencing the effect in an embodied, intuitive way. Moreover, the indirect perspective of interacting with a miniature via proxies or simplified figures further limits the user's ability to grasp the full effect of an augmented environment. For instance, while a product changing color based on a customer's shopping list could be shown in a miniature, the actual usability of this feature in a bustling, real-world retail space remains uncertain. This illustrates the difficulty of replicating the complexities of real environments in an abstracted representation, underscoring the need for more sophisticated prototypes that can translate the high-fidelity of full-scale augmented experiences in a manageable scale.

5.2. The Role of Augmented Miniatures in the Design Process

Allowing stakeholders to experience the key qualities of SAR firsthand is crucial for aligning design activities—such as discussions and creative exploration—with the intended outcomes of the technology. Through their tangible nature, physical miniatures provide representations that enable designers to engage directly with the spatial aspects of SAR environments. These models facilitate an understanding of scale, proportion, and physical interaction dynamics within augmented spaces. Additionally, when implemented in combination with dynamic digital content, miniatures also bring a temporal dimension to the experience that allows for a more intuitive exploration of users' engagement with the system. For example, the workplace miniature allowed stakeholders to directly control operators and test different task flows and timing routines, revealing potential coordination challenges that might not be evident in purely digital representations.

Moreover, physical models also serve as effective communication tools, particularly when conveying complex interaction concepts to both technical and non-technical stakeholders. The novelty of SAR as a medium, combined with the intricacies of spatial design, often complicates understanding of the technology's possibilities, for which physical prototypes play a crucial role in translating conceptual ideas into practical implementations [34]. The primary function of the supermarket miniature was to serve as such a communication tool, retaining the integration of physical and digital elements to fulfill this role. The open-ended nature of the miniature fostered diverse interpretations, encouraging creative discussions on potential applications and improvements. This collaborative engagement underscores the value of physical models in deepening stakeholders' understanding of SAR's benefits, enhancing communication and reflection throughout the design process.

Although the two miniatures developed for these case studies were effective as exploratory and communicative tools, it is essential to acknowledge their limitations in evaluation activities, such as the testing of specific functions or routines in depth. Previous research has underlined the importance of testing AR applications in real-world settings, where contextual elements play a critical role in performance [40]. Thus, while these miniatures are invaluable for exploring and testing initial SAR concepts, they cannot directly replicate the complexity of real-world situations. Therefore, the results of exploratory activities with augmented miniatures cannot be directly translated to full-scale conditions, where real-world variables and human dynamics increase in complexity. Future research must address this challenge, possibly through comparative studies that assess the specific benefits of different types of prototyping methods for augmented environments, such as traditional on-screen versus physical augmented miniatures.

Additionally, developing SAR miniatures requires significant technical expertise, especially when synchronizing digital elements with physical components. While advancements in fabrication, such as 3D printing, have simplified the production of physical components, the creation of dynamic digital content still requires specialized skills, including animation, projection mapping, and synchronization techniques [32,41]. This complexity, compounded by fragmented workflows and incompatible tools, raises the technical threshold for non-expert designers, limiting the accessibility of such tools [33]. However, as the field evolves, advancements in software and more integrated design platforms may reduce these barriers, allowing designers to prototype and iterate across both the physical and digital domains more efficiently. Such progress could ultimately enhance the design process and foster greater innovation in SAR applications.

In summary, the two miniatures developed for these case studies served complementary roles in the broader design process of SAR applications. The retail model acted as a communicative tool, making SAR's potential more accessible and facilitating creative dialog, while the manufacturing miniature functioned as an exploratory tool, enabling the iterative testing and refinement of SAR's interaction routines. Together, these miniatures underscore the value of augmented prototypes in exploring and communicating the unique experiential qualities of SAR, offering a tangible means to test, refine, and communicate complex digital–physical systems.

6. Conclusions

This paper has examined the critical role of physical scale models as immersive prototypes in the development of SAR environments. Drawing insights from two case studies—retail navigation and manufacturing operations—we have demonstrated how augmented miniatures provide valuable tools for exploring and communicating some of SAR's key experiential qualities throughout the design process. Our analysis highlighted that miniatures effectively present these qualities by enabling the natural interaction between physical and digital content while preserving the context of use. These characteristics foster a deeper understanding of how SAR enhances spatial reasoning and facilitates coordinated activities, helping users visualize and comprehend complex dynamics that might be overlooked through conventional design methods.

Additionally, the augmented and tangible nature of these miniatures promotes collaborative dialog among stakeholders, encouraging creativity and innovation. By bridging the gap between abstract concepts and practical applications, these miniatures served as dynamic platforms for refining design ideas and reflecting on the implications of SAR technology. Their ability to convey nuanced interactions and foster shared understanding makes them indispensable in the iterative design process.

Ultimately, this study underscores the critical importance of incorporating physical models into SAR design practices to unlock the full potential of this technology across diverse applications. By leveraging their unique strengths, designers can more effectively prototype, iterate, and realize SAR systems that seamlessly integrate digital and physical realms.

As we envision the future of SAR, it is essential to consider a transformative shift in how technology is integrated into people's everyday environments. Currently, projections are often designed to fit into existing physical spaces, but as SAR technology becomes more accessible and pervasive, there is the potential to simultaneously design the physical space alongside the digital projected content. This holistic approach could redefine our interactions with augmented environments, enhancing the user experience in unprecedented ways. Given the convergence of digital and physical realms, understanding the experiential qualities of this type of design will be crucial as we navigate the complexities of integrating technology into our everyday lives.

Supplementary Materials: The following supporting information can be downloaded at: https://drive.google.com/drive/folders/1579Rfn21MtzqpZSSmF823xNcBMPno5hk?usp=sharing (accessed on 1 December 2024).

Author Contributions: Conceptualization, L.V.C.; methodology, L.V.C. and I.D.; investigation, L.V.C., I.D. and O.M.G.; validation, L.V.D. and L.V.C.; writing—original draft preparation, O.M.G.; writing—review and editing, O.M.G. and L.V.C.; software, L.V.D.; resources, L.V.D.; visualization, L.V.D. and O.M.G.; project administration, L.V.C.; funding acquisition, L.V.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by VLAIO—Agentschap Innoveren en Ondernemen Belgium, grant numbers HBC.2018.0249 and HBC.2021.0682.

Data Availability Statement: The original contributions presented in the study are included in the article and Supplementary Material; further inquiries can be directed to the corresponding authors.

Conflicts of Interest: Author Lucas Van Dorpe was employed by the company Dott Achilles. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Carmigniani, J.; Furht, B.; Anisetti, M.; Ceravolo, P.; Damiani, E.; Ivkovic, M. Augmented Reality Technologies, Systems and Applications. *Multimed. Tools Appl.* **2011**, *51*, 341–377. [CrossRef]
2. Bosch, T.; Van Rhijn, G.; Krause, F.; Könemann, R.; Wilschut, E.S.; De Looze, M. Spatial Augmented Reality: A Tool for Operator Guidance and Training Evaluated in Five Industrial Case Studies. In Proceedings of the 13th ACM International Conference on PErvasive Technologies Related to Assistive Environments, Corfu, Greece, 30 June–3 July 2020; Association for Computing Machinery: New York, NY, USA, 2020; pp. 296–302.
3. Schmidt, S.; Steinicke, F.; Irlitti, A.; Thomas, B.H. Floor-Projected Guidance Cues for Collaborative Exploration of Spatial Augmented Reality Setups. In Proceedings of the ACM International Conference on Interactive Surfaces and Spaces, Tokyo, Japan, 25–28 November 2018; Association for Computing Machinery, Inc.: New York, NY, USA, 2018; pp. 279–289.
4. Nikolakopoulou, V.; Printezis, P.; Maniatis, V.; Kontizas, D.; Vosinakis, S.; Chatzigrigoriou, P.; Koutsabasis, P. Conveying Intangible Cultural Heritage in Museums with Interactive Storytelling and Projection Mapping: The Case of the Mastic Villages. *Heritage* **2022**, *5*, 1024–1049. [CrossRef]
5. Verlinden, J.C. Developing an Interactive Augmented Prototyping Methodology to Support Design Reviews. Ph.D. Thesis, TU Delft, Delft, The Netherlands, 2014. [CrossRef]
6. Dey, A.; Billinghurst, M.; Lindeman, R.W.; Swan, J.E. A Systematic Review of 10 Years of Augmented Reality Usability Studies: 2005 to 2014. *Front. Robot. AI* **2018**, *5*, 37. [CrossRef] [PubMed]
7. Jin, Y.; Seo, J.O.; Lee, J.G.; Ahn, S.; Han, S.U. BIM-Based Spatial Augmented Reality (SAR) for Architectural Design Collaboration: A Proof of Concept. *Appl. Sci.* **2020**, *10*, 5915. [CrossRef]
8. Syed, T.A.; Siddiqui, M.S.; Abdullah, H.B.; Jan, S.; Namoun, A.; Alzahrani, A.; Nadeem, A.; Alkhodre, A.B. In-Depth Review of Augmented Reality: Tracking Technologies, Development Tools, AR Displays, Collaborative AR, and Security Concerns. *Sensors* **2022**, *23*, 146. [CrossRef] [PubMed]
9. Iwai, D. Is Projection Mapping Natural? Towards Physical World Augmentation Consistent with Light Field Context. In Proceedings of the International Display Workshops, Virtual, 1 December 2021; Society for Information Display: Campbell, CA, USA; p. 964.
10. Krauß, V.; Jasche, F.; Saßmannshausen, S.M.; Ludwig, T.; Boden, A. Research and Practice Recommendations for Mixed Reality Design—Different Perspectives from the Community. In Proceedings of the 27th ACM Symposium on Virtual Reality Software and Technology, Osaka, Japan, 8–10 December 2021. [CrossRef]
11. Kraus, V.; Berkholz, J.; Recki, L.; Boden, A. Beyond Well-Intentioned: An HCI Students' Ethical Assessment of Their Own XR Designs. In Proceedings of the 2023 IEEE International Symposium on Mixed and Augmented Reality, Sydney, Australia, 16–20 October 2023; Institute of Electrical and Electronics Engineers Inc.: Piscataway, NJ, USA, 2023; pp. 59–68.

12. Slater, M.; Gonzalez-Liencres, C.; Haggard, P.; Vinkers, C.; Gregory-Clarke, R.; Jelley, S.; Watson, Z.; Breen, G.; Schwarz, R.; Steptoe, W.; et al. The Ethics of Realism in Virtual and Augmented Reality. *Front. Virtual Real.* **2020**, *1*, 512449. [CrossRef]
13. Roo, J.S.; Hachet, M. One Reality: Augmenting How the Physical World Is Experienced by Combining Multiple Mixed Reality Modalities. In Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology, Québec City, QC, Canada, 22–25 October 2017; Association for Computing Machinery, Inc.: New York, NY, USA, 2017; pp. 787–795.
14. Bekele, M.K.; Champion, E. A Comparison of Immersive Realities and Interaction Methods: Cultural Learning in Virtual Heritage. *Front. Robot. AI* **2019**, *6*, 91. [CrossRef] [PubMed]
15. Peffers, K.; Tuunanen, T.; Rothenberger, M.A.; Chatterjee, S. A Design Science Research Methodology for Information Systems Research. *J. Manag. Inf. Syst.* **2007**, *24*, 45–77. [CrossRef]
16. Clark, W.L. Being There: Putting Brain, Body, and World Together Again. *Hosp. Health Netw.* **1996**, *70*, 28. [CrossRef] [PubMed]
17. Dourish, P. *Where the Action Is: The Foundations of Embodied Interaction*; MIT Press: Cambridge, MA, USA, 2001. [CrossRef]
18. Van Campenhout, L.; Frens, J.W.; Vaes, K.; Hummels, C. The Aesthetics of Coupling: An Impossible Marriage. *Int. J. Des.* **2020**, *14*, 1–16.
19. Dalsgaard, P.; Halskov, K. Tangible 3D Tabletops: Combining Tangible Tabletop Interaction and 3D Projection. In Proceedings of the 7th Nordic Conference on Human-Computer Interaction, Copenhagen, Denmark, 14–17 October 2012; pp. 109–118. [CrossRef]
20. Baumeister, J.; Ssin, S.Y.; Elsayed, N.A.M.; Dorrian, J.; Webb, D.P.; Walsh, J.A.; Simon, T.M.; Irlitti, A.; Smith, R.T.; Kohler, M.; et al. Cognitive Cost of Using Augmented Reality Displays. *IEEE Trans. Vis. Comput. Graph.* **2017**, *23*, 2378–2388. [CrossRef] [PubMed]
21. Bartuska, B.; Teischinger, A.; Riegler, M. Effects of Spatial Augmented Reality Assistance on the Efficiency of Prefabricating Timber Frame Walls. *Wood Mater. Sci. Eng.* **2023**, *18*, 860–869. [CrossRef]
22. Morosi, F.; Becattini, N.; Caruso, G.; Cascini, G. Measuring the Impact of Augmented Prototyping Systems in Co-Design Activities. *Multimodal Technol. Interact.* **2023**, *7*, 108. [CrossRef]
23. Van Dijk, J. Designing for Embodied Being-in-the-World: A Critical Analysis of the Concept of Embodiment in the Design of Hybrids. *Multimodal Technol. Interact.* **2018**, *2*, 7. [CrossRef]
24. Van Campenhout, L.; Vancoppenolle, W.; Dewit, I. From Meaning to Expression: A Dual Approach to Coupling. *Designs* **2023**, *7*, 69. [CrossRef]
25. Houde, S.; Hill, C. What Do Prototypes Prototype? In *Handbook of Human-Computer Interaction*; Elsevier: Amsterdam, The Netherlands, 1997; pp. 367–381. [CrossRef]
26. Lim, Y.K.; Stolterman, E.; Tenenberg, J. The Anatomy of Prototypes: Prototypes as Filters, Prototypes as Manifestations of Design Ideas. *ACM Trans. Comput.-Hum. Interact.* **2008**, *15*, 7. [CrossRef]
27. Schön, D.A. The Reflective Practitioner: How Professionals Think in Action. In *The Reflective Practitioner: How Professionals Think in Action*; Basic Books: New York, NY, USA, 1983; pp. 1–374. [CrossRef]
28. Buchenau, M.; Suri, J.F. Experience Prototyping. In Proceedings of the Conference on Designing Interactive Systems, New York, NY, USA, 17–19 August 2000; ACM: New York, NY, USA, 2000; pp. 424–433.
29. Kim, H.J.; Kim, J.W.; Nam, T.J. MiniStudio: Designers' Tool for Prototyping Ubicomp Space with Interactive Miniature. In Proceedings of the Conference on Human Factors in Computing Systems—Proceedings, San Jose, CA, USA, 7–12 May 2016; Association for Computing Machinery: New York, NY, USA, 2016; pp. 213–224.
30. Rossi, D. Smart Architectural Models: Spatial Projection-Based Augmented Mock-Up. In Proceedings of the 2013 Digital Heritage International Congress, Marseille, France, 28 October–1 November 2013; Volume 2, pp. 677–684.
31. Porter, S.; Marner, M.R.; Eck, U.; Sandor, C.; Thomas, B.H. Rundle Lantern in Miniature: Simulating Large Scale Non-Planar Displays. In Proceedings of the International Conference on Advances in Computer Entertainment Technology, Athens, Greece, 29–31 October 2009; pp. 311–314. [CrossRef]
32. Ashtari, N.; Bunt, A.; McGrenere, J.; Nebeling, M.; Chilana, P.K. Creating Augmented and Virtual Reality Applications: Current Practices, Challenges, and Opportunities. In Proceedings of the International Conference on Human Factors in Computing Systems, Honolulu, HI, USA, 25–30 April 2020. [CrossRef]
33. Krauß, V.; Boden, A.; Oppermann, L.; Reiners, R. Current Practices, Challenges, and Design Implications for Collaborative AR/VR Application Development. In Proceedings of the International Conference on Human Factors in Computing Systems, Virtual, 8–13 May 2021; Association for Computing Machinery: New York, NY, USA, 2021.
34. Krauß, V.; Nebeling, M.; Jasche, F.; Boden, A. Elements of XR Prototyping: Characterizing the Role and Use of Prototypes in Augmented and Virtual Reality Design. In Proceedings of the International Conference on Human Factors in Computing Systems, New Orleans, LA, USA, 30 April–5 May 2022; Association for Computing Machinery: New York, NY, USA, 2022.
35. Lopiccolo, O.S. Improving Spatial Reasoning Ability While Learning Energy Efficient Construction: Students Who Build Physical Models vs. Students Who Develop 3D Computer Models. In Proceedings of the 2014 Conference of the American Society for Engineering Education, Bridgeport, CT, USA, 3–5 April 2014; IEEE Computer Society: Piscataway, NJ, USA, 2014.
36. Hull, C.; Knudsen, S.; Carpendale, S.; Willett, W. Simultaneous Worlds: Supporting Fluid Exploration of Multiple Data Sets via Physical Models. In Proceedings of the Graphics Interface, Montréal, QC, Canada, 16–19 May 2022; pp. 22–24.

37. Hiton, C.; Pan, X.; Koeck, R.; Yu, H. Prototyping Large Scale Projection Based Experiences in VR. In Proceedings of the 2023 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops, Shanghai, China, 25–29 March 2023; Institute of Electrical and Electronics Engineers Inc.: Piscataway, NJ, USA, 2023; pp. 1005–1006.
38. Shapira, L.; Amores, J.; Benavides, X. TactileVR: Integrating Physical Toys into Learn and Play Virtual Reality Experiences. In Proceedings of the IEEE International Symposium on Mixed and Augmented Reality, Merida, Mexico, 19–23 September 2016; Institute of Electrical and Electronics Engineers Inc.: Piscataway, NJ, USA, 2016; pp. 100–106.
39. Piumsomboon, T.; Dey, A.; Ens, B.; Lee, G.; Billinghurst, M. The Effects of Sharing Awareness Cues in Collaborative Mixed Reality. *Front. Robot. AI* **2019**, *6*, 428079. [CrossRef] [PubMed]
40. Zhang, V.; Albers, A.; Saeedi-Givi, C.; Kristensson, P.O.; Bohné, T.; Tadeja, S. Should I Evaluate My Augmented Reality System in an Industrial Environment? Investigating the Effects of Classroom and Shop Floor Settings on Guided Assembly. *IEEE Trans. Vis. Comput. Graph.* **2024**, *30*, 3456208. [CrossRef] [PubMed]
41. Nebeling, M.; Speicher, M. The Trouble with Augmented Reality/Virtual Reality Authoring Tools. In Proceedings of the IEEE International Symposium on Mixed and Augmented Reality, Munich, Germany, 16–20 October 2018; Institute of Electrical and Electronics Engineers Inc.: Piscataway, NJ, USA, 2018; pp. 333–337.