Hospitals of the Future: Designing Interactive Robotic Systems for Resilient Emergency Departments

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The Emergency Department (ED) is a stressful, safety-critical environment, which is often overcrowded, noisy, chaotic, and understaffed. The built environment plays a key role in patient outcomes, experiences, and the mental health of healthcare workers (HCWs). However, once a space is built, it is difficult to change it; so the modularity and adaptability of new technologies such as robots could potentially help stakeholders mitigate some of these challenges; yet, there is a lack of research in this area, particularly in the ED. In this paper, we address this gap by engaging HCWs in a research-through-design process, utilizing design fiction, to envision a future resilient ED. Here, robots scurry along the ceiling, provide help at the bedside, and smart furniture and walls provide spaces for privacy and calm. We co-created design prototypes of future intelligent systems that can modify the built environment to support resilience, which we then used to co-create a Design Catalog with HCWs, which contains a collection of future technology prototypes contextualized within the ED. We found that HCWs envisioned many ways for intelligent systems to help them reimagine the built environment, including ways to enhance HCW-patient communication, improve patient experience, support both HCW and patient safety, and use reconfigurable spaces to support privacy. We hope our work inspires further exploration into using new technologies to reimagine and reconfigure the built environment to support resilient hospitals.

CCS Concepts: • **Human-centered computing → User centered design**; • **Computer systems organization → Robotics**; • **Applied computing → Health informatics**.

Additional Key Words and Phrases: human robot interaction, built environment, emergency department, healthcare worker burnout, resilience, design fiction, speculative design

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1 INTRODUCTION

The emergency department (ED) is a busy, chaotic, safety-critical environment where healthcare workers (HCWs) treat patients with critical conditions [72] (see Figure 1). Even before the COVID-19 pandemic, ED HCWs were under high physical and psychological strain, with some enduring

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Fig. 1. Emergency departments are crowded and chaotic on a daily basis (from [1]).

physical attacks from patients [26, 115]. Since COVID-19 the situation has been exacerbated, with many HCWs leaving the field, causing further workforce shortage [3]. HCWs that stayed are experiencing high rates of burnout due to lack of support, which cascades to poor patient outcomes [57]. Indeed, the pandemic has highlighted how fragile and inflexible healthcare systems are, ill-equipped to quickly change to meet increasing demands [28]. Robots have been used to help reduce HCW workload; however, there is a lack of work that employs robots in the ED. To address this gap, we explore how robots and intelligent systems (IS) can support future resilient hospitals by focusing on ways to improve healthcare quality and safety, and reduce HCW workload in the ED.

Recent work identifies the importance of adapting the built environment[1] to design *resilient* hospitals and healthcare systems [28, 46]. For example, Studio Elsewhere designed 'recharge rooms' for HCWs, which can be personalized to provide relaxing, nature-based spaces and reduce HCW stress [98]. Other facilities reconfigured their environments to support infection control and patient surges, such as by adding 'pods' for less-acute COVID-19 patients to prevent disease spread [8]. Also, healthcare facilities created visual signage to support patient and HCW wayfinding in the face of new environmental changes [56, 105, 106]. Our work explores how intelligent systems can help HCWs cope with challenges caused by their built environment to create a resilient ED.

In recent years, there has been increasing work in the Computer Supported Cooperative Work (CSCW) community at the intersection of resilience and technology design [88, 128, 134, 134]. For instance, researchers have explored strategies for COVID-19 vaccination to improve future healthcare system design for building resilience in older adults [11]. Nikkhah et al. [88] explored family resilience during prolonged hospital visits for children with cancer. Haesler et al. [48] explored resilient digital cities using an application that helps citizens prepare for major crisis events (e.g., earthquakes, attacks on infrastructure, and flooding). Others have explored resilience practices of people that experience disruptions to activities of daily living [110], and for people with low socio-economic status [128].

[1]The built environment is defined as the physical human-made environment that we live in [38].

In our work, resilience refers to preserving high-quality care delivery under challenging conditions such as during patient surges, or needing to treat a high number of COVID-19 patients simultaneously [15]. A key means to doing this is to employ evidence-based design practices to engage in *future-proofing*, which refers to rapidly adapting, responding, and recovering from existential challenges, e.g., natural distasters, terrorism, and pandemics [33]. By engaging in *future-proofing*, healthcare organizations can apply lessons learned to help prepare for similar situations in the future. This can enable the design of spaces that are more flexible and can support HCWs during challenging conditions, while preserving the quality of care and protecting HCWs from additional psychological strain [28, 49, 85]. Researchers suggest well-designed, and well-contextualized technology has a key role to play in resilience building efforts [28], and can improve communication between HCWs and patients, patient monitoring, and operations management [95].

In this paper, we explore resilience from the perspective of human-robot interaction (HRI) –that is what role can robots and other intelligent systems (IS) play in re-designing the built environment to create resilient hospitals? We are inspired by recent work in HRI which explores robots' capacity to change the built environment. For example, researchers have designed interactive, adaptive walls that can create private spaces [86, 130], modular adaptive furniture that reconfigures itself to provide assistance [51, 87], and interactive furniture which encourages human use [6, 43, 113] or healthy postures [23, 66]. These types of systems are well-suited to meet the challenging demands of the ED. They can be very adaptive to quickly-changing spaces, can adopt tedious tasks and roles to support HCWs (such as supply delivery), and can provide comfort and emotional support to patients in need [16, 59, 109, 120]. However, to our knowledge, little work has explored the use of robots that can change the ED built environment.

In our work, we explore how to design intelligent systems to support HCWs in the ED. We use the lens of the built environment, with a specific focus on space, layout, visibility, and adaptability, to catalyze future technology design. We enable HCWs to envision future technology through a speculative design process, where we use design fiction [31, 97] to imagine a futuristic ED. By visualizing the future ED through our design probe, we explore bridging the work-as-imagined (WAI) vs. the work-as-done (WAD) divide, i.e., what we expect to do in theory vs. what we actually do in practice. Specifically, Work-as-Imagined (WAI) is what designers, healthcare leaders, and other non-end-users imagine occurs in the built environment. In contrast, Work-as-Done (WAD) is the actual activity such as– what the end users of the built environment do.

We engaged in a Research-through-design (RtD) process with ED HCWs to envision a futuristic ED. We encouraged our participants to compare a futuristic ED to their current work environment, which enabled them to imagine a future facility that addresses the challenges they face today. Based on this work, we introduce a new *Design Catalog* that envisions a future resilient ED where HCWs and patients no longer face the challenges of today. Lastly, we explore HCWs perceptions of futuristic intelligent systems, their impact on resilient design concepts, and how HCWs envision using and interacting with these systems.

Our **contributions** are as follows. 1) We reflect on design prototypes of future robots and intelligent technologies that support HCWs while considering the ED built environment. 2) We present a *Design Catalog*, co-created with HCWs, which features a collection of prototypes showing future technologies. 3) We provide a roadmap of our design process and the creation of the catalog, which can be used as a design tool by other researchers who want to design robots for hospitals. 4) We found that HCWs envisioned many ways for intelligent systems to help them cope with the built environment, including ways to enhance HCW/patient communication, improve patient experience, support HCW and patient safety, and use reconfigurable spaces to support privacy.

We hope this work promotes further investigation into designing systems to support healthcare system resilience, which can reduce stress on HCWs and patients.

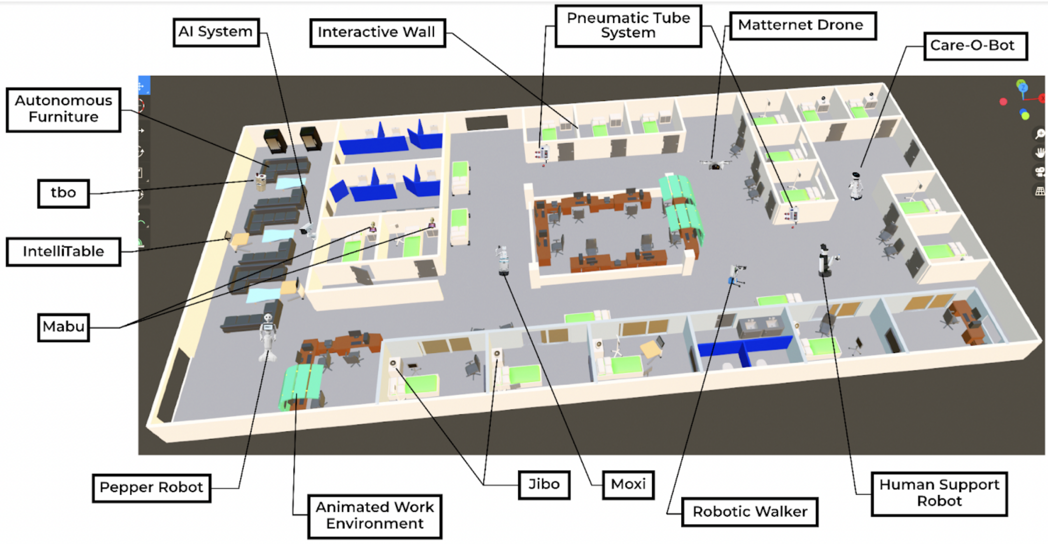


Fig. 2. This shows the design probe used in our design fiction, which shows a futuristic ED that features intelligent, interactive technologies to support HCWs including assistive robots, robot furniture, and interactive walls.

2 RELATED WORK

2.1 The Healthcare Built Environment

In hospitals, features of the built environment, such as light, sound, layout, and materials can affect healthcare delivery and outcomes [125, 126]. Researchers suggest that it is essential to address such design features in the built environment to support people with behavioral and mental health comorbidities, which account for as many as 25%-45% of hospitalized patients [29]. Many researchers have explored ways to facilitate healing and promote psychological well-being in healthcare facilities by changing hospital layouts, open spaces, ergonomics, and by providing noise control and privacy [29, 136]. Other work focuses on how the spatial design of the built environment impacts clinical workflow and safety [47, 84].

Unfortunately, the literature shows there is a gap between the built-environment-as-imagined and built-environment-as-done [100]. Researchers have explored the built environment's crucial role in supporting resilient healthcare environments, for example, designing for resilient hospital facilities in Intensive Care Units (ICU). However, the persisting gap between WAI and WAD demonstrates the disparity between ideal and reality [28, 33, 52, 92, 100]. This gap can lead to designs that are infeasible or are far beyond state-of-the-art to realize today.

We aim to bridge this gap by designing intelligent systems that can help HCWs cope with challenges in the built environment. Here, we asked participants to design for the future based on what can be done today. For instance, we presented a futuristic ED that features several intelligent systems that are being used today, although no EDs currently have these technologies. By exploring our problem domain using a fictional version of the ED, participants can more easily envision near-future systems to support and empower them and their patients.

2.2 Robots in Healthcare

There are many robots designed to support people in terms of health and wellbeing [72, 102, 103]. For example, social robots are used to support older adults with and without cognitive impairments [71, 73, 135], and robotic wheelchairs are used to support patient mobility [60, 69]. Robots also perform non-patient-facing tasks, such as fetching and delivering supplies [9, 9, 119, 119, 121], to free up time for HCWs to focus on patient care. They are also used to support nurses with triage [9] and lifting patients [74]. Other robots are used to support telemedicine [58, 82, 104] and medication adherence [44, 111].

However, to our knowledge, there is a lack of work on designing robots that can support healthcare system resilience by reconfiguring the built environment to support ED HCWs and patients. This is a missed opportunity, as clinical environments can be enhanced by robots that are adaptive and flexible, and have shown great potential to assist HCWs [2, 93, 119].

2.3 HRI for the Built Environment

Prior work on building robots while considering the built environment lies at the intersection of architecture and HRI. The architectural perspective is typically concerned with building efficiently in small spaces. The prior work in this area lies in two themes including space-making robots [130] and interactive walls [130, 131]. Space-making robots define, configure, or are embedded in physical environments [130]. Interactive walls react to people by acting as tables, room dividers, and emotion regulation systems [130, 131]. People also perceive responsive walls and provisional presences differently from a static wall. Responsive walls feel less confining, can block distracting views, and can change to evoke various human emotions, which reveals much potential in using space-making robots to build more functional, emotionally supportive spaces [86].

The HRI perspective typically focuses on designing furniture, making it more interactive, and studying how people perceive it. Prior work in this area includes interactive furniture [43, 87] and modular robots and surfaces [61, 129, 130]. There is much work on interactive furniture including systems that are embodied as a table [35, 43, 87, 96], an ottoman [51, 113, 113], and an interactive door [64]. Modular robots are used as reconfigurable pieces of furniture including a stage [61, 130], a reconfigurable mobile robot-cube, and a continuum-robotic lamp [127].

Although great progress has been made on creating robots that react to the built environment, there is a lack of understanding of how to design robots for *healthcare* built environments, particularly in the ED to support HCWs. To address this gap, our work explores robot design for resilient ED environments, where we aim to understand how robots can help HCWs and patients cope with built-in challenges. For instance, robots can be used as a means of increasing visibility to patients and space-making robots could serve as a means of creating collaborative or private spaces.

Another relevant field is human-building interaction (HBI). HBI is a field at the intersection of human-computer interaction (HCI), architecture, and urban design [10]. HBI aims to study the evolution of HCI and built environments, understand how spaces are used, and empower users by giving them more control over and awareness of their environments [10, 21]. This research involves engaging with users in interviews, workshops, walkthroughs, and speculative futuring [83, 86]. The research most relevant to ours involves adding actuation to building components and furniture. For instance, Agnihotri et al. [5] explored how users interact with robot-actuated furniture that can engage with users by inviting people passing by to use the furniture. Others have included actuation in the environment to adjust to users' preferences [13, 55, 63].

2.4 Design in HRI

As more robots are developed to interact with people in the real world, more in-context studies are required to understand how people interact with robots in social settings and how this varies between diverse social contexts and cultures [91]. Research-through-design (RtD) is a research practice that uses design thinking, processes, and products as a methodology of producing knowledge [79–81]. It offers the freedom to explore unfamiliar design spaces, thereby leading researchers to "make the right thing" instead of designing the best solution with little value [81]. As HRI researchers, we adopt this perspective to close the gap between built-environment-as-imagined and built-environment-as-done. We use several RtD approaches in our work to achieve this goal including co-design, storyboarding, and design fictions.

Co-design is a user-centered design method that views users as experts in their own lives enabling them to express their point of view on the problems and solutions. Engaging in long-term co-design processes allows end-users to create more informed and educated opinions around their technology, desires, and perspectives [91, 112]. This promotes more sustainable, engaging, and responsible technologies [112]. Some common co-design methods are art-based image-making, rapid prototyping, storytelling, and design guideline generation sessions [91, 112].

Storyboarding is a co-design method frequently used in design and HCI as a low fidelity technology prototype that demonstrates a useful scenario for users and how they would interact with it [124]. A storyboard contains panels with images and text arranged in a sequence in order to convey a story (see Figure 5). Storyboarding is a design tool that many researchers have employed to design robots [12, 18, 42, 68, 80, 116, 123]. For example, in co-designing a social robot for teens' stress management, pairs of teens collaboratively storyboarded scenarios where the robots would interact with a student in their school [18]. Storyboarding has also been used to study how attitudes toward robots are affected by perceived anthropomorphism and gender [116].

Design fiction is a method that uses a fictional situation to enable users to imagine a future technology [19, 89]. This can take the form of a variety of mediums, including but not limited to, written narratives or stories [7, 27], prototypes [114], probes [89], film and videos [133], or catalogs [24]. Design fiction has been used to avoid technosolutionism, where the technology solutions proposed only provide quick, superficial fixes to complex issues aiming to address problems that do not currently exist [20, 77]. Design fiction addresses solutionism by promoting discussions about technology and its role in society instead of proposing technology as the solution [20].

In developing our design process, we were inspired by two examples of design fictions involving a built environment. The first is the Hawkeye design fiction probe [89]. Here, participants were shown a design fiction probe and asked to pretend they were controlling Internet-of-Things systems and objects in the home of a person with dementia. This fiction contains places, the participant in the caregiver's role, and allows them to imagine how they would interact with this technology [89]. We drew inspiration from the 'Future IKEA Catalogue', a catalogue where academic researchers collaborated with industry to imagine what a catalogue in the future would look like [24].

2.5 Characterizing the Emergency Department

Violence against HCWs has reached epidemic levels in the U.S. [99]. HCWs have experienced violence in hospitals, particularly in EDs, with attacks such as biting, scratching, spitting, kicking, and punching. These working conditions cause significant mental and physical trauma on HCWs [4]. In 2013, 70% of nurses experienced violent events from their patients, and this percentage is even higher for ED nurses and many occurrences go unreported [25, 94, 115, 132].

The pandemic has further exacerbated the occurrences of violence against HCWs due to environmental design, patient surges, 24-hour access, long wait times [88], and the uncertainty of

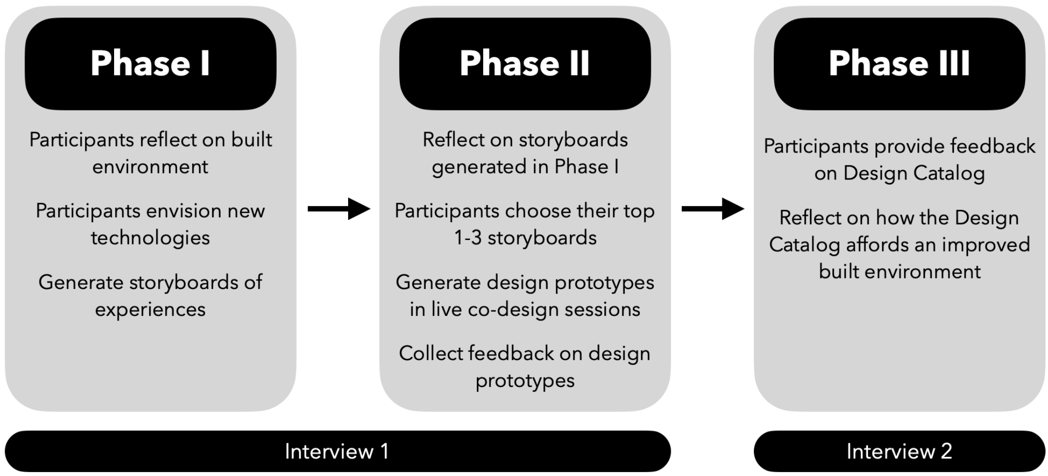


Fig. 3. We conducted a three-phase study. Phase I focused on interviewing participants to understand how intelligent systems can support them while considering the built environment. In Phase II, we shared storyboards of participants' experiences, generated design prototypes, and collected feedback on them. Phase I and II were conducted in a single interview, and lasted about an hour. In Phase III, we collected all design prototypes in a *Design Catalog* and reflected on them with participants. This took place either during a 15-minute interview or via a questionnaire, depending on participants' availability.

working with a diverse patient population e.g., mental health, substance abuse, and psychiatric patients [26]. To mitigate these challenges, healthcare systems have adopted various strategies and trainings for HCWs to cope with violence in the workplace. For instance, they established clear policies on workplace safety and provided de-escalation training [25]. Although this training is useful for preparing HCWs to de-escalade a situation, using robots to monitor the ED could provide opportunities to prevent these occurrences. However, monitoring systems in the ED could further exacerbate negative environmental conditions by creating spaces reminiscent of the panopticon.

Bentham's and Foucault's panopticon exemplify how architectural and spatial components create a *surveillance environment*. The structure of the panopticon encourages self-surveillance where prison guards control prisoners through the belief that they could be watched at all times, even though that may or may not be true [40]. This creates an environment where individuals feel they are always under surveillance [32].

Prior work shows that panoptic systems have great implications in healthcare settings in terms of ethics and asymmetrical power dynamics [53]. Discussions about panoptic surveillance systems have been conducted in a variety of different areas of healthcare [32, 36, 39, 53]. Analyzing these surveillance technologies can help reveal power imbalances in healthcare and hierarchies between patients and HCWs [39]. Surveillance technologies can negatively affect patients by taking away their privacy and minimizing the respect for their personhood through the replacement of human contact provided by HCWs with devices to monitor patients [53, 90]. As HRI researchers, we consider these implications in our work and the potential for them to further imbalance hierarchies in environments where they can be harmful to patients.

3 METHODOLOGY

Over the past several years, we have closely collaborated with HCWs to co-design technology to empower and support their work [82, 119, 120, 122]. In this work, we engaged in speculative design by imagining a fictional future ED and allowing participants to interact with this fiction through co-designing technology for the ED built environment. Through this process, we sought to understand their everyday clinical practices, built environment challenges, and how technology may help mitigate those challenges.

3.1 Participants

We recruited 12 ED HCW participants for a multi-week study, conducted over Zoom. We recruited participants by distributing our study advertisement via email and word of mouth. Participants included Residents (2), Attending Physicians (6), Physician's Assistant (1), Nurse Practitioners (2), and Registered Nurses (1). There were 8 men and 4 women. Their ages ranged from 27 to 66 years old (mean = 44.3 years, SD = 11.4 years), and had between 2 and 45 years of experience (mean = 13.0 years, SD = 11.9 years). Participants worked at teaching (9), non-teaching (1), urban (1), and rural (1) hospitals across a range of different health facilities, including older facilities that serve a low socioeconomic demographic with a large unhoused population, and newer facilities that primarily serve wealthy patients, but whom are quite ill.

3.2 Research Process

We performed a three-phase study with ED HCWs (see Figure 3). Phase I focused on interviewing participants to understand how intelligent systems can improve clinical workflow and patient experience while considering the built environment. In Phase II, we shared storyboards of participants' experiences, generated design prototypes, and collected their feedback on those prototypes. Phase I and II were conducted in a single interview, and lasted about an hour. In Phase III, we collected all design prototypes in a *Design Catalog* and collected participants' feedback on them. This took place either during a 15-minute interview or via a questionnaire, depending on participants' availability. We discuss all phases in detail below (see the Appendix for interview materials).

3.2.1 Phase I: Present Design Fiction and Reflect on Built Environment Challenges. The goal of Phase I was to explore how HCWs envisioned using intelligent systems to cope with the ED built environment. One challenge with co-designing robots with HCWs is that they are often unfamiliar with robotic technology; as a result; they have trouble imagining future technology that could support them in their daily work. To address this challenge, we employed design fiction to help participants imagine future systems. Our design fiction encouraged participants to reflect on the challenges of the ED built environment where they work today as compared to an advanced, futuristic ED. This helped to immerse participants into a fictional story that depicts a futuristic ED which has state-of-the-art interactive technologies (see Figure 4).

We began by discussing our design fiction where we showed participants images of a 3D model of our fictional ED. Our **design fiction narrative** was as follows:

> "In this study, you will imagine that we are collaborating with you and an architectural firm to help build a futuristic ED. The futuristic ED, although fictional, contains some of the features of real EDs. The fictional features include, but are not limited to, existing intelligent systems such as robots and interactive systems to support healthcare workers and patients. Keep in mind that we have unlimited resources, so feel free to chip in your ideas and we can build them. In the end, we will produce a fictional catalog for workers like you to 'shop' and add to the ED based on your experiences."

We created a **design probe** i.e., a 3D futuristic ED that features robots and interactive technologies as discussed earlier in this section (see Figure 2). We presented the design probe to participants and summarized the categories of interactive systems. More specifically, we stated:

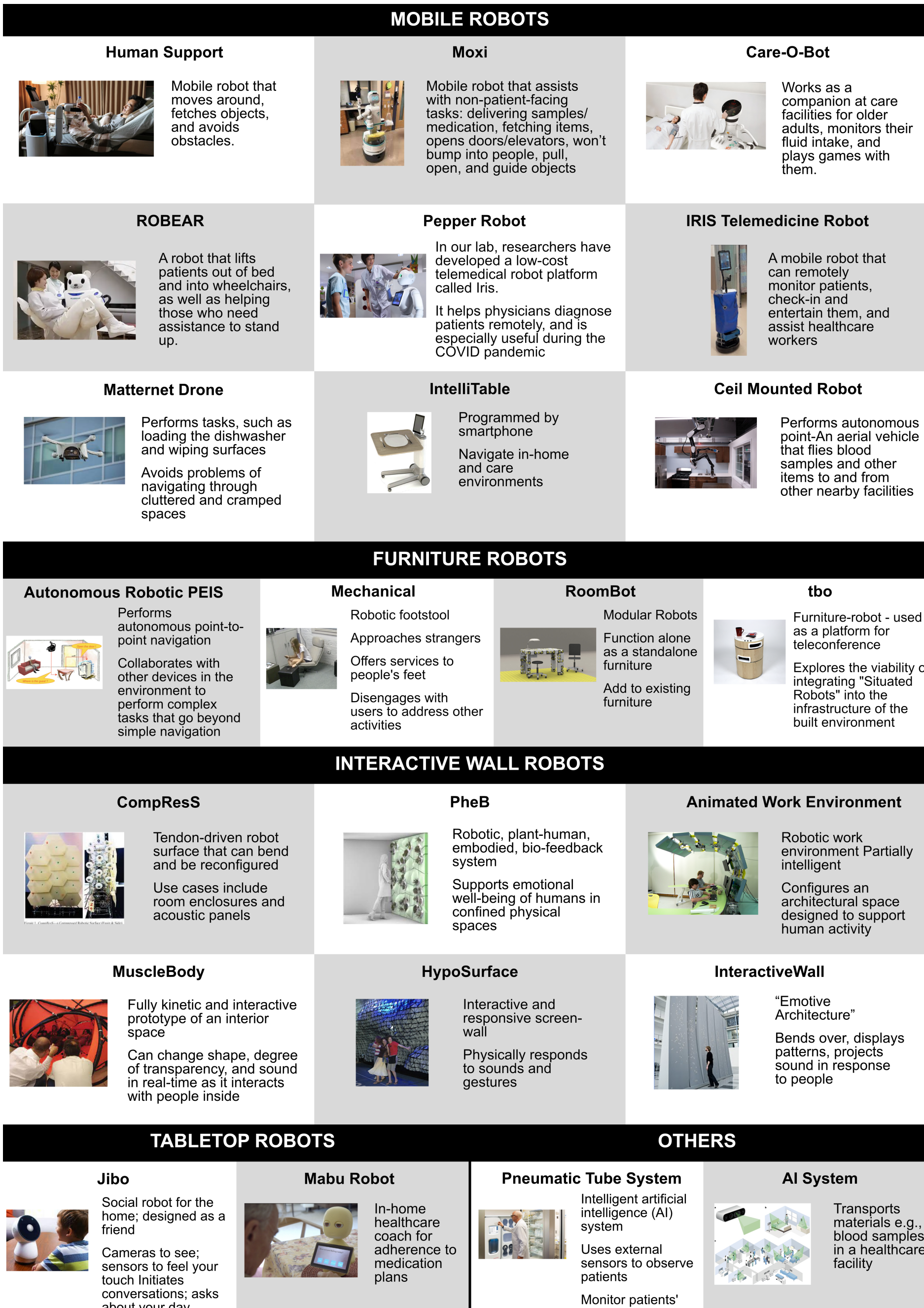


Fig. 4. The Robot Cheat Sheet, showing the intelligent, interactive systems included in our design probe. Participants referred to this throughout Phase I and Phase II interviews.

"The new ED features various interactive systems that fall within five categories. We will walk you through each category and collect your feedback on how useful they would be to help you in your daily work. These categories include mobile robots, tabletop robots, interactive wall robots, furniture robots, and others. Some of these systems have already been used in healthcare settings and others have not. We encourage you to think about how you might use these systems in the Emergency Department where you work or you can come up with your own system."

Then, we gave participants time to observe the design probe. We encouraged participants to reflect on differences in the built environment of the EDs they work at compared to our futuristic ED. We placed emphasis on particular use-cases where these robots can help participants think about how they might utilize such a robot e.g. robots that lift patients for them so they don't strain their back, or a robot to fetch and deliver supplies.

Before presenting the robots in our design fiction, we provided participants with a *Robot Cheat-sheet* which is a quick reference to the robotic and interactive systems discussed in our interviews (see Figure 4). Then, we iteratively showed participants these technologies (five categories total), via the design probe, and asked them questions about how they envisioned using these systems at the ED where they work today and in our futuristic ED. These categories included: mobile robots, tabletop robots, furniture robots, interactive wall robots, and others in order to familiarize them with existing/near future robotic technologies.

Mobile robots were described as being able to move around the ED and can assist with delivery, cleaning, monitoring, and more [2, 82]. We defined tabletop robots as sociable, personal robots, to be used for entertainment, communication, and education [65]. Furniture robots are reconfigurable systems that adjust to patient needs e.g., Roombots can change from a table to a chair [43, 87]. Interactive wall robots adapt to people in the ED environment by adjusting the size of rooms [54, 130]. Other systems included a monitoring system [50], a pneumatic tubing system [118], and environment augmentation, such as real-time visual directions for navigation [67]. We described these capabilities to participants and showed them pictures of these systems.

Participants answered questions about what they liked/disliked about the intelligent systems, and how they imagined using them to support their work, and patients, while considering the ED where they currently work. We asked participants what scenarios they envisioned using these systems to support them in and how the built environment plays a key role in their daily work. We also discussed aspects of their daily work which can be offloaded or automated by robots.

Then, participants ideated on ways to address some of the work-related challenges using intelligent systems (while referring to the Robot Cheat Sheet). As participants ideated, a member of our team created storyboards that captured the participant's experiences and depicted the use cases for the technology they imagined (see Figure 5). At the end of each interview, we collected several storyboards for each participant (mean = 6.17 storyboards, SD = 1.27, minimum = 4, maximum = 7).

3.2.2 Phase II: Generate Design Prototypes for a Resilient ED. In Phase II, we were interested in exploring how HCWs envisioned future technology to support them by helping them directly and supporting patient care (see Appendix A.2 for interview materials). The goal of this phase was to generate design prototypes that can potentially help HCWs and patients in the ED. Some designs specifically focused on the built environment, such as how it can affect patient accessibility and patient safety.

We started Phase II by performing artifact analysis, which involved reflecting on the storyboards generated in Phase I and discussing potential solutions or design prototypes. Participants could suggest changes to the storyboard, provide additional commentary on the situation depicted, or confirm that the storyboard accurately depicted the use cases they had described earlier in the interview. After we reviewed the storyboards with participants, we asked them to choose their

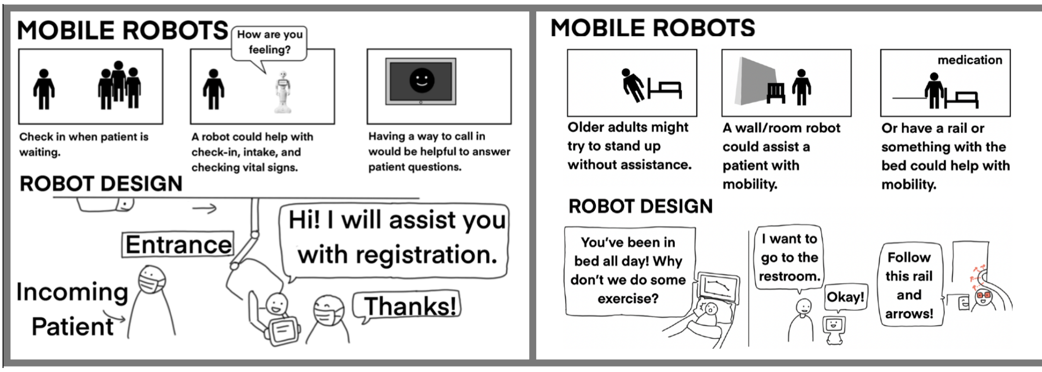


Fig. 5. Example artifacts from the live co-design session between HCWs and researchers in Phase II. *Left:* A storyboard using a ceiling robot that checks patients. *Right:* A wall robot that evaluates patient mobility and a tabletop robot and AR glasses that gives direction to patients.

top 2-3 most important ideas. This allowed us to focus on scenarios that participants believed were the most impactful or timely. Then, we encouraged them to reflect on how they use space, consider patient accessibility, safety, and mobility; how they contextualized technology use within the ED, and any concerns they had about future technology designs. Finally, we reflected on the participants' designs and what it means to use future technologies in their current workplace.

As participants shared their feedback on the storyboards, a researcher performed live co-design by drawing design prototypes on a tablet using the Procreate app to reflect participants' proposed solutions (see Fig. 5). Then, we presented these design prototypes to participants and collected additional feedback on them. For example, we asked participants what they would like to change about the prototype and if they thought of particular scenarios where the prototype would be useful, and why.

3.2.3 Phase III: Post-study interview on Design Catalog. The goal of Phase III was to collect participants' feedback on design prototypes in the *Design Catalog* to ensure that we fully captured participants' perspectives. The *Design Catalog* is a collection of design prototypes generated from co-design sessions (see Figure 7 and Appendix A.3 for interview materials)[2].

In Phase III, we created 3D models of the robot prototypes designed in Phase II using Blender, a free 3D computer graphics software package. We then positioned and posed each robot in a 3D setting, such as a patient room or an ED waiting area, and rendered the scenes into 2D images. Using the prototyping tool Figma and the publishing software Affinity Publisher, we created a catalog using the images of the co-designed robots in their environments. The *Design Catalog* was modeled after furniture and home decorating catalogs, so it displayed the robots as products, showing them in an environment where it would be used in and robot features.

We performed iterative design and updates on the *Design Catalog* to capture the envisioned ideas of all participants as well as their concerns for intelligent systems working in the ED. In this phase, we conducted 15 minute interviews with participants from Phase I and II or administered a questionnaire. During these interviews, we showed participants the *Design Catalog* we created and focused our questions on three main themes that were revealed in our thematic codes, and were the most important ideas to participants in Phase I and II. These included robots that monitor and prevent patient agitation, robots that increase communication between patients and HCWs, and

[2]https://heyzine.com/flip-book/c5280437fa.html

reconfigurable systems that create areas of privacy and peace. We asked participants questions such as which robots they think could address these themes, what they liked/disliked about those systems, what was missing from the catalog that they want included, and how they thought patients might perceive these systems.

3.3 Data Collection and Analysis

During the teleconference interviews, we recorded videos of participants during all phases with their permission. We extracted audio to use for data analysis and destroyed the image data. We transcribed the interviews using Microsoft Stream's caption service.

Three researchers analyzed the interview transcripts using thematic analysis [22], which involves a systematic review of ideas discussed in the interviews. This includes reading through transcripts, generating codes that describe high-level ideas, generating themes, and refining them independently. Ultimately, we labeled a total of 450 codes and identified key ideas discussed in the interviews. We then iterated on our codes by comparing them among coders and negotiating on the final codes for each quote. We computed the inter-rater agreement using Krippendorff's Alpha as we used multiple codes for each quote. We found α=0.83 which is considered near-perfect agreement.

4 FINDINGS

Through our design process, we identified design concepts for robots that could help HCW cope with the ED built environment which hopefully leads to more resilient healthcare systems, and less burned-out HCWs. We received feedback and suggestions on the use of robots to support HCWs, as motivated by our design probe. Our key themes included: 1) the importance of using robots to create reconfigurable spaces for privacy and peace, 2) how HCW-patient communication can be bolstered using robots as a communication medium, and 3) identifying connections between HCW safety and patient emotional support. We discuss these findings in detail below.

4.1 Reconfigurable Spaces to Support Privacy and Peace

All participants highlighted the importance of using robots to create reconfigurable spaces for privacy and peace. We identified three design concepts that HRI researchers can employ to design robots to promote resilience in ED environments. First, we co-designed robots that adjust to human-occupied spaces, using *situational reconfiguration* to create areas of compassion for particular situations. This includes systems that can create private spaces for grieving, or places to communicate difficult information to patients, away from the busy, loud ED. Also, our participants envisioned interactive systems that support *population-based spatial reconfiguration* to adjust to different populations of the ED occupants including older adults, patients with mental health issues, substance abuse issues, and psychiatric patients. Lastly, our work revealed that HCWs have concerns about the cost and feasibility of robot systems for the built environment in one robot category i.e., wall robots.

4.1.1 Reconfiguring Spaces. Our study showed that HCWs envisioned robots that can create private areas and acuity-adaptable spaces. This was motivated by built environmental challenges that ED occupants experience, including loud sounds/alarms, smells, and high levels of patient acuity [34, 108]. HCWs often have difficult conversations with patients under these conditions.

Furthermore, these patients sometimes receive life-changing information in open spaces which can take an emotional toll on them. This situation also occurs during conversations with family members of patients. When patients pass away in the ED, families are often left in the hallways to mourn their loved ones while being surrounded by loud noises and intense sights and smells.

> "And then I think for the hallways – if you could create temporary barriers that have some sense of privacy, we will see patients who need a pelvic exam and they are assigned beds in the hallway and that's not going to happen, that just crosses a line. You're not going to do a pelvic exam the hallway. Same thing for rectal exams and so that's another big area where if there's a way to create a temporary solution that is good enough that they have privacy and if they're sleeping in the hallway overnight – what a horrible thing to do to somebody who's feeling horrible to start. And then, they have to sleep in the hallway with the lights on, and our little fixes or ear plugs and light shield for the eyes – it's not great. So I think flexibility is the key, with some overarching principles of figuring out how to keep everything clean, how to keep everything durable and how to be able to create space you need depending upon the situation" - MD, 15 years of experience

To address these challenges, participants envisioned intelligent systems that could create *compassionate spaces* for ED occupants to have difficult conversations. HCWs discussed using robots to create "privacy pods" for private HCW-patient consultations e.g., in the waiting room [8]. This will reduce the environmental distractions that hinder patient and family healing such as noises, smells, and crowds of people. Another problem that participants envisioned using these pods for are ad-hoc examination rooms. For instance, they discussed using temporary or adjustable walls that can easily be constructed, broken down, and removed to save space. These walls could give patients privacy to help speed up treatment time as this mitigates the need to wait for a patient room to become available.

> "If [the robot] could create private areas, that would be very helpful [because] a huge problem nowadays is overcrowding, and trying to examine or talk with a patient privately is very difficult, especially when they're in the hallway. So I think this would help improve the patient experience and that we could maybe be more efficient and could examine and talk to them all at once and not have to wait till a room opened up. [It] would certainly make the patients happier. Many of our discussions are very difficult with patients and their families. Talking about difficult issues, if robots could make the room more comfortable, maybe that would help the families." – Attending Physician, 21 years of experience.

4.1.2 Population-Based Reconfiguration.

4.1.2 Population-Based Reconfiguration. Another concept to support resilience revealed in our data was *population-based spatial reconfiguration*. This refers to designing adaptive intelligent systems that can react to different populations of people, including older adults, patients with mental health issues, substance abuse issues, and psychiatric patients. These populations have particular needs that impact their experience when they visit the ED.

For example, older adults often experience *deskilling* during hospitals stays, where they struggle with activities of daily living which were previously non-problematic (e.g., temporarily lose the ability to walk [14]). Deskilling is often caused by resting in bed for extended periods of time, and is associated with an increased risk of falls [14]. To address this challenge, participants envisioned a robotic wall with a guard rail to help patients reduce their risk of falling. This railing could be placed around the patient's bed or around the wall of the patient's room.

> "Maybe if there's a wall-mounted rail that could [help walk] the patient over to the door. Have something come out of the bed to help them get up. I can't say enough about how big of an issue that is in the ER with our elderly patients who fall because they want to go to the bathroom." - Resident, 11 years of experience.

Another population participants discussed were patients with mental health and substance abuse issues. These individuals may be more prone to agitated and aggressive behavior, which can lead to violent acts against HCWs [117]. Consequently, these patients are often placed in rooms alone or with a HCW monitoring them. However, when isolated these patients experience loneliness, which can lead to acts of self-harm.

> "I like the AI monitoring system because unfortunately, with the nature of emergency department, there are cases where patients have been placed in a room in the back that's not monitored and we've had patients kill themselves in those rooms because they had a condition that went unnoticed or unrecognized. We've had patients fall in those rooms, so I think the AI monitoring system could help prevent some of those issues." – Attending Physician, 21 years of experience.

Additionally, a few participants stated that these patients may need ways to configure a more calming environment, as agitation can be contagious.

> "[Psychiatric patients] kind of feed off of each other's [behavior]. You know, one starts getting riled up, then the other one starts getting riled up. So if you could put up one of those noise canceling walls in between the two patients instead of just a curtain that might help keep those patients more calm." Attending Physician, 21 years of experience.

HCWs in our study discussed several ideas for population-based spatial reconfiguration for patients with mental health, substance abuse, and psychiatric issues [4, 29]. First, they discussed using interactive wall robots to show soothing visualizations to patients and play relaxing music to calm them. Second, participants discussed using interactive walls to separate patients when one of them starts getting agitated. The hope is that by separating these patients, we can prevent them from feeding off each other's energy and becoming more agitated. Also, they discussed using monitoring systems to automatically detect when patients are getting agitated and the systems can 'talk patients down' to keep them calm.

An important design consideration that we discussed for this population is robot morphology. Participants discussed how too much technology can potentially overwhelm these patients (e.g., causes disorientation) and technology must be designed carefully to account for this.

> "For an elderly patient with dementia, having an isolation area for the purpose of creating a calming environment would actually be super. I mean, usually, we just have a single room with a sitter and it's not calming. It's very kind of like AD SEG [solitary confinement] in prison." - Nurse Practitioner, 45 years of experience.

Participants were excited about using robots to support them and patients in the ED to build a more resilient environment. However, they expressed several concerns as well. For example, some participants found value in using robots to support them, but some found it difficult to envision the appearance and functionality of future systems and how they could interact with patients, e.g., interactive wall robots. Nevertheless, some participants envisioned interactive wall robots that could promote patient privacy, but they emphasized the need to maintain patient visibility. Other participants discussed the need for cost effective systems, and that it might be challenging to justify their costs. For example, the interactive wall that shows patterns to entertain patients is a luxury and *"we have bigger fish to fry"* - Resident, 4 years of experience.

> "The only thing I would like to add to this futuristic ER is transparent walls that, so that I could keep eyes on my patients at all times. Because, like I said, those non-verbals are what [help] me do most of my job." - Registered Nurse, 6 years of experience.

4.2 Enhancing Patient-HCW Communication

A common problem that 11/12 participants discussed was the need to increase communication between HCWs and patients. Patients are experiencing longer ED visits, with stays up to days (or weeks) at a time due to the COVID-19 pandemic [78]. Patients do not receive frequent updates on the status of their care, as HCWs are often busy treating the sickest patients first, and they do not speak to their physician often. Thus, patients are often left unaware of their treatment status, and how long it will take see a doctor. Some participants discussed how these patients sometimes die in the ED waiting room because they have a condition that deteriorates over time, and it is not visibly obvious what their condition is [41, 107]. Also, oftentimes patients leave the ED without being treated due to long wait times, which has negative implications for the patients e.g., their condition likely gets worse, and for the ED itself because HCWs are evaluated on what they call 'Leave Without Being Seen' rate which could impact a hospital's funding in the future [37].

> "And it happens all around the country where unfortunately people die in the waiting room and so I think [AI monitoring] could be very helpful for identifying higher risk patients or change in patient status while they wait." - Resident, 2 years of experience.

To address these challenges, participants envisioned *robots that support patient education* to help the patient and HCW have common ground. Oftentimes, HCWs are treating patients from diverse backgrounds, with different education levels. Therefore, HCWs need to communicate with diverse patients in a manner that laypersons can understand, which can be challenging. Our participants envisioned ways that robots could provide medical information about the patients' conditions (e.g., symptoms, visualizations of affected organs) in layperson's terms.

Participants also envisioned technologies which could inform patients on the next steps in their treatment, which could hopefully relieve patient frustration about long wait times. For instance, participants envisioned AR systems that educate patients, to provide background information about their condition as well as what their physician is working on or waiting on (e.g., labs or tests), to complete their treatment.

> "Do you think you'd be able to [use AR glasses] for patient education? That would be nice to have to show a patient, 'hey, put the [AR] glasses on,' you walk [them] through 'hey this is your this is your lung. This is a blood clot in your lungs. This is what we're worried about." - Physician Assistant, 8 years of experience.

As previously mentioned, HCWs are often busy and do not have time to provide patients with frequent updates. Thus, participants envisioned robots that deliver periodic updates to patients, e.g., when tests are complete, updated estimated time of arrival to be seen. These robots could provide updates on-demand about their treatment. For example, as a way to monitor patients and detect health deterioration, HCWs envisioned that *robots could triage patients and monitor their vitals* throughout their time in the waiting room, so they could detect when a patient's condition is deteriorating.

> "If it was able to transmit [vital sign assessments] to the main nurse's station, we can also keep a better eye on how everybody's vital signs are doing, because those are pretty telling [whether] somebody is getting sicker so that would be useful. Even while they're

> in the ER, if they're not hooked up to telemetry you don't know if they're getting sicker so again, a wearable tech would be great." - MD, 15 years of experience

HCWs envisioned using robots as a communication medium with patients which they hoped would prevent patients from leaving the ED without being treated. They discussed robots that could alert them when patients need to ask questions, and they were interested in using robots as a telepresence device to video chat with patients when there is an emergency. They envisioned the robot acting as an information delivery device where patients can leave a message for their provider. Also, they envisioned systems that could handle patient intake, provide preliminary information on the patient's condition, and perform patient discharge. A key design consideration for this idea was to ensure that information flows from patients to nurses, and, if needed, to the physician.

> "I would use [tabletop robots] a lot, probably in every discharge that had medications, and even if not medication, if [the robot] could discuss follow-ups. I think that would also be helpful." - Registered Nurse, 6 years of experience.

However, participants also mentioned there are tradeoffs between additional means for communication and alert fatigue. As HCWs are already overwhelmed with noises and alarms, and have no way to know which alarm is for which patient (unless they walk to the nurse's station to check).

> "In terms of alarm fatigue, it's just a cluster of alarms without the ability to really differentiate, like who that alarm is for and what's important. So if there's a way to make it very clear that these are my patients. So if I hear an alarm, the alarm I'm hearing matters because it's my patient. [That] would be helpful." - Resident, 2 years of experience.

Participants suggested additional systems for receiving alerts could be helpful, such as wearables. Others envisioned that these alerts could be incorporated into the electronic health record system; although many participants indicated that they are not often at a computer, this technology would be useful to HCWs based on what is most convenient for them.

Participants also envisioned AR systems that provide navigation instructions to lost visitors, provide educational information as discussed earlier, and can be used to help HCWs with patient treatment. The participants discussed the need to help answer frequently asked questions from patients and their families. Also, travel nurses often need help becoming familiar with facility layouts as they often work in different hospitals and need to re-learn a new layout when they work at a new facility. Thus, participants envisioned using AR systems to assist patients, families, visitors, and HCWs.

> "Yeah, I think that [AR glasses] would be useful in a code situation. The ER physicians run the code blues in the hospital. So if you had AR glasses that could show you exactly where the patient's bed is because that was always an issue." - Resident, 11 years of experience.

Additionally, the participants discussed how useful AR systems could be for supporting HCWs, who often visit their computers to look up information needed to treat patients. To address this challenge, they envisioned AR systems that enabled them to search for content online when needed, which would alleviate the need for HCWs to leave their patients to search for information. Instead, the HCWs can search for information on demand and can potentially provide faster treatment to patients because this could reduce delays caused by searching for information online.

> "Hospitals are perfect examples of where AR allows you to know more about an environment and enhance your understanding and knowledge in time critical scenarios. We're getting to a point where it's increasingly a 'have to have' not a 'nice to have' because

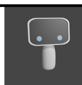
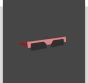
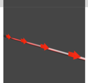
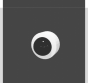
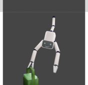
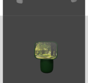
Robot Name	Design	Type	Theme(s)	Use Cases
Lito		Tabletop	Privacy and Peace, Communication, Safety	• Monitors patient's room • Company and entertainment for patient • Allows HCW to communicate with patient
Go!/Health		Other	Privacy and Peace	• Shows HCW or patients where they need to go
Retract Rails		Interactive Wall	Privacy and Peace	• Give user something to hold onto • Guide patient on where to go
Secure		Other	Safety	• Monitors room to provide security • Alert staff during emergencies
Lift		Mobile/Ground	Privacy and Peace, Communication, Safety	• Lifts heavy equipment • Helps patients get out of bed
Sky		Mobile	Communication, Safety	• Delivers supplies between buildings and EDs • Monitors patient activity
Procedurebot		Mobile	Safety, Communication	• Delivers supplies • Assists physicians with medical procedures
Waterbot		Mobile/Ground	Privacy and Peace, Communication	• Delivers supplies such as food, water, and blankets
Delti		Mobile	Privacy and Peace, Communication	• Delivers supplies • Lifts and carries patients
Curry		Mobile/Ground	Communication, Safety	• Assists in patient check-ins • Monitors waiting room or triage area
Peace		Interactive Wall	Privacy and Peace	• Provides privacy for patients • Provides barriers between patient and rest of ED to create calming environment
Calm		Tabletop	Privacy and Peace, Communication	• Displays nature scenery • Walks patient through breathing exercises
Supplybot		Mobile	Privacy and Peace	• Delivers food and supplies to patients and HCWs
Storagebot		Mobile	Privacy and Peace, Safety	• Allows patients to securely store their items
Sliding Wall		Interactive Wall	Privacy and Peace, Communication	• Allows spaces to be reconfigured to provide privacy where needed

Fig. 6. This shows design prototypes generated from interviews.

more and more [ER doctors] look [for] things up here and there – beta dose and antibiotic. And that's just going to increase. If you want to look at the treatment pathways for a novel illness or one that you haven't dealt with recently." - Attending Physician, 20 years of experience.

4.3 Impact of Patient Experience on HCW Safety

The ED is considered the highest risk area in the hospital for violence against staff, patients, family, and visitors [75, 94]. This is due to numerous factors, including long wait times, substance abuse issues, patient stress, and the ED's 24-hour access [94]. Also, due to a reduction in mental health beds, patients are often placed in rooms alone or with a HCW responsible for monitoring them. Furthermore, with overcrowded jails, inmates are placed in the ED as it is the only location some people can be placed [26, 75]. All these factors combined result in escalation to violence [75].

All participants in our study envisioned ways intelligent systems could support HCW safety, as this is a common concern for HCWs, particularly recently.

> "[The] AI does intrigue me in the sense of notifying security, we have an intense amount of a need for security and our ER. And because assaults are on the rise, for healthcare workers, I think it would be super-efficient to have a monitoring system so that our security could respond quicker and so that maybe we could lessen those assaults." - Registered Nurse, 6 years of experience.

To address this challenge, participants envisioned *robots that could detect and monitor aggressive or unusual behavior* which could include people showing signs of onset aggression, such as being loud, or showing signs of aggression towards others and themselves. When this behavior is detected, HCWs and security should be notified so they can respond in a timely manner to de-escalate the encounter. They also discussed robots that could continuously monitor patients to detect dangerous objects, such as weapons, which could be a sign that a violent encounter is about to take place. Furthermore, they envisioned robots that monitor patient vital signs to detect agitation before it escalates. Some participants were interested in using robots to record these violent encounters and use this content for educational purposes to learn strategies of de-escalation and violence prevention.

> "So currently what we have is [...] a central monitoring station [...] usually in the middle of a nursing station, and it basically has all of their vital signs, including like a telemetry monitor where we see their EKG rhythm strip. It has [the patients'] most recent blood pressure or heart rate. But what we don't have on that is the actual response, and for the patient themselves, so having eyes on the patient to see if there are any signs of physical distress that would be useful. If there are any questions or issues that the patient has in real time, they could just tell the robot." - Resident, 11 years of experience.

As another way to reduce violent encounters, participants discussed that improving patient experience may improve their overall mood which could potentially reduce violent encounters. For example, many of the HCWs discussed how patients often request food and drink, but they often do not have time to fetch these for patients because they must prioritize treating critical patients. Also, oftentimes patients cannot eat or drink because they must wait until their diagnosis is complete which is a frequent cause of delays in patient treatment. Thus, participants envisioned robots that could deliver food and beverages with the approval of HCWs. Once patients have been allocated a room, participants envisioned that patients can use a system similar to the pneumatic tube, but for delivering food to patients' rooms. Participants hoped that systems such as these could reduce patient frustration.

> "I think [pneumatic tubes are] a great idea and it could get stuff from everywhere. One of the hospitals I was at actually had it connected to the kitchen as well so [patients] could

> get [...] food [quickly] rather than having [to wait for] someone [to] bring it up." - Nurse Practitioner, 14 years of experience.

While HCWs were excited about these possibilities, two participants were concerned with delays in communication between robots and security when dangerous behavior is detected. Delays in security responses to violent encounters have detrimental consequences for ED occupants, sometimes resulting in human deaths [25, 26, 75]. Furthermore, HCWs' licenses could be revoked as a consequence of these delays from intelligent systems. Thus, monitoring systems employed by ED security require extensive validation to ensure the accuracy of detecting violent encounters, and these encounters must be reported as soon as they are detected.

> "My concern (that I've heard from other ER nurses, and so I can't quite take it as my own) is that if it's a [technology] monitoring for safety or things like that there's a time lag, [...] which is a concern for me because ultimately my license [depends] on the safety of the patient, so I would feel a little uncomfortable defaulting to something that's not human." - Registered Nurse, 6 years of experience.

5 A NEW DESIGN CATALOG FOR HRI

Here, we present the *Design Catalog*, which features intelligent, interactive systems that we co-designed with participants to envision resilient ED environments of the future (see the catalog in Fig. 7 and a detailed description of the systems in Table 6). We categorized these systems as robots that prioritize safety, move supplies efficiently, speed up patient check-ins, improve communication, promote peace and calm, and improve patient comfort. Overall, these systems aim to improve the experiences of both HCWs and patients.

Safety: There are several robots that prioritize safety. For example, the Lito robot (Page 1, Item #1) monitors patients' rooms (with their permission), keeps patients company, provides entertainment, and enables HCWs to have a telepresence in the room to consult with patients. The Go!/Health robot (Page 1, Item #2) helps HCWs, patients and their families, and visitors navigate the ED so they do not get lost. The Secure robot (Page 1, Item #3) monitors the patient room to provide security and alert HCWs and security staff during emergencies. The Retract Rails system (Page 1, Item #4) provides a rail to prevent patient falls; it can also provide directions to patients using voice activation. Lastly, the Lift robot (Page 2, Bottom-Right) provides cushion hands and arms to lift patients safely.

Transportation: Participants also envisioned robots that move supplies efficiently. For instance, the Procedure robot (Pages 9-10, Center) is a ceiling robot that folds up to reduce space, easily avoids getting in HCWs way, and can clean surfaces. The catalog also includes robots that lift heavy objects which will reduce the risk of HCWs injuring their back. Also, the Sky robot (Page 9, Left) is a drone that delivers materials between buildings which can help reduce the time needed to test samples, and patients can use a phone application to receive updates on orders, tests, and treatment plans.

Communication: Furthermore, there are robots that speed up patient check-ins and provide patients updates on their treatment status. For instance, patients can receive status updates on their treatment via smart watches or robots. The catalog includes mobile robots that provide safety and security by monitoring the environment for aggressive or usual behavior. When this behavior is detected, the robot alerts ED security with concerns. The Curry robot (Pages 4, 6) is a kiosk for patients to check-in when they arrive at the ED, provide updates on their status/ETAs, and monitor the waiting room or triage area for security concerns. To help reduce the frustration of ED patients, the robot provides education to patients to inform them on the status of their diagnosis.

Fig. 7. The *Design Catalog* features interactive, robot systems that prioritize safety, speed up check-ins, improve communication, help patients feel like they left the ED, and create a more comfortable, private, and peaceful environment.

Environment: The catalog also features robots that promote peace and calm. For instance, the Sliding wall (Page 2, Bottom-Left) can divide a room to house multiple patients. It also has a folding chair that comes out from the wall to save space and provide privacy. Another interactive wall is the Peace robot (Pages 11-12, Item #1), that provides privacy for patients with barriers stationed between them which is particularly useful during the COVID-19 pandemic. To increase communication and provide a peaceful environment between patients and HCWs, the Calm robot (Page 11, Item #2) displays nature scenery to patients to keep them calm and walks patients through breathing exercises to reduce stress. Additionally, these robots provide sound insulation, ventilation, and create a relaxing environment to rest.

Comfort: Finally, several robots provide patient comfort. For example, the Supplybot (Page 7, Item #1) provides food and drink to patients, with their provider's approval. The Waterbot (Page 5, Top-Left) also can deliver food, water, and supplies. The Storagebot (Page 8, Item #3) can be used by patients to store their belongings, which is particularly useful during long wait times in the ED should they need to get up to use the restroom or make a call.

6 DISCUSSION

Our study revealed many exciting ways that robots can help HCWs cope with their built environment which can lead to resilient healthcare systems that help reduce HCWs workload in the ED. We encapsulated these robots in a Design Catalog that has the potential to reduce wait times, block smells and sounds of the ED, prevent patient self-harm and harm to others, and empower patients by helping them be more involved in their care. In this section, we discuss the implications of these robots on the ED built environment as well as ways to avoid technosolutionism and ethical concerns of these technologies. We then briefly discuss designing for resilience in challenging, real-world built environments, and we provide a roadmap for other researchers wishing to explore this topic. Finally, we discuss limitations and future work.

6.1 Design Catalog Implications

6.1.1 Preventing Patient Agitation. Participants envisioned novel ways to use robots to prevent patient agitation, particularly for patients with mental health disorders. This included providing entertainment, visualizations of nature scenes, and playing soothing music to keep patients calm. This can enable resilient healthcare systems in terms of reducing violence against HCWs and preventing patient self-harm.

Participants also envisioned how robots can take on the role of monitoring patients and alerting HCWs when detecting unusual or aggressive behavior. This was seen as something that could both reduce HCW burnout (as it is difficult to witness and experience violence in the workplace), and possibly free up some HCW time to attend to critical patients with time-sensitive conditions.

While many methods exist to support detection of aggressive behavior, there is a danger they will be prone to either false positives (due to bias) or false negatives (due to occlusion, noise, and frequently-changing ED environments). Also, standard, low-cost camera systems may not be as successful at detecting fine-grained motion [70]. Additionally, there are numerous privacy considerations to be mindful of [45, 104]. Systems must be designed in a flexible way to enable patients (and HCWs) to easily opt-out when they are uncomfortable having systems monitor them. For example, patients might want these devices turned off during exams, when they need privacy, or because they simply do not trust the technology. Also, these systems need to be well-designed to prevent further exacerbating asymmetrical power dynamics in the ED [119]. It is critical that these systems are carefully designed and tested to ensure high fidelity, safety, and reliability to ensure they do not cause additional patient harm.

6.1.2 Increasing Communication between Patients and HCWs. Participants envisioned interesting ways of using robots as a communication medium to increase HCW-patient interactions. Our study revealed that these robots can enable resilient healthcare systems in terms of reducing HCW workload, encouraging patients to avoid leaving without being seen, and empowering patients to feel involved in their care. Similar systems are investigated in CSCW, e.g., computer-mediated communication systems, which moderate interactions between people rather than just being a tool [101]. When deploying computer-mediated systems, it is important to ensure that users maintain social agency. Social agency refers to a person having the feeling of controlling their experiences with their body and external environment [76].

Our study highlighted the criticality of HCWs maintaining social agency for sensitive conversations with patients, such as when delivering devasting news [76]. Participants stressed the importance of maintaining social agency in these conversations because they are very difficult for patients and their families. Related work in CSCW and HRI shows that robots change the way people interact in terms of affecting spatial configurations [93], trust [17], and social shaping [30]. Thus, further research is required to understand to what extent robots can be employed ethically in clinical environments to handle sensitive conversations with patients.

6.1.3 Robots that Create Reconfigurable Spaces for Privacy and Peace. Our study discovered new ways to use robots to reconfigure spaces to create areas of healing, privacy, and peace. This can enable resilient healthcare systems in terms of reducing smells, sounds, and sights of the ED. Also, these robots can create new spaces for patient consultation, which hopefully reduce delays in patient treatment, and improve privacy.

Since the COVID-19 pandemic, healthcare systems have rapidly adopted the use of patient isolation pods as a means of infection control. Our participants envisioned similar pods that can provide a soothing, nurturing, and healing environment for patients. Furthermore, these systems have the potential to reduce occurrences of violent events as a result of reducing patient stress.

6.2 Avoiding Technosolutionism and Ethical Concerns

While both the participants in this study and the authors are excited about the potential for new technologies to change the built environment to build more robust health systems, we are also cognizant of the fact that it is easy to fall into the trap of technosolutionism. Many of the problems HCWs face are not only a result of the physical built environment but of the healthcare system within which it resides. Better healthcare systems design, improved human factors, an increased valuation of its workforce, and major paradigm shifts in how care delivery is conceptualized will ultimately yield greater benefits than specific new technologies.

Furthermore, we acknowledge that any new technology introduced into an already-overwhelmed system may simply cause more burnout to the workforce rather than alleviating it (c.f., electronic health records). Thus, designing for the future requires a participatory approach that captures the contextual insights of work as done in addition to the more technology-driven design fiction of work as imagined.

Several ethical questions arose during the research process. One example which raised a number of quandaries were monitoring systems. While they may have value to HCWs (and patients), they have the potential to create panoptic systems, which can be harmful to patients on many levels, particularly with regard to their privacy, autonomy, and dignity (see Section 2.5). Here, robots may be used as a "policing" mechanism, perhaps to subdue agitated patients. Just like policing in non-health contexts, work by Joh [62] and others suggests a range of concerns can arise, including perpetuating social inequity and infringing on a person's rights. These questions require careful consideration and further research in close concert with law and policy researchers.

Another ethical question which arose in our study is the robots' role within care contexts. For example, as one participant said, "I would feel a little uncomfortable defaulting to something that's not human." Smart furniture is inherently quite different than a social robot that is evaluating a patient or providing them with discharge instructions. In addition to the professional risks clinicians have by delegating tasks to machines, patients are also at risk as they may be receiving a lower standard of care.

Finally, several participants discussed issues relating to cost. Several of our participants work with underserved populations at poorly-funded hospitals, and while this technology would be "nice to have", it paled in comparison to more pressing concerns faced by these institutions. While we wanted to avoid constraining participants in their ideation process, cost is a valid concern when it comes to considering new technology, and also is closely tied to health equity. Thus, we encourage technology designers to consider ways to allow participants the space to consider technology affordability throughout their ideation processes.

6.3 Designing for Resilience: A roadmap

To support researchers interested in designing for resilience in challenging, real-world built environments, we provide a brief roadmap describing our research process.

Taking a systems-level perspective In our research process, our goal was to design for resilience at the healthcare systems-level (rather than at the individual level), we sought to focus our research on problems within the broader ecosystem of care as opposed to just a single problem users faced. This approach enabled our work to address multiple concerns within the built environment, thus making our research better contextualized and, hopefully, more impactful to our participants.

Enabling Active Ideation via Design Fiction: One challenge we encountered when working with HCWs is a low level of technology familiarity or literacy. Thus, it can be difficult for them to envision future systems when they are unaware of what systems currently exist. Also, HCWs are usually significantly time-limited, so we can not always provide a lengthy orientation during design sessions. To address this, we designed a fictional scenario that helped HCWs place themselves in a future environment by incorporating existing/near-future technology (i.e., design fiction). In order for technology designers to create a fictional scenario, we encourage them to engage with users, identity the most significant challenges they face, and use this as intuition for a future fictional scenario. Our fictional narrative helped participants place themselves as key stakeholders in designing a future environment – that is, we gave them a feeling of "having a seat at the table" (see Section 3.2.1).

Resilience for All: Another important factor in our roadmap is reflecting on what resilience means within the context of a research domain. For instance, in our work, resilience refers to designing technology to help HCWs cope with the built environment. Thus, we identified several built environmental challenges in healthcare from our literature search which helped shape our interview questions. By making connections between the built environment and the challenges of our users, we enabled our participants to compare their current challenges to those they expect to experience in the future, which led to new technology designs that mitigated those challenges.

Reconciling the Present and Future: The last factor in our roadmap is thinking about ways to help participants reconcile differences between their current workplace and the future. During Phase III interviews, participants reflected on how useful the prototypes are for their work today and expressed their enthusiasm for a future ED as depicted in the catalog. By helping HCWs imagine the design of future technologies, we hope to close the gap between HCWs' current working conditions to what we can achieve in the future. Thus, this process was helpful because it enabled us to realize the technological challenges that require addressing before we can achieve more adaptable, safe, and cost effective healthcare environments.

6.4 Limitations and Future Work

While our work introduces new ideas about using robots to support adapting the healthcare built environment, there are some limitations to note about our research. First, due to COVID-19 restrictions on research imposed on our healthcare systems, we were not able to include patients or their families in our research. This is an important stakeholder group to include, as ultimately many of these technologies would be patient-facing. Thus, we intend to include this population as soon as our institution relaxes these research restrictions. However, we would like to note that HCWs are an important stakeholder group to include, and offer important contributions. Even before the pandemic, frontline HCWs were suffering at work; and since then things have gotten exponentially worse [25, 94, 115, 132]. Thus, their voices, too, need to be centered in research.

Second, our sample size was somewhat smaller than we had originally hoped for. This, too, was a reflection of the pandemic - ED HCWs are on the frontlines, and it was very difficult to schedule them for participation in our study. We had a difficult time recruiting a large number of nurses, who are some of the most essential healthcare workers in this discussion. In future work, we plan to include more nurses and other ED HCWs, including technicians, radiologists, and medical assistants, who will also provide unique perspectives on this topic.

In this paper, we explored how HCWs envision using robots and other intelligent systems to help them cope with their built environment. We co-designed robot prototypes to support patients and healthcare workers in the ED, which can potentially improve safety and experience of patients and HCWs, and, thus, resilience. Our work could provide insights to the CSCW community on using intelligent systems to help HCWs cope with different built environments.

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A APPENDIX

A.1 Phase I - Interview Checklist, Script, and Questions

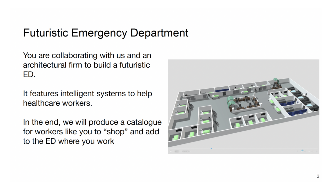
(1) Introduction (See Fig. 8a): “We are exploring how to design intelligent systems to support healthcare workers and patients in the Emergency Department (ED) while considering the built environment. In this study, you will imagine that we are collaborating with you and an architectural firm to envision and build a futuristic ED.”

(See Fig. 8b) “The futuristic ED, although fictional, contains some of the features of real EDs. The fictional features include, but are not limited to, existing intelligent systems such as robots and interactive systems to support healthcare workers and patients. Keep in mind that we have unlimited resources so feel free to chip in your ideas and we can build them. In the end, we will produce a catalog for workers like you to “shop” and add to the ED based on experiences you have had working in local EDs.”

(See Fig. 8b) “You will participate in a two-phase study. In the first phase, we will ask you to reflect on the challenges of the built environment. We will provide an overview of different robots used within and outside of healthcare that could be useful for you in your daily work. We will ask you questions about how you envision using these systems in our futuristic

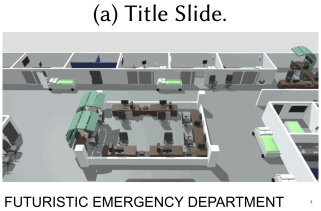
ED. In the second phase, we will work together to envision and design new technologies to address any challenges that you came up with in Phase I. ”

(a) Title Slide.

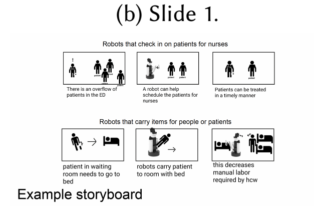


(b) Slide 1.

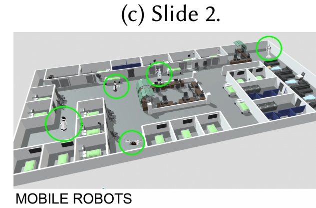
(c) Slide 2.



(d) Slide 3.



(e) Slide 4.



(f) Slide 5.

Fig. 8. PowerPoint slides 1-5 shown on Zoom during Phase I interviews.

(2) Transition (See Fig. 8c) : “The new ED features various interactive systems that fall within five categories. We will discuss each category and collect your feedback on how useful they would be to help you in your daily work. These categories include mobile robots, tabletop robots, interactive wall robots, furniture robots, and others. Some of these systems have already been used in healthcare settings and others have not. We encourage you to think about how you might use these systems in the Emergency Department where you work.”

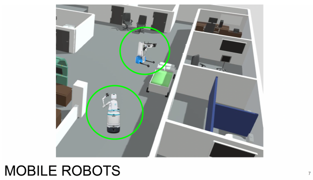
(See Fig. 8d) Allow participants to observe the futuristic ED design probe: “Let’s take a closer look at the new ED. We will talk about the various intelligent systems you see here.”

(See Fig. 8e) “As you talk through your experiences, my colleagues will record them in what we call a storyboard. These are used to reflect on experiences and how we can design intelligent systems for particular situations that occur. For example, on the top, we see a storyboard of a robot that checks in on patients for nurses. On the bottom, we see a storyboard about a robot that carries items for people in the ED.”

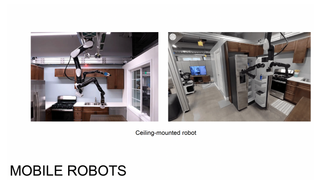
(3) (See Fig. 8e) Ask the participants questions about the technology they were just shown: “Before we move on to the next part of the interview, is there anything that was unclear, or do you have any questions?”

(4) Help participants setup their desktop with Zoom window and ‘Robot Cheat Sheet’: “You should have received an email with a ‘Robot Cheat Sheet’. You can refer to that to remember what the various robots do that we plan to discuss today. Can we ask that you place the ‘Robot Cheat Sheet’ on the same window on your desktop as the zoom meeting? This will help you easily reference it during the study.”

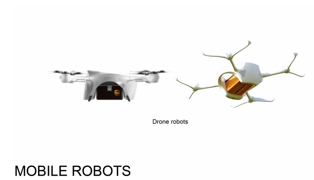
(5) Transition to Mobile Robot Category (see Fig. 8f): “The first category are ground robots. These robots typically move around and have a mobile manipulator that can pick and place objects.”



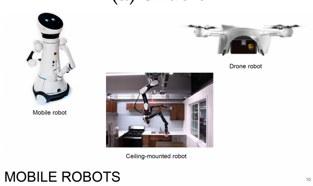
(a) Slide 6



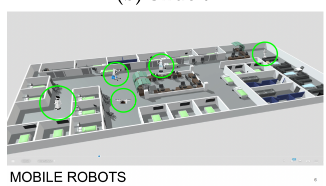
(b) Slide 7



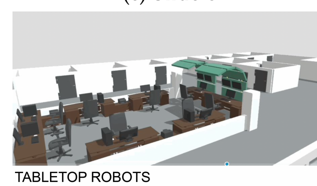
(c) Slide 8



(d) Slide 9



(e) Slide 10



(f) Slide 11

Fig. 9. PowerPoint slides 7-12 shown on Zoom during Phase I interviews.

(See Fig. 9a): “These types of robots can perform many tasks including: supporting healthcare workers directly, delivering supplies, medication, lifting patients, and they can act as robotic walkers.”

(see Fig. 9b): “We also have ceiling mounted robots. Here, you can see a robot recently built by Toyota Research built. This robot moves around the ED, deliver supplies, and clean surfaces.”

(See Fig. 9d): “Recently, UC San Diego hospital has been using drone robots to deliver COVID-19 tests and blood samples. We also feature these robots in the new ED.”

Interview Questions (see Fig. 9e):
- What do you think about the robots in this category?
- What parts of the robots did you like/dislike when you imagine using this system for you/your patients at the ED where you work today?
- Can you walk us through a scenario where you would use this robot/system in the future ED?
- Can you describe/point to where this situation typically occurs?
- When you think about using this type of robot, what would you change about the future ED and why (e.g., what would you add, remove, change, etc)?
- Do you have any additional comments or thoughts?

(6) Transition to Tabletop Robot Category (see Fig. 10a): “Next, we will talk about the tabletop robots featured in the new ED as shown here. For example, the new ED has the Jibo and Mabu robots which talks to patients, can provide entertainment, and socially support patients.”
(7) Ask about current situation in the ED (see Fig. 10b): “When you imagine using this system for you/your patients at the ED where you work today, what parts of the robots did you like/dislike?”
Interview Questions:
- What do you think about the robots in this category?
- What parts of the robots did you like/dislike when you imagine using this system for you/your patients at the ED where you work today?
- Can you walk us through a scenario where you would use this robot/system in the future ED?

- Can you describe/point to where this situation typically occurs?
- When you think about using this type of robot, what would you change about the future ED and why (e.g., what would you add, remove, change, etc)?
- Do you have any additional comments or thoughts?

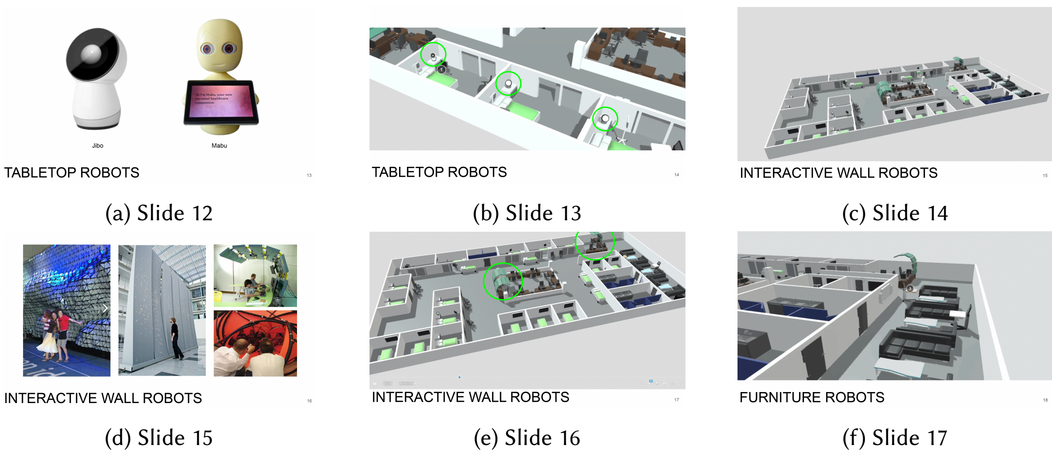


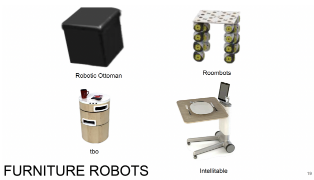
Fig. 10. PowerPoint slides 13-18 shown on Zoom during Phase I interviews.

(8) Transition to Interactive Wall Robot Category (see Fig. 10c): "Let's talk about interactive wall robots working in our futuristic ED. These systems adapt to people in the environment is several ways. They move to support user's needs e.g., move to make the room smaller or larger, create private areas for patients, their family, etc. "

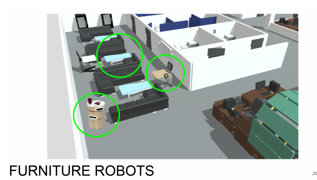
Interview Questions (see Fig. 10d and 10e):
- What do you think about the robots in this category?
- What parts of the robots did you like/dislike when you imagine using this system for you/your patients at the ED where you work today?
- Can you walk us through a scenario where you would use this robot/system in the future ED?
- Can you describe/point to where this situation typically occurs?
- When you think about using this type of robot, what would you change about the future ED and why (e.g., what would you add, remove, change, etc)?
- Do you have any additional comments or thoughts?

(9) Transition to Furniture Robot Category (see Fig. 11a): "Another interesting feature of the new ED are furniture robots. For instance, it features couches that are mobile and can support patient mobility They communicate with other devices in the environment to support patient care The furniture is also modular – meaning that it can change in size, be stationary/mobile, attach to different furniture."

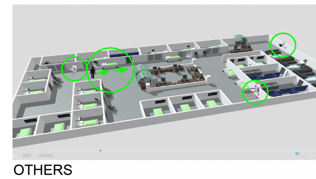
Interview Questions (see Fig. 11b):
- What do you think about the robots in this category?
- What parts of the robots did you like/dislike when you imagine using this system for you/your patients at the ED where you work today?



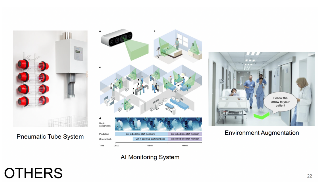
(a) Slide 18



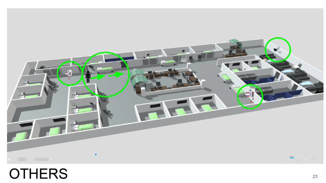
(b) Slide 19



(c) Slide 20



(d) Slide 21



(e) Slide 22

(f) Conclusion Slide.

Fig. 11. PowerPoint 18-22 slides used during Phase I of the interviews.

- Can you walk us through a scenario where you would use this robot/system in the future ED?
- Can you describe/point to where this situation typically occurs?
- When you think about using this type of robot, what would you change about the future ED and why (e.g., what would you add, remove, change, etc)?
- Do you have any additional comments or thoughts?

(10) Transition to Other Robot Category (see Fig. 11c): "We included an additional category which shows systems that some hospitals have today and an additional idea to explore for this work which we would like your feedback on. I'm sure you are familiar with Pneumatic Tube System which is typically built into the walls of the ED. It transports labs, medications, and other items. Recently, a hospital at Stanford has explored artificial intelligence (AI) systems that monitor patients from a video stream and provides healthcare workers feedback on when patients fall and when they are in distress."

Interview Questions (see Figs. 11d and 11e):
- What do you think about the robots in this category?
- What parts of the robots did you like/dislike when you imagine using this system for you/your patients at the ED where you work today?
- Can you walk us through a scenario where you would use this robot/system in the future ED?
- Can you describe/point to where this situation typically occurs?
- When you think about using this type of robot, what would you change about the future ED and why (e.g., what would you add, remove, change, etc)?
- Do you have any additional comments or thoughts?

A.2 Phase II - Interview Checklist, Script, and Questions

(1) Transition to Phase II: "Next, we will reflect on the ideas you talked about in Phase I and discuss how you envision designing intelligent systems that can address challenges caused by the built environment. We will sketch a prototype of your designs on an iPad. Finally, we

will reflect on how you envision using these systems. Let's recap the ideas that you discussed in Phase I."

(2) Show storyboards generated from Phase I in PowerPoint and share screen: "Let's recap the ideas that you discussed in Phase I."

(3) Ask participants to choose their most important ideas: "Of all the storyboards we summarized, which are your top 2-3 most important ideas?"

(4) Share Procreate/iPad screen: "So now, I'll ask my colleague to share their screen. So we can review the storyboards that you found most important and start the co-design process."

(5) Show participants their prototypes and get their feedback: "Now, we will show you a prototype of the idea that you just designed."

Interview Questions:
- Ask for feedback on future ED design: "What would you change about the future ED and why (e.g., what would you add, remove, change, etc)?"
- Is this what you envisioned? Is there anything you would modify or add?
- Can you think of any additional use-cases for this system?
- How should the system look/appear? How would it interact with people?

(6) Demographic questions (Send in Zoom chat): "Thank you for your time today! We just have a few more questions to wrap up." [SHARE DEMOGRAPHIC SURVEY URL WITH PARTICIPANT]

(7) Conclusion: "Thank you for your time and participation. All of this information has been very helpful!"

A.3 Phase III - Interview Checklist, Script, and Questions

(1) Introduction: "Hello, [PARTICIPANT NAME]. We would like to thank you again for participating in our study and for meeting with us to provide feedback on our Design Catalog. The catalog is a collection of design prototypes that are the result of these interviews. We would like to present the designs to you and get your feedback on them. Keep in mind these are only prototypes, so please feel free to be honest and give us constructive feedback to improve the designs. Our goal is to have a conversation and learn more, not build products."

(2) Ask if they have questions: "Before we begin, do you have any questions for us?"

(3) Test audio: "Do we have your permission to record this meeting?"

(4) Transition: "Now, we will give you time to review the Design Catalog, and then we will ask you questions to collect your feedback": [PROVIDE URL TO DESIGN CATALOGUE] Let us know when you are done reviewing the catalogue."

(5) HCW Safety/Ethical Concerns: "In our earlier discussions, people talked about how many HCWs are concerned for their safety around agitated/dangerous patients."

Interview Questions:
- Look through the design catalog. Are there technologies that could help de-escalate agitated patients?
- What do you like/dislike about these technologies?
- What is missing/what would you change?
- How do you think patients would perceive these technologies?

(6) HCW <-> Patient Communication

Interview Questions:

- Another topic that came up earlier was the need for increased communication between patients and HCWs. Take a look through the Design Catalog. How might some of these technologies affect communication?
- What do you like/dislike about these technologies?
- What is missing/what would you change?
- How do you think patients would perceive these technologies?

(7) Creating Reconfigurable/Re-purposed Spaces

Interview Questions:

- Another topic that came up earlier was the need for spaces that can be re-configured or re-purposed to create privacy and quiet.
- Take a look through the Design Catalog. How might some of these technologies support reconfiguring spaces for privacy and quiet?
- What do you like/dislike about these technologies?
- What is missing/what would you change?
- How do you think others (patients, family members, your colleagues) would perceive these technologies?

(8) Design Catalog Feedback

Interview Questions:

- What do you think is missing from the Design Catalog?/What would you like to see in the catalog?
- Do you have any additional comments or thoughts?
- Thank you for your time and participation. All of this information has been very helpful!

A.4 Design Catalogue

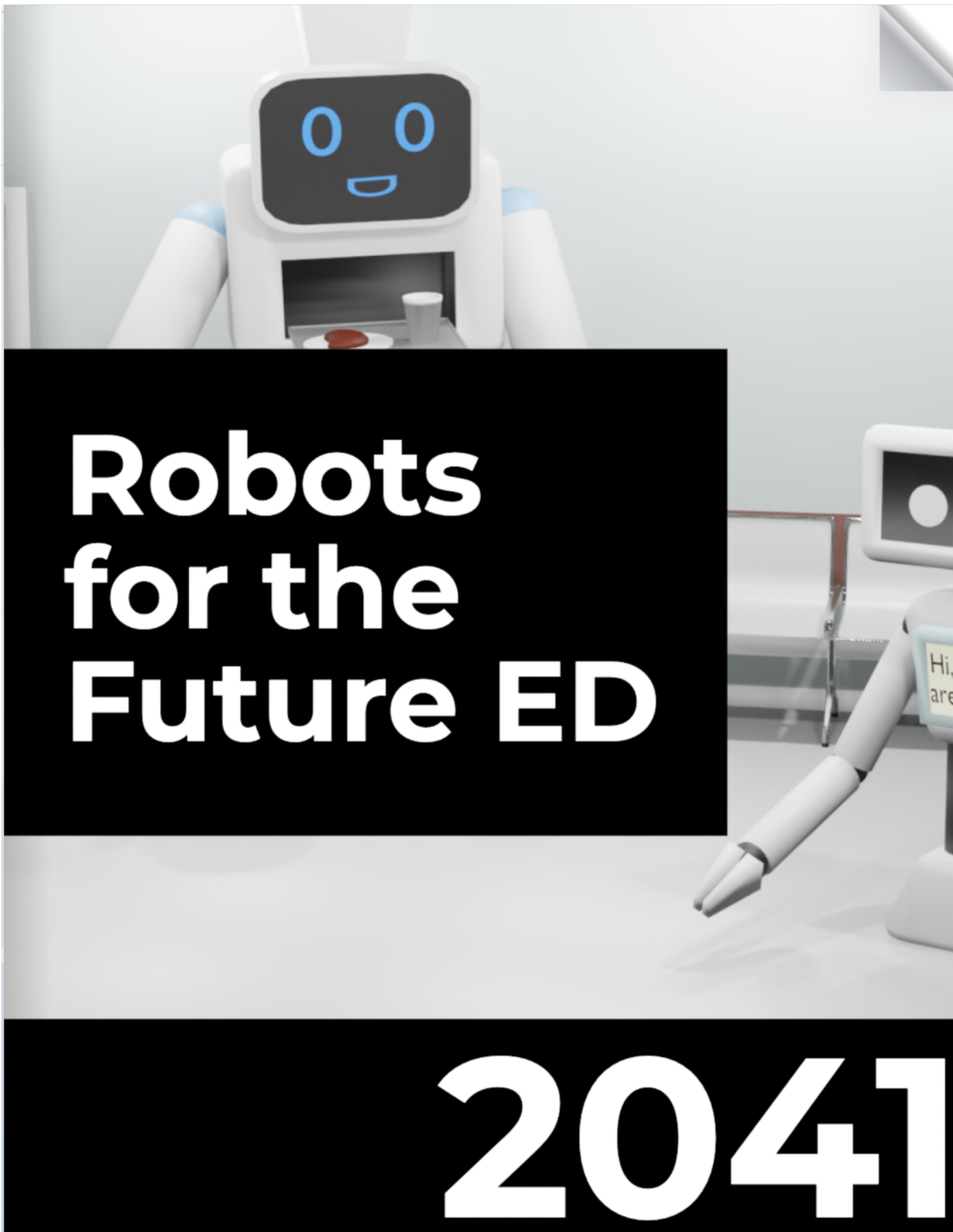


Fig. 12. Front Page of *Design Catalog*.

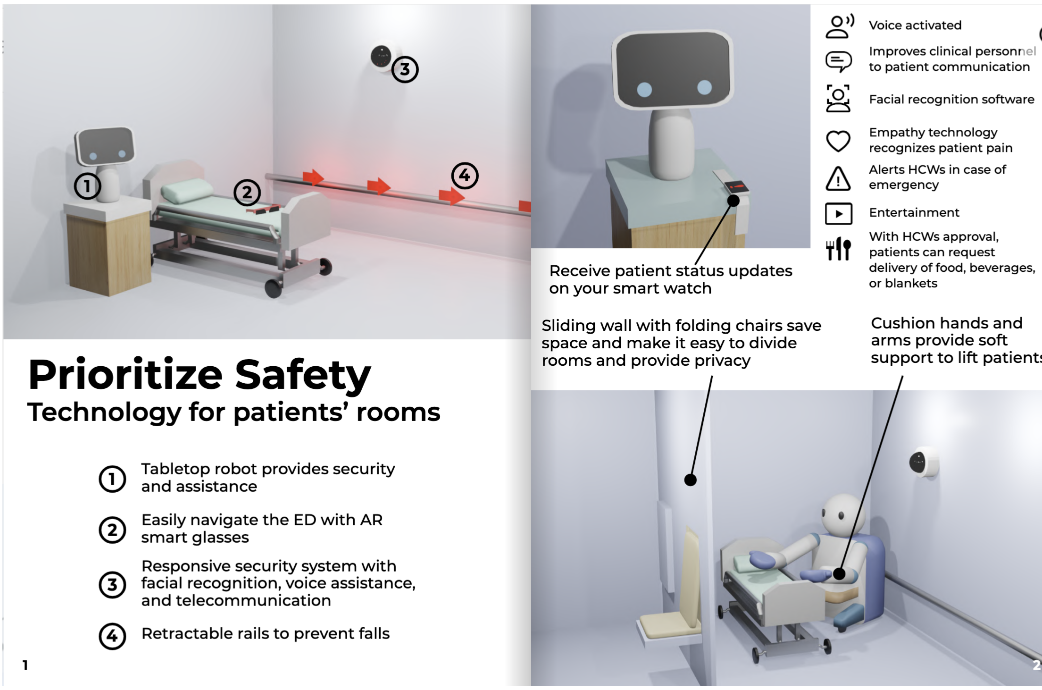


Fig. 13. Page 1-2 of *Design Catalog* on patient safety.

Received January 2022; revised April 2022; accepted May 2022

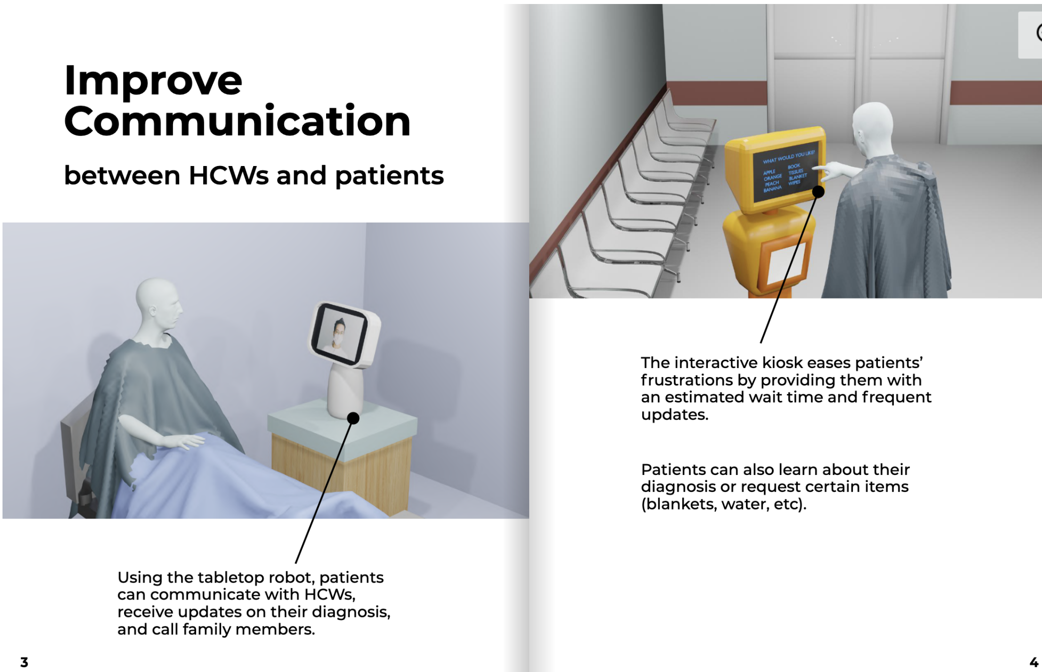


Fig. 14. Page 3-4 of *Design Catalog* on improving communication between healthcare workers and patients.

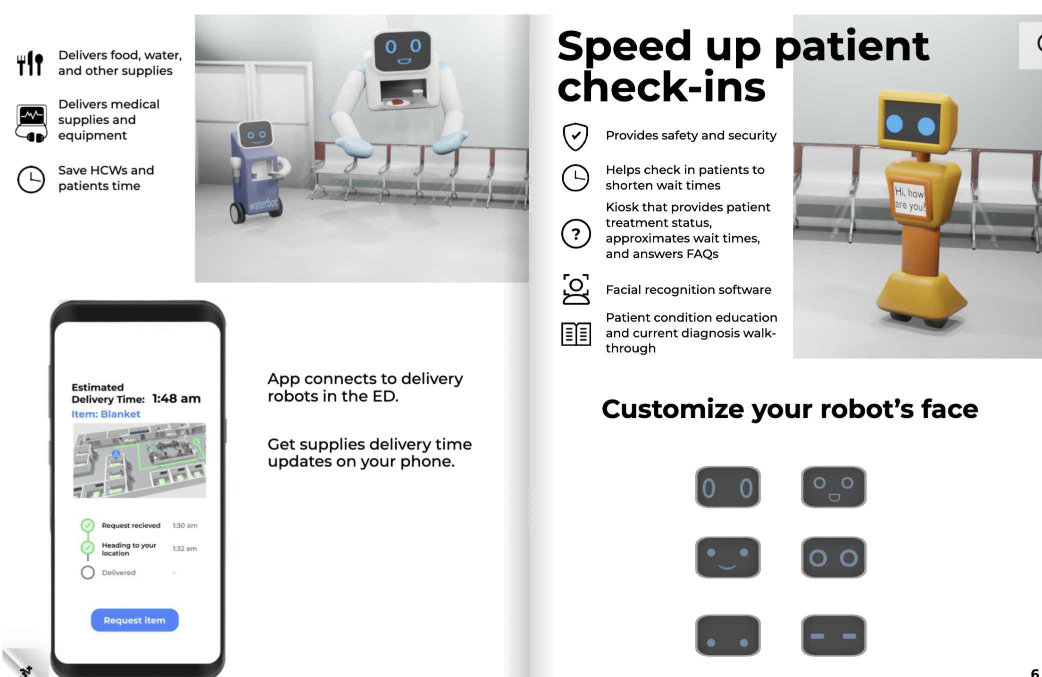


Fig. 15. Page 5-6 of *Design Catalog* on improving patient comfort and speeding up check-ins.

Fig. 16. Page 7-8 of *Design Catalog* on improving patient comfort.

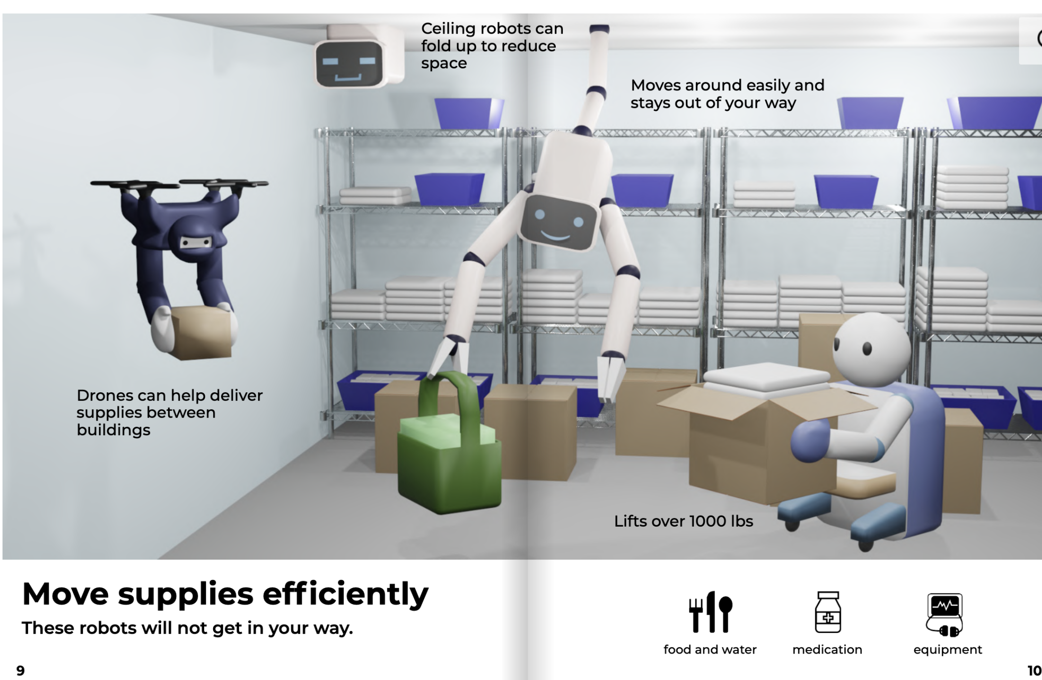


Fig. 17. Page 9-10 of *Design Catalog* on moving supplies efficiently.

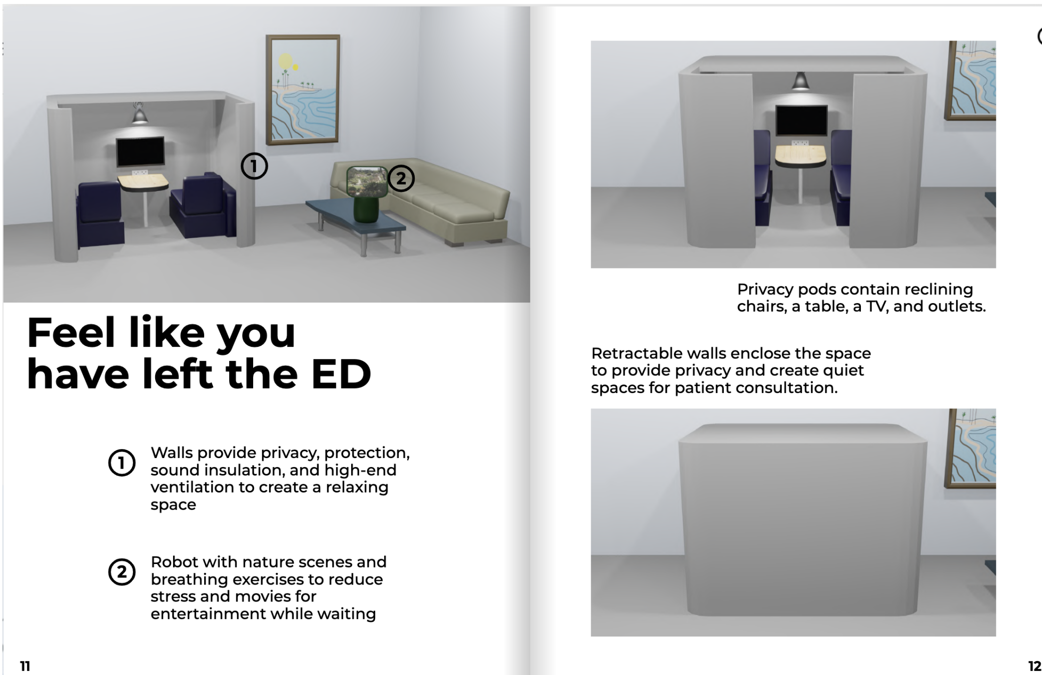


Fig. 18. Page 11-12 of *Design Catalog* on creating areas of privacy and peace.