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RESEARCH ARTICLE

SUPPORTING COMMUNITY FIRST RESPONDERS IN AGING IN PLACE: AN ACTION DESIGN FOR A COMMUNITY-BASED SMART ACTIVITY MONITORING SYSTEM[1]

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To maintain elderly individuals' ability to live independently in their own homes, technologies such as sensors and the internet of things can be used to facilitate real-time monitoring and automate emergency detection and alerts to enable first responders to deliver help on time. This study examines the design problems associated with such activity monitoring systems, particularly how to support the situational awareness of community first responders who are located remotely and do not have professional healthcare knowledge. Based on a three-year action design research study that investigated a sensor-based monitoring system for elderly people deployed in a natural community setting, we developed abstract design knowledge. Four design principles aimed at enhancing responders' perceptions, comprehension, and projection of information are proposed to promote informed decision-making and timely responses by drawing on the situational awareness model. In addition to the nascent design knowledge regarding remote activity monitoring in different instances, this study extends our knowledge of the community-based model by foregrounding its multiplicity and the active roles of community stakeholders in providing care to elderly people.

Keywords: Activity monitoring systems, community-based model, elderly care, situational awareness, IoT, sensor-based monitoring systems, action design research, ensemble IS

Introduction

The combination of the aging global population and the decreasing cost of internet of things (IoT) technologies has led to a new development that focuses on community-based smart activity monitoring systems to overcome the costly and labor-intensive nature of institutionalized elderly care and address the desire of elderly individuals to maintain independence within their own homes (Mettler et al., 2021; Zhu et al., 2021). In this new context, rather than relying on

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hospitals or nursing facilities, nonprofit organizations or government agencies oversee the implementation of smart monitoring systems. The first responders in these community-based systems are typically family members, neighbors, or volunteers who are familiar with the elderly individuals being monitored. In this study, we refer to these individuals as community first responders (CFRs) and our research focus is on their situational awareness (SA) in this distinct community-based smart monitoring context.

From a practical standpoint, we observe that community-based smart monitoring has several empirical challenges in addressing CFRs' SA needs. CFRs, who are not full-time healthcare workers, have limited medical knowledge and experience. This must be considered in the design of monitoring and emergency response systems for CFRs' SA (Jiang & Cameron, 2020; Marcilly et al., 2018). Unlike traditional patient monitoring with wearable devices, community-based smart activity monitoring systems need to be designed with a range of situational factors in mind. Senior homes are unique in their characteristics, underscoring the importance of physical materiality such as motion sensors because their placement and coverage can affect the effectiveness of CFRs' SA in assessing elderly people's health-related conditions (Mettler et al., 2017). Furthermore, the community and voluntary aspects of this type of monitoring necessitate effective digital communication mechanisms to support timely information sharing and coordination among CFRs when assessing elderly people's conditions and responding to emergencies. These considerations vividly illustrate the complexity of interconnections between smart technologies, both physical and digital materiality, and the structuring of community-based monitoring in shaping CFRs' SA. However, the literature on aged care monitoring systems with a focus on elderly individuals has not theorized about the challenges encountered by CFRs or how we can better assist them. Thus, motivated by practical and theoretical imperatives, this study investigates the question: *How can we support community first responders' situational awareness in the context of remote activity monitoring*?

To address this problem class (i.e., supporting CFRs' SA), we exploited a rare opportunity to conduct a 3-year action design research (ADR) study in Singapore. Our proposed solution class, named the community-based smart activity monitoring system, accounts for the diversity of community members and their active role as agents of change (McLeroy et al., 2003). We developed and implemented a sensor-based elderly monitoring system (SEMS), an activity monitoring system that utilizes in-home sensors to detect prolonged inactivity, which triggers an emergency alert to CFRs. Our entry point for this ADR project was based on the evaluation of existing IT solutions for remote elderly care and the original problems thus diagnosed. Once the problem class was defined, we iteratively redesigned and modified the artifact to align with the project's goals and evolving needs. Through iterative interventions, reciprocal sharing, and reflection, we not only implemented a refined information system artifact but also derived a set of design principles to support CFRs' SA by investigating the dynamic interaction, integration, and coevolution of such ensemble artifacts over time.

To theorize the complexity and address the practical problems of implementing smart technologies in a community-based elderly care setting, we adopted "a processual logic where interactions [between technologies and CFRs] and outcomes are seen to be mutually dependent, integrative, and co-evolving over time" (Orlikowski & Scott, 2008, p. 446). In addition, taking an ensemble view of IS artifacts helped us communicate the relationship between the material and organizational features of the system (Orlikowski & Iacono, 2001). For example, a community-based smart activity monitoring system consists of physical materiality, such as sensors that "can be seen and touched" (Yoo et al., 2012 p. 1398); digital materiality, such as software applications with reprogrammability and data homogenization; and "new forms of organizing" (p. 1403) through collaboration with a group of volunteers in the community. We posit that to sustain the success of such a system, its design and implementation efforts must effectively integrate contextual factors, supporting CFRs' SA to ensure the overall effectiveness of their emergency responses without draining their resources.

Drawing upon the SA model, this study derives four key design principles to augment CFRs' abilities to perceive, comprehend, and project information, thus facilitating informed decision-making and expeditious responses. In addition to enriching the existing body of design knowledge on remote activity monitoring applications across various contexts, this research extends the understanding of the community-based care model. It highlights the diverse and active roles played by community stakeholders in the provision of care for elderly individuals.

The rest of the paper is organized as follows. In the next section, we introduce monitoring systems and existing design knowledge. Then, we describe the research method and case. Thereafter, we present the design theory in terms of a set of design principles. Finally, we conclude by discussing the contributions and limitations of our study.

Foundations and Related Work

Monitoring Systems for Elderly Healthcare

Broadly, we identified two types of monitoring systems used for the elderly population: patient monitoring systems for individuals with chronic diseases, such as heart disease and diabetes, and aged care monitoring systems for general health and activity monitoring.

Patient monitoring systems are used to remotely gather patient information outside of traditional healthcare institutions to support medical interventions or disease management involving professional clinicians (Paré et al., 2007). The remote nature and critical implications of these personal medical conditions have prompted a significant focus on technical aspects in design-related studies. These studies focus on technical capabilities such as network stability and signal transmission (Chatterjee et al., 2018; Sneha & Varshney, 2013; Varshney, 2008). Another prominent design concern involves helping clinicians maintain consistent awareness of patients' situations considering their demanding workloads (Fore & Sculli, 2013). To enhance emergency health workers' SA, some improvements include personalizing alarm thresholds and enhancing the relevance of data displays (Marcilly et al., 2018; Varshney, 2008).

Another area that is frequently examined in the healthcare monitoring literature is aged care monitoring. This involves tracking the daily lives of elderly individuals to assess their overall health and detect incidents such as falls. Various technological solutions, including wearable devices such as smartwatches, are utilized to measure vital health information such as pulse rate and to assess mobility and physical activity performance based on acceleration and muscle activity measurements (Schwenk et al., 2015). Unlike wearables, nonwearable in-home sensor solutions, such as environmental and motion sensors that track movement patterns (Ni et al., 2015) and magnetic contact sensors on doors that monitor instances of going out, have received increasing attention due to their unobtrusiveness (Zhu et al., 2020). The primary focus of these studies has been the data modeling or outcome of activity monitoring or the factors related to elderly individuals' adoption and use (Abouzahra & Ghasemaghaei, 2022). Researchers have found that unlike the commonly reported privacy and ethical concerns related to surveillance or monitoring systems, elderly individuals prioritize safety over privacy and ethical issues related to the constant tracking of their activities (Mettler et al., 2017; White & Montgomery, 2014).

Relevant Design Knowledge of Monitoring Systems in Healthcare

We build on three aspects of monitoring systems—physical materiality, digital materiality, and organizing—for elderly care and review existing design knowledge.

Our review shows that while physical materiality, such as wearable devices and sensors, comes in a variety of sizes and shapes and "can carry social meanings of appropriate use" (Yoo et al., 2012 p. 1398), very few studies specifically discuss the design choices of physical artifacts. One notable exception is the work by Chatterjee et al. (2018), which highlights the need to consider the subject's preference when implementing various IoT devices in an elderly person's home. In studies that have explored this aspect, the primary focus has been on ease of use, physical elements of the solution, or technical capabilities, such as the common tendency of elderly individuals to forget to wear or charge the devices (Chernbumroong et al., 2014) or the advantage of in-home sensors over wearable devices due to the IoT's low levels of power consumption and minimal disruption to the elderly person's daily routine (Bakkes et al., 2011).

With respect to digital materiality, we identified two areas of research interest. The first area focuses on the design of algorithms, modeling methods, and data analytics (Gochoo et al., 2018; Son et al., 2020; Yu et al., 2022). Accuracy is paramount because precise output recognition is critical to the success of the entire monitoring process. However, data are voluminous and complex in these contexts (Ni et al., 2015) due to the fact that human activities are often highly ambiguous (McClain, 2018). Consequently, extensive scholarly efforts have been devoted to developing activity recognition algorithms (Noury et al., 2011). For instance, Zhu et al. (2020) reported that despite being privacy-friendly and unobtrusive, motion sensor-based systems encounter obstacles such as insufficient labeled data and difficulty identifying specific individual activities in settings with multiple residents.

The other stream of research on the digital aspect of IT artifacts focuses on the design of emergency alerts, messages, and interfaces, especially for use by professional healthcare workers (e.g., Marcilly et al., 2018). To optimize the accuracy of the resulting alert, researchers have proposed that it is essential to personalize predefined alert thresholds and patterns because different individuals exhibit unique ranges of "normal" vital signs and behavioral patterns (Marcilly et al., 2018; Varshney, 2008). With regard to interface display and alert messages, existing design knowledge suggests that they should remain simple and display only relevant information so users can find relevant information quickly and make informed decisions (John & Smallman, 2008; Marcilly et al., 2018). Notably, researchers have also debated the trade-off between simplicity and adaptability, with the latter pointing to the importance of providing contextualized, personalized, and situated information in alert displays (Mettler et al., 2017).

Finally, regarding organizing and local practices for elderly care or patient monitoring systems, we similarly identified only a few studies that explicitly address relevant design decisions. Examples of organizing practices include the use of social influence to motivate elderly individuals to increase their activity levels through wearable devices (Abouzahra & Ghasemaghaei, 2022), the deployment of a do-it-yourself approach to engaging with elderly users (Mettler et al., 2021), and the regular dissemination of tailored newsletters to patients with diabetes and their family members in order to enhance their understanding of the disease and promote the effective use of an in-home monitoring system (Chatterjee et al., 2018). Interestingly, consistent with our earlier literature review of the aged care monitoring system, focal attention to the design and intervention of organizing has been centrally placed within the elderly population and the challenges encountered by health professionals or CFRs have not been addressed.

In sum, two salient and interrelated research opportunities were identified for our study: adopting an ensemble view to understand the elderly care monitoring system and considering the needs of CFRs as the actual users. First, the relationship between the system and users may be responsible for these outcomes. It is imperative to understand the organizing aspects in tandem with the physical and digital aspects of a system to develop an ensemble view of IS artifacts that incorporates both social and technical dimensions (Orlikowski & Iacono, 2001). Furthermore, researchers have called for an integrative approach to consider the interactions between technology and people in the monitoring literature (Kitsiou et al., 2015). Given that previous studies on healthcare monitoring systems have not fully captured the interdependencies of social and technical systems, our study complements existing work by simultaneously focusing on physical materiality, digital materiality, and organizing aspects.

The second opportunity pertains to the stakeholders who must be considered when generating design knowledge for aged care monitoring systems. Our review found that studies that have examined the design of alert messages have considered only elderly individuals in the case of self-monitoring (Chatterjee et al., 2018) and professional first responders (Marcilly et al., 2018; Varshney, 2008). Very little attention has been given to the needs of CFRs. Because the characteristics of CFRs differ from those of health professionals, the solution to developing their SA when responding to emergencies will undoubtedly be different. Furthermore, our review of materiality and organizing is reminiscent of Barley's (1988) viewpoint: We need to avoid an overemphasis on technology as a mere physical object or social production, which can lead to technological or social determinism. This view highlights that the interactions between the materiality and social elements of an ensemble artifact are dynamic, embedded, and emergent (Ciborra et al., 2000). To better understand these mutually dependent and coevolving interactions, it is crucial to be mindful of how the material aspects of a system are (re)construed to shape and support CFRs' SA as it is built and used while also examining the emergent and unintended consequences for users that shape the system design and implementation (Orlikowski & Iacono, 2001; Orlikowski & Scott, 2008).

Research Field and Research Design

In Singapore, the Ministry of Social and Family Development has organized community-based social services to support vulnerable seniors. The staff of nonprofit voluntary welfare organizations (VWOs) conduct home visits and organize activities through senior activity centers to ensure that elderly individuals remain physically and socially engaged. However, despite these efforts, between 2007 and 2014, it was reported that more than 50 elderly individuals who lived alone died at home (Toh, 2014); in some cases, it took days or even weeks before the death was discovered (Ho, 2023).

Hence, as part of the Smart Homes and Intelligent Neighbors to Enable Seniors (SHINESeniors) project, a SEMS was launched in 2015 to enable CFRs to detect in-home emergencies—particularly unusually long inactivity, which could signal a fall or fainting—to ensure that help could be delivered on time. Because the VWOs oversaw the provision of caregiving and social services to the elderly population, the setup represented a distinct environment in which the SEMS could be deployed in a real-world community network.

The project seeks to develop an effective SEMS to enhance CFRs' SA, thus enabling them to understand elderly people's activities quickly and make independent assessments of the situation. Methodologically, ADR is a natural choice in this context since the design of the artifact lies at the intersection of design-oriented design research and organization-oriented action research (Sein et al., 2011). Its success entails both an innovative application of technology and the implementation of an IS that involves unconventional groups of users (i.e., elderly individuals and CFRs). ADR is suitable because the outcomes of the implementation of such IS applications are rarely final, and the IS artifact emerges from the interaction between design efforts and contextual factors (Jones & Gregor, 2007; Sein et al., 2011).

ADR Research Collaboration

Founded in early 2016, the ADR team consisted of the implementation team and four ADR researchers from the disciplines of information systems, social sciences, and computer science. The ADR team oversaw the design, development, implementation, evaluation, and refinements of the system and led the interventions by collaborating with elderly individuals, CFRs, and VWOs. Appendix A presents the key stakeholders and their relationships; we also detailed the ADR team's distribution of work in Transparency Material A.[2]

The research for the SHINESeniors project involved three key community stakeholders: elderly individuals, VWO staff, and CFRs. The elderly individuals who participated in the project were individuals who lived alone, and they provided consent for sensors to be installed in their homes. VWOs are community organizations that provide elderly care services. In this project, dedicated VWO staff provided organizational resources, including organizing training for CFRs on how to use SEMS and providing guidelines such as emergency response protocols. They also acted as a bridge between the ADR team and the elderly individuals. By leveraging the trusted relationships they had previously built with elderly individuals, they collected data regarding their experience with the system.

CFRs are community members who offer emergency support to elderly individuals. Before the system was implemented, some of them had already worked closely with VWOs to deliver caregiving services to elderly individuals, such as home visits. CFRs are the direct users of SEMS; they receive the alert triggered by the SEMS and respond to those alerts so that appropriate help can be delivered to the elderly participants. However, none of them had undergone the formal emergency support training required for professional health workers or paramedics. CFRs collaborated directly with the ADR team to inform the interventions and design of the system, which, in turn, helped them to better understand the situation of the elderly individuals.

Data Collection in ADR Cycles

In addition to the ingrained contextual understanding of the two ADR researchers who led the project implementation, we employed various data collection methods, summarized in Appendix B, to design interventions to support CFRs. Through a general survey and a focus group conducted with CFRs in mid-2015, the team gathered information about elderly people's needs and contextual conditions in addition to information about the needs of CFRs and the issues they faced when using the initial version of the system. This feedback informed the first stage of ADR, problem formulation.

Subsequently, the ADR involved two cycles of artifact design that focused on *building the IT artifact, intervening in its use,* and *evaluating the process* (BIE) (Gregory & Muntermann, 2014; Sein et al., 2011): the alpha and beta cycles. Appendix C shows the timeline of the initial, alpha, and beta versions of the systems and ADR cycles. Unlike in software development, where alpha and beta have specific meanings, in this context, we use these terms to simply represent the two cycles and system versions. In each cycle, various data collection mechanisms, including participant observations, regular meetings, and interviews, were employed to gather firsthand feedback from key stakeholders regarding the design changes.

To learn about CFRs' SA and how well the system supported their SA, we gathered evaluative feedback from both the CFRs and the elderly individuals. We were able to involve all the CFRs who provided emergency support for the elderly individuals. Four CFRs had been involved since the beginning of the ADR; as the project scaled with more elderly individuals, the number grew to eight (see Appendix C). Through a focus group session, we gathered information on CFRs' needs and challenges, which informed the problem formulation of this ADR. Throughout the project, all the CFRs participated in quarterly meetings with the ADR team and provided feedback on how the system supported their assessment of alerts and emergency situations and the challenges and concerns regarding system use. In addition to these meetings and focus group sessions, we separately conducted semistructured interviews with two CFRs to gather in-depth data about whether and how well their SA improved over time.

Because we understood that CFRs' SA is directly affected by the conditions, responses, or needs of the monitored subjects, the evaluative feedback from the elderly individuals helped the team better understand how the system should be designed. The data from these recipients offered insights into CFRs' SA. Our ADR project began with 30 elderly participants, and this number increased to 87 by the end of the ADR project. The data were collected from a general survey, observations, and interviews. The survey helped the team understand the needs and contextual conditions of elderly individuals. With bimonthly participant observations supported by two VWO staff members who had a trusted relationship with the elderly people, we also

[2] The transparency material is available at https://osf.io/rbwq3/?view_only=52cd88c67390432083df2b536727786f

gathered information about individuals' behavior in their natural home environment (Gorman & Clayton, 2005; Pearsall, 1970). This information included how well they were supported by the system, which was expected to enhance CFRs' SA, and details about their living habits and behaviors that might contribute to challenges in accurately identifying an emergency. This information was corroborated by six interviews with elderly individuals.

When gathering evaluative feedback, we paid attention to the intended and unintended consequences of users' interaction with the system. Focusing on these consequences helped us to better understand the interplay between planned design and in situ use and thus allowed us to capture the emergent nature of ensemble artifacts (Sein et al., 2011). In particular, the realization of intended outcomes served to verify that the implementation of new design decisions is a valid implementation of the design principle's prescription. Conversely, unintended consequences could suggest a return to the process of problem structuring, albeit in a new cycle (Gregory & Muntermann, 2014; Markus et al., 2002). Notably, we adopted a position that a formal, final evaluation of the emerged design theory is unnecessary (Gregory & Muntermann, 2014; Sein et al., 2011). Thus, in our study, the evaluation of the artifact and design principles occurred concurrently with the iterative design and reshaping of the artifact (Sein et al., 2011).

To address the unintended consequences we identified, we then translated our revised design principles into new design decisions, which included a new set of system features such as functions, interfaces, data flows, and analytic algorithms. In the first cycle, the new design features were incorporated into the alpha version implemented in August 2016. Eight months later, we introduced the beta version. In each BIE cycle, the new system replaced the previous version. Following the implementation of the new versions, we conducted training sessions with the CFRs and, if necessary, provided guidance to the elderly individuals.

Toward the end of each cycle, a formative evaluation was conducted based on discussions within the ADR team and at quarterly meetings with the CFRs and VWO staff with the aim of generating a set of design principles (this point refers to the reflection and learning stage of ADR). The ADR team reflected on the evolution of the design principles and focused on "thinking back on what we have done to discover how our knowing-in-action may have contributed to an unexpected outcome" (Schön, 1987, p. 26). In line with the ADR principle of guided emergence, we constantly challenged ourselves by asking how the design principles thus derived were guided by the theory we applied (situational awareness theory, which will be introduced later) but were shaped by the organizational use and participants in the context of an authentic evaluation (Sein et al., 2011). Subsequently, during the formalization of the learning stage, this learning was abstracted into a set of principles after we engaged in further reflection to ensure that the principles were applicable to a broader class of problems instead of merely being applicable to our specific problem. In both the iterative reflection/learning stage and the formalization of the learning stage, we cycled back and forth between abstraction and de-abstraction (Gregory & Muntermann, 2014), guided by (1) the theory during the process of reflection and learning and (2) the class of problems during the formalization of learning.

ADR Cycles

Our goal was to develop design principles to support CFRs' SA. Our analysis employed Sein et al.'s (2011) ADR stages and Markus et al.'s (2002) inductive approach. We presented our problem formation (Stage 1 of the ADR method), analysis of the iterative BIE cycles (Stage 2 of the ADR method), reflection and learning (Stage 3 of the ADR method), and conceptualization of design principles as the formalization of learning (Stage 4 of the ADR method).

Problem Formulation

At our point of entry into the research field, we focused on the initial SEMS system, which was already implemented in the homes of 30 elderly people. The system featured three components: (1) an in-home sensor network, (2) an alert and response component, and (3) a web portal/mobile app. The sensor network comprised a set of passive infrared (PIR) sensors, a door contact sensor, a panic button, and a gateway for receiving data. The PIR sensors (motion sensors) sent a signal at 10-second intervals to indicate whether motion was detected, and the door contact sensors sent a signal when the two magnets were separated to indicate a door opening or closing. Each elderly participant was also given a panic button to call for help in emergencies. The gateway acted as the central receiver that collected the sensor data and sent them to the backend servers. The sensor network layout is shown in Figure 1. The second component, the alert and response, was a messaging platform that notified the CFRs about two types of alerts: (1) panic alerts that occurred when an elderly participant pressed the panic button and (2) inactivity alerts when prolonged inactivity was detected by the sensors. In the initial system, the alerts were sent via an SMS. A WhatsApp group, which was separate from the SEMS, was created for CFRs to discuss and evaluate alerts. The third component was the web portal/mobile app, which displayed real-time sensor readings. CFRs could log into the system to retrieve visualizations of current and past sensor readings.

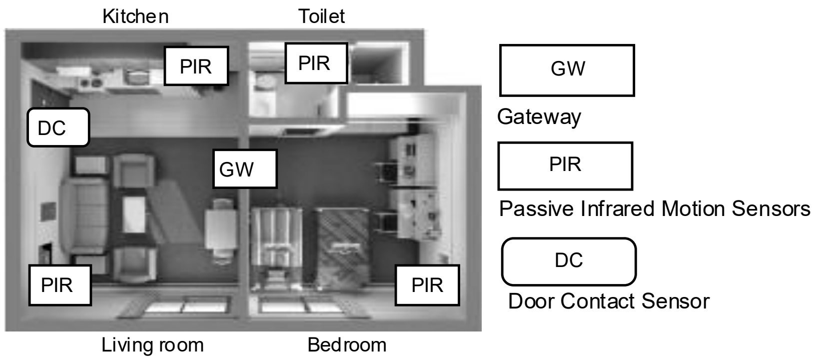

Figure 1. Layout of the Sensor-Based Elderly Monitoring System in A Typical Home

Table 1. Problems with Existing SEMS

Problems (Uncertainties)	**Initial SEMS in use**
Data unreliability Unreliable data caused by sensing devices	• The collected data were incomplete due to sensor coverage and the limited number of sensors that could be deployed at individuals' homes. • The sensor location was not the same for all elderly individuals' homes due to varying layouts. • No sensor reading would be collected if an elderly individual was in a blind spot; prolonged "inactivity" could generate a false alarm, and no data would be available for CFRs to manually interpret the situation.
False alarm High false alarm rate caused by the use of fixed thresholds (an order-dependent technology) in a disorderly real-world environment	• The use of a fixed threshold to determine inactivity on the part of elderly individuals resulted in a high false alarm rate. • CFRs experienced alarm fatigue and risked lowering their guard due to the high false alarm rate.
Situational delay Changes in the situation are not reflected in time due to the fragmented communication channel for responders	• The system did not capture the information provided by the CFRs to update an alarm situation; the components of the system were not fully integrated with each other. • Actions taken to address an alarm were not immediately available to everyone; CFRs might respond to an alarm that was already addressed or closed. • Over time, some CFRs develop familiarity with particular elderly individuals. Thus, once an alert occurs, CFRs often discuss the situation and evaluate it among themselves before responding. Due to the fragmented communication channel, this task was time-consuming and challenging.

Between early and mid-2015, we conducted focus group interviews with CFRs, surveys of elderly individuals, and quarterly team meetings with CFRs and VWO staff to gain insights into system usage and collect concerns from different stakeholders. Concurrently, we reviewed the literature on healthcare monitoring systems (see Transparency Material B), which helped us to identify three aspects of IT artifacts that existing scholarly design knowledge revolves around. More importantly, this knowledge provides us with a structure to frame the three pressing design problems with the initial SEMS implementation (detailed in Table 1). Our research not only addressed specific concerns related to SHINESeniors but also encompassed a class of field problems, namely, supporting the SA of CFRs in remote activity monitoring.

We drew on the theory of situational awareness to structure the research field problem. SA involves being aware of what is happening and understanding what information means in relation to a particular goal. Endsley (1988, p. 97) defined SA as "the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future."

SA determines the information that is important with regard to accomplishing a specific goal or task (Endsley & Jones, 2012) and thus focuses on information that is required to assess and cope with a situation (Yang et al., 2012). This notion has been widely studied in the context of supporting operators in dynamic environments such as the military (Sonnenwald & Pierce, 2000), aviation (Jones & Endsley, 1996), and emergency response (Yang et al., 2012). Specifically, SA involves three levels: perception, comprehension, and projection (Endsley, 1995). Perception is the ability to perceive the status, attributes, and dynamics of relevant elements in the environment. Comprehension refers to the ability to grasp a situation fully and understand the significance of the relevant elements in light of the actor's goal. Projection is the ability to project the future states of these elements, including those that are acquirable only over time (Endsley, 1995). These three levels of SA, as illustrated in Figure 2, play a crucial role in decision-making.

Guided by SA theory, we identified three problems, summarized in Table 1. The first problem pertains to sensor data reliability, an issue associated with Level 1 SA; that is, incomplete or missing data prevents CFRs from accurately perceiving the activity of elderly individuals. Since the system was commissioned in 2015, the technical personnel from the ADR implementation team have encountered challenges related to data uncertainty and sensor positioning. While sensor placement in smaller spaces is relatively straightforward, larger areas such as living rooms require more fine-tuning. Maintaining unobtrusiveness with only one sensor per room can potentially introduce errors and data incompleteness. As one of the technical personnel stated:

> *The motion sensors are very dependent on the placement. For example, if I put a sensor behind you in your office, it will definitely detect you. When we visit the house, the elderly person may sit at one location, or the person would tell me the usual place he/she sits. So I would put the motion sensor there. But that is not really where the person usually sits.... So after deploying the sensor, we need to monitor for the next few days. We may realize that we don't see the person for a few days even though we know he/she is there. So maybe the positioning of the sensor is not ideal. Then we would go down [to the elderly person's house] again to adjust the sensor position.*

Unlike other monitoring systems in which predefined data trigger emergency alarms (e.g., pressing a button to indicate an emergency), unlabeled sensor data lacks clear definitions, characteristics, and classifications. These data capture natural behaviors in complex and noisy contexts, including irrelevant or misleading information. The uncertainties that we identified correspond to the data uncertainties that Endsley and Jones (2012) classified as directly impacting Level 1 SA because they relate to "the basic data available to the operator regarding the state of the environment" (p. 113).

The second uncertainty pertains to the high false alarm rate resulting from the fixed standard inactivity threshold of the original SEMS design, which was set at eight hours based on elderly people's average sleep duration. This situation led to a high number of false alarms. One CFR described the risk: "If there are twenty beeps and all of them are not emergencies, and the twenty-first beep is an emergency and we choose to ignore it, I'm not saying that we will, but it can lower our guard." False alarms were triggered on certain occasions due to the failure to detect activities such as sleeping, being on vacation, or being hospitalized. Such uncertainty may result from the ambiguous interpretation of sensor data in complex human settings. While IoT devices may capture activity data "correctly," interpreting these data accurately requires a contextual understanding of an individual's lifestyle, preferences, and unique circumstances. However, technology alone may not account for real-world ambiguity and open-ended settings, causing representation errors that affect Level 2 SA. In such cases, relevant information in emergency situations could be perceived accurately (i.e., prolonged inactivity is detected) but misinterpreted (e.g., CFRs interpret inactivity as unconsciousness instead of resting).

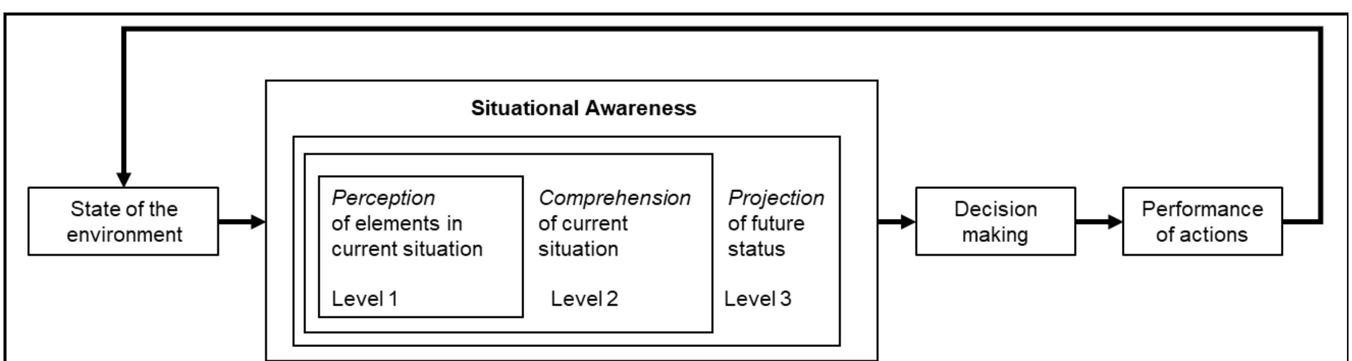

Figure 2. Levels of Situational Awareness (Endsley & Jones, 2012)

Finally, responders' comprehension (Level 2 SA) may also be challenged by the limitations of monitoring systems with regard to capturing responders' informal knowledge and actions that alter the situation, all of which are critical for alarm interpretation and the maintenance of CFRs' SA. The SHINESeniors project involved a group of CFRs who had different types of information about an elderly person, such as information concerning their vacation or hospitalization status. This information was not captured by the system or shared effectively among CFRs. Additionally, when coordinating a response, CFRs were required to initiate a conversation in the WhatsApp group, and after resolving the case, they needed to update their status in the SMS, WhatsApp, and the web portal/mobile app. This fragmented information hindered alarm assessment and SA maintenance when CFRs responded to alerts. As one CFR highlighted: "The downside of WhatsApp is it is unable to consolidate the same conversation in the same thread; there can be many conversations going around at the same time once an alert is received."

Thus, in the problem formulation stage, we diagnosed uncertainties that affected CFRs' SA as the central issue with the SHINESeniors' SEMS, particularly at Levels 1 and 2. However, we found that the design knowledge on supporting SA in such a context is limited. Previous studies have focused mainly on the technology itself. Our subsequent ADR cycles go beyond this technology-centric approach by emphasizing the need to consider how these systems work with people (Orlikowski & Iacono, 2001). In addition to the analytic processes provided in Section 4, we provide an overview of our data analysis across the ADR stages in Transparency Material H.

First BIE Cycle (August 2016 – July 2017): The Alpha Version

Building on feedback collected from the initial group of elderly individuals and CFRs, the ADR team identified three design principles (DPs) that could support the CFRs' SA. Figure 3 summarizes the initial problems, design principles, and data sources that informed the actions and corresponding design decisions in the alpha version. Notably, while we categorized the design decisions into physical and digital materiality and organizing separately for clearer presentation, these decisions and insights emerged from the observation and learning on the reciprocal interplay between the technical artifact and the organizing intervention.

To address the issue of data uncertainty affecting Level 1 SA perception, the team quickly realized that the flexibility to adjust sensor positions in elderly individuals' homes is an important prerequisite for removing blind spots. We formulated the first design principle, DP1, to ensure flexibility when (re)deploying the sensors. The derivation of this DP was based on feedback provided by one of the technical personnel, who commented on the challenges they faced when installing the sensor network, as well as interviews with the elderly participants and observations made by the VWO staff during the sensor network installation. Given the variety in the layouts of elderly individual homes, a one-off, preplanned determination of sensor positions based on a single home layout was inadequate. The team had to adjust the sensor positions several times to accurately detect movement. The DP was implemented by employing a new set of sensors considering the ease of reinstallation. These sensors were three times smaller than the original sensors and could be attached to or detached from the wall using double-sided tape (see Figure 4). The technical personnel considered the fact that these features that facilitated easy sensor (re)installation eliminated blind spots and ensured that essential data for monitoring and anomaly detection were captured. As a result, this shift not only reduced the installer's workload but also preserved the aesthetics of the elderly persons' homes since no wall drilling or patching was needed. In addition to this design decision, which affected the physical aspect of the system, the involvement of VWO staff, who collected feedback from the elderly people and CFRs regarding system use, was instrumental in establishing relationships with the elderly individuals and ensuring their cooperation in granting access to adjust the devices multiple times.

To address the problem of high false alarm rates that may affect CFRs' understanding of the situation (Level 2 SA), the technical personnel agreed that they would need to personalize the alarm threshold (DP2). This DP highlighted the need for personalized inactivity thresholds that consider individual behavior and activity levels. Accordingly, the historical data of elderly individuals (as opposed to the average for all individuals) were used to determine the personalized alert thresholds. More critically, the VWO staff emphasized the importance of considering individual living habits, such as typical sleeping times, patterns of going out, napping trends, tendency to fall asleep while watching TV, and visitor frequency. To implement this personalized alarm threshold, the ADR team worked with VWO staff to collect information regarding elderly individuals' living habits. The VWO staff visited the elderly individuals twice a month to observe their activities whenever possible and to interact with them to identify less observable aspects of their daily activities, such as sleep patterns, social interactions, and medical checkups. The threshold was incorporated into the algorithm, thus modifying the digital aspect of the artifact. CFRs received formal training and regular updates on individual situations to understand how the thresholds were determined.

Level of SA and Problems	Sources of data that inform the design principles	Design principles of the Alpha version	Design decisions
L1 Perception: Data unreliability	Feedback from the technical personnel of the ADR implementation team in the fortnightly and quarterly team meetings Semistructured interviews with elderly participants Bimonthly observations	**DP1: Ensure flexibility when (re)deploying the sensors**	***Physical materiality*** • ADR team replaced the sensors with smaller and lighter ones so their positions can be adjusted easily at elderly homes of different layouts to reduce blind spots • ADR team attached sensors to walls using double-sided tape to reduce the workload while preserving the aesthetics of the elderly home ***Organizing*** • ADR team involved the trusted VWO staff to ensure that the elderly would permit the installer to access their home on multiple occasions
L2 Comprehension: False alarm	Existing design knowledge from the literature Quarterly team meetings	**DP2: Personalize alarm threshold**	***Digital materiality*** • ADR team changed the alert threshold from a general inactivity average applicable to all elderly individuals to a personalized threshold • ADR team considered individual living habits and activity level in determining the threshold ***Organizing*** • ADR team leveraged the trusted VWO staff to collect the living habits information through observations • ADR team provided training to help CFRs understand the determination of the threshold
L2 Comprehension: Situational delay	Focus group session with the CFRs Quarterly team meetings	**DP3: Integrate alerts and responses**	***Digital materiality*** • ADR team replaced the one-way SMS notification system with Slack to allow CFRs to respond to the alert, and communicate among themselves • ADR team incorporated a group-based communication in the Slack notification design ***Organizing*** • VWO staff developed a response protocol for the CFRs

Figure 3. Summary of the Alpha Cycle

Figure 4. New Devices Used in the Alpha Version

To resolve the third problem, i.e., the tendency of fragmented communications to cause inaccurate interpretations of an alarm, the ADR team decided to integrate alerts and responses (DP3). This integrated communication channel facilitated the rapid dissemination of emergency dynamics and maintained CFRs' SA after initiating a response. We also reasoned that the DP would explicitly allow for the input of other informal information by human operators beyond that captured by the sensors, such as situations in which CFRs use a response function to inform others about an elderly person's absence due to vacation when an inactivity alarm is triggered. In the context of SHINESeniors, which leverages a group of responders rather than a single individual, a crucial design consideration was the need for such group-based interactions. To enhance communication and coordination among CFRs, the system transitioned from an SMS-based approach, i.e., one-way alert messaging, to a Slack-based notification system (Figure 5). Slack is a communication platform that facilitates persistent channels (chat rooms) for text-based messaging, calls, and file sharing, thereby making seamless communication possible within the CFR group. CFRs could use the messaging feature to discuss an alert and coordinate their responses. Furthermore, CFRs received training on how to coordinate on Slack, and a response protocol (provided in Transparency Material I) was developed to outline the procedures, roles, and response times required when responding to an alarm.

Concurrent Evaluation

The three proposed DPs were implemented in the SEMS alpha cycle. The refined system was deployed at the homes of 47 elderly individuals, and four CFRs were involved. Ongoing evaluation of the system in use was conducted at quarterly team meetings with reference to bimonthly observations conducted by the VWO staff during their visits to the elderly participants. At the quarterly meetings, CFRs provided feedback on how the revised system supported (or did not support) their understanding of the elderly people's situations. At the same time, the observation data of elderly people's use and living habits would elucidate the accuracy of the system in detecting emergencies or intricate issues underlying false alarms, thus complementing our understanding of CFRs' SA. We also focused on understanding both the intended and unintended consequences of system use. These formative evaluations showed improvements in the accuracy of the CFRs' SA; however, some unanticipated problems were observed, as summarized in Table 2.

Based on these evaluations, it is evident that while our proposed DPs contributed to the task of addressing the three identified problems, they were inadequate. As we reflected and learned from the alpha cycle, we reaffirmed the need to consider the real-world complexity that makes it impossible for surveillance and identification technologies to detect and represent an emergency perfectly. For instance, we found that the involvement of organizational participants such as VWO staff in the intervention process was essential. This finding led to a second BIE cycle to further embed an ensemble view of artifacts and to explicitly consider real-world complexities by conducting a larger-scale evaluation.

Second BIE Cycle (July 2017 – May 2018): The Beta Version

Based on the reflection and learning facilitated by the alpha version, we refined the design principles. Figure 6 summarizes the changes made to the three DPs, as well as the emergence of a fourth DP. These changes were instantiated and evaluated based on the beta version of the artifacts, which replaced the alpha versions at 47 homes in July 2017 and were further introduced to the homes of an additional 40 elderly individuals through a comprehensive intervention. Additionally, four more CFRs joined. This BIE cycle included a total of 87 elderly participants and eight CFRs.

While DP1 addressed the data reliability issue, it was limited when the subject's behavior deviated from the designer's expectation. As summarized in the previous evaluation results (see Table 2, row 1), we learned that expecting human behavior to conform to predefined patterns was unrealistic. To account for behavioral anomalies, we reformulated DP1 as combining multiple sensor modalities for behavioral anomalies. As suggested in the alpha cycle and further validated through the bimonthly observations, we found that detecting when elderly individuals went out was important for assessing an inactivity alarm. The revised DP was implemented with the introduction of a beacon, i.e., a proximity sensor attached to items that are typically carried by elderly individuals when they leave their homes. This additional sensor modality reduced reliance on door contact sensors, which often conveyed inaccurate signals when deviations from the expected behavior occurred. The implementation of these additional devices improved data accuracy and accounted for human behavior anomalies, which are crucial for developing situational awareness. The role of VWO staff remained significant, as they detected behavioral anomalies during their visits and observations of elderly individuals' habits, thus facilitating the identification of discrepancies leading to sensor data inaccuracies. These new design decisions are summarized in Figure 6.

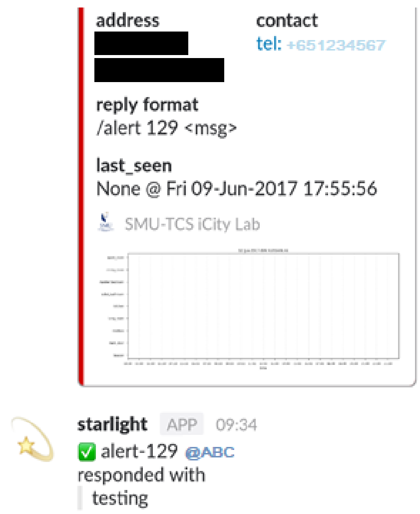

Figure 5. Example of Slack-Based Alerts

Table 2. Evaluation of the First BIE of the SEMS (Alpha Version)

Design principle	Consequences
DP1: Ensure flexibility when (re)deploying the sensors	• (Anticipated) CFRs' Level 1 SA improved as a result of eliminating blind spots in movement detection, allowing CFRs to access the enhanced sensor readings without missing data. • (Unanticipated*)* The ADR researchers realized that the sensors' reliability in terms of data accuracy was influenced by the monitored person's behavior. As one ADR team member noted at a fortnightly meeting, "If an elderly individual left the door open while visiting neighbors, the system would incorrectly assume that the person was still inside, leading to false alarms when the inactivity threshold was exceeded." Upon investigation, the team identified limitations with the deployed sensors, particularly the door contact sensor, which required strict compliance with the directive to close the door to ensure data reliability.
DP2: Personalize the alarm threshold	• (Anticipated) CFRs' Level 2 SA improved as a result of the reduction in false alarms. CFRs could rely on the accurately represented emergency alert to better understand the elderly individual's situation. • (Unanticipated) The system continued to detect false alarms. The inactivity alert notification lacked descriptive details about the situation. To differentiate between a false and a true alarm, the CFRs needed to either be familiar with the elderly individuals' usual sleeping patterns or access the web portal to retrieve past sensor readings to gain insight into their typical routines. As one of the technical personnel noted: "CFRs had to log in to the web portal to know what happened to the senior before they decided what they could do about it. It was too much of a hassle."
DP3: Integrate alerts and responses	• (Anticipated) CFRs' Level 2 SA improved as a result of streamlined communication and coordination on Slack. CFRs could assess informal, up-to-date information to enable them to obtain a better understanding of the elderly individuals' actual situation. • (Unanticipated) The alerts and conversations were shown chronologically via a unified interface that resembled a WhatsApp group communication. However, this format caused confusion when new alerts appeared before earlier ones had been addressed, which complicated the task of pinpointing the specific alerts being discussed. Moreover, CFRs seeking to review the resolution of a specific alert later had to manually search the entire conversation to find discussions or actions relevant to that alert. As one CFR told us: "The downside is that it is unable to consolidate the same conversation in the same thread; there can be many conversations going around at the same time once an alert is received."

Level of SA	Sources of data that inform the refined design principles	Design principles of the Beta version	Design decisions
L1 Perception	Feedback from the technical personnel of the ADR implementation team in the fortnightly and quarterly team meetings Semistructured interviews with elderly participants Bimonthly observations	**DP1: Combine multiple sensor modalities for behavioral anomalies**	***Physical materiality*** • ADR team introduced a portable beacon for elderly, such that the system did not rely solely on door sensor data when they leave home. ***Organizing*** • The trusted VWO staff were tasked with observing and recording any changes in elderly individual's habits that may result in sensor data inaccuracy
L2 Comprehension	Feedback from the technical personnel of the ADR implementation team in the quarterly team meetings Bimonthly observations Two semistructured interviews with the CFRs	**DP2: Support human-based high-order assessment of personalized alarm**	***Digital materiality*** • ADR team provided information in alert display such as last seen location and usual sleeping time, for CFR's assessment • ADR team provided a shortcut link for CFRs to quickly access the raw sensor data ***Organizing*** • The CFRs shared and learned among themselves via the messaging platform how to interpret the alert and assess the situation • The technical personnel from the ADR implementation team shadowed the CFRs and supported the learning of the alert interpretation
	CFR feedback in the quarterly team meetings Two semistructured interviews with the CFRs	**DP3: Integrate team-based, closed-loop response in the alerts**	***Digital materiality*** • ADR team made changes to the message platform, allowing the CFRs' communications were appended to the alert message • ADR team indicated clearly the alert status (from open/unattended to closed/attended) through change in message colour
L3 Projection	CFR feedback in the quarterly team meetings Bimonthly observations Two semistructured interviews with the CFRs	**DP4: Support proactive monitoring**	***Digital materiality*** • ADR team visualized the elderly daily movement data collected to detect changes in behavior for managing their physical health ***Organizing*** • ADR team recruited a behavioral scientist to explore preemptive care opportunities

Figure 6. Summary of the Beta Cycle

Our evaluation of the alpha cycle also uncovered further issues related to DP2. Although personalization in alarm thresholds reduced the number of false alarms, our observations showed that CFRs could not depend solely on the alarm when making subsequent decisions about whether to activate a response. In ambiguous situations such as where a "movement" was detected when a cat entered an empty house via windows and left without the door sensor capturing the "exit" movement, an alarm would be triggered when the threshold was reached even though the resident had been away the entire time. In these situations, CFRs rely on their familiarity with elderly individuals' habits (i.e., their usual sleep duration) and past sensor readings to identify noise and gain a more comprehensive understanding of in-house activity.

Therefore, instead of modifying the alarm threshold or the algorithm to improve detection accuracy, the team adopted a revised DP that focused on the symbiotic relationship between machines and humans in decision-making. Through multiple rounds of discussion among the technical personnel and CFRs (see Figure 6 for the data sources), the design focus in the beta cycle shifted toward supplying information alongside the alert. We revised DP2 to support human-based high-order assessment of personalized alarms. This personalization was implemented by displaying the last seen location and usual sleeping time in the alert message (Figure 7). Additionally, a link to the relevant activity chart was provided to access the sensor readings without the need for separate logins to the web portal. This approach aimed to enhance the ability of CFRs to interpret alarms swiftly. CFRs also learned from one another through the shared messaging platform on how to assess the alarms. This experiential and cross-learning process exposed CFRs to various possible patterns of alert and contextual situations, thus enhancing their recognition of situations that were not included in the formal training documents.

"…later on, we decided to take all these pain points into consideration. Therefore, in the new version, we wanted to ensure that if an alert sounded, it showed all the contextual information related to the alert. If it is an inactivity alert, when was the last activity so that you can determine whether it is critical or not. [It shows] their sleep duration so you can know whether it is likely a case of a senior sleeping longer than usual. (lead of technical team)

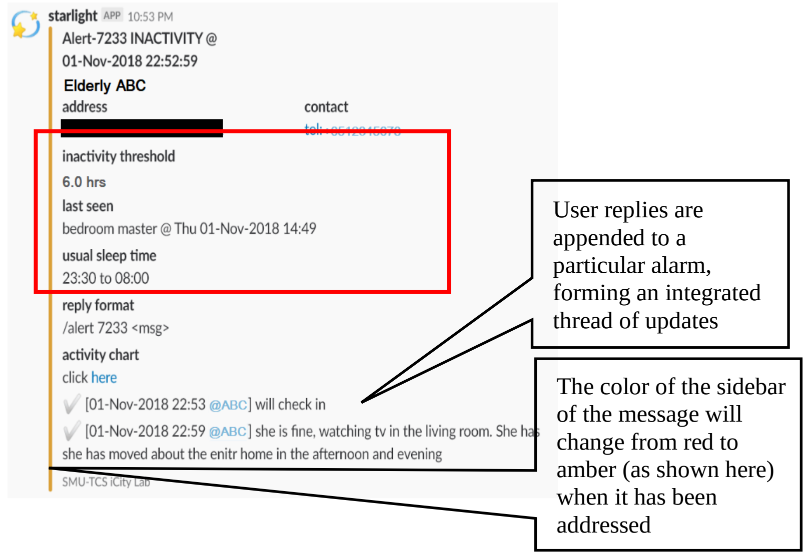

Figure 7. Illustration of the Need for Situational Information and the Beta Alert Interface

Table 3. Evaluation of the Second BIE (Beta Version Of SEMS)

Revised design principle	Consequences
DP1: Combine multiple sensor modalities to detect behavioral anomalies	• (Anticipated) CFRs' Level 1 SA improved as a result of more accurate detection of elderly individuals' activities, such as going out, and the identification of discrepancies • (Unanticipated) While the beacons compensate for behavioral anomalies exhibited by elderly individuals, they must still carry the alternative device. One CFR said: "I think the beacon has helped us understand the seniors' patterns. With that, we can also rule out many false alarms. I think the challenge is that some seniors do not bring it with them, so it makes no difference."
DP2: Support a human-based, high-order assessment of personalized alarms	• (Anticipated) CFRs' Level 2 SA improved as a result of the enhanced support for human-based integration of information for judgment. • (Unanticipated) While the DP aimed to enhance CFR's comprehension of the situation, some CFRs maintained old habits of contacting the elderly person directly to verify an alarm, which may cause irritation, especially if the alarm is false. One CFR said: "It might be during the middle of the night that an alarm goes off. So we contacted the elderly person, and they could be irritated because they were woken up from their sleep".
DP3: Integrate team-based, closed-loop responses into the alerts	• (Anticipated) CFRs' Level 2 SA improved as a result of a more organized team-based communication in response to alarms. • (Unanticipated) N/A
DP4: Support proactive monitoring	• (Anticipated) CFRs' Level 3 SA improved as a result of extended data use to identify abnormal performance in daily living activities. • (Unanticipated) CFRs showed keen interest in leveraging behavioral data for preemptive care delivery, recognizing its potential in evaluating the elderly participants' physical, mental, and social well-being. A CFR said: "They are vulnerable... more work can be done to notify us early on if an elderly person's typical routine is changing…".

The evaluation of the alpha cycle also informed our proposed change to DP3 (see Table 2, Row 3). As the team streamlined the CFRs' communication, we observed that confusion could arise when multiple alerts occurred in the integrated communication channel. This point is particularly relevant in a setting in which a team of CFRs, rather than a single CFR, is responsible for responding to an alert. Accordingly, we included those considerations in the refined DP3 by integrating team-based, closed-loop responses in the alerts. To facilitate prompt decision-making, critical information on the alert and the elderly person was appended to the alert event, allowing the entire team of responders to maintain SA throughout the response process. Figure 7 shows that the replies were appended in the beta version to facilitate tracing and updating. Furthermore, the team reconfigured the message color to change from red (see Figure 5) to orange (see Figure 7) once a response to the alert was issued, thereby making unattended alerts more easily identifiable. These design improvements also enabled CFRs to retrieve historical information about an alert quickly and to thus provide more effective support for maintaining their Level 2 SA than was possible during the alpha cycle.

A new design principle emerged in the second BIE cycle. Feedback from CFRs and VWO staff highlighted the system's potential for projecting elderly individuals' future conditions based on long-term behavioral data. Since the beginning of the project, the ADR team collected behavioral data from at least 20 elderly individuals for more than a year. Experienced CFRs recognized the data's potential for preemptive care, such as by identifying changes in going-out behavior as indicators of deteriorating mobility. While this proactive approach was beyond the initial scope of the system's ability to detect elderly individuals' inactivity, the project team acknowledged the value for predicting physical health-related emergencies, thereby supporting CFRs' Level 3 SA (projection). Therefore, we formulated the fourth DP as supporting proactive monitoring. To implement this DP, the ADR team exploited the data collected by incorporating a data visualization feature to illustrate changes in behavior. A newly recruited behavioral scientist (to the implementation team) analyzed the sensor data to establish each elderly person's daily routine and identify deviations in behavior, such as the changes in toileting frequency exhibited by an elderly male (chart provided in Transparency Material J) that could trigger an investigation of potential prostate problems. This proactive approach enabled CFRs to make informed decisions and manage elderly people's physical health more effectively.

Concurrent Evaluation

In Table 3, we provide the summative evaluation based on ongoing discussions among the ADR team, CFRs, and VWO staff as well as semistructured interviews with the CFRs and technical personnel conducted toward the end of the second cycle. Similar to the evaluation in the alpha cycle, the eight CFRs (including the four from the previous cycle) shared how the system changes might have improved their SA (or not), and elderly people's insights about CFRs' SA were shared by the VWO staff. The validation outcomes confirmed the effectiveness of our design principles while also yielding unexpected user feedback.

The evaluation of DP4 is important. CFRs expressed interest in expanding the use of the data for predictive care delivery given the potential of the data to facilitate the assessment of individuals' physical, mental, and social well-being. In response to the evaluation of DP4, the technical personnel initiated the development of a new data visualization prototype. Although the prototype was not implemented at the end of the project due to time constraints, it allowed the team to reflect on the DPs that have been thus far reactive in nature. The team hoped that by generating a predicted frailty score based on the extended periods of inactivity (the example is provided in Transparency Material K), the CFRs could identify individuals who required assistance and introduce more targeted programs, such as by encouraging their participation in center-based activities before any serious issues developed.

Formalization of Learning

This study aimed to address the design problems associated with supporting CFRs' SA in the context of remote activity monitoring. Our findings are summarized in Figure 8, which depicts the DPs and their refinements throughout the ADR project.

Design Principle 1: Our first DP is related to responders' Level 1 SA (perception). As shown in Figure 8, the refinements of DP1 are evident in the changes to the design decisions that modified the system's physical aspects and organization over time. The first step in promoting SA is to perceive the information in the environment. Our initial cycle confirmed the imperative of minimizing disruption to elderly residents. However, despite the improved accuracy of sensors in recording activity data, the system may still misperceive the behavior of subjects when it deviates from the expected norms encoded in the system (e.g., not closing the door when they go outside). The implementation of a new sensor (beacon) in the beta cycle, while helpful, could not fully circumvent the constraints of technologies in discerning the real-world intricacy of varied behaviors. Although the IoT was embedded in their living environment, user adaptation was still needed. Our ongoing assessment of the interventions showed that users must be persuaded of the need to adapt their behavior, and the trusted VWO staff whom they met regularly could remind them of the need to carry the beacon with them when they left the house. Thus, we refined the first DP to consider subject adaptation rather than merely adapting sensor technology.

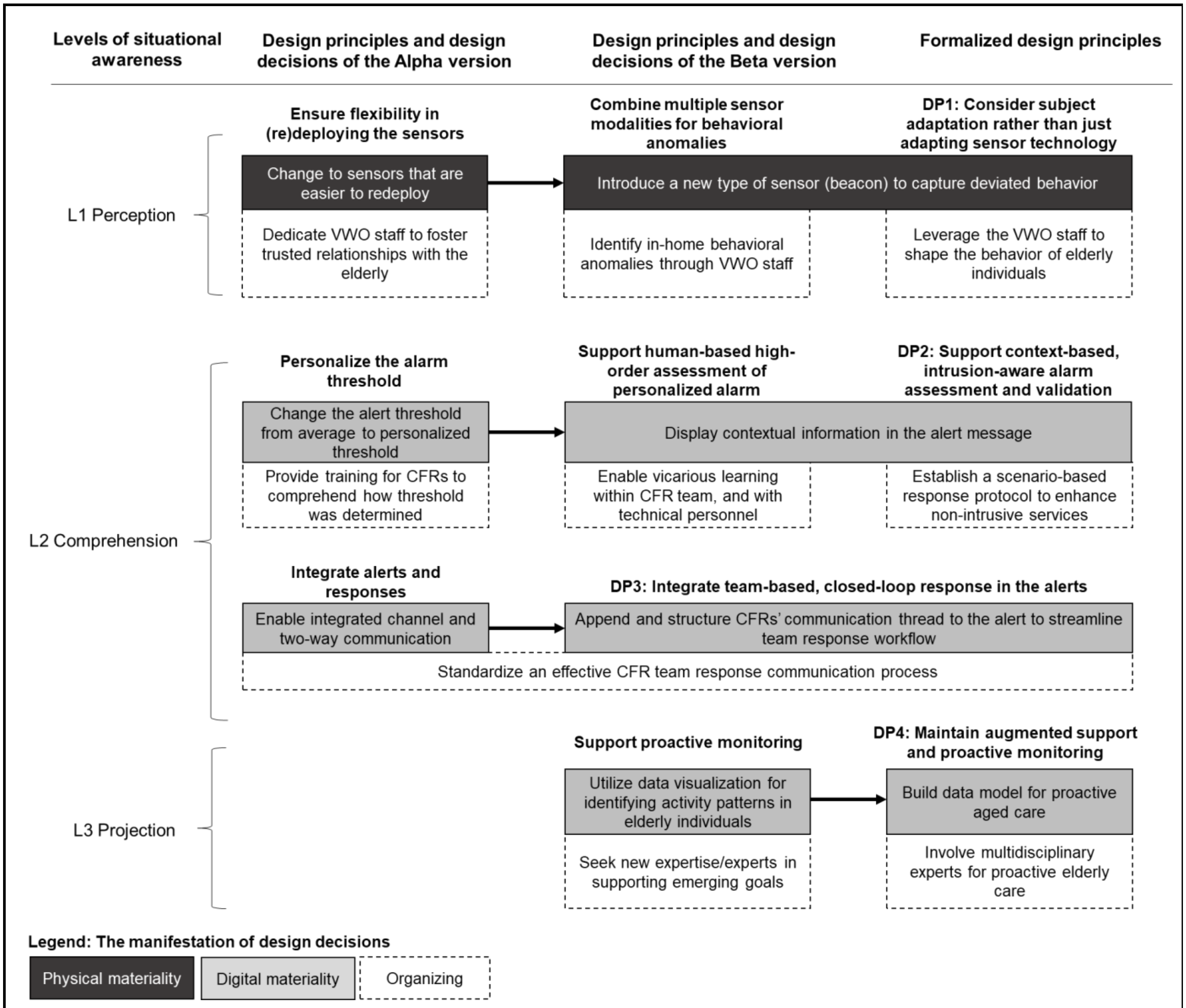

Figure 8. Summary of the Changes Made in the Design Principles and the Artifacts

The resulting DP1 extends our knowledge about improving Level 1 SA (perception) in the context of remote activity monitoring. The SA literature has identified different types of data uncertainty as well as contributing factors and solutions (Endsley & Jones, 2012). Two broad strategies are relevant: first, the acquisition of additional information, and second, the representation of uncertainties in the system to assist users in determining the level of confidence they should attribute to a piece of information. In particular, one design principle proposed by Endsley and Jones asks designers to "explicitly identify missing information." We acknowledge the significance of these proposals but argue that they primarily presume that the objects being monitored, such as the terrain, the weather, and fire, are either static or unchangeable, leaving designers to manipulate only the sensing devices or the information display. Similarly, monitoring studies in the IS field have often suggested that sensor hardware must be adapted to accommodate users' daily routines (Mettler et al., 2017) or preferences (Chatterjee et al., 2018). This suggestion again implicitly assumes that the users or the subjects being monitored are, at best, the target of interventions and are as fixed as the monitored objects commonly studied in the context of SA. These assumptions are less applicable in our case, where the human subjects being monitored could be regarded as "integral components" of the ensemble artifact. To avoid missing data, we can work "with" the subjects to ensure that they adapt their behavior to fulfill the designer's needs with regard to sensing. Our claim also resonates with McClain's (2018) ideas about the IoT that "in the absence of technologies capable of handling the real-world mess of a heterogeneous public environment, the world itself must cooperate" (p. 49). In essence, elderly individuals are not merely passive participants or end beneficiaries but rather active participants who can adapt and are supported by a network of trusted community stakeholders (McLeroy et al., 2003).

The ongoing adaptation of the ensemble artifact necessitates modifications to community-based organizing (Sein et al., 2011). To facilitate subject adaptation, the ADR team recognized the vital role of VWO staff as intermediaries, linking the ADR team with elderly individuals. While this boundary-spanning role is not uncommon in system implementation studies, the context of this study, which focuses on personal living spaces and personalized support, might involve a uniquely individual-centric approach, such as through the dedicated role of VWO staff who are trusted by the subjects and can observe them closely to understand any behavioral anomalies that deviate from the system designers' expectations. When establishing such bridging roles, the project team could leverage the subjects' preexisting social networks by identifying community members—i.e., members or staff of community organizations—who have already developed rapport with them. In summary, our case highlights that analyzing the interdependent relationship between the sensing technology and the subject is necessary to ensure the meaningfulness and representativeness of the data, and this analysis can be facilitated by a designated bridging role.

Design Principle 2: Our second DP is related to responders' Level 2 SA or comprehension. The phenomenon of alert fatigue has been documented in previous studies, according to which responders can become overwhelmed by a high volume of alerts and false alarms that they must address in addition to their regular duties (Brohman et al., 2020). This issue, as identified in the problem formulation stage, is especially concerning for CFRs who are not bound by the work responsibilities of professional responders and could withdraw from their roles at any time. To address these challenges, we made several modifications to the digital aspect of the IS artifact, first to the alert threshold and later to the information displayed in an alert, as well as the corresponding organizing aspect (see Figure 8). Based on initial user feedback and our acquaintance with the patient monitoring literature, the ADR team changed the fixed inactivity threshold to a personalized threshold to reduce false alarms. Despite the resulting improvement in the system's interpretative accuracy, CFRs indicated that when assessing alerts in practice, they must consider other types of information, including information that is shared with them informally but not captured by the system (such as whether an elderly person is away on vacation), and further scrutinize past sensor reading patterns and noisy data.

This observation and subsequent discussion with the technical personnel highlighted two findings that contributed to the final conceptualization of DP2. First, it became evident that system-generated alerts do not replace responders' cognitive processing. This point is in line with one of the principles proposed by Endsley and Jones (2012), which advocates for SA support rather than decision-making replacement. Building on alarm signals generated with raw activity signals, CFRs interpret the origin, meaning, and significance of such alarm signals by integrating other contextual information. Their interpretation determines how they respond to the alarm (Endsley & Jones, 2012). Furthermore, it is infeasible to rely on technology such as the IoT to detect all possible ambiguities and noise in human activity and real-world environments (McClain, 2018). Consequently, attempting to encode the vast array of conditions that human processing considers into the alarm criteria is unrealistic. The most effective approach that has emerged is a combination of machine and human processing. Accordingly, DP2 was revised in the beta cycle to incorporate human-based high-order thinking, and contextual information was provided in addition to the alarm to facilitate the process of human assessment.

The second finding pertains to the organizing aspect that led to our final DP2. The system modifications entailed changes in the organizing of community-based aged care services. The results of the evaluation of the beta cycle indicated that although a symbiotic relationship between the system and CFRs could be developed with DP2, some CFRs were inclined to validate the alarm by phoning the elderly person directly. Although it is faster and more accurate, validating an alert by calling the subject directly is viewed as intrusive. It could also be inappropriate and infeasible if the elderly person is asleep or does not have a phone. To minimize disruptions to elderly individuals, the community organization could implement a response protocol outlining the expected actions in various scenarios. Accordingly, we refined DP2 to support context-based, intrusion-aware alarm assessment and validation. The inclusion of the term "intrusion-aware" integrates insights from both elderly monitoring studies that have advocated for reduced disruptions to elderly individuals and the SA literature that has highlighted the importance of minimizing alarm disruptions to responders' ongoing activities.

Design Principle 3: The third DP is also related to responders' Level 2 SA. When responders act on alerts and provide updates in the system, they contribute to an updated understanding of the situation (e.g., by clarifying that the subject is away on holiday) and/or to a change in the situation (e.g., by indicating that help has arrived for the subject). This updated understanding is essential for facilitating an appropriate response and coordination among the responder team. A life-critical emergency response solution often necessitates the involvement of multiple community responders. This could include a team of CFRs, as in our case, or backup family members in scenarios where the primary responder is unavailable. When communications are fragmented, it becomes challenging for the responder team to maintain a high level of SA. To improve communications, especially in a multi-responder setting, we made several changes to the digital aspects of the artifact and the organizing. We started with the integration of disparate communication channels and incorporated CFR responses into the alert messages. This streamlined information sharing and ensured that responders remained aware of the latest developments in the situation. The evaluation from the CFRs indicated that further modifications were needed to facilitate more effective and structured information sharing, searching, and communication in response to an alert. We observed that these changes in the design and use of the communication technology also restructured or were restructured by CFRs' communication and collaboration processes over time. As a result, DP3 was revised to accommodate both multi-responder settings and the occurrence of multiple alarms. We now refer to DP3 as integrating team-based, closed-loop responses into the alerts.

DP3 represents an advancement in our understanding of emergency alerts and responses, which is informed jointly by monitoring and the SA literature. In the patient and remote monitoring literature, IS researchers focus primarily on the design of alert messages, emphasizing simplicity and conciseness to avoid overwhelming responders' cognitive resources (Mettler et al., 2017). Scholars have also emphasized the need to minimize the amount of information presented in alerts (Brohman et al., 2020; John & Smallman, 2008) and to include actionable tools in the displayed data to support decision-making (Marcilly et al., 2018). To our knowledge, no previous studies have explored the inclusion of responders' feedback in the display, a crucial aspect for maintaining SA in a multi-responder setting. Drawing on an SA principle proposed by Endsley and Jones (2012), we posit that appropriate feedback is critical to keep the responder in control and in the loop. With DP3, we extend this SA principle by suggesting that it is insufficient for responders to be involved as passive recipients of information. Instead, responders' feedback must be captured in the system to provide updates regarding the latest situation or actions taken in reaction to the alert to promote better coordination among a team of responders, a model that more accurately reflects real-world situations.

Our DP3 also extends the notion of shared SA among a team of responders by highlighting the importance of maintaining responders' shared SA. We argue that closed-loop communication is imperative and takes multiple forms. First, given that responders may possess informal knowledge that influences the interpretation of an alarm signal, their communication must be appended to the alert, leading to a closed alert-validation loop that promotes a comprehensive understanding of the situation. Second, because an emergency alarm is safety-critical, it is important not only to ensure that the alarm is addressed but also to communicate the status change (from unattended to attended) transparently to avoid further repetitive actions. This situation leads to a closed alert-response loop of communication. Third, the system must record the actions or corrections taken after the case is closed (including in the event of a false alarm) to ensure that the data can improve future interpretation and the analysis of new alarms, thus forming a data-feedback loop between the current situation and future applications.

Design Principle 4: Our final emergent DP focuses on Level 3 SA or projection, which pertains to the future state of the subject monitored. Based on the assessment of DP4 in the beta cycle, we observed a shift in user goals that extended beyond reactive care to include preemptive care delivery. We revised DP4 to maintain augmented support and proactive monitoring, which is evident in the changes in design decisions that modified the digital aspect of the IS artifact and new form of organizing. The renewed principle expands the data analysis from a focus on identifying past data patterns associated with issues that had already occurred to an analysis based on the use of data models to predict events or emergencies that have not yet occurred. Furthermore, the principle highlights the potential of granular and real-time data to offer valuable insights into individuals on a continuing basis. When analyzed alongside other contextual factors and healthcare records, more algorithms and models can be developed to facilitate the early detection of health conditions at the personal and aggregated population levels.

To support the change to the solution, the technical personnel emphasized the need for multidisciplinary expertise considering the CFRs' lack of technical knowledge. Expert knowledge is recognized as an essential factor in the development of robust data models that enhance proactive monitoring capabilities. DP4 extrapolates the value of data collected through in-home activity monitoring to proactive monitoring, thus facilitating the anticipation and resolution of issues before they escalate to major incidents. IoT solutions enable continuous data collection and processing, facilitating the identification of the movement and behavioral patterns of individual subjects that offer insights into the individual's well-being. This utilization of previously untapped data demonstrates that health analytics can extend beyond the level of physical health to encompass mental and social well-being (Son et al., 2020). Moreover, the high level of granularity in the collected data not only facilitates precision monitoring but also contributes at a broader level to personalized healthcare, a prominent area of focus for healthcare IS (Finchman et al., 2011). We contend that effective data-driven preventive aged care requires united efforts from stakeholders who are knowledgeable about the needs of the participants, recognize the potential applications of data, and are skilled in the technical, psychological, and medical domains. This collaborative endeavor is vital for maximizing the benefits of proactive care and enhancing the overall well-being of monitored individuals.

Furthermore, our findings show that the Level 3 SA in our study might be different from this notion in existing theory. While Endsley and Jones (2012, p. 18) argued (as depicted in the framework shown in Figure 2) that "a person can achieve Level 3 SA only by having a good understanding of the situation (Level 2 SA)," our findings show how a responder can detect possible emergencies through data visualization (Level 3 SA) without fully comprehending how the alarm is generated or interpreted (Level 2 SA). On the one hand, we must acknowledge that the derived design principles were partly due to the distinctive objectives of Level 2 and Level 3 SA in our project. The former aimed to identify physical emergencies, whereas the latter focused on recognizing concerns related to mental or social well-being. On the other hand, we also recognize the potential of intimate personal data and data analytics in enhancing our awareness of future situations. This aspect challenges the conventional boundary of the "near future" in the definition of projection (Endsley & Jones, 2012). Our study demonstrates that modern technology can enhance the ability to detect potential mental and social well-being concerns, thereby advancing our understanding of proactive monitoring beyond the scope of conventional SA frameworks.

Discussion

Our study unveils four design principles that correspond to the three levels of SA. Next, we discuss how the problem class can be addressed through the design of a community-based smart activity monitoring system—that is, the solution class—in three respects: (1) the use of SA theory to structure the challenges faced by CFRs in remote activity monitoring, (2) the active roles played by multiple community stakeholders in support of the design principles, and relatedly, and (3) the account of our design principles with regard to the ensemble view of artifacts that capture localized community organizing.

Situational awareness: SA is an important precursor to decision-making. This study examines the application of SA theory to the challenges faced in situ by CFRs, who are the key decision makers in the context of IoT-enabled remote monitoring. As summarized in Figure 8, the three levels of situational awareness provide a structure for understanding uncertainties related to data, comprehension, and projection in this particular context.

Our findings extend the existing knowledge of the SA model and shed light on the nuances of SA-oriented design. Unlike most previous SA studies, our unique context involves monitoring humans. Therefore, to address issues related to Level 1 SA, we challenge the implicit assumption in the literature that has viewed the objects being monitored—often the terrain, the weather, and fire—as nonmalleable. This study demonstrates that data uncertainty can be alleviated by leveraging malleable human behavior and ensuring that the "monitored" objects adhere more closely to the requirements of the sensors (e.g., by attaching a beacon to a keychain and carrying it when one exits the house). Moreover, DP2 and DP3 also enhance the understanding of how Level 2 SA can be supported more effectively. When responders' comprehension is affected by ambiguous interpretations, it is essential to reserve high-level cognitive tasks for human responders, enabling them to handle those ambiguities more effectively. This approach suggests a delicate balance between improving the accuracy of the algorithm for alert detection and preserving human involvement. On the one hand, as we improve the algorithm for alert detection, these principles incorporate insights drawn from previous work on alert responses, indicating that designers should avoid overwhelming CFRs. On the other hand, it is crucial not to diminish CFRs' active participation, as they play a vital role in accounting for intricate contextual variables and unforeseen situations that are challenging to encode into an algorithm. As technologies increasingly facilitate more efficient and continuous monitoring, the system's accuracy and reliability should be prioritized. Our findings highlight the significance of human involvement in achieving this objective.

Simultaneously, our analysis of how Level 2 SA can be shaped suggests that the feedback loop included in the SA model may be endogenous. The current SA model (Figure 2) presents a feedback loop according to which the performance of action, driven by SA, affects the state of the environment. We identify the presence of an additional endogenous feedback loop: as CFRs respond with the intention of improving their overall comprehension of a situation, they could also perform an action, thus affecting the state of the environment. These dynamics can result in changes to the situation, necessitating careful consideration by designers seeking to facilitate real-time communication among multiple responders as well as multiple alarms (Endsley & Jones, 2012). Finally, through our DP4, we demonstrate that Level 3 SA may not always rely solely on Level 2 SA. By harnessing the predictive capabilities of data analytics, designers can go beyond the level of projecting the near future and predict emergencies that might arise in the longer term. This capability offers insights to support proactive monitoring and the comprehensive maintenance of well-being.

Community-based smart activity monitoring system: Through close collaboration with practitioners, this study highlights the multiplicity of community stakeholders who are involved in the implementation of such in-home activity monitoring systems as well as the active role that each stakeholder plays in implementing the new aging-in-place care model. In addition to the ADR team, three key user groups are notable: CFRs, elderly participants, and community organizations. While the literature has predominantly focused on the use of such systems by professional responders and treated elderly individuals as passive consumers of services, our study focuses primarily on CFRs. We firmly believe that these responders play a crucial role in the implementation of initiatives that rely on community resources. Contrary to prior studies, which have emphasized elderly individuals' adoption of monitoring technologies and their privacy concerns, we build on the insight that safety takes precedence over privacy for elderly individuals (Mettler et al., 2017; White & Montgomery, 2014). This perspective enables us to explore how elderly individuals can actively contribute to the solution. As demonstrated in DP1, adapting their behaviors and habits can significantly improve data uncertainty. By shifting scholarly attention from elderly individuals' passive adoption to their active involvement, this study highlights the potential of empowered CFRs and elderly individuals to collaboratively enhance the effectiveness of activity monitoring systems.

Furthermore, the adoption of an ensemble view also highlights the significance of another important role and community stakeholder. As discussed in DP1, VWO staff are identified as a designated bridge between elderly individuals and the project team. In addition, the organizing arrangement impels us to recognize the critical role of the community organization (i.e., the voluntary welfare organization in our case). Community organizations have the capacity to maintain a network of CFRs, who are difficult to recruit and retain. These organizations contribute to sustaining community initiatives by providing an organizing structure to support CFRs based on response protocols (DP2) and a team-oriented communication approach (DP3). By adopting an aggregated view of the community, they can identify and validate the future needs of these systems to ensure that decisions are not dictated solely by the system providers, who tend to be driven by economic benefits. Recognizing the multiplicity of community stakeholders as change agents, we characterize our solution class of smart activity monitoring as community based. Unlike other understandings of community-based interventions that have viewed the community as a mere setting (location) or target, our design principles highlight the adaptive and developmental capacities of the community in actualizing and sustaining aging in place for and by the community (McLeroy et al., 2003).

Ensemble view of artifacts: The design principles resulting from our study provide prescriptive knowledge of both the material properties and the organizing of monitoring systems. With regard to the material properties, we extend the focus of the extant literature on the physical aspect of ensemble artifacts such as sensing devices and the digital aspect of artifacts such as alert thresholds, alert displays, communication and channels, and data modeling. In addition, we explicitly consider the incorporation of organizing to capture the community's localized arrangement and practices (Leonardi, 2012). We emphasize the importance of viewing this IoT/sensor-enabled monitoring system as an ensemble because it involves monitoring individual activities. Therefore, users and their situational factors should be central to the design process. In fact, the questionable success (Reeder et al., 2013) and delays of many past projects (Yefimova, 2016) may indicate a lack of understanding about the interdependencies between these systems and people who are "mutually dependent" (Orlikowski, 2007, p. 1437). In other words, designers must account for a contextual understanding of their use in situ, which may deviate from the designer's expectations and go beyond what users could articulate in advance. As McClain (2018) suggested regarding the study of a monitoring system: "What appears technologically feasible at the planning stage can apparently be undermined by the most ordinary reasons in a specific context or practice" (p. 47).

We argue that the ensemble view allows us to capture users' experience during the utilization and feedback processes that take place between the system and users. We can understand the design in use or how the design will be used, interacted with, and experienced by users in real-world situations. Echoing the viewpoint of Sarker et al. (2019), our ADR study shows "social considerations as being inscribed within technological artifact" (p. 703) by accounting for CFRs' communication practices and elderly people's lifestyle within the design artifact. As shown in Figure 8, the four design principles encapsulate three aspects of ensemble artifacts. The four DPs address either physical materiality (such as the fact that sensing devices are a unique aspect of the IoT) or digital materiality (in line with the properties of alert response systems). Furthermore, they also provide prescriptive insights into the corresponding organizing, such as the design of the response protocol, the responder team and communications, and the capacity and expertise of the project team. It is also noteworthy that relevant community care arrangements and practices are integral to the realization of each design principle. For instance, DP1, which focuses on the issue of data unreliability, goes beyond merely adapting the sensor devices; it requires collaboration with the subjects to adapt their habits through a trusted relationship with community aged care volunteers. This situation demonstrates that the social and technical subsystems mutually shape one another and are "jointly optimized (Emery, 1959) such that the demand of one system fits the demand of the other" (Leonardi, 2012, p. 41).

Contributions

Our work makes three contributions. First, our ADR study contributes design knowledge that can be used to solve a class of problems pertaining to the need to promote CFRs' SA in the context of remote activity monitoring. The four resulting design principles of nascent design theory (Gregor and Hevner's [2013] Level 2 contribution) constitute the primary contribution of this research, and this proposed solution can be generalized to other problems. For instance, these design principles are relevant to other personal safety and emergency monitoring systems and can benefit various individuals with mobility difficulties or medical conditions. These principles also offer guidance for incident response and safety compliance in workplace environments, such as for park rangers, all-night service station workers, and smart factory workers. Our findings can enhance the responses of human supervisors or other informal responders, such as family members or friends. Design knowledge can also support neighborhood watch initiatives through digitally enhanced intrusion monitoring systems. Home security alarms already distinguish between various activities to avoid false alarms. Our DPs extend the alert response network to the community level, thus enhancing neighborhood watch practices through technological development, which is especially valuable for crime detection in rural areas with limited police presence (Aransiola & Ceccato, 2020).

Our second contribution lies in the fact that we advance the healthcare literature in an IS context by moving away from an isolated view that focuses on specific stakeholders to a more integrated approach. Our review and observations indicate that (1) previous IS studies on elderly care have mostly focused on elderly individuals' technology adoption, (2) previous IS studies on patient and healthcare monitoring have primarily attended to the needs of professional healthcare staff, and (3) the actual progress of elderly care monitoring systems seems to be driven mainly by technological solution providers. However, IS scholars have long argued for the alignment of user needs and orientation in the context of IS design and implementation (Jiang & Cameron, 2020). Hence, when proposing actionable design knowledge, our research adopts an integrated and balanced approach based on varying perspectives and needs to generate two specific insights. First, at the intersection of remote monitoring, aged care, and, more generally, healthcare, we construct users who match real-life users. By emphasizing the real users of remote monitoring systems, i.e., the CFRs in this problematization, our study reflects the actual needs and challenges of these responders, who could be family members or informal or volunteer caregivers, rather than reiterating the needs of physicians or health insurance providers (Mettler et al., 2017). Second, and more importantly, our work highlights the necessity of the systematic and holistic involvement of different community members to unlock the full potential of community-based care delivery. The conceptualization of our proposed solution class—the community-based smart monitoring system—captures the diversity of community members and their active roles in implementing this relatively new model of care delivery. This collaborative approach, which includes elderly people's informal social networks, neighborhoods, and voluntary agencies, addresses important social problems without the need for direct professional intervention (McLeroy et al., 2003). More profoundly, this appreciation of community ecology and capacity can precipitate a shift of focus toward community building when leveraging technology to meet people's needs.

Our third contribution relates to how we divide an IS artifact into its material and organizing aspects to provide a structured approach to operationalizing the ensemble artifact and closely adhering to the sociotechnical perspective on IS when formulating design principles. Although Sein et al. (2011) identified the artifact in ADR as an ensemble version that incorporates managerial policies and practices and claimed that the central concept of the IS discipline and other design science studies focus on sociotechnical systems (Niederman & March, 2012), few studies have explicitly integrated this view into their design knowledge (Jones & Gregor, 2007). Two notable exceptions include an ADR study conducted by Dremel et al. (2019), who applied sociotechnical systems theory in their design artifact, and Chandra et al. (2015), who proposed action- and materiality-oriented design principles that stipulated that "the system should allow users to do this or that by providing this or that feature" (Chandra et al., 2015 p.4042). Our study provides an alternative approach to the operationalization of the sociotechnical dimensions of IS artifacts by considering the ensemble artifact in terms of its physical materiality, digital materiality, and organizing. This approach allows us to capture design decisions and generate design knowledge that explicitly and deeply engages with both the technological system and diverse human, organizational, and social contexts (Sein et al., 2011). We argue that this approach is particularly relevant to our understanding of the design and use of the IoT and smart systems, which often prioritize technical aspects. Our study highlights the criticality of the ensemble view when designing and making sense of smart activity monitoring because it is intricately woven into individuals' daily lives. The success of smart applications depends not only on their technical superiority and seamless integration into the living environment but also on human adaptation and use.

Our study also makes practical contributions. First, it offers operational design principles, also known as the Level 2 contribution type of design science research, besides a situated implementation of artifact, which is a contribution type at Level 1 according to Gregor and Hevner (2013). The ADR team successfully overcame the challenge of supporting the CFRs while preventing them from becoming overwhelmed by the automated identification of emergencies. Moreover, our study features an empirical investigation of the challenges encountered in the application of smart technologies to the process of digitally assisted aging in place. It presents solutions and strategies for overcoming these challenges through the continual adaptation of systems. Notably, personal monitoring systems that facilitate preemptive medical care are increasingly becoming a key focus in healthcare. Through engaged research, we contribute directly to the development of an IT artifact that enables other solution providers to expedite the time to market for similar digital solutions, ultimately making assistive technologies for elderly individuals more affordable in the long term. In addition to hardware-software instantiation, our ensemble artifact design perspective accounts for organizational practices and the specific context of this project. This perspective elucidates the experiential learning required by CFRs (Brohman et al., 2020; Khalemsky & Schwartz, 2017) when adopting new systems and practices, in contrast to professional responders, who are assumed to possess a mental model and schemata and to know how the overall response mechanisms function. Finally, the implications of our findings extend to policymakers and sponsors at the national level, such as the committee for the Active and Assisted Living (AAL) Program (European Commission, 2017). Our study's evidence-based insights can inform policymakers. We encourage replication and validation in local settings to strengthen the foundation we provide for effective decision-making.

Limitations and Conclusion

This study is not without its limitations. The first limitation pertains to the singular context of the analysis. The sensor-based system was implemented to monitor single individuals in indoor spaces, and the findings might not apply directly to scenarios involving multiple individuals or public spaces located outdoors. Further investigation is necessary when extending the use of the design principles beyond the original context. For example, our final DP1 may not be adequate to ensure device performance under harsh weather conditions or to maintain data accuracy in light of the myriad of external factors and noise outside a contained space such as a home. Furthermore, while the monitoring system may effectively detect prolonged inactivity, it may fail to promptly detect sudden and acute health conditions such as a stroke or heart attack (unless the elderly person presses the panic button).

The second limitation is related to the measurement of SA, particularly with regard to objective measures of SA (Endsley, 2021). The objective measurement of SA focuses on how SA associated with operators' knowledge of the current situation can be assessed based on real-time probes as they perform their tasks. This measurement provides a more direct measurement of the degree of SA. However, considering the time criticality of responders' decision-making, a direct, objective measure of SA during the scenario would be challenging to implement in our study. Consequently, we chose to employ a subjective measurement of SA, which relied on the responders' self-assessment of their SA and confidence level (Endsley, 2021). This approach was more feasible and relevant to our research study.

The limitations of this study indicate directions for future research on the use of sensors to deliver aging-in-place care and the tentative nature of design principles. To enhance the generalizability of the outcomes, subsequent research could include an applicability check to allow practitioners to provide feedback regarding the suitability of the design principles in their local contexts (Rosemann & Vessey, 2008). In the future, researchers could consider a longitudinal study to explore how the relationships between elderly persons and responders may evolve over time due to the implementation of monitoring systems. Unintended impacts may emerge, and responders, particularly those who are not directly involved in system implementation, may potentially lose track of how the monitoring system generates alarms. At the same time, elderly individuals may develop concerns about the possibility of the technology eventually replacing caregiver visits and affecting the elderly person's relationship with the caregiver. Another issue that warrants further investigation is the consideration of ethical issues such as those related to data privacy in community-based care delivery models. Given the multiplicity of stakeholders who are involved in such a model and the movements of CFRs, ethical issues must be addressed to ensure the responsible and respectful handling of sensitive information, such as the movement data and patterns of elderly individuals.

Despite its limitations, we believe that our study is of interest to both practitioners and researchers. As people continue to live longer, our work lays the foundation for future researchers to design digitally assisted elderly care systems. Moreover, practitioners seeking to extend the functionality of such systems to include other aspects of elderly individuals' well-being, such as the monitoring of physiological and social parameters, may find our study useful. The design principles have broader applicability, including contexts such as personal emergencies, health tracking, and crime prevention. Our empirical findings can inspire smart home and smart factory design to take advantage of the IoT and sensors (Lee et al., 2020). Furthermore, by emphasizing the integrative efforts of community stakeholders, we improve our understanding of how costly institution-centered care systems can be supported by a community-based model based on a multistakeholder ecosystem (Liu et al., 2016). This approach is in line with the recognition of communities' capacity to address their problems instead of relying on external interventions (Leong et al., 2015), thereby promoting sustainable healthcare and overall social care development (McLeroy et al., 2003). Finally, our analysis offers a practical approach to the task of operationalizing the ensemble view of IS artifacts when formulating design principles. We hope that this analysis can provide a basis for a deeper but nevertheless manageable investigation of the complex interactions between systems and users through the use of the ADR approach by IS scholars and, at a broader level, bring behavioral science and design science researchers somewhat closer together.

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About the Authors

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Hwee-Pink Tan was the chief data officer and director of Research Collaboration and Analytics at Singapore's Health Promotion Board (HPB) between 2021 and 2023. He led a newly set-up office to advance the data-driven and citizen-centric approach to health promotion through best practices to maximize data quality while promoting the safe usage of data. Since April 2024, he has taken a consultancy role in Data Partnerships and Change Management for HPB. Between 2015 and 2020, as associate professor of information systems (practice) at Singapore Management University (SMU) as well as academic director of the SMU-TCS iCity lab, he led a team of technology and social science researchers to bring together internet of things technologies and social-behavioral research to enable and sustain aging in place, in close partnership with industry, government agencies, regional health systems, and social service agencies. Between 2008 and 2015, as the SERC program manager for the A*STAR Sense and Sense-abilities Program at the Institute for Infocomm Research, he led a team of research scientists and engineers to design, pilot, and evaluate architectures to support large-scale and heterogeneous sensor systems to enable Smart City applications. He graduated from the Technion, Israel Institute of Technology, Israel in 2004 with a Ph.D.

Appendix A

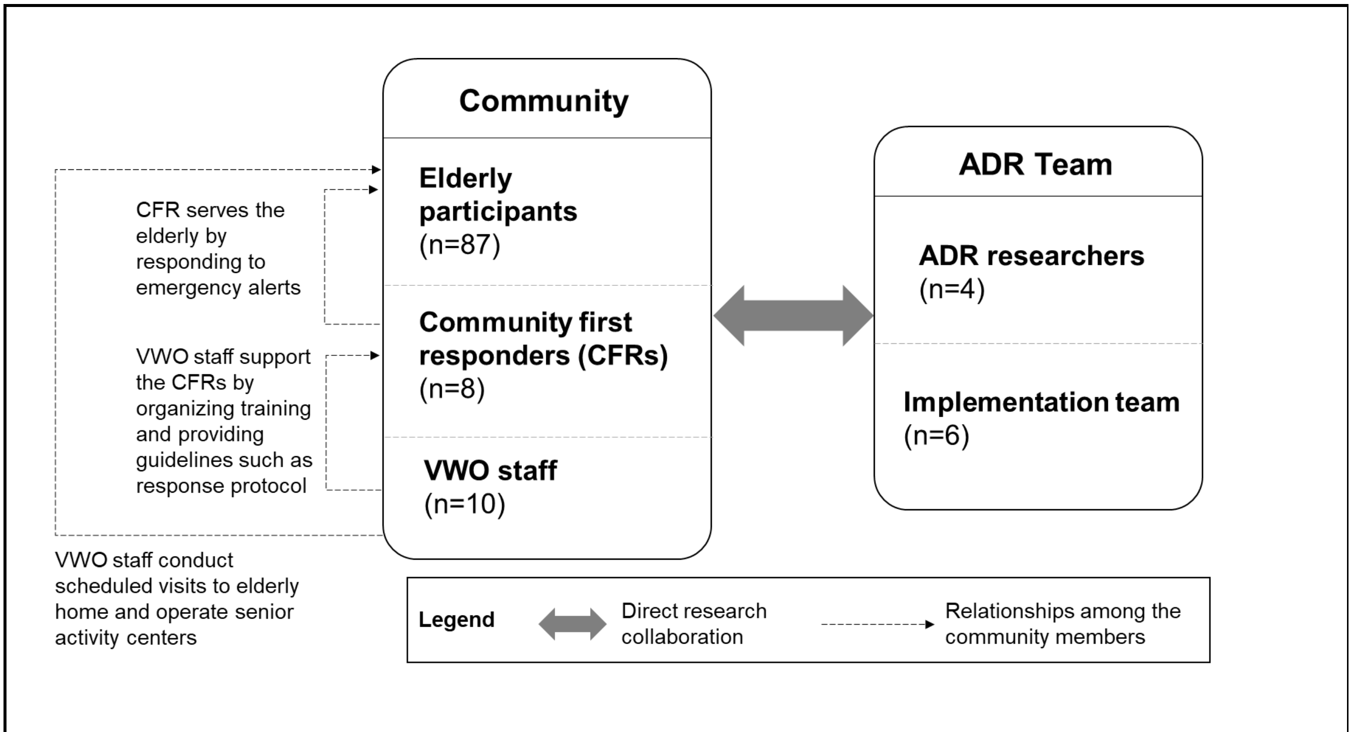


Figure A1. Key Stakeholders

Appendix B

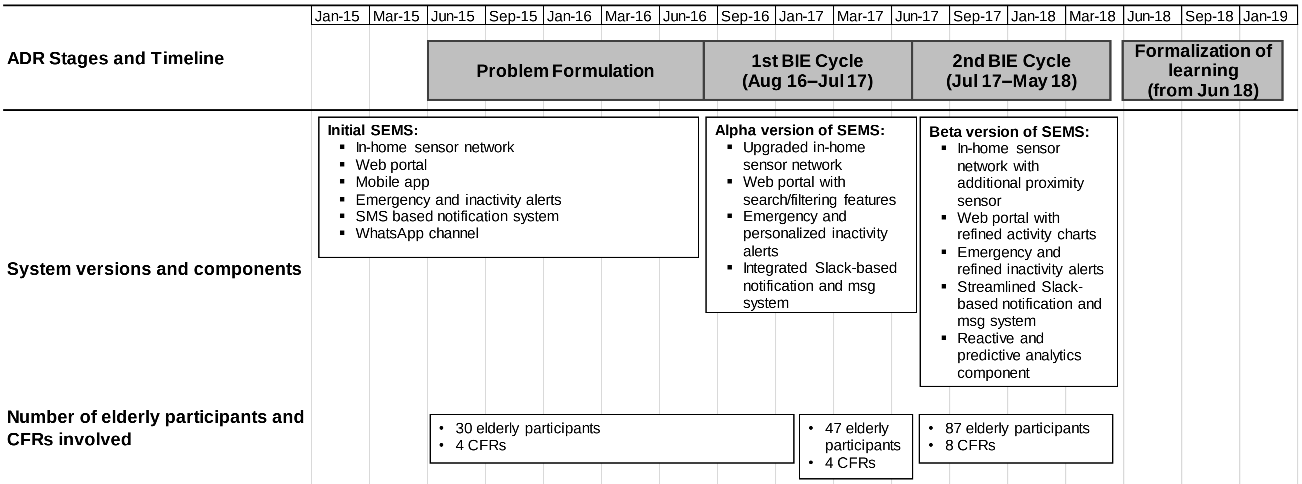
Table B1. Data Collection

Method and period	Description	Role of data in our ADR process
General survey* (Early 2015)	The survey collected information on the needs and expectations of the 30 elderly individuals who had participated since the initial stage of the project as well as their living habits.	The data provided insights into the priorities and contextual conditions of elderly individuals. The survey informed us of the various needs in aged care services, including medication management, fall monitoring, medication reminders, assessing fall risk, assistance in activities of daily living, food and water intake, and movement monitoring. Notably, approximately 54% of the requests were related to monitoring movement and detecting falls. The survey also collected information on the individuals' living situations, such as whether they were alone at home during the day. CFRs' SA is directly affected by the needs and conditions of elderly individuals. These data would help the ADR team understand how systems should be designed to support CFRs' SA.
Focus group* (Mid 2015)	A focus group discussion involving four CFRs was conducted during the problem formulation stage in 2015 to gather their feedback on the initial SEMS.	The discussion focused on (1) current practices in the delivery of care to elderly individuals, including home visits and frequency; (2) system usage, issues, and challenges while using the system, and suggestions for potential improvements; and (3) intended and unintended consequences of the initial SEMS use. The data were useful for capturing system and usage issues as well as identifying the CFRs' needs and challenges in the initial SEMS use. These data played a crucial role in problem formulation for this ADR project and informed the design of our initial interventions at the alpha cycle.
Bimonthly observations* (Twice a month from Sep 2015 to May 2018)	Two VWO staff conducted bimonthly visits to each elderly individual. During these visits, some of which coincided with the system installation, VWO staff would observe the elderly individuals' behavior in their natural home environment. Through observations and interactions with them, information was collected regarding the elderly individuals' opinions of the system, how well they were supported by the CFRs, and their living habits in relation to the monitoring system.	The observation notes were recorded in a web-based system and shared with the ADR team. In total, 946 observation notes were recorded. Below, we describe how the data served as input for understanding how well elderly individuals are supported by CFRs with enhanced SA. First, the observations of their living habits could uncover latent issues that might not be immediately observable but that could become noticeable through continuous observation, thus informing the design of interventions. For instance, individuals might take a nap in their living room instead of the bedroom, which would require fine-tuning the sensor data to accurately capture the inactivity alert. These visits and interactions with individuals also helped the team to understand temporary changes to living conditions, such as a hospitalization or short-term visit by a relative, which must be considered by CFRs when interpreting an alert. Second, the VWO staff played a role in assisting the ADR team in following up on the frequent false alarms that occurred for specific individuals. They did this by observing individuals' daily living habits and system use. An example is that an elderly person may leave the door open while visiting a neighbor, which could trigger a false alarm.

		Third, the observations of the system used in a natural setting could help the ADR team identify potential operational issues, such as the need for ad hoc system maintenance. For instance, an elderly individual may turn off the gateway because of concerns about electricity costs. The VWO staff can support the ADR team by communicating with the elderly individuals about how the system works. Finally, interactions with elderly individuals can identify the consequences of system use or implementation on their needs or concerns, thereby informing the design of interventions. For instance, some elderly individuals mentioned the false alarms, while others have recalled the timely assistance they received due to the use of the system. Collectively, these data helped the ADR team understand the level of support elderly individuals received from CFRs with enhanced SA. CFRs' SA is directly affected by the needs, conditions, and reactions of elderly individuals, and these factors may evolve over time. Ongoing observation data on elderly individuals will provide a contextual understanding of emergency scenarios and their behavior to identify issues that could contribute to incorrect alerts and subsequently impact CFRs' SA.
Quarterly team meetings of VWO staff and CFRs, ADR team (quarterly from Q1 2015 to Q3 2018)	This meeting facilitated direct interaction among the key stakeholders. CFRs provided their feedback and evaluation to the ADR team, and the VWO staff shared feedback received from the elderly participants. The ADR team updated CFRs and VWO staff on system improvements and project status.	Through regular interactions and recorded meeting minutes, we captured feedback from the CFRs regarding the system's effectiveness in supporting their assessment of elderly people's situation or their SA. CFRs raised issues they encountered, including how the system supported and challenged their SA as well as new requirements or unexpected consequences. VWO staff shared elderly individuals' assessments of the system's effectiveness in providing support, which they collected via bimonthly observations. These assessments also served as an evaluation of the accuracy and reliability of CFRs' SA. This active, direct, and continuous engagement with the ADR team played a crucial role in designing the interventions.
Fortnightly ADR team meetings (fortnightly from Jan 2016 to Jun 2018)	These meetings focused on evaluating the system's performance, designing the interventions, and reflection.	During these meetings, the follow-up action items that were initially outlined in the quarterly meetings were discussed and prioritized. The team reflected on what did and did not work when formulating the interventions for the subsequent cycle. This reflection also contributed to the learning process of the ADR team.
Semistructured interviews* Sept. 2015, March and Sept. 2016, March and Oct. 2017, May 2018 (elderly participants), Apr/May 2018 (CFRs), Apr 2018 (technical personnel)	Semistructured interviews of approximately 30-60 mins with six elderly participants, two CFRs, and two technical members were conducted to gain insights into their experiences with the system, including the intended and unintended consequences of the system use.	The recorded and transcribed interviews with the elderly individuals provided the ADR team with a comprehensive understanding of system usage, situational conditions, and implementation challenges at various stages of the project. This information informed the team in formulating or revising design principles for the project. The data collected from the CFRs elucidated the improvement of their SA over time and how it was supported by the system toward the end of the project. In these interviews, CFRs also shared their thoughts on new requirements or unforeseen consequences.

Note: *The transparency material contains CFR demographics (Transparency Material C), protocols of the general survey (Transparency Material D), focus groups (Transparency Material E) and interviews (Transparency Material F), and a sample of the observation data (Transparency Material G).

Appendix C



Data collection methods

	Jan-15	Mar-15	Jun-15	Sep-15	Jan-16	Mar-16	Jun-16	Sep-16	Jan-17	Mar-17	Jun-17	Sep-17	Jan-18	Mar-18	Jun-18	Sep-18	Jan-19
General survey with the elderly participants		x															
Focus group with the CFRs			x														
Observations				Bimonthly from Sep 2015 to May 2018													
Quarterly team meetings of VWO staff and CFRs, ADR team	x	x	x	x	x	x	x	x*	x	x	x	x*	x	x	x	x*	
Fortnightly ADR team meetings					Fortnightly from Jan 2016 to Jun 2018												
Semi-structured Interviews																	
- Six semi-structured interviews and a short survey with the elderly participants				x		x		x		x		x		x			
- Two semi-structured interviews with the CFRs														x			
- Two semi-structured interviews with the technical personnel of ADR implementation team														x			

x* indicates the quarterly meetings targeted at gathering user feedback of the new features

Figure C1. Timeline of the SHINESeniors Project: System Rollout and Data Collection