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Preserve Autonomy - Developing and Implementing a Design Theory for Augmented Living Spaces

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Preserve Autonomy – Developing and Implementing a Design Theory for Augmented Living Spaces

Completed Research Paper

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Abstract

The everyday life of elderly and cognitively impaired people can be significantly supported through information technology solutions, with spatial augmented reality being a promising one of them. With our solution approach, we are developing an Augmented Living Space (ALiS), whereby content is projected and communicated within the living space. Thus, individual, needs-oriented functionalities can be provided ergonomically and, yet immersively. The aim is to enable affected people to live autonomously for longer without having to rely on portable technology and, hence, provide user-centered support in the areas of perception, mobility, organization, and medicine. In this paper, we formulate and implement a design theory as well as showing a derived IS architecture. It is grounded on a three-step structured literature review, moderated focus group, and observation study. The evaluation hereby validates our theoretical design and architecture implementation to develop a general-accessible, context-aware, and user-centered augmented living space.

Keywords: Spatial Augmented Reality, Design Theory, Augmented Living Space, IS Healthcare

Introduction

In general, cognitive impairment is perceived as a loss of mental capacity, and consequently as disturbances in perception, recognition, memory, thinking, and judgment (von Arnim et al., 2019). Cognitive impairment is hereby not synonymous with dementia and its severe/dysfunctional consequences, but it often poses a high risk for dementia development (Gauthier et al., 2006). Von Arnim et al. (2019) and Gauthier et al. (2006) state that people with mild cognitive impairments who have not yet been diagnosed with dementia can continue to manage their daily lives autonomously, but they must accept losses in cognitive performance that can affect processes in everyday life (cooking, dressing, etc.). Nowadays, information technology solutions offer a wide range of possibilities to support the lives of elderly and cognitively impaired people. One approach currently under discussion is specifically the use of augmented reality (AR) to help cognitively impaired people cope with everyday life and related tasks. In practice, this primarily involves the use of head-mounted displays (HMD), which merge the boundaries of the real and virtual world (Azuma et al., 2001). In a first research cycle that followed a design science research (DSR) approach (Böhmer et al., 2021), we found that besides the usually low battery capacity, the complex menus, or the reduced field of view, HMDs cannot be worn without exception. An alternative approach to AR-based support can be provided by spatial augmented reality (SAR) which uses visual projections and auditory communication (Raskar et al., 1998) and thus, makes wearables obsolete. The application of SAR allows to reduce the cognitive load of the user's environment and at the same time increases their everyday suitability (Baumeister et al., 2017). However, solutions for the application of SAR in healthcare are scarce, as its application in practice is primarily focused on industrial production and maintenance (Rupprecht et al., 2020; Cardoso et al., 2020; Tavares et al. 2019). Isolated applications of SAR in the context of cognitive impairment deal with projection robots that visualize reminders (Yang et al., 2018) or project notifications in smart-home environments (Wegerich et al., 2010). However, these approaches cannot fully address the healthcare and preservation of autonomy regarding elderly and cognitively impaired individuals due to their inability to dynamically address complex processes. One approach to make this possible is the connection of SAR with context-dependent sensors and workflow management systems (WFMS) in the everyday living environment of the users. Current state-of-the-art sensor technology, including wearable sensors, enables a robust basis for real-time data transmission that is predestined for WFMS and its application in health care (Baig et al., 2019; Mshali et al., 2018). To our best knowledge, an information system (IS) exhibiting the aforementioned characteristics is lacking so far. An important first step to conceptualize an IS is the identification of design requirements (DRs) and the definition of corresponding design principles (DPs) to address those. Together, the DRs and DPs constitute a design theory (DT) for a type of IS, which systematically supports IS designers and developers when designing IS architectures (Baskerville and Pries-Heje, 2010). As yet, there are no DTs or IS architectures for a context-aware IS incorporating SAR, diverse sensors, and WFMS in support of cognitively impaired individuals in their living spaces. Consequently, we define our research questions (RQ) as follows:

RQ 1: *What are the design requirements and design principles of a universally accessible augmented living space based on spatial augmented reality to holistically support the elderly and people with mild cognitive impairments?*

RQ 2: *What are the components of a technical IS architecture for augmented living spaces with regards to a prototype reference scenario implementation?*

We address these questions by applying a DSR approach to develop a DT for ISes utilizing SAR, diverse sensors, and WFMS in support of cognitively impaired persons, which we term *augmented living spaces* (ALiS). Our contribution therefore simultaneously extends the research field of SAR, DSR, ambient assisted living (AAL), and IT healthcare by defining user-specific as well as technical DRs for an ALiS. In addition, DPs are identified as general solution approaches for the underlying DRs. Ensuring tangibility and feasibility, we also develop design features (DF) for a concrete implementation of our ALiS prototype and derive a technical system architecture for our implemented prototype scenario. The applied research paradigm of DSR and its methodological foundation for designing an ALiS are presented in detail in the next section. Subsequently, the research issue is derived from a three-step structured literature review (Cooper, 1988; Vom Brocke, 2009) as well as a moderated focus group (MFG) (Morgan, 1997) and observation study, elucidating the findings and adaptions from the first DSR cycle. Building upon the problem awareness, related work is discussed and put into context. Furthermore, the subsequent section relates those findings to the intermediate evaluation and literature, describing the adaption of the initial DT and its novel features. Based on the DT, a novel IS architecture is derived and a prototype implementation is proposed, describing technical components and functionalities. Consequently, the revised DT is evaluated by researchers and experts according to the items of *Perceived Usefulness* (Davis 1989), whereas the prototype implementation is assessed by our target group and experts in think-aloud sessions. Finally, the findings of this paper and the potential for future research are discussed.

Research Method

To ensure scientific rigor and to implement the structural approach for an ALiS, the well-known DSR methodology of Vaishnavi and Kuechler (2015) was applied, which includes the following five steps:

awareness of problem, suggestion, development, evaluation, and conclusion. We chose the methodological framework of Vaishnavi and Kuechler (2015) over other approaches (e.g. Peffers et al., 2007; Hevner et al., 2004) since it has an explicit focus on the development of theoretically sound DRs and DPs to guide the development of an IS architecture. Hereby, the DSR methodology is a valid approach to conceptualizing requirements and proposals regarding information systems in digital health care (Miah et al., 2017). Our multi-cyclical research design follows the work of Meth et al. (2015), whereas two DSR cycles have been completed and further cycles can be applied if required (Figure 1). In this regard, our paper focuses primarily on the second completed design cycle, the outcome of which is an adapted DT and technical system architecture that is implemented within a prototype reference scenario. This paper addresses and presents the DRs, DPs, and DFs in more detail, as they are the foundation of a design theory and contribute to the solution of the problem (Baskerville and Pries-Heje, 2010). Here, the DRs describe the principle objectives and, in a sense, represent meta-requirements for the subsequent prototype artifact (Baskerville and Pries-Heje, 2010; Walls et al., 1992). The DPs of ALiS are prescriptive and universal in that context, specifying how a prototype should be designed to meet the DRs of our target group (Fu et al., 2016). In this context, the DPs were derived by a supportive approach following Möller et al. (2020), whose a priori specification suggests a prescriptive wording (Fu et al., 2016). In our paper, the DFs refer to our specific prototype development of an ALiS. Furthermore, our DSR approach is oriented towards the ISO 9241-210:2020 standard and the human-centered design of interactive systems.

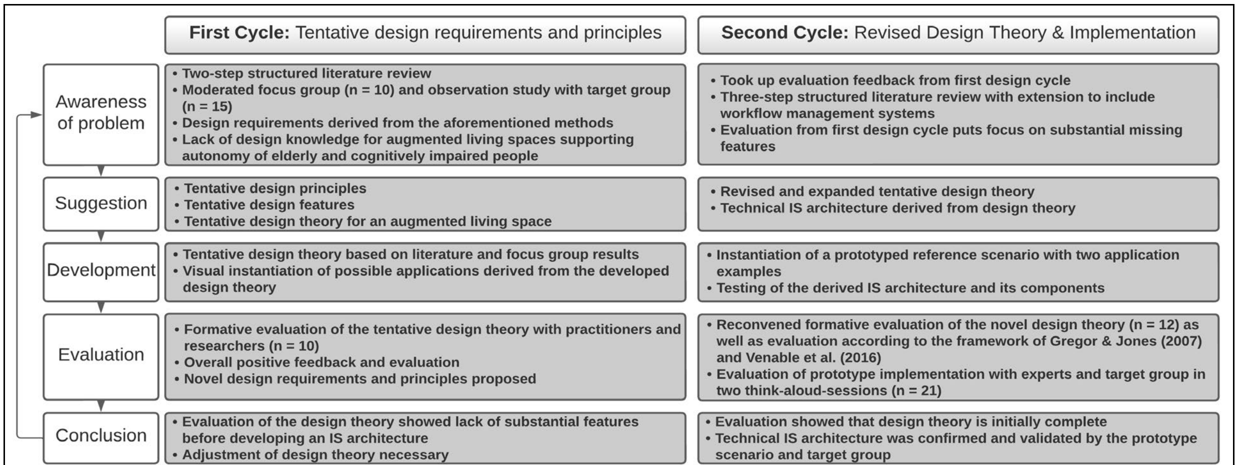

Figure 1. Design science research approach (following Meth et al. 2015)

Awareness of Problem

In our DSR approach, a three-step structured literature review (SLR) according to Vom Brocke et al. (2009) was conducted, the results of which can be found in Table 1 along with the SLR characteristics according to the taxonomy of Cooper (1988). We chose the well-known methodology of Vom Brocke et al. (2009) as it allowed us to conduct a comprehensible, stringent, and sound literature review, and chose it over alternative approaches, as it either incorporates them (Webster and Watson, 2002) or is more widely cited (Okoli, 2015a; Okoli, 2015b). In pursuit of a rigorous and traceable approach, we conceptualized three search strings with the topic-relevant terms for each SLR, identified further relevant search terms and synonyms in the first step as well as used the *OR* operator to account for these synonyms and alternative spellings. To overcome database faults and inaccuracies, we used an array of literature databases (see Table 1) and re-evaluated our respective search strings after the initial search within a database. We conducted three rigorous review phases for selection. In the first phase and after the initial database hits, articles were first filtered and selected by title and abstract. In the second phase, we analyzed and reviewed the full text of the relevant hits. To ensure a representative and exhaustive coverage, phase three included a forward and backward search of the significant hits, resulting in 25 articles with top relevance for further literature analysis.

To ensure state-of-the-art results, *SLR 1* was performed on current ontologies and techniques of SAR, where key findings cover error-free compensation methods for projection (Huang et al., 2021), projection manipulation (Miyamoto et al., 2018; Lindlbauer et al., 2017), ideal projection surfaces (Ro et al., 2019) and successful practical applications of SAR in different areas such as cooking assistance for cognitively impaired people (Kosch et al., 2019). *SLR 2* is aimed at neoteric digital assistance systems as well as ambient assisted living (AAL) in health care, identifying possible technical and conceptual IS architectures that capture the essence of existing applications and could serve as a guide for developing user-centric requirements. Key findings include guidelines for projection design (Morris, 1994), SAR as a method for digital assistance in health care (Yang et al., 2018), and sensor technology for digital assistance systems (Luis-Ferreira et al., 2019). Moreover, we identified conceptual (Tazari et al., 2010) and technical (Antonino et al., 2011) reference architectures (RA) for digital assistance and AALs for the elderly. Beyond that, Garces et al. (2020) and Memon et al. (2014) showed that current systems lack a holistic approach, quality, and modularity while being elusive and difficult to understand. After evaluation feedback, *SLR 3* extended the initial two-step SLR to review state-of-the-art RAs for WFMS that could potentially serve as blueprints or guidelines for developing concrete workflow concepts behind ALiS and thus, being consistent with the definition of RAs according to Cloutier et al. (2009). We found the WFMC (1995) as the most popular RA, with the architecture of Pourmirza et al. (2019) building upon that and providing an RA for business process management systems.

	SLR 1	**SLR 2**	**SLR 3**
Search string	("spatial augmented reality" OR "spatial mixed reality") AND ("architect*" OR "ontology" OR "design")	("digital support" OR "digital assist*") AND “elderly” OR (“cognitive” AND ("impairment" OR "guidance"))	(“workflow management” OR “process management”) AND (“architect*” OR “ontology”)
Search fields	title, abstract	title, abstract	all search fields
Databases	ScienceDirect, ACM Digital Library, AIS electronic Library, SpringerLink, IEEE Xplore, Web of Science, EBSCOhost, JSTOR, Google Scholar, PubMed		
O/TA/F/BF/TR	442 / 147 / 65 / 80 / 7	6.353 / 241 / 38 / 21 / 17	1.465 / 171 / 3 / 5 / 1
	Characteristics according to the taxonomy of Cooper (1988)		
Focus	research outcomes, theories, applications	research outcomes, theories, applications	applications & research outcomes
Audience	specialized & general scholars	specialized & general scholars	specialized scholars
Coverage	representative	representative	exhaustive & selective
Goal	integration		
Organization	conceptual		
Perspective	neutral representation		

Table 1. Details and characteristics of the three-step structured literature review

Note. O = original hits, TA = after title & abstract filter, F = after full text eval., BF = after back- & forward search, TR = top relevance

Furthermore, the first DSR cycle included an MFG and observation study which were aimed to rigorously derive DRs and establish them in the initial DT. According to Morgan (1997), this qualitative research method is especially predestined for extensive insights into a subject and the development of prototypes. For this purpose, our MFG consisted of n=10 participants, including five caregivers in the field of cognitive impairment, two AR experts, and three IS researchers. The MFG was subjected to a qualitative content analysis according to Mayring (2015). On the other hand, the observation study (n=15) of our target group was conducted in a care facility for elderly and cognitively impaired people. However, feedback from the first DSR cycle showed a lack of workflow management, context-awareness, and universal design (UD) within the initial DT that we addressed in the second DSR cycle. To the best of our knowledge, a holistic, dynamic, and modular approach to supporting the elderly and cognitively impaired does not exist in the literature and is therefore taken up with ALiS. Moreover, there is no DT and technical IS architecture that guides developers and researchers through the conceptualization and implementation of ALiS systems.

Related Work

The foundation of our work and the associated conceptualization of an ALiS is the basic work on SAR by Raskar et al. (1998), defining the term "spatial augmented reality". Specifically, surface shape extractions, rendering methods, and acquisition artifacts were presented, which were picked up by subsequent contributions in this research field and identified by our structured literature review. A subsequent forward search of SLR 1 located the contribution by Grundhöfer and Iwai (2018), which bundles current state-of-the-art algorithms, hardware, and applications of the projection mapping used in SAR. In terms of technical realization, the contribution of Di Donato et al. (2015) is significant, who explored different surface projections and thus were able to determine the most adequate surfaces for SAR. Enabling projection onto moving objects, including the use of artificial intelligence, appears equally relevant (Gomes et al., 2021; Kobayashi and Hashimoto, 2014; Lee et al., 2019). A stringent forward search of SLR 2 identified the work of Baig et al. (2019), who conducted a systematic analysis of wearable sensors in the IoT context for people in need of care. In addition, the work of Fernando et al. (2016) provides foundations and requirements for smart assisted living, whereas Block et al. (2020) conducted interviews with caregivers of cognitively impaired people to elicit the use and acceptance of digital assistance systems. As such, caregivers perceive these systems as enrichment in health care (Saborowski and Kollak, 2015). Furthermore, the contribution of Kosch et al. (2018) shows to what extent DRs and DPs can be formulated for a smart-kitchen environment for cognitively impaired persons and to what extent design implications can be derived. Concerning digital assistance systems for elderly persons, the ethical consideration is also of great relevance and is addressed by the contribution of Mueller and Heger (2018). The authors have translated fundamental values into concrete norms and thus formulated specific design requirements for a digital assistance system in physiotherapy, which can be used to defuse potential conflicts. In SLR 3, we looked for RAs of WFMSs and found a service-oriented design for a "visual scientific" WFMS by Lin et al. (2008). Rodriguez and Buyya discuss a cloud-based WFMS for scientific processes (2017). Pourmirza et al. (2019) RA for BPM systems draws on the WFMC's (1995) as well as Grefen and Vries' RAs (1998). The WFMC (1995) RA is now the most representative RA for WFMS, with 23 references in 171 reviewed publications.

Suggested Design Theory for ALiS

The first DSR cycle proposed an initial design theory that was based on the literature as well as an extensively described focus group and observation study results (Böhmer et al., 2021). For the revision of the DT, we methodically followed the approach of Möller et al. (2020) which allowed us to develop DPs containing design knowledge that is generally applicable and can be transferred from one application to multiple application scenarios regarding the respective target group. This allows us to intuitively adapt the system in different scenarios without having to redefine DRs and DPs. The revised DT now also contains DPs which are not dependent on a specific target group and hence, should be considered by any ALiS instantiation. Analysis of the evaluation feedback from the first DSR cycle as well as the SLRs and the moderated focus group resulted in 4 essential DRs, which are further addressed by 12 target group-specific DPs and 13 specific use case-derived DFs for our implementation of an ALiS design (Figure 2). Hence, the DRs and DPs describe components that every ALiS for the elderly and cognitively impaired should be built upon, whereas the DFs refer to our prototype development features and do not represent an explicit component of the DT. We further defined hatched DPs (Figure 2) that are generally applicable and describe principles any ALiS should consider to target their respective audience.

Theoretically grounded on the ISO 9241-11:2018 standard for "usability" we derived the DRs user satisfaction (**DR1**), efficiency (**DR2**), and effectiveness (**DR3**). The DT was now expanded by the addition of the general accessibility (**DR4**) requirement, theoretically underpinned by the ISO 9241-171 standard for ergonomics of human-system interaction and the ISO/TR 22411 report for corporality that helps us to apply a universal design according to Connell (1997) and the Center of Universal Design (CUD). We aim to make ALiS generally accessible to everyone which requires principles like "equitable use", "flexibility in use", "simple and intuitive use" or "low physical" effort (CUD, 2008). Moreover, the ISO standards enable us to design human-centered augmented living spaces that address the needs of elderly and cognitively impaired persons.

DP1 addresses a user-centered, personalized, and intuitive interaction with the ALiS serving the need for individuality within digital assistance systems (Blackler et al., 2020; Graf et al., 2019; Morris, 1994). With **DP2** we further ensure that the communication with the ALiS is individual, adapted to the specific impairments, and provides a satisfactory experience as emerged from the MFG and literature (Kosch et al., 2018; Morris, 1994). **DP3** implements modularity which enables the system to allocate individual needs-oriented features and be vastly flexible at the same time (Antonino et al., 2011; Garces et al., 2020; Graf et al., 2019; Kosch et al., 2018; Tazari et al., 2010). **DP4** was introduced to establish the principles of UD and general accessibility (Connell, 1997; ISO 9241-11; ISO/TR 22411). **DP5** proposes the need for low-threshold user interfaces to reduce the cognitive load which is a key technology acceptance and comprehension factor (Garces et al., 2020; Tazari et al., 2010). Privacy-related, **DP6** ensures personal data protection which further fosters user acceptance (Garces et al., 2020; Tazari et al., 2010). An ALiS shall not be seen as a mandatory burden but rather as supporting and service-oriented which is addressed with **DP7**.

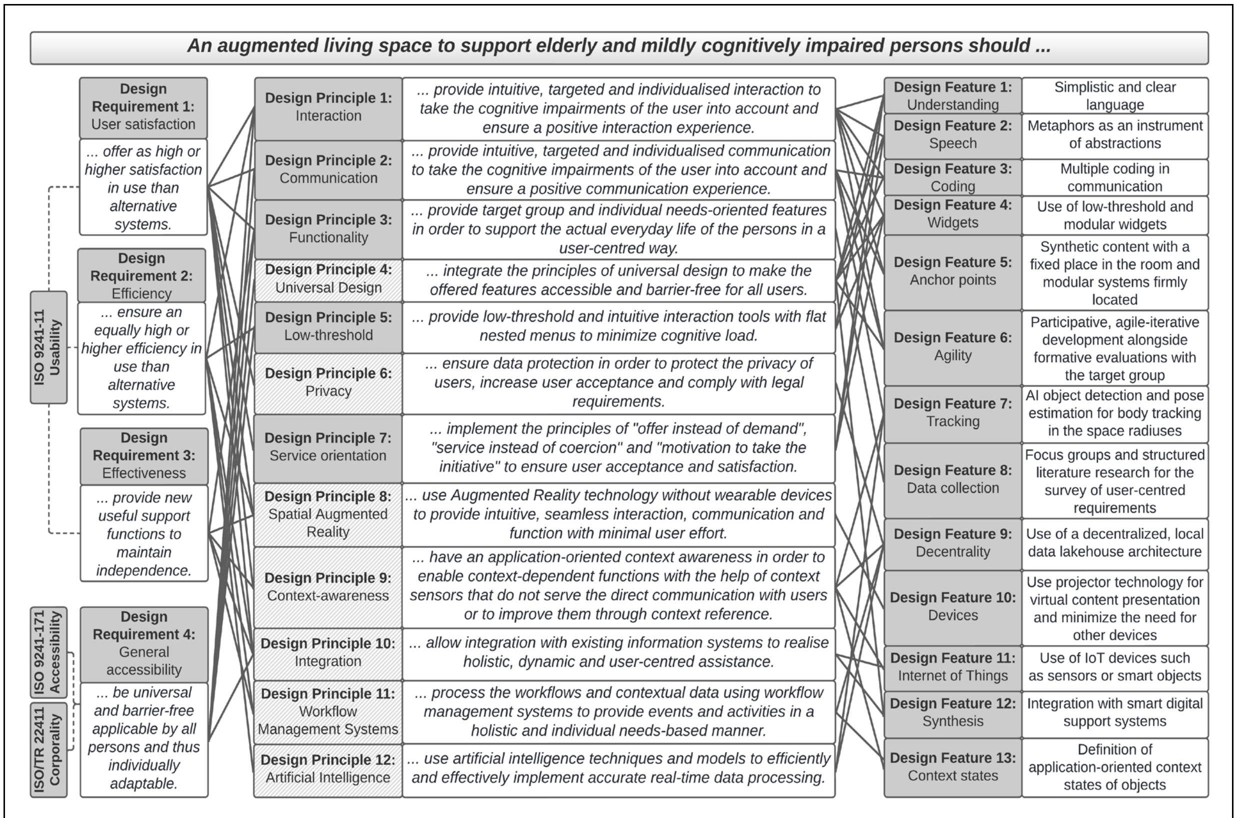

Figure 2. Design theory containing design requirements and design principles for ALiS with additionally derived design features

Subsequently, we specify the use of SAR with **DP8** which reduces cognitive load via non-wearable devices and ensures minimal user effort (Raskar et al., 1998). **DP9** addresses the context-awareness and reasoning of ALiS as a novel component that is based on the RAs for context-aware systems according to Alegre et al. (2016) and Costa et al. (2005) and uses the context modeling techniques of Strang and Linnhoff-Popien (2004) as well as the concept of *Pervasive AR* by Grubert et al. (2016). With **DP10** a seamless integration with existing IT systems is proposed to provide a dynamic, flexible, and holistic user experience with user-centered features. Moreover, **DP11** focuses on the novel WFMS component of the revised DT and is closely connected to the WFMC (1995) reference architecture which enables ALiS to adequately process sensory data, contextual states, and triggers the projection respectively auditory information. **DP12** adds artificial intelligence (AI) as a component to enable real-time object detection, pose estimation, and body tracking due to precise context reasoning.

The described DRs and DPs act as a general and conceptual foundation for the development of ALiSes by researchers and practitioners. They symbolize target group-related design guidelines to meet the specific needs of elderly and cognitively impaired people. Based on the findings, we derived 13 specific DFs which we used as a framework for the development of our ALiS prototype as they particularize the depicted DPs within our prototype implementation. These will be explained in the following section.

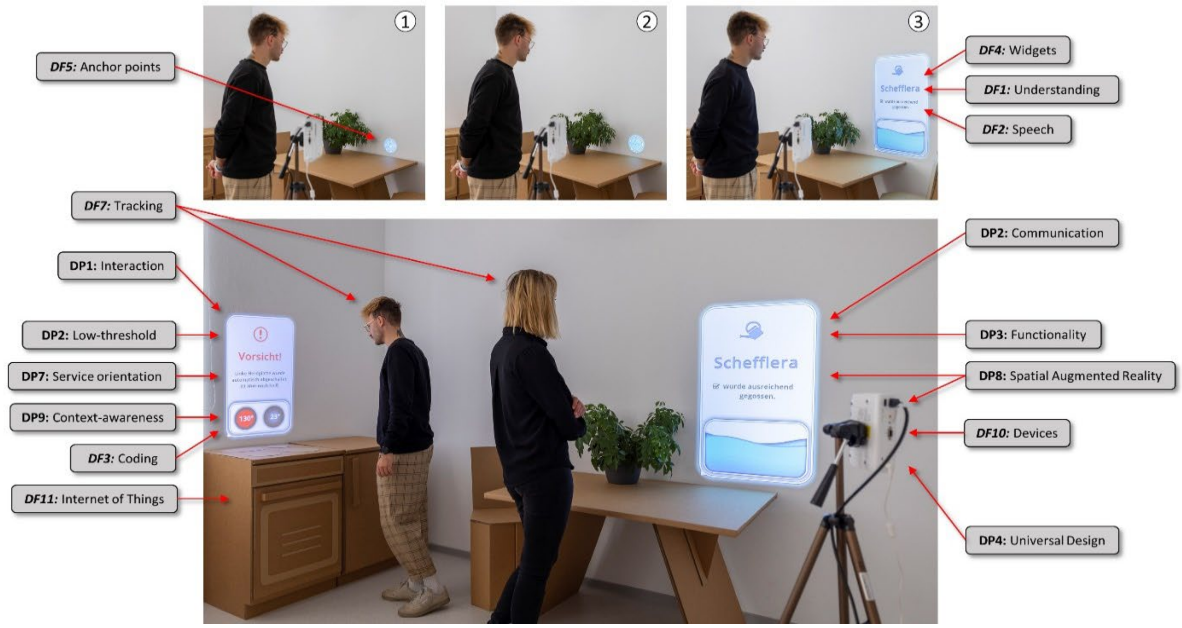

Figure 3. Visual instantiation of our early ALiS prototype with idle (1), focus (2), and active state (3)

Prototype Implementation

The development of the specific ALiS-prototype (Figure 4) involved several steps that will be explained in more detail according to the proposed DFs (see Figure 2) which have been used to conceptualize a technical IS architecture as shown in simplified form in Figure 5. After conceptualizing a DT, this embodies the next logical step in developing ALiSes and, thus, adding research value.

DF1 (Understanding) focuses on the perception of the projected or communicated information. This feature is derived from *DP1*, *DP4,* and *DP7,* and, therefore, the adequate and universal communication with our target group users. Since most of these people struggle with hearing and vision impairments, we make use of simple and clear language in regards to the communicated information. Especially in dangerous situations (i.e. a hot stove or flooded sink) which require fast action, our target group needs to process information quickly and comprehensibly. Within our technical IS architecture (see Figure 4), we have a projection interface containing pre-defined word masks that is responsible for the communication and is implemented through *Unity3D*. *DF1* was seen as an integral component of the architecture development throughout the evaluations of both design cycles as it directly affects the user experience of our target group.

DF2 (Speech) connects closely with *DF1* as it further defines how the communicated tone needs to be conveyed. Therefore, our implementation follows the slogan “metaphors as an instrument of abstractions” which does not target to digitize the real world but rather integrate virtual information into it which is also underpinned by *DP1*, *DP4,* and *DP7*. Elderly and cognitively impaired people need to feel comfortable using an ALiS which is directly related to the form and tone of speech, which requires a patient and low demanding or determining communication with users.

DF3 (Coding) aims at an adequate visualization and sound, which can be individually adapted to the respective user. Thus, it realizes the need for individualized interaction (*DP1*) and communication (*DP2*) as well as satisfying the requirement of universal accessibility (*DP4*). As can be seen in Figure 3, our prototype uses different color schemes to emphasize information that suits the receptivity of our target group. That is, for instance, reflected in effective color combinations (that is warnings colored *red* or water-related information colored *blue*) and sharp contrasts (Morris 1994) that are created in *Unity3D*. However, we do not only code visual but also auditive information for people with severe vision impairments. This includes several different voices that primarily communicate information in a pleasant and non-demanding manner as proposed by many experts in our initial focus group.

Figure 4. Prototypical implementation of ALiS along with visionary visualization

DF4 (Widgets) has been defined to build a highly flexible and customizable ALiS. Since every user is unique and has different habits or limitations, ALiS should take these into account to provide a useful experience. This design feature builds upon the individualized interaction (*DP1*), universal design (*DP4*), and service orientation (*DP7*). Widgets can thereby be wide-ranging as there are no limits to the purpose, composition, and shape, again using *Unity3D*. Blackler et al. (2020) showed that people with mild cognitive impairments often struggle with the comprehension of communicated information, which led us to conceptualize low-threshold widgets. The widgets are designed to be intuitively understandable, thus reducing the cognitive load for the respective user. As can be seen in Figures 3 & 4, we also designed different widget states (*idle*, *focus*, *active*) to communicate the appropriate amount of information when necessary.

DF5 (Anchor points) now specifies where these widgets are projected. Early focus group results and target group observations within the first design cycle showed that elderly and cognitively impaired people tend to focus their attention on certain objects within the living space (oven, plants, pictures, etc.). With our projection interface, we aim to reinforce these objects and expand them digitally to some extent which enables users to communicate (*DP2*) and interact (*DP1*) individualized. This approach leads to our communicated information being more receptive, as the focus of our users is already on the real living space objects. Furthermore, using anchor points establishes a memory reference which was considered exceptionally important in the evaluation.

DF6 (Agility) refers likewise to *DP1* and *DP2* as well as *DP4* and the principle of Universal Design. Our system architecture is designed to be agile in regards to hardware or software components, functionalities, and user-specific criteria. As our development over the two design cycles was participative and agile-iterative, the system architecture is aligned accordingly and was evaluated throughout. That is, for instance, an exchangeable workflow interface and engine as well as various possible databases or sensor interfaces. Moreover, the projection hardware (visual and auditory) can be selected according to the requirements and impairments of the users. As a result, all possible applications of ALiS are conceivable, from plain warnings up to therapeutic measures. This design feature emerged rather naturally throughout the two design cycles and suits the agile-iterative manner of the design science research methodology.

DF7 (Tracking) is an integral design feature for ALiS and is responsible for an accurate user or object tracking within the living space. Located within our sensor interface it is the prerequisite for projecting warnings or information adequately into the field of view. This design feature is closely connected to *DF4 (Widgets)* as tracking is where the course is set for the state in which a widget is displayed. Derived from

DP2, *DP9,* and *DP12*, the ALiS is divided into three tracking areas (see Figure 6) with each representing a widget state. Within our sensor interface, we developed a state-of-the-art deep learning object detection model that is capable of locating objects and people all around the living space with a 360-degree fish-eye camera. Our model not only detects these objects or people but also sends positional tracking data which is fed into the database and workflow interface. From there, the workflow engine knows where the user or a certain object is located and triggers the appropriate widget-state at the correct location within the room. In our example, as seen in Figure 6, the user is located in an active state area, hence triggering an active-state stove widget, whereas the plant widget is idle. Evaluation results showed that this type of tracking reduces errors since no wearable sensors are needed and tracking is unobtrusive.

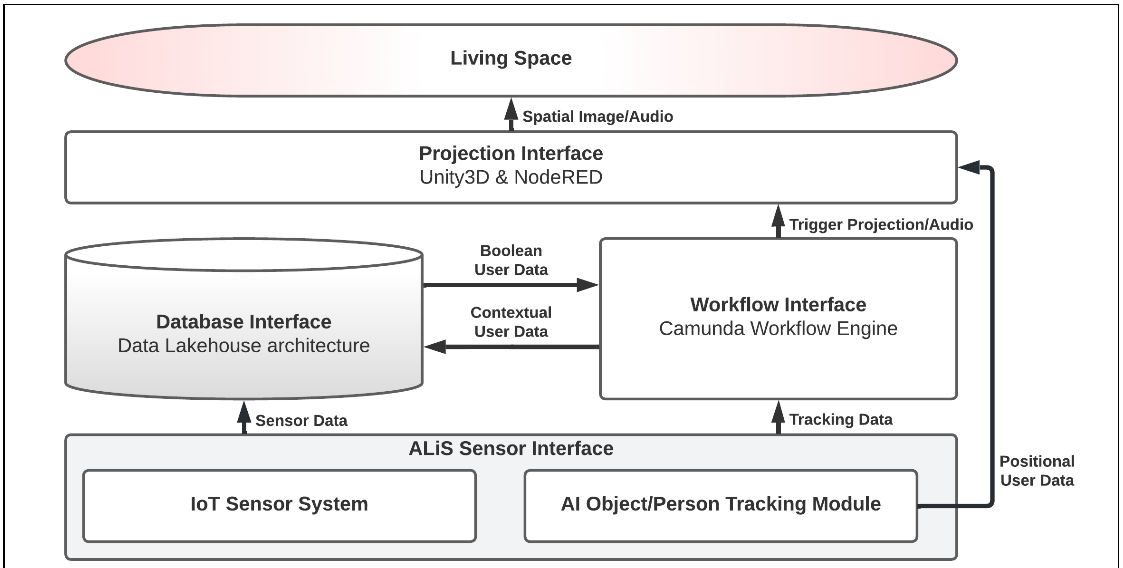

Figure 5. Simplified IS architecture of the ALiS prototype reference scenario

DF8 (Data collection) addresses the target group, and needs-oriented features for our prototype, and is therefore backed by *DP3*. In its quintessence, this design feature aims to conceptualize a highly individual and user-centered ALiS. We achieved this by conducting structured literature reviews, focus groups, and observations to identify the most relevant and critical design requirements for ALiS regarding our target group. Since the system is user-centered and needs-oriented, we needed to gather data right from our target group of elderly and cognitively impaired persons as well as experts working with them.

DF9 (Decentrality) is further an important aspect when working with sensitive data, such as positional tracking, sensor, or health data. It strongly connects to *DP6*, *DP9*, *DP11* as well as *DP12*. Since we are working with sensitive and unstructured data, using a local network with a *data lakehouse* (Armbrust et al. 2021) seems appropriate. It combines the merits of a data warehouse with rapid processing of unstructured deep learning data, while at the same time being isolated from external services and interfaces. Our database interface collects sensor as well as contextual user data and sends boolean user data when needed. With our prototype, we propose a secure and standalone system architecture where data is protected at any time, which was reinforced several times throughout the evaluation cycles.

DF10 (Devices) addresses the target group related *DP8* and the use of Spatial Augmented Reality (see Figure 4), since the fewer devices, the better. With this specific design feature, we aim to reduce the number of operable devices, such as smartphones, tablets, or smartwatches and thus, reducing the cognitive load of the respective users. The projection interface of our prototype uses lightweight projection technology to communicate information within the living space that is also capable of projecting in daylight conditions via our *Unity3D* application (see Figure 3). Users do not need to actively operate any device, which was seen as a hurdle for elderly and cognitively impaired people and was recognized through the evaluation in the first design cycle.

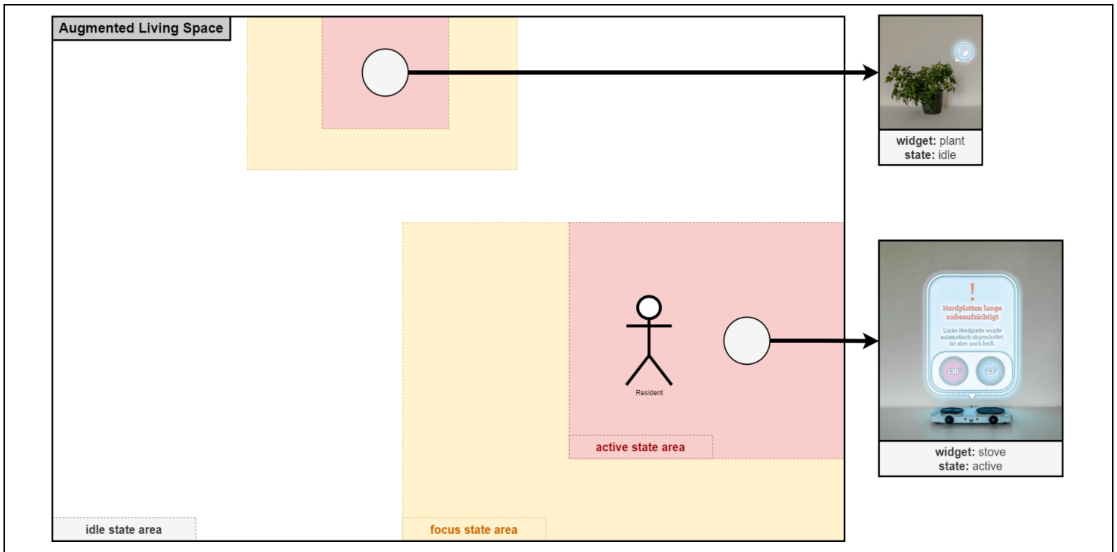

Figure 6. Simplified visualization of action areas and states within ALiS

DF11 (Internet of Things) is an integral feature regarding the context-awareness (*DP9*) and integration (*DP10*) of ALiS. To adequately project meaningful information, necessary data needs to be gathered through sensors. These can either be object-integrated sensors (stove), manually placed sensors (humidity), or optional wearables for health purposes. Sensor data is gathered by the sensor interface and sent to the database interface, where it will be stored. Subsequently, this sensor data will be sent to the workflow interface, where a contextual state is established and a rule-based projection action is triggered. That is, for instance, the warning of a too hot and unused stove if the user is currently in a different living space area, which is detected by our deep learning model. Therefore, the workflow interface is responsible for transforming the raw sensor data into contextual information. In our prototype scenario, we use heat sensors for the stove and liquid sensors for the plant widget.

DF12 (Synthesis) aims at a flawless integration of ALiS with other smart home applications and is therefore based on *DP4* and *DP10*. Our technical system architecture and especially the workflow engine *Camunda* enables us to integrate these optional applications as external services via the REST-API. Thus, the ALiS can be designed in a modular and functionality-oriented manner while satisfying the user's needs. Conceivable here would be smart home services such as *Alexa* or *SensFloor*.

DF13 (Context states) is strongly connected to our workflow interface and the workflow engine while being derived from *DP9* and *DP11*. As mentioned earlier, the workflow engine *Camunda* is responsible for transforming the raw sensor data into contextual object data. The application-oriented context state of a certain object (stove) is of utmost importance to communicate adequate information. Without context states the workflow engine could not run processes accordingly and, thus, would not be able to trigger the right events. The context state of a certain object shows us, for instance, if a user action is required because a hot stove is unwatched for too long or if a medication box is empty and needs a refill. However, context states are further used to assemble highly individualized ALiSes that are tailored to the specific needs of the user. For some users, it might be helpful to trigger warnings if the stove is used after 10 pm when it normally should be idle at that time. Thus, object-specific context states can be defined which the system automatically detects. This design feature was obtained through the evaluation of the first design cycle and has been added to our IS architecture within the second cycle.

Evaluation

As can be seen in Figure 7, the evaluation strategy of our design science approach follows the well-known evaluation framework of Venable et al. (2016). Designing ALiSes for elderly and cognitively impaired people is significantly influenced by societal variables: On one hand the social behavior and human-factor of people using the system, their individual needs-oriented requirements as well as characteristics, and on the other hand, the ALiS team that is intended to set up, compose and maintain the system. Hence, the main risks in designing and implementing such an ALiS are user-oriented, for which Venable et al. (2016) recommend the evaluation strategy "Human Risk & Effectiveness" which was followed throughout both DSR cycles (Figure 7).

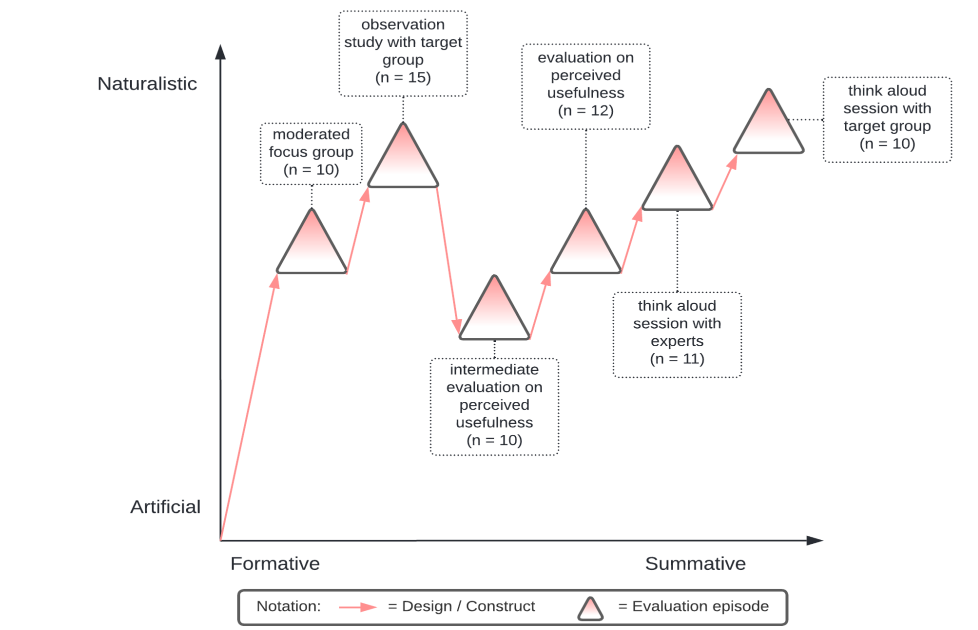

Figure 7. Evaluation strategy of ALiS (following Venable et al. 2016)

In pursuit of a rigorous and adequate strategy, we involved our target group, experts, and researchers early on by conducting an initial MFG with caregivers (n=10) and an observation study (n=15) with our target group in a facility for elderly and cognitively impaired people, the results of which are thoroughly explained in Böhmer et al. (2021) and led to the derivation of initial DRs and DPs. Regarding the evaluation of our DT, we followed the approach of Venable et al. (2017) and hence, conducted early formative evaluations by following the "10+-2 rule", which states that the problem detection rate of subjects increases only marginally when the sample size exceeds 12 (Hwang and Salvendy, 2010). We place great emphasis on the practical use of the artifact concerning the development of context-aware ALiS systems by developers and to maintain or extend the autonomy of our target group. Therefore, we continued our evaluation strategy in the first DSR cycle by developing a questionnaire that asked experts, practitioners, and researchers from the field of care, the AR research field as well as the general IS community about the perceived usefulness of the tentative DT. The experts were asked to evaluate the tentative DT and its influence on developing ALiSes. For this purpose, we used the six items of *Perceived Usefulness* according to Davis (1989). The six items were rated anonymously from the personal perspective of the subjects (n=10) on an interval-scaled verbal-numerical 7-point Likert scale (1=don't agree at all, ... , 7=strongly agree). Our tentative DT was mostly evaluated positively by the experts, who stated that the DRs were met by the DPs while further being consent with the perceived usefulness. However, despite the tentative design theory from the first DSR cycle being grounded on a two-step SLR, MFG and an observation study, the intermediate evaluation with target group experts revealed gaps that were addressed by the second DSR cycle. Experts indicated that the DPs of a workflow engine should be considered, which led us to expand the SLR to include WFMSs to develop process-based and highly agile ALiSes. Moreover, the evaluation results suggested adding the DR of general accessibility as all people, regardless of their impairments, should be able to use a barrier-free system. Thus, we added DP which addresses UD, context-awareness, WFMSs, and artificial intelligence. Another valuable feedback from the intermediate evaluation questionnaire proposed the conceptualization and labeling of general applicable DPs which are independent of our specific target group and hence, embody principles every ALiS should be built upon.

Component	Description
Purpose and scope	The goals of an ALiS are providing a satisfactory user experience for interaction with ALiS (DR1), improving efficiency for ALiS and therefore low effort interaction (DR2), providing holistic health care and everyday life functionalities (DR3), and ensuring a universal design that is generally accessible for everyone (DR4).
Constructs	Augmentation, SAR, WFMS, Workflow, AI, Universal design, IS architecture, Healthcare, AAL
Principles of form and function	DP1: interaction, DP2: communication, DP3: functionality, DP4: universal design, DP5: low-threshold, DP6: privacy, DP7: service orientation, DP8: augmented reality, DP9: context-awareness, DP10: integration, DP11: workflow management systems, DP12: artificial intelligence
Artifact mutability	ALiS can be used in different environments, is accessible for everyone, and does not relate to specific hardware/software. The projection design, auditory communication, and scenario functionality is modular and can be adapted for different user use cases. It can be tweaked based on specific practical, personal, or theoretical requirements.
Testable propositions	An ALiS for supporting the elderly and people with mild cognitive impairments offers higher user satisfaction, efficiency, effectiveness, and accessibility than alternative AAL approaches.
Justificatory knowledge	A three-step literature analysis, moderated focus group, and observation study justify the derivation of DRs and DPs. Two reconvened intermediate evaluations justified that the DT for ALiS was overall perceived as useful for developing ALiSes from a practitioner and researchers' perspective. An evaluation of user satisfaction, effectiveness, efficiency, and accessibility was conducted through two independent think-aloud sessions which further assessed and validated the derived system architecture. Close evaluation with the target group is vital since ALiS offers novel possibilities for non-wearable devices and digital, smart, and context-aware health assistance.
Expository instantiation	Development of a technical IS architecture and thereupon a prototype implementation, encompassing the derivable components of the DT within two reference scenarios.

Table 2. Components of a design theory for ALiS (following Gregor and Jones 2007)

Note. ALiS = augmented living space, SAR = spatial augmented reality, IS = information system, WFMS = workflow management system, AI = artificial intelligence, AAL= ambient assisted living, DT = design theory, DP = design principle, DR = design requirement.

Within the evaluation phase of the second DSR cycle, the focus was set on assessing the revised DT as well as evaluating the IS architecture along with the prototype through experts and our target group. After addressing the proposed revisions in regards to the initial DT, we once again evaluated it with caregiving experts and researchers using the six items of *Perceived Usefulness* by Davis (1989) as well as extending these to assess the conciseness, extendibility, and explanatory power of the DT. Regarding task completion time (i.e. designing neoteric ALiSes), the subjects stated that they could accomplish tasks more quickly compared to the initial DT, with answers ranging from partial to strong agreement. The respondents further stated that the revised DT would improve their job performance compared to the initial DT and showed strong agreement with the statement that using the revised DT would increase their productivity. The majority of the subjects also agreed on the fact that the revised DT would see them improve their effectiveness on the job (i.e. designing a neoteric ALiSes), with only two people partly disagreeing. Furthermore, the consensus on the simplicity of a task showed great agreement with the statement that the revised DT would make it easier to complete the task successfully. Only two subjects disagreed and attributed this to the now more complex DT and the additions to it. Overall, the subjects found the revised DT useful for the task of developing a neoteric ALiS, expressing that the specific DPs helped them visualize a possible solution. Moreover, the subjects agreed on the statement that the number of meta requirements and principles allows the revised DT to be meaningful without being unwieldy or overwhelming, with only one subject disagreeing partially, which underlines the significance of the revised DT in terms of content. Regarding the extendibility of the revised DT, respondents showed partial to a strong agreement that new meta-design requirements or principles can be added to it easily. Lastly, all of the participants agreed on the statement that our meta DRs and DPs are sufficiently explained within the revised DT.

To ensure scientific rigor as well as a functioning system, the technical IS architecture was implemented in an initial prototype scenario and evaluated in two independent sessions. The first session was directed to get feedback from IS researchers and caregiving experts (n=11), whereas the second session was aimed at evaluating the system use by our target group (n=10). We followed the qualitative research method of "Concurrent Think-Aloud" (Van Den Haak et al., 2003) where users are asked to use the system or complete a set of tasks and verbalize their thoughts to evaluate the software design. To conduct the think-aloud sessions, we followed the three steps applied in Schoormann et al. (2018): (1) provision of information about the system prototype and the task to be performed, (2) systematic protocolling of verbalized user thoughts, and (3) analysis of protocols. Seeking qualitative rigor in these sessions, we followed the well-known method of Gioia et al. (2012) and developed *first-order concepts*, *second-order themes* as well as *aggregate dimensions* based on the thoughts expressed by the subjects. Subsequently, we assigned the clustered comments to the respective design principles to assess how the DT was implemented through the IS architecture. Table 3 contains the clustered results as we could derive both positive aspects (marked by "+") and potential for improvement (marked by "o").

DP	Clustered verbalized thoughts
DP1 *Interaction*	+ Intuitive user interface and technology access without the need for extra devices + Overall positive user experience due to low entry barriers and fast understanding
DP2 *Communication*	+ Colour schemes and animations are helpful in regards to information assimilation o Certain objects within the living space could be emphasized through projection techniques
DP3 *Functionality*	+ Different use cases and scenarios are well implemented + Necessary functionality and information are provided in a needs-oriented manner + Transition between action areas and the respective widget state is perceived as useful
DP4 *Universal Design*	+ Communicated information is easily accessible and comprehensible o Auditory information could be improved by adding different voices and alert types
DP5 *Low-threshold*	+ Cognitive relief due to minimized complexity + Cognitive relief due to easily understandable and object-oriented information
DP6 *Privacy*	+ A data privacy concept fosters user acceptance o Privacy and data protection should be made more transparent
DP7 *Service Orientation*	+ Individual and functionality-oriented widgets are perceived as useful + Content of communicated information is sufficient o Widgets should always represent the real object (i.e. number of stovetops)
DP8 *SAR*	+ Cognitive relief due to pleasant and naturally fitting projections o Some widgets within the active state area could be displayed smaller
DP9 *Context-awareness*	+ Context-specific information is useful and clearly communicated + Cognitive relief due to individual needs-oriented assistance
DP10 *Integration*	+ Cognitive relief due to reduced amount of specialized smart systems o ALiS should cooperate with and integrate local community initiatives
DP11 *WFMS*	+ Intuitive workflow management interface for developers + Use of process-oriented data streams fosters user experience regarding delays
DP12 *AI*	+ Gaze-based projection facilitates the perception of communicated information + Monitoring was perceived as useful in regards to anomaly detection or emergencies

Table 3. Results of the think-aloud sessions

Note. DP = design principle; + = positive aspect; o = potential for improvement

The results of the two think-aloud-session can be summarized as follows: The ALiS system with tracking- and event-based projections has been characterized as intuitive to use since no other devices need to be operated or worn. The participants commented that the widget view, which builds on the contextual data, provides useful and concise information that is easy to understand. It was particularly emphasized that the color schemes, as well as the communicated information with Spatial Augmented Reality, represent a great cognitive relief which was seen as a key factor for people with mild cognitive impairments. The proposed improvements do hereby not require a revision of the IS architecture but rather minor adjustments.

Extending the positive formative and qualitative evaluations, we further validated the quality of the revised DT by applying the framework of Gregor and Jones (2007). The framework defines six mandatory and two facultative components that should be included in a DT. To this effect, we are convinced that our revised DT fully complies with this framework (Table 2). Moreover, our DT enables us to classify ALiS as *Passive Pervasive Assistant* (type 4) according to Knote et al. (2019), since it acts unobtrusive, suggestive, and converges into a digitally enhanced experience.

Conclusion

The paper has shown a general design theory for ALiSes which was implemented in a prototype scenario and that can be considered a promising solution to support the autonomy of elderly and cognitively impaired people. Consequently, to answer the initially formulated research questions of this paper, we presented the results of our DSR approach throughout two completed design cycles. We presented a DT and were able to show its technical architecture and implementation. The positive evaluation substantiates the practical relevance of the DT and architecture as practitioners can adapt our DT to develop new, related, and context-aware ALiS systems using the generally applicable and target group independent DPs as well as showing a positive user experience of our target group. Moreover, our defined DRs and DPs merged in an inter-field DT (Darden and Maull, 1977), and the derivation of DFs enabled an IS architecture implementation, thus, contributing to the prescriptive knowledge base of the IS community according to Gregor and Hevner (2013) along with the IS design science knowledge base according to Woo et al. (2014). Meanwhile, in the context of the utility of our DT and prototype, the following limitations should be considered: On the one hand, DRs, DPs, and DFs are based on the subjective creativity of the researchers even after rigorous SLRs or MFGs. However, not all design decisions can or should be stemmed from behavioral or mathematical theories since a degree of creativity is vital to developing a cutting-edge design artifact (Hevner and Chatterjee, 2010; Baskerville et al., 2016). Our DT is further supported by the methodological approaches of Möller et al. (2020) and Fu et al. (2016) regarding scientific rigor. On the other hand, as with any other evaluation, our results describe only a few samples, and our qualitative think-aloud sessions were subject-specific, which means that different results could be expected by choosing other participants or a different focus. Hence, this challenge could be addressed in future research or by fellow researchers. We cannot assume that our DT contains all necessary DRs and DPs for the development of an ALiS and therefore this could be addressed in future research as well. With the presented DT and prototype artifact of this paper, future research could be conducted regarding quantitative target group evaluation concerning the three components of usability (Venable et al., 2017; ISO 9241-11:2018). In regards to our prototype reference scenario, the scalability of the current setup is still limited and was aimed at validating the theoretically derived IS architecture. Based on these findings, future research can be conducted concerning the form factor, scalability, and projection mapping. It is thereby expectable to work with even smaller, yet more powerful laser projectors in the future to compensate for lighting challenges.

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