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Designing and Evaluating an Intelligent Augmented Reality System for Assisting Older Adults' Medication Management

Esteban Guerrero[a,*], Ming-Hsin Lu[b], Hsiu-Ping Yueh[b], Helena Lindgren[a]

[a] *Department of Computing Science, Umeå University, Sweden*
[b] *Human Performance and Technology Lab., National Taiwan University, Taiwan*

Abstract

Intelligent Assistive Systems (IAS) are developed for the purpose to provide personalized support to individuals to increase an individual's autonomy and competence in conducting activities. Personalization of such technology represents a particular challenge since the individual's ability typically change over time. The aim of this research is to explore a theory-based activity-centered framework for the development of IASs that facilitates the active involvement of caregivers and target users, and allows for adaptation to the individual over time.

The activity to manage medications was focused as a case study. Three older adults and two caregivers were involved in a co-design process of the IAS prototype system MED-AR, which uses projection-based *augmented reality* as user interface technology. Activity theory was used as a theoretical framework for the design and evaluation of MED-AR. Formal argumentation theory was used for the decision-making process of MED-AR. The major contributions of the study are i) a formal framework for understanding level of independence in activity and how IAS can tailor support to an individual and a situation including caregivers; and ii) a model for involving older adults and caregivers in a co-design process in the first phases of developing IASs.

Keywords: Intelligent assistive technology, Augmented reality, Medication

*Corresponding author esteban@cs.umu.se

distribution, Activity theory, Argumentation theory, participatory design, older adults

1. Introduction

Active assistive technologies can provide advanced and proactive support to an individual in her or his conduction of activities. Such systems embed typically modules based on artificial intelligence, and can be denoted *Intelligent assistive systems* (IAS). Since personalization is key to providing optimal support, such technology needs to embed the following functionalities: i) assessment of the individual's current ability to perform and complete an activity in a way that is satisfactory to the individual in a certain situation, and ii) decide the extent and nature of the assistance that needs to be provided in a certain situation.

IAS design and development has multiple open research questions. In this investigation the following two are addressed:

1. RQ1: How to solve the automatic adaptation of an IAS to changing contexts and abilities in the individual? Particular cases in this study are how the IAS collaborates with the individual to be supported, and with potential other persons such as caregivers?

2. RQ2: How can such systems be co-designed and co-developed together with potential users and health experts?

Involving potential users has shown to provide increased understanding of the contextual factors of use [1]. However, participatory methods for designing adaptive and personalized systems are largely unexplored, since these are expected to change following the situation, and consequently, they do not adhere to traditional design methods [2].

The objective of this study is to explore a combination of theories and methods to further advance the understanding of how assistive technology can adapt to changing situations. We include in personalization both the purposeful situated support: i.e., what the content of the support is, and the tailored interaction to a specific situation, *i.e.*, how the support is mediated. A particular focus is set on situations where the IAS supports health-related decision making, for example, when managing medication as part of activities of daily living. The selected case study focuses the distribution of medication, and a prototype system was developed. The primary purpose of the case study is to explore a set of complementary instruments and theories for co-design and formative evaluation of IASs that can provide a holistic framework for human-system interaction design in IAS development. The selected instruments cover both instrumental and psychological aspects of use, and were evaluated together with the prototype in a pilot study. Furthermore, models of human activity were formalised based on the theories.

This paper is structured as follows. Related work is introduced in Section 2 and discussed together with the results in Section 8. Two theories that are fundamental for this research are summarized in Section 3. Methods and instruments are described in Section 4. The results from the initial step that formed the base for design is summarised in Section 5. The MED-AR prototype and theoretical contributions are summarized in Section 6. In Section 7 results of the pilot study are presented and the conclusions are summarised in Section 9.

2. Related Work

The abundant research on medical technology (*e.g.*, [3]) has shown that intervention technology, such as current approaches of *assistive technology*, is unlikely to increase older adults' medication adherence and managing to take the correct medication following prescriptions. Moreover, some interventions using for example *Augmented Reality* (AR), also fail providing effective activity support due to their technology-driven motivations [4]. AR can be categorized based on how the AR is mounted and projected, e.g., head-attached displays, hand-held displays, spatial displays and projected AR displays. Earlier studies have proposed AR applications with different displays to support home-care activities [5, 6, 7]. Older adults' performance improves better using AR interfaces than using traditional interfaces [8]. AR has been used in health-care to aid older adults recognize the medication in the dispenser, to manage their medications, to remember to take medication and to manage their appointment schedule [4, 9]. Although AR shows advantages for older adults, the outcomes still can be improved especially in health-care contexts. As a previous study suggested [10], health-care intervention needs to be aligned with the user's literacy, language, culture, and social contexts and be accessible, understandable, interactive and motivating. Therefore, integrating a framework based on co-design with potential users and caregivers is important.

Combining synergistic efforts between information science, design science, and behavioral science to design and develop AI systems is an important trend [11]. This approach would connect to an increased application of participatory design with grounding in situated and behavioral theory to improve the understanding of users needs and the acceptance and effectiveness of AI systems. Previous studies, which use participatory design to design AI systems [2, 10, 12], suggested that seeing: bringing in design ideas, moving: selecting a design idea and concretizing it and seeing: evaluating the result are three main processes. The keys to success and to avoid the failure of past eHealth/AI efforts are user-centered design, evaluation from the beginning and interdisciplinary collaboration with medical experts. On the other hand, unforeseeable effects of choices in AI systems on designs, evaluation of possible futures rather than the correctness of the design decision and distinguishing between normal use and training are three main challenges of using participatory design to design and develop AI systems [2]. The presented work is targeting a set goal in medication distribution scenario, to understand the needs of older patients who use pill dispensers and involve them and stakeholders including health experts and caregivers in a collaborative process of design and development of the IASs [13].

3. Theoretical Base

Two foundational theories are used in this study: *Activity Theory* [14] and *formal argumentation theory* [15]. Activity Theory provides informal models for human activity and development of skills, while formal argumentation theory provides a framework for the system to manage knowledge, reason and explain its reasoning. The theories are introduced in the following sections.

3.1. Activity Theory

Activity theory is used in this study for three purposes: 1) to frame the structure of an individual's activities; 2) to understand the potential level of activity achievement of a person; and 3) as an instrumental function to detect *breakdown situations* in an activity being performed.

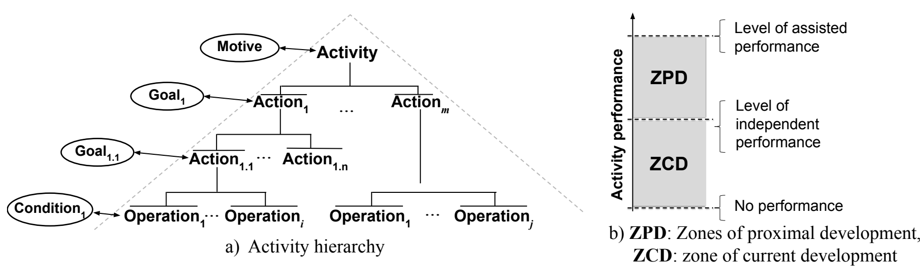

Figure 1: a) Hierarchical structure of an activity. Adapted from [16]; b) Zones of proximal and current development. The zone of current development (ZCD) represents the level that an individual can reach through independent problem solving and the zone of proximal development (ZPD) as the potential distance an individual could reach with the help of a more capable peer.

Activity as complex structure. Activity theory defines an activity as a hierarchical entity consisting of a set of *actions* (see Figure 1a). An action may consist of sets of *operations*, which correspond to the lowest level of the hierarchy [16]. Actions are oriented to goals and are executed by an individual at a conscious level, in contrast to operations, which do not have a goal of their own and which are executed at the lowest level as automated, unconscious processes.

Activity Theory provides a general framework to represent knowledge about activities. In this regard, an *activity model* functions as knowledge, which an agent may use for taking decisions.

Definition 1 (Activity model). *Let* Ax*,* Go *and* Op *be sets of actions, goals and operations respectively. An activity model is a tuple* $\langle \mathsf{Ax}, \mathsf{Go}, \mathsf{Op} \rangle$

Potential level of activity achievement. Vygotsky [17] proposed to measure the level of development not through the level of current performance, but through the difference ("the distance") between two performance indicators: 1) an indicator of independent problem solving, and 2) an indicator of problem solving in a situation in which the individual is supported by a more knowledgeable peer [16]. This indicator was coined as the *Zone of Proximal Development* (ZPD) and it has been used extensively to understand changes of individuals during assisted learning processes [18, 19, 20, 21]. The *Zone of Current Development* (ZCD) was introduced by Harland [22], which represents the activities that an individual can accomplish through independent problem solving (Figure 1b). ZPD is applied in this research to 1) specify formally, the role of the IAS in relation to a situation involving the user and potentially, a care provider; and 2) to assess level of independence when conducting the target activity using the prototype system.

Breakdown situations. When the individual's ability or knowledge, and the requirement of the activity do not match, breakdown situations may occur. The person needs to change the situation, by acquiring the necessary knowledge, or change the way an activity is conducted. The reason for detecting breakdown situation and their causes, is to know if the system design should be changed, or its behaviour adapted. Breakdown situations are seen as positive, and necessary in order to develop knowledge and skills.

3.2. Formal argumentation theory

Argumentation-based systems have become influential in AI, particularly to build the internal reasoning process and behaviour of software agents. The useful characteristics of an agent's argument-based reasoning process are: 1) its *non-monotonic* behaviour, *i.e.,* ability to changing the conclusion when more knowledge is added, and 2) its *traceability*, providing explanations of the reasoning process. At the core of this process is the notion of an *argument*, which is an *explainable* piece of knowledge providing a *support* for a proposed *conclusion*. An argument is typically defined as a tuple of the form: $\langle support,\ conclusion\rangle$, where the support is a set of both (defeasible) facts and rules.

In this section we introduce key definition for an argument-based reasoning process performed by the assistive technology.

Definition 2 (Hypothetical assistance). *Let Δ be a set of propositional formulae (a knowledge base) and an activity model $AM = \langle \mathsf{Ax}, \mathsf{Go}, \mathsf{Op}\rangle$ and let $a, g \in \Delta$ be an agent's action and an agent's goal. An hypothetical assistance is a tuple $H = \langle F, (a, g)\rangle$ such that: 1) $F \subseteq AM \subseteq \Delta$; 2) $F \nvdash \bot$; 3) $F \nvdash (a, g)$; and 4) $\nexists F^{'} \subset F$ such that $F^{'} \nvdash (a, g)$.*

In Definition 2, F can be seen as a *fragment* of the activity (from the activity model Definition 1). Different fragments define *assistance scenarios* where if an (hypothetical) action a is performed by an agent, the agent's goal g may be achieved. Let us denote $\mathcal{H}$ the set of all possible hypotheses that an agent may build.

An agent may build different assistance hypotheses some of them with conflicting information. We use a function $\mathsf{Support}$ to retrieve the fragment F from an assistance hypothesis $H = \langle F, (a, g)\rangle$, *e.g.* $\mathsf{Support}(H) = F$ and the function $\mathsf{Decide}(H) = (a, g)$ to retrieve the hypothetical goal and its respective action.

Definition 3 (Conflicting decisions). *Two hypothetical assistance structures $H_1 = \langle F_1, (a_1, g_1)\rangle$ and $H_2 = \langle F_2, (a_2, g_2)\rangle$ are in conflict (defeat) if the following holds: 1) $\mathsf{Decide}(H_1) = \overline{\mathsf{Decide}(H_2)}$; and 2) $\mathsf{Support}(H_2) = \overline{\mathsf{Decide}(H_1)}$, where $\overline{\alpha}$ is the complement of α.*

We can define an *argument-based assistive system* as a deductive system as follows:

Definition 4 (Argument-based assistive system). *Let $\mathcal{H} \subseteq \Delta$ be a set of hypothetical assistance structures and $\mathcal{C}$ be the set of their conflicts. An argument-based assistive system is a tuple $AAS = \langle \Delta, \mathcal{H}, \mathcal{C} \rangle$*

Different *argumentation semantics* have been developed for evaluating and selecting arguments, most well-known are Dung's work on formal argumentation frameworks [23]. Based on Dung's work, we can say that a set S of hypothetical decisions *defends* an hypothetical decision HA_1 *iff* each decision that conflicts (defeats) HA_1 is defeated by some hypothetical decision in S. We can also say that S is *conflict-free iff* there exist no HA_i, HA_j in S such that HA_i defeats HA_j.

Definition 5 (Acceptability semantics). *Let S be a conflict-free set of hypothetical decisions, $HA \in \mathcal{H}$ and let $E : 2^{\mathcal{H}} \rightarrow 2^{\mathcal{H}}$ be a function such that $E(S) = \{HA | HA \text{ is defended by } S\}$. We say that S is admissible iff $S \subseteq E(S)$. S is a complete extension iff $S = E(S)$. S is a preferred extension iff S is a maximal (w.r.t set inclusion) complete extension; and we say that S is a grounded extension iff it is the smallest (w.r.t set inclusion) complete extension.*

We denote these semantics as a function called SEM, which returns *acceptable hypothetical decisions*. More formally, let $SEM(AAS) = \{E_1, \ldots, E_n\}$ be a function returning n *non-conflicting* sets of hypothetical assistance structures from an argument-based assistive system, which are denoted *extensions*, with $E_i = \{H_1, \ldots, H_m\}$.

Definition 6 (Justified decisions). *Let $AAS = \langle \Delta, \mathcal{H}, \mathcal{C} \rangle$ be an argument assistive system. If $\mathsf{SEM}(AAS) = \{E_1, \ldots, E_n\} (n \geq 1)$, then*

- $\mathsf{Decisions}(E_i) = \{\mathsf{Decide}(H) | H \in E_i\} (1 \leq i \leq n)$
- $\mathsf{Common} = \bigcap_{i=1,\ldots,n} \mathsf{Decisions}(E_i)$

Decisions in Definition 6 is a function returning the set of decisions that an agent should take in a particular assistive scenario, *i.e.* considering an extension

E_i as a collection of fragments of activities explaining the current situation of a client and her/his context. On the other hand, Common retrieves the common decision among all the alternatives suggested by different extensions.

4. Methods

The study takes as starting point the use case of distributing medication into a pill dispenser with boxes for a week's consumption. A participatory design methodology [24] was applied, involving older adults and caregivers. The research study proceeded along the following four steps, where older adults and caregivers participated in the first and fourth steps.

Step 1: Involving the older adults and caregivers As a first step, interviews were conducted with older adults and nurses to discuss topics relating to how the activity is conducted, and on needs and perspectives on technology aid for the activity. The semi-structured interview was conducted following the Activity Checklist. Three target users were interviewed in their home or community and their habits and experience of medication management and expectation of the medication distribution supporting technology were explored. In addition, two caregivers participated in the interviews and their experience of supporting older adults managing medications were explored. Unfamiliar technology concepts such as augmented reality (AR) was explained to the participants during the interviews.

Step 2: Activity analysis and preparation of evaluation protocols In the second step, an activity analysis of the activity was conducted, partly based on the interview results and partly based on theories on human occupation, activity and development. The activity analysis informed the design of the AAIMA protocol to be used for evaluation in the fourth step. The following four scenarios for different levels of support were identified based on Activity theory and the activity analysis:

$Case_1$ (ZCD): Individual with assistive needs (a client) conducts the activity independently. No caregiver is present. IAS observes and decides to take no action.

$Case_2$ (ZPD_H): A client conducts the activity and is supported by a caregiver. IAS observes and decides to take no action.

$Case_3$ (ZPD_S): A client conducts the activity and is supported by an IAS. The caregiver is not present.

$Case_4$ (ZPD_{H+S}): A client conducts the activity and is supported by both a caregiver and an IAS at the same time.

These scenarios form the base for the adaptive behaviour of the IAS, and were used when setting up the pilot evaluation study in the fourth step.

Step 3: Build the prototype In a third step the results of the first and second steps were used as base for developing a prototype system, called MED-AR based on technology for multi-agent systems (MAS) and augmented reality (AR). Part of the system's functionalities were collected and inspired by interviews with an expert nurse in elderly care. The MED-AR development was gradual and iterative, testing and presenting partial results to the expert nurse, discussing suitable features of the system.

Step 4: Hands-On experience session and pilot evaluation study In a fourth step, older adults and caregivers participated in sessions of hands-on using the prototype, partly for the purpose to providing them experience of the new technology so that they can further contribute to the design process, and partly to test a set of instruments. Complementary instruments were selected that could provide different aspects of a use situation, and that could contribute to a formative evaluation study of the prototype that would allow the inclusion of personalization functionalities into the re-design of the prototype.

Participants were asked to read a MED-AR system instruction manual, then they distributed three medications with different prescriptions using the system. The session was recorded and analyzed following the AAIMA protocol. Afterwards, participants were asked to complete the NASA Task Load Index

Tool	Aim	Ref.
Activity Checklist	Checklist "perspectives" were applied in the initial interview	[25]
Assessment of Autonomy in Internet-Mediated Activity (AAIMA) protocol	AAIMA applied as tool for activity performance analysis and *breakdown* detection	[26]
Raw NASA Task Load Index (RTLX)	Task load evaluation of the medication distribution activity	[27, 28]
System Usability Scale (SUS)	Employed to analyze the user experience of using the MED-AR to accomplish the medication distribution activity	[29]

Table 1: Instruments used in the study.

(NASA-TLX) questionnaire and the System Usability Scale (SUS) questionnaire to evaluate the cognitive load and user experience of the system. Subsequently, short interviews were conducted to explore their general satisfaction and suggestions of improvements of the prototype.

4.1. Tools and Instruments

Four different tools/instruments were used in this study: 1) the Activity Checklist; 2) the Assessment of Autonomy in Internet-Mediated Activity; 3) the Raw NASA Task Load Index; and 4) the System Usability Scale. Table 1 presents a summary of the aim and the reference for every tools used in this study. In the following, they are presented and motivated.

4.1.1. The Activity Checklist

The Activity Checklist was developed to operationalize activity theory and used as a guide in early design stage. It has four sections that correspond to the four main perspectives on the design of a target technology. The perspectives were applied to conduct the initial interview and translated to the themes of the content analysis of the initial interview data [30, 31]. The themes were: 1) means and ends, which means the extent of activities and potential conflicts of the system using, 2) environment, which means the extent of existing resources which can be integrated into the implement of the system, 3) learning, which means the extent of representations of the system design, and 4) development, which means the extent of anticipated positive changes.

4.1.2. Assessment of Autonomy in Internet-Mediated Activity (AAIMA)

The medication distribution activity to be supported by the MED-AR was analyzed based on the results from the initial interviews. The AAIMA (Assessment of Autonomy in Internet-Mediated Activity) protocol [26] was adapted based on the results, and applied as tool for observation in the pilot evaluation study. In order to observe and analyze users' performance of main activity, the distinction of different level of activity were defined according to the knowledge and skills required to complete the main activity. In addition, four levels of complexity of different level of activities were described, corresponding to the knowledge and skills required to accomplish the task. Users' potential knowledge and mental process were analyzed by the level of independence between 1) when the user can complete the activity autonomously without guidance; 2) when the activity lied in the ZPD where the user could be guided by the system as the more capable peer (ZPD-S); 3) when the activity lied in the ZPD where it was judged that the further support from more experienced human peers was needed (ZPD-H); and 4) when the user need to be supported by the system and man peers at the same time (ZPD-H+S). The observer acted as the more skillful peer to guide users towards a higher level when they encountered breakdowns. As soon as users could transform to the higher level of the activity, their independence was increased. Reasons for breakdowns were also identified that could be caused by the design of the system.

4.1.3. Raw NASA Task Load Index (RTLX)

In order to explore the task load of using the MED-AR to support medication distribution activity, this study adopted Raw NASA Task Load Index

(RTLX) questionnaire as an evaluation tool. The RTXL questionnaire includes six load indices (mental demand, physical demand, temporal demand, performance, effort and frustration) measured using a scale from 0 to 100 increments of 5 anchored by bipolar descriptors (low and high) [27, 28].

4.1.4. System Usability Scale (SUS)

The System Usability Scale (SUS) [29] was employed to analyze the user experience of using the MED-AR to accomplish the medication distribution activity. SUS is a ten-item and 5-point Likert-type scale (1 = strongly disagree; 5 = strongly agree) giving a global view of subjective assessments of usability. According to the definitions of the user experience indicators of instrumental and psychological tools [32], this study categorized the ten statements into two dimensions: instrumental experience and psychological experience. The instrumental experience statements indicated that there are no unnecessary complications in using the tool and feelings of achievement such as "*I think that I would like to use this system frequently*" and "*I thought there was too much inconsistency in this system*". The psychological experience statements illustrated that the user is confident in using the tool and the tool is embodied to the extent that the usage feels effortless and natural such as "*I thought the system was easy to use*" and "*I felt very confident using the system*".

4.2. Study Participants

This study involved five participants comprised of three *target users* (TA-1, TA-2, TA-3) at the ages between 57 and 72, with chronic diseases as target users who were home-bound and who had used medication dispensers to manage their medications for a longer period than six months. Two caregivers (S-1, S-2) were recruited to contribute with the professional perspective on medication management.

4.3. Background and motivation to the use case scenario

Routine Activities of Daily Living (ADL) may be complex and challenging for older adults with impaired physical and cognitive functioning [33, 34].

Participation	Age	Sex	Profession
TA-1	67	M	Retirement (worked in journalism)
TA-2	71	M	Retirement (worked in deaconess)
TA-3	57	F	Computer science and law
S-1	50	F	• Health and nursing science for more than 20 years • Registered nurse for 9 years
S-2	25	F	• Human-computer interaction for more than 2 years • Elderly care for more than 4 years

Table 2: Demographics of participants

Medication distribution was seen as a complex activity that requires different cognitive and physical skills, and was therefore selected as an activity of interest to be supported. Older adults have been found to use an increasing number of medications as they become older and prior study has shown that 25% to 40% of adults aged 65 years or older are prescribed at least five medications [35, 36]. Declining functions such as attention, executive functioning, memory, etc., may challenge older people to follow medication instructions and distribute medication in dispensers [37].

5. Base for Design

The participating older adults relied on using medication dispensers to manage medication. When they distributed their medications to dispensers, they need certain information about the medication and prescription, which is the same as caregivers' need. The information includes the patient information (name and birthday since there can be more than one person in the household), the name of medication, the dosage (time and amount), the way to take the medication such as crushing, and when to be cautious about e.g., side effects. Some of this information is needed every time medicine is put into the dispenser, other is needed at the point of taking the medication. The information is provided in paper, and typically also as oral instructions by prescribing physician and when buying the medicine at the pharmacy. The different sources of information were viewed at as source for stress and confusion, and worries that they may miss something important. In addition, sometimes the medication could be provided that looks different from time to time, since the cheapest brand is provided, which changes over time. As a consequence, while health-care institutions such as hospitals and pharmacies played important roles in the older adults' medication management, they also caused some confusion. Therefore, after the older adults received a medicine prescription from doctors, they relied on the help from nurses and pharmacists for distributing the medicines.

The caregivers emphasised that support from caregivers and an IAS has to be consistent and coordinated. This view was supported by the older adults' concerns regarding inconsistencies in information from different sources.

The older adults tended to preserve their medications in certain cabinets, which follows a pattern found in other studies [38, 39]. Older adults took out the medications from cabinets and then distributed the medications to the dispensers. However, medications in cabinets may belong to different family members who lived together and/or visited occasionally. Moreover, older adults mentioned that some medications that were not recently used were preserved in cabinets as well.

It was observed that the older adults used dispensers and the process of distributing medications to support other goals. Placing the dispensers where the person would see it, reminded to older adults to take the medications, and whether or not they had taken the medication.

All the participants expressed a desire to receive personalised support in different health-related activities (*e.g.,* distributing medication among other activities of daily living). This view is in line with research on tailoring health-care systems ([40, 41, 42]).

To summarise, the following are the key requirements for an IAS obtained in the first stage: i) personalised support; ii) transparent information with source information; iii) information both at medicine distribution and when taking medication; iv) context awareness: e.g., information if some medicine is old or prescribed to other person in the household; v) coordination between human and IAS support.

As a consequence, the analysis of the activity distributing medication into a pill dispenser resulted in a modified AAIMA protocol (Table 5). Focus was put on understanding instructions, since this was most important to the participants. Different levels of potential understanding and capability were specified, to assess level of need for support.

6. The Prototype System MED-AR

In this section, the IAS MED-AR that was built and tested is presented. A detailed analysis is provided of the MED-AR activity reasoning module that is in charge of the automatic adaptation to situations of different need for assistance, which is a main focus of this research.

MED-AR is an IAS oriented specifically to support an older adult in the activity: *medication management* using a *smart medicine cabinet*. The MED-AR architecture is presented in Figure 2 and the different modules are illustrated in Figure 3.

MED-AR consists of five main parts: 1) gestures recognition: obtaining observations from individuals using Kinect cameras; 2) text recognition using another Kinect camera with Google API text recognition (`https://cloud.google.com/vision`); 3) an argument-based reasoning process, the main agent-based mechanism for reasoning about the client's activities and environment; 4) the outcome of reasoning provided the client as support through AR: a module to generate support as projections in the smart environment; and 5) a database of medicine doses to obtain appropriate messages.

Three 3D cameras were used for capturing: 1) observations of an individual that may need help in an activity; 2) observations of the smart environment, including potential other persons; and 3) information about the gestures re-

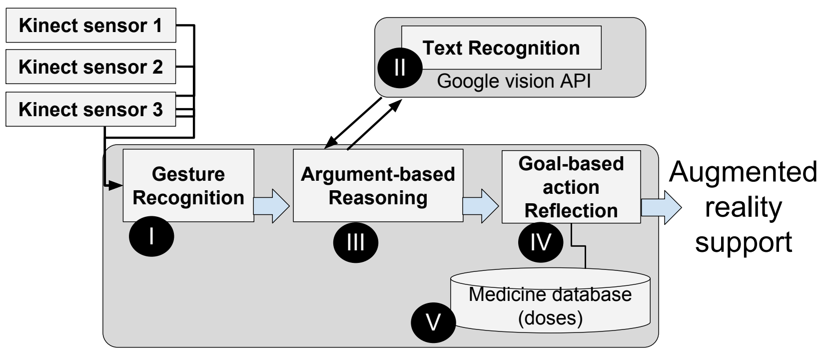

Figure 2: General architecture of the knowledge management of the MED-AR system using formal argumentation theory and augmented reality. I) Gesture recognition using three Kinect cameras, one for client body capture, another for assistant personal gesture recognition, last one (Kinect sensor 2) on the top of the cabinet to recognize text from medicines boxes; II) Google API for text recognition; III) argument-based reasoning; IV) the outcome from the automated reasoning provided as support to the client through AR; V) database containing doses and timing of pill intake.

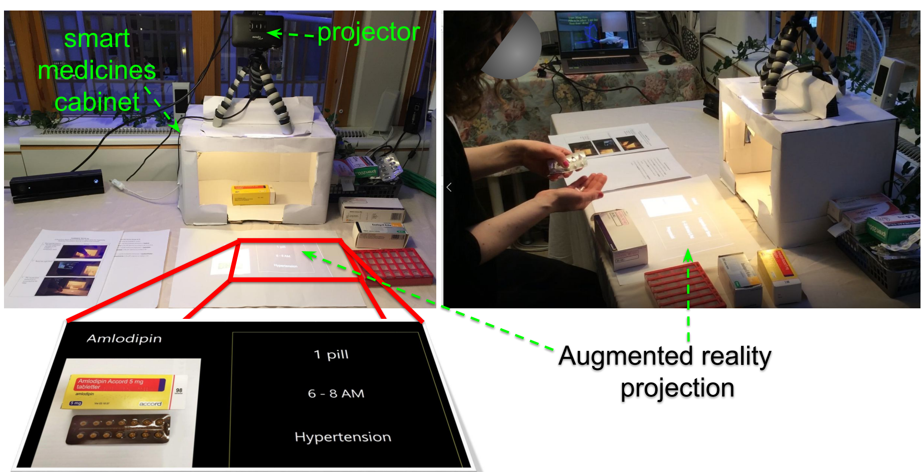

Figure 3: Smart medicine cabinet using argument-based reasoning and an augmented reality projection. Technology shown includes kinect sensors for gesture recognition and recognizing text from medicines boxes and the AR projection.

quired for medicine manipulation. A computer was connected to the cameras, processing the information in real-time analyzing gestures of individuals as observations. The agent platform, JaCaMo [43] was used to build the agent. An

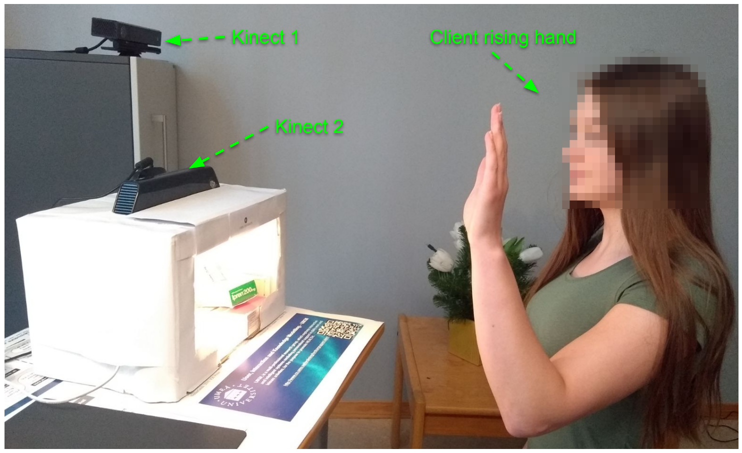

Figure 4: Demonstration of how a client activates MED-AR rising an arm. Kinect camera 1 detects the gesture activity and Kinect camera 2 (inside of the smart cabinet) captures a RGB image of the available medicine.

argumentation process was used using an argumentation library previously developed (see [44]).

The smart cabinet connected to MED-AR was built using a box to make the access easy for the client, see Figure 4. It has a bulb inside to allow the client to see what pill boxes are inside. Moreover, the internal light of the cabinet facilitates a better quality of the pictures taken by the RGB camera of the Kinect.

MED-AR interacts with a client as follows (see Figure 4): 1) Client approaches to MED-AR cabinet; 2) Client rises an arm; 3) Kinect camera in the smart cabinet takes a picture of the medicine labels and sends picture to Gesture Recognition module; 4) Text of medicine labels is identified by Google Vision API and returned to MED-AR; 5) Argument-based reasoning starts and retrieves information from Medicine Database about doses; and 6) An image of the medicine with the doses is projected as AR on the table close to the smart cabinet.

The argument-based reasoning module manages the knowledge of an IAS. A general architecture of this module is presented in Figure 2. Five subsystems are defined, which implement the underlying argumentation theory.

6.1. Argumentation-Based Reasoning about Level of Support

In this section we present how the *Activity Reasoning* module (Figure 2) selects a decision in the four case scenarios. Key part of the analysis of ZPD and activity change in general, is the detection of *breakdowns* of an activity. To characterize a breakdown framed by an activity model $AM = \langle \mathsf{Ax}, \mathsf{Go}, \mathsf{Op} \rangle$ we use a function $\mathsf{Achieved}(F, R) : F \subseteq AM \times R \subseteq AM \to \mathbb{R}[0,1]$ which compares a "distance" function between the fragment of activity F detected by the assistive system with respect to another fragment that we call *reference* R.

Proposition 1 (Activity breakdown). *Let AAS be an assistive system evaluated with a semantics $\mathsf{SEM}(AAS) = \{E_1, \ldots, E_n\}(n \geq 1)$, an activity breakdown is detected if the following conditions hold:*

- $\mathsf{Achieved}(F, R) = \emptyset$
- $Common \neq \emptyset$

Proposition 1 establishes a *boundary* of what we designate a breakdown, with a first condition when an individual is not achieving a part of an activity that is supposed to be executed, and when the assistive system generates a support. We will use conditions of Proposition 1 to investigate four scenarios proposed in Section 4.

ZCD: independent activity execution

In this scenario, the client performs an activity without the support of another human or software agent. This scenario provides a baseline of the current performance of a client, we call this information as a set of *reference* observations. Moreover, the assistive system does not take any decision oriented to support the activity, *i.e.* it takes the purposeful decision to do nothing.

In the following, some conditions for a ZCD scenario are identified, establishing general *constraints* of the decision-making mechanism based on an argument-based reasoning process for such scenario. In this paper, the selection of an argumentation semantics SEM is not explored [45, 46] but included in the following presentation.

Property 1 (ZCD scenario). *In a ZCD scenario where an* $AAS = \langle \Delta, \mathcal{H}, \mathcal{C} \rangle$ *defines the decision space of an assistive system, and* $\mathsf{SEM}(AAS) = \{E_1, \ldots, E_n\}(n \geq 1)$ *generates* n *different assistive scenarios, the following holds:*

- $\mathsf{Achieved}(F, R) = \emptyset$
- $\mathsf{Decisions}(E_i) = \{\emptyset,\ do\_Nothing\}$
- $Common \neq \emptyset$

In Property 1, $do\_Nothing$ is an action that an assistive system decides to take which is to take no action. In a ZCD scenario, the intelligent assistive system obtains a set of observations $O^{'} \subseteq F$ of the client and her/his environment. In the test sessions, MED-AR used three different 3D cameras to obtain observations from gestures of the client, her/his room environment and labels of the pill boxes. In the sessions, this "null-action" was suggested by SEM when reference observations R were obtained. In fact, we use machine learning to record such reference set of observations.

ZPD_H: activities supported by caregiver

In this scenario, an individual receives support from another person, for example a caregiver. Similarly to the ZCD scenario, the role of an assistive system is observe and learn without suggesting active support.

Property 2 (ZPD_H scenario). *Let* $AAS = \langle \Delta, \mathcal{H}, \mathcal{C} \rangle$ *be a decision space of an assistive system and* $\mathsf{SEM}(AAS) = \{E_1, \ldots, E_n\}(n \geq 1)$ n *different assistive scenarios. In a* ZPD_H *scenario the following holds:*

- $\mathsf{Achieved}((F \cup F^{'}), R^{'}) = \emptyset$
- $\mathsf{Decisions}(E_i) = \{\emptyset,\ do\_Nothing\}$

- $Common \neq \emptyset$

Formal conditions for this scenario are extended from Property 1. In a ZPD_H scenario, new activity fragments of the caregiver $F^{'}$ are analyzed by the assistive system. The set $R^{'} \subseteq AM$ is a joint reference activity information about the client and the caregiver. Similarly to scenarios where the assistive technology analyzes independent execution, decisions do not involve any active support (see condition 2 in Property 2).

In our pilot scenario using MED-AR, we did not capture activity gestures from the caregiver given the lack of computational power of our system to add another 3D camera. We plan to extend MED-AR with measurements of activity gestures for caregivers as part of our future work.

ZPD_S: activities supported by an assistive system

In this scenario, an assistive agent takes the decision to support an individual by taking *active* decisions.

Property 3 (ZPD_S scenario). *Let AAS be a decision space of an assistive system and $\mathsf{SEM}(AAS) = \{E_1, \ldots, E_n\}(n \geq 1)$ n different assistive scenarios. In a ZPD_S scenario the following holds:*

- $\mathsf{Achieved}(F, R) = \emptyset$
- $\exists a \in \mathsf{Decisions}(E_i) \neq \{\emptyset,\ do\_Nothing\}$
- $Common \neq \emptyset$

Main property of a ZPD_S scenario is the existence of a decision warranting a non-passive behavior, *i.e.* different than *do nothing*. The last condition in Property 3 $Common \neq \emptyset$ provides a *strong* requirement for an assistive system. In fact, for an argument-based reasoning process, this last condition implies a careful selection of SEM.

ZPD_{H+S}: activities supported by both caregiver and agent

This scenario involves the joint support provided the client by both a caregiver and an assistive system. A main challenge for the assistive system is to detect: 1) actions that the caregiver executes, and 2) observations of the caregiver and client. This complex scenario involves same conditions than ZPD_S however some constraints need to be defined to keep consistency among caregiver and assistive system support decisions.

Property 4 (ZPD_{H+S} scenario). *Given a decision space of an assistive system AAS and* $\mathsf{SEM}(AAS) = \{E_1, \ldots, E_n\}(n \geq 1)$ *n different assistive scenarios and* $AM = \langle \mathsf{Ax}, \mathsf{Go}, \mathsf{Op} \rangle$ *be an activity model. A* ZPD_{H+S} *scenario has the following characteristics:*

- $\mathsf{Achieved}((F \cup F^{'}), R^{'}) = \emptyset$
- $\exists a$ *such that:*
    - $a \in \mathsf{Decisions}(E_i) \neq \{\emptyset,\ do\_Nothing\}$*; and*
    - $a \neq b \in \mathsf{Ax}_{caregiver}$
- $Common \neq \emptyset$

Property 4 can be seen as a first step in the formalization of general logical assistive constraints for intelligent systems supporting individuals. In our future work, we would like to extend to more complex scenarios in order to cover different interactions among a client, a caregiver an assistive system.

7. Results of the Pilot Evaluation Study

The purpose of the pilot evaluation study was to introduce the new technology to the participants to increase their knowledge and experience so that they could better contribute to the design process, and to evaluate the prototype and the complementary instruments selected for the purpose.

In this section, results regarding the users' performance and experience are presented from the perspectives of instrumental and psychological functions, in relation to an activity outcome, procedure, and experience by the individual (Table 3).

	Performance: outcome	**Way of acting: core task orientation**	**User experience: potential use development**
Instrumental function	• Task completeness • Errors • Time	• Breakdowns	• Impressions of a Well-functioning tool
Psychological function	• Task load	• Transformation between activity levels	• Embodiment feeling • Self-confidence

Table 3: Perspectives on the medication distribution activity and their indicators applied in the evaluation study of the MED-AR system.

7.1. Instrumental Functions

In order to evaluate how the system MED-AR supports the medication distribution activity, different characteristics of activity fractions (tasks) were investigated: completeness, failures, time of the tasks, breakdowns during a task, and instrumental experience items from SUS questionnaire. An overview of the results are shown in Table 4.

Breakdowns, understood as abrupt interruption of task execution, occurred at all levels of activity (see Table 5). The three participants faced problems detecting gesture (Operation level 2 and Activity level 2). The gesture sensor could not detect the defined gesture (raise right hand) to start the medication detection.

TA-1 was confused about dosage at the beginning but he conducted the task in a correct way after some thinking (Action level 1, Table 5). In addition, TA-1 distributed one kind of medication in the wrong way (Activity level 3, Table 5).

Item	TA-1	TA-3	S-2
I think that I would like to use this system frequently	3	1	4
I found the system unnecessarily complex	2	4	2
I found the various functions in this system were well-integrated	5	2	4
I thought there was too much inconsistency in this system	1	4	1
I would imagine that most people would learn to use this system very quickly	4	2	4

Table 4: Overview of the results relating to instrumental experience. 1 means strongly disagree, 5 strongly agree.

He read the medication instruction but grabbed the medication box, which was located next to his hands instead of the correct one, which was placed on the shelf.

To summarize the participants' experience, TA-1 and S-2 had more positive familiarity using assistive systems compared to the rest of participants (see summary in Table 4). TA-1 and S-2 perceived the system as not complex, well integrated, consistent and easy to learn. TA-1 considered he has gotten used to managing the medication that he already had so this system would be more useful when he had to take new medication. He also thought that the equipment and the setting up of this system might cause a bit complexity and longer time of learning. S-2 would like to use this system because she viewed the new technology as a new way to support relatives and expressed excitement about this. When TA-3 used the system, the gesture sensor could not detect her gestures well and it took a while to solve. This problem caused more negative instrumental experience of using this system.

To summarize the observations during the pilot study, the participants understood the way of conducting the proposed activity, although the augmented reality component was new to them. Even if the gesture detection was not easy to be completed and caused breakdowns, participants handled them by an external support provided by a caregiver (ZPD-H). Afterwards, participants

Level of activity	Activity description	Level of independence		
Activity	**Distribute Medication**	**TA-1**	**TA-3**	**S-2**
Level 0	Understands the purpose of the activity but does not participate	A	A	A
Level 1	Contributes with operation information	ZPD-S	ZPD-S	A ZPD-S
Level 2	Contributes with medication information	ZPD-S	ZPD-S	A ZPD-S
Level 3	Completes the medication distribution	ZPD-H	ZPD-S	A ZPD-S
Action	**Understand Medication Instruction**			
Level 0	Able to trigger the projection of medication instruction	ZPD-S	ZPD-S	A ZPD-S
Level 1	Understands the different contents of medication instruction	ZPD-S	ZPD-S	A ZPD-S
Level 2	Able to use the instruction to distribute medication	ZPD-S	ZPD-S	A ZPD-S
Level 3	Full understanding of the function of the system and its role in medication distribution	ZPD-S	ZPD-S	A ZPD-S
Operation	**Interact with interaction devices**			
Level 0	Basic tasks have a objective in itself, i.e., are executed as activities	A	A	A
Level 1	Basic tasks have partly been integrated in activity as goal-oriented actions among other actions	A	A	A
Level 2	Basic tasks are partly operationalised, cause breakdowns, but are handled by the participant	ZPD-H	ZPD-H	A ZPD-H
Level 3	Basic tasks are operationalised	ZPD-S	ZPD-S	A ZPD-S

Table 5: The AAIMA protocol, and the assessment of participants level of independence when conducting the activity using MED-AR as a tool.

were able to operate the gesture detection by following the guidance of the system (ZPD-S). Generally speaking, MED-AR guided all participants to be able to understand the medication instructions (ZPD-S) and distribute medications (ZPD-S). However, TA-1 did not complete the activity correctly when he distributed the last kind of medication and needed the observer to explain his mistakes (ZPD-H).

7.2. Psychological Functions

In order to explore how participants learn and develop the activity of distribute medication by using the MED-AR, their task load was analyzed together with the transformation between activity levels and the psychological experience, see Table 6.

Item	**TA-1**	**TA-3**	**S-2**
Mental demand	0	5	5
Physical demand	5	65	20
Temporal demand	15	5	5
Performance	50	10	0
Effort	0	65	20
Frustration	5	75	15
Raw workload score	11.67	37.50	10.83

Table 6: Overview of the results relating to task load, the values can range between 0-100, where 100 is maximum task load.

TA-1 perceived higher performance failure because he dropped down some medications on the floor when he executed the tasks. TA-3 perceived higher physical demand, effort and frustration because she felt annoyed when the gesture detecting did not work well. S-2 perceived she managed the tasks well but she sometimes felt worried about that if the system successfully detects her gestures.

Table 5 shows the users' transformation between activity levels and the need for support at different levels. Participants were all skilled computer users, and familiar with the tasks of medication distribution without technology aid.

An overview of the results from the evaluation of psychological experience is provided in Table 7. TA-1 and S-2 perceived the system as easy to use and that prior knowledge and skills were not needed. TA-1 also considered the system as smart to use and safe. S-2 thought the medication information provided by the system was easier to read and understand than the one of prescription label on the medication box. However, TA-3 and S-2 commented that the system instruction and the gesture detecting could be improved to optimize the use experience.

Item	TA-1	TA-3	S-2
I thought the system was easy to use	5	2	4
I think that I would need the support of a technical person to be able to use this system	3	4	2
I found the system very cumbersome to use	5	4	1
I felt very confident using the system	5	2	2
I need to learn a lot of things before I could get going with this system	1	3	1

Table 7: Overview of the results relating to psychological experience, 1 means strongly disagree, 5 strongly agree.

8. Discussion

In *human-computer interaction* (HCI) research, activity theory has been used as an analytic tool to analyze and describe human activities, and for designing computer-based systems [47, 48]. Activity theory has been materialised into instruments for design and evaluation of interactive systems as part of research. This study applies the Activity Checklist [49], the amended analytic framework in [32], and the Assessment of Autonomy in Internet-Mediated Activity protocol (AAIMA) [26]. The Activity Checklist reflects the five basic principles of activity theory, which provides guidance in the earliest stages of exploring of how a technology might come into being. It especially used to explore the context of use of a technology and analyse how people use the technology as a tool for mediation. In [50] the Activity Checklist was employed to construct interview questions to evaluate the BUILD-IT system as a projection-based AR tool for computer-supported collaborative work (CSCW). Ssozi-Mugarura *et.al.* in [51] adopted Activity Checklist as the structure of coding themes to analyze how computer-based technology can be used to manage water resource by people with lower literacy and less experience of technology. Savioja and colleagues incorporated the concepts of activity theory to develop an evaluation method for control rooms in safety-critical industry [32]. The method highlighted the principles of activity theory *object-orientedness* and *mediation*, and the embodied interaction between human beings, artifacts, the context and the social culture.

In contrast to aforementioned work, we use activity theory as a foundational framework for different purposes in different stages, e.g.; the activity theory-based scenarios to inform the design of the system, the internal reasoning of the system about what type of support to generate in the different situations, the methods how evaluating the use of the system in the different situations, and also how this could be done over time when the persons ability changes. MED-AR aims at functioning as a *mediating* assistive tool, while the client is focusing on the medication distribution as the objective (*object-orientedness*). In addition, in this study activity theory was complemented with a focus on evaluating instructional and psychological functions when individuals use MED-AR. The AAIMA protocol was adopted to add the perspective of hierarchical structure of an activity, *internalization*, *externalization* and development (see Table 3). The AAIMA protocol was used for structuring observations of the individual's skills development. This was done by applying the concept of Zone of Proximal Development -ZPD- to different levels of activity, and by observing the transformation between levels caused by breakdowns and conflicts. In earlier studies, the AAIMA protocol was applied to evaluate a clinical decision-support system [52], with focus on how clinicians developed their knowledge and skills by using the system as the more capable peer. The hierarchical structure of activity as defined by activity theory has been used as framework to represent knowledge of software agents (*e.g.* [53, 54, 55, 56]). This work applies the same approach, but extending to incorporate also ZPD as means for automating adaption of support to the individual and to the situation. This research is in its early stages, both in the development of theory-based person-tailored automated support and the presented study is also in the earliest stage of a participatory design process, where the older adults and caregivers are becoming prepared to become fully participants in the further development. When familiarity with new technology is sparse, it is valuable to present opportunities in the form of interactive prototypes early in the design process to encounter and experience new technology to move further in the design process.

8.1. Argumentation-based decision-making approach for assistive systems

The four scenarios based on ZPD investigated in this paper to understand how assistance can be provided and in what situations, have been extensively investigated in the social sciences literature (see for example [57]). However, from an artificial intelligence perspective, there is scarce research covering such complex scenarios. Furthermore, there is a considerable lack of proposal introducing general principles or foundations that an intelligent system (software agents) should follow to fulfill a minimal criteria of consistency. We propose general properties that an assistive system based on artificial intelligence should follow based on logic, inputs and outputs of the decision-making process (Properties 1, 2, 3 4). The properties are expected to be general enough to be applicable for building assistive systems also in other domains, which will be further investigated in future work.

Another research line to explore, is to investigate the behavior of the decision-making process when different argumentation semantics are applied. The typical outcome of applying argumentation semantics (e.g. preferred, complete, grounded) is one of the following three: *accepted*, *rejected* or left *undecided*. In order to always provide assistance (see condition 2 in Property 3 and 4), the use of *stable* semantics that is most cautious, may not be recommended. In fact, *frustration* felt by some of the pilot users (see Table 6) could increase if an assitive system would not suggest a particular decision, *i.e.* $\mathsf{SEM}(AAS) = \emptyset$.

Formal argumentation theory research dedicated to investigating quality of argumentation-based systems has resulted in a set of soundness and completeness postulates (see [44, 58, 59, 60]). As a future work, general principles for argumentation-based assistive systems covering also other deductive systems could be proposed.

9. Conclusions

The main contribution of this paper is an empirical and formal understanding of the interplay between an assistive agent-based software, a person to be assisted and a caregiver.

The motivation for using activity theory was to understand an activity from different perspectives covering users' needs, potential to develop skills and ability and limitations including needs for support. An aim of the study was to explore means to engage older adults and caregivers from the start in a participatory design process. This was accomplished through initial activity theory-based interviews when the participants reflected upon potential use of intelligent AR technology. They gained knowledge about AR and IAS technology and the empowerment that could be provided by technology. In a next phase, they further developed knowledge, experience and opinions when using the prototype as tool when conducting the target activity, which allowed them to further contribute to the development of the prototype system.

Moreover, the pilot user study showed that MED-AR has some properties to support users in medication distribution, which were in line with the object-orientedness and mediation perspectives of activity theory. For example, the task load was low and some participants perceived this system was not complex, instead well-integrated, consistent and easy to learn.

The Zone of Proximal Development (ZPD) was formalized and implemented in the prototype system MED-AR for medication management as an aid for personalization of its behavior, and to coordinate cooperation between the user, the caregiver and the IAS.

Formal argumentation theory was used for building the decision-making process of the system. Two important formal contributions were introduced in this paper: 1) a formal characterization of an *breakdown situations*, which follows an activity theoretical approach and is general enough to be used in other decision-making process for deductive systems; and 2) a formalization of different scenarios based on ZPD where activity development is detected. This approach will be applied in other application domains, and further evaluated to see if the four categories of situations are covering the situations that may occur in actual use.

9.1. Limitations

Results relating to user experience and performance obtained in the pilot study are only indicative, since the number of participants was limited. Moreover, the ecological validity of the study was limited, since part of the study was conducted in a laboratory environment. In order to move further in the participatory design process, a new group of older adults and caregivers will be involved in order to further evaluate and develop MED-AR. MED-AR will also be used in home environments with more participants to study the use over a longer period of time.

Some technical limitations of MED-AR will be solved by replacing the Kinect cameras (v1 and v2) with faster and portable 3D cameras.

Acknowledgments

The authors are grateful to the participants. The research was partly funded by the Kempe Foundation.

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