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LONG PAPER

Usability, accessibility and ambient-assisted living: a systematic literature review

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Abstract Ambient-assisted living (AAL) is, nowadays, an important research and development area, foreseen as an important instrument to face the demographic aging. The acceptance of the AAL paradigm is closely related to the quality of the available systems, namely in terms of intelligent functions for the user interaction. In that context, usability and accessibility are crucial issues to consider. This paper presents a systematic literature review of AAL technologies, products and services with the objective of establishing the current position regarding user interaction and how are end users involved in the AAL development and evaluation processes. For this purpose, a systematic review of the literature on AAL was undertaken. A total of 1,048 articles were analyzed, 111 of which were mainly related to user interaction and 132 of which described practical AAL systems applied in a specified context and with a well-defined aim. Those articles classified as user interaction and systems were further characterized in terms of objectives, target users, users' involvement, usability and accessibility issues, settings to be applied, technologies used and development stages. The results show the need to improve the integration and interoperability of the existing technologies and to promote user-centric developments with a strong involvement of end users, namely in what concerns usability and accessibility issues.

Keywords Ambient-assisted living · User interaction · Usability · Accessibility · Systematic literature review

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1 Introduction

A digital environment with a pervasive and unobtrusive intelligence that is able to proactively support people in their daily lives is the fundamental idea of the ambient intelligence (AmI) concept [1]. Ambient intelligence deals with new paradigms where computing devices are spread everywhere (ubiquity) to allow intelligent and natural interactions between the human beings and the physical environment.

As a consequence of AmI developments, AAL emerges as an important instrument within the required strategies to face the societal challenges related to the demographic aging [2]. The general goal of AAL solutions is to apply the AmI concept and technologies to enable people with specific needs (e.g., elderly) to live longer in their natural environment.

In technological terms, AAL comprises a heterogeneous field of technologies, products and services ranging from quite simple devices such as intelligent medication dispensers, fall sensors or bed sensors to networked homes and complex interactive systems [2]. The automation of an AAL environment can be viewed as a cycle that goes from perceiving the state of the environment to reasoning about it in order to achieve a specific goal or anticipate outcomes of possible actions and acting upon the environment to change its state [3].

Like all intelligent agents, AAL systems rely on sensory data collected from the outside world. The perception of the outside world requires that devices are embedded in the environment with the purpose to allow the interaction of the human beings with the technology. Data collected by the sensors have to be transmitted by communication networks and preprocessed by complex components, which collate and harmonize data from different devices. To make that information useful to the occupants of the environment, AAL systems must have high-level reasoning and decision-making abilities in order to arrive at a correct diagnosis and advice or assist the users accordingly [3]. Action execution flows top down. It is transmitted by the communication networks to the physical actuators. These change the states of the surrounding environment according to the instructions received.

Therefore, sensing, communicating and acting are crucial issues in the AAL paradigm [4, 5] for a number of reasons: (1) sensing—a sensorial network is indispensable to obtaining accurate information about the environment and its users; (2) communicating—all the components of an AAL environment have to be interconnected in order to communicate among them; (3) acting—any AAL system must be able to act, through various types of actuators, in order to achieve its objective.

Effective architectures are required to mask the effects of heterogeneous physical devices, communication networks, intelligent components and systems. Furthermore, AAL systems must be able to properly distinguish the users present in the environment, recognize the individual roles, needs, preferences and limitations, evaluate different situational contexts, allow different answers according to personal requirements and situational contexts and anticipate desires and needs without conscious mediation.

Having all the information about their users, AAL systems are able to decide what services to provide and to whom, how and when they should be provided. Moreover, the users should use, enjoy and be involved in AAL technologies, products and services. Therefore, user interaction is another important component of the AAL paradigm and should assist the users in their daily activities, making their lives more comfortable and helping them to participate in all areas of life, as well as be accepted and included. This means that AAL systems must have a broad range of intelligent functions in terms of user interaction, supported by usable and accessible interfaces with adaptive mechanisms [6].

The term usability is often used to refer to the capability of a product or a service to be easily used. This corresponds to the definition of usability as a software quality in ISO9126-1: "a set of attributes of software which bear on the effort needed for use and on the individual assessment of such use by a stated or implied set of users" [7, 8]. However, the concept of usability also assumes qualities such as fun, well-being, collective efficacy, esthetic tension, enhanced creativity, support for human development and many others. Usability is the extent to which a product or a service may be used by specific users in a given context of use, to achieve specific goals with efficiency and effectiveness, while promoting feelings of pleasure [9, 10]. Good usability has several benefits, such as [11, 12] reduced error rate, minimized training requirements, improved acceptance and increased efficiency and productivity. Furthermore, good usability has a strong impact in users with specific needs.

Accessibility can be viewed as the ability to use and benefit from an entity (e.g., device, interface, resource, system, service or environment) and is used to describe the degree to which different entities can be used by as many people as possible. Accessibility is often used to focus on people with disabilities and their right to access to the available products and services, often through the use of assistive technology. However, some issues typically considered as accessibility problems also affect non-disabled users because accessibility is not only influenced by the individual characteristics of the user, but also dependent on the context of use, the scope and nature of tasks being performed and the technological devices and infrastructures used [13, 14]. Closely related to the accessibility concept, universal access promotes the usability and accessibility of products and services by all users, independently of individual abilities and characteristics, the scope and nature of tasks and the contexts of use [15].

Usability and accessibility should not be considered all-or-nothing binary properties, but continuous properties with a complex set of attributes, most of them dependent on different levels of subjectivity. Therefore, to establish the usability and accessibility of a product or a service, it is necessary to evaluate it with individual users, possibly using specific assistive technologies if the users have impairments that prevent them from interacting directly.

Usability and accessibility evaluation is an important part of the overall design of user interaction systems, which consists of interactive cycles of design, prototyping and validation. The vast majority of development processes focus entirely on adherence to technical and process specifications. This is one of the main reasons why some products or systems have failed to gain broad acceptance [12]. The introduction of user-centered methods ensures that "real products can be used by real people to achieve their tasks in real world" [11].

The emergence of the "living laboratory" concept represents a user-centric research methodology for sensing, prototyping, validating and refining complex solutions in multiple and constantly evolving real-life contexts. The purpose of such concept in a wider use is to enhance innovation, inclusion, usefulness, usability and accessibility of information and communication technologies and its applications in the society [16]. A central idea is the strong and active involvement of end users in all development phases, since the conceptual design and, later, during the validation and evaluation of the prototypes.

The objective of this paper is to systematically review and classify the AAL literature and to establish the current position with regard to user interaction, namely in terms of usability and accessibility, and, consequently, to evaluate how universal access is implemented within AAL environments. Furthermore, since user-centered design must be emphasized for the development of systems with high user interaction requirements, other goals are to analyze how are end users involved in the development life cycle of AAL systems and to evaluate if user-centric methodologies, in particular living laboratory methodologies, are being used by AAL developers.

The paper is organized as follows: Sect. 2 presents the methods used for the systematic literature review, Sect. 3 contains the detailed presentation of the results, and Sect. 4 discusses the results and presents the conclusions.

2 Methods

The methodology used to conduct this systematic literature review is detailed in the following sections.

2.1 Data sources and searches

Studies were sought using general databases (Web of Science, Academic Search Complete and Science Direct), computer, information science and electrical engineering databases (CiteSeer and IEEE Xplore) and a healthcare database (PubMed).

Two keywords were used without language restriction: Ambient-assisted living, as this was the main focus of this review, and ambient intelligence because AAL is a subarea of AmI. This means that technologies such as user interaction or context awareness that are classified as AmI technologies are also used in the AAL. However, not all AmI systems are considered AAL systems.

The search was performed on February of 2012 and included all references published since the January 1, 2007 till December 31, 2011. This date limit was established as 2007 was the year the "Ambient Assisted Living" Joint Programme was launched by the European Commission [17].

2.2 Study selection and analysis

Abstracts were reviewed by two of the authors, and those not related to AAL were excluded. Included abstracts were then classified by three of the authors into one of 7 areas: (1) conceptual articles (innovative concepts related to AAL or contributing to its development); (2) architectures and frameworks (abstraction of the structure and rules needed to reason about AAL systems and how to implement them, including different middleware approaches, and methodologies required to enable efficient AAL systems engineering, deployment and runtime management [18]); (3) privacy, security and safety (reliability, security and privacy methodologies for increasing human safety [19, 20]); (4) physical devices (the hardware components required for the implementation of an AAL system, including networks of sensors and actuators, to collect and disseminate environmental data and to change the state of the surrounding environment [21]); (5) context awareness (technologies and methodologies to abstract and model the situation of a person, place or object considered relevant to the interaction between a user and a system and able to detect daily patterns, abnormal behaviors and emergency situations); (6) user interaction (advanced and natural human interfaces for multimodal user interaction and methodologies that enhance the effectiveness, usability and accessibility of the systems and theirs interfaces); (7) systems (practical AAL systems applied in a specified context and with a well-defined aim [22]).

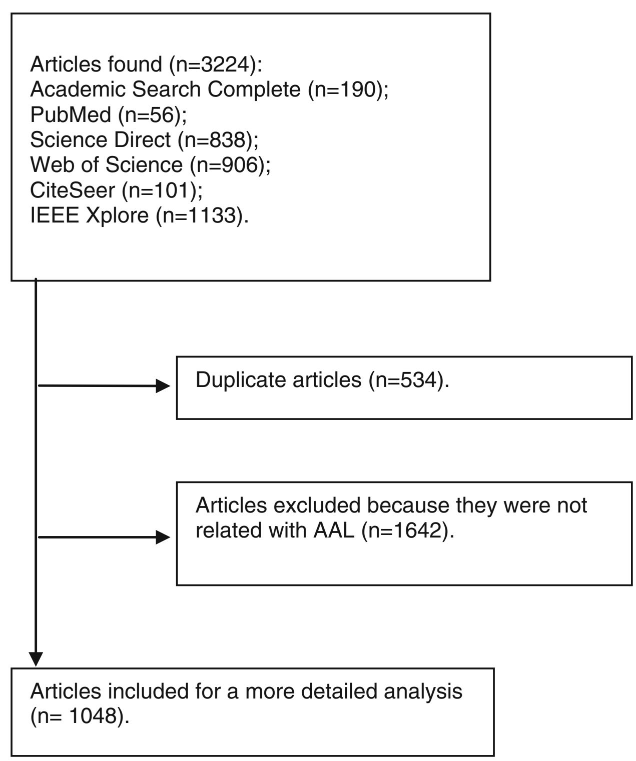

Fig. 1 Flowchart describing the process followed for the systematic literature review

Considering the research objectives, a deeper analysis of the articles related to user interaction and articles reporting systems was performed. Those articles were further characterized in terms of objectives, target users, users' involvement, usability and accessibility issues, settings of application, technologies used and development stages.

3 Results

The database searches resulted in 3,224 references, of which 534 were duplicates and 1,642 were not related to AAL and were therefore excluded. Thus, a total of 1,048 references were included in this review (Fig. 1).

Of the 1,048 included studies, 56 (5 %) were classified as conceptual articles defining innovative concepts, 234 (22 %) were classified as presenting architectures and frameworks, 37 (4 %) were considered as related to privacy, security and safety, 174 (17 %) were classified as describing physical devices, 304 (29 %) were considered related to context awareness, 111 (10 %) were classified as related to user interaction, and 132 (13 %) were classified as describing systems.

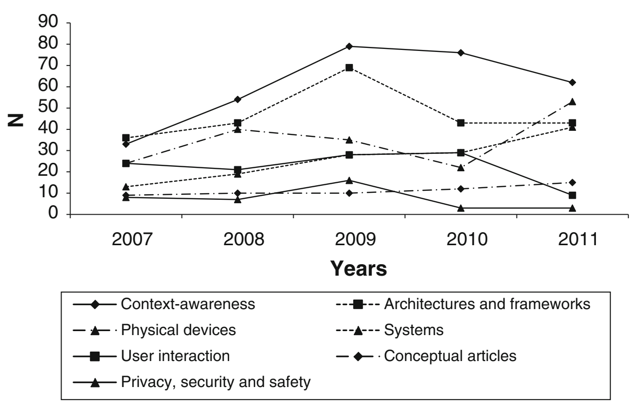

Fig. 2 AAL articles output according to area of classification and year of publication

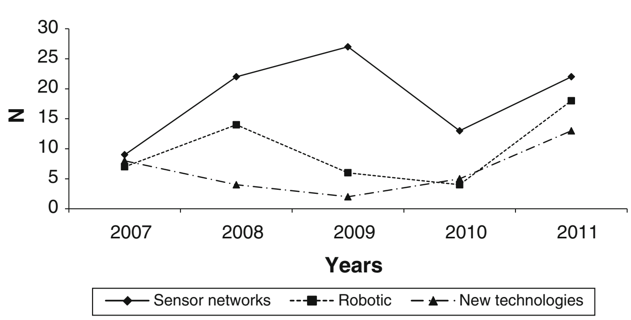

Fig. 3 Output of articles related to physical devices, according to subarea of classification and year of publication

An analysis of publication output by year of publication showed an increase from 2007 to 2009 and a decrease in 2010, with the exception of the number of publications on systems, user interaction and conceptual articles, which are relatively stable or increase slightly from 2009 to 2010. In 2011, the publication output increases (Fig. 2), particularly the number of articles on physical devices and systems (Figs. 3 and 4).

It was necessary to further divide the seven major thematic areas initially identified into subareas because the areas covered very broad subjects. Thus, the conceptual articles were classified on the following subareas: sensor networks, technological development, context awareness, living laboratory methodologies and future challenges for

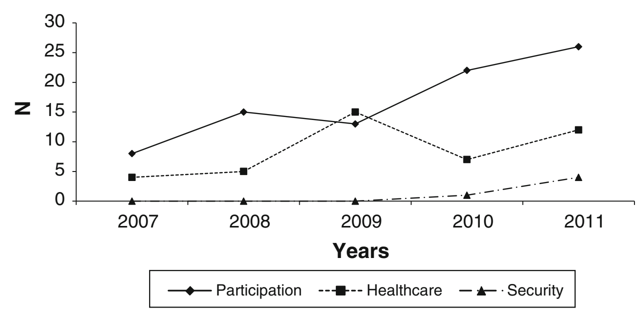

Fig. 4 Output of articles related to systems, according to subarea of classification and year of publication

Table 1 Number of articles in each thematic area and subarea of classification

Conceptual articles (56)

Sensor networks (4); technology development (11);

context awareness (6); living laboratory methodologies (4); future challenges for the AAL systems (31).

Architectures and framework (234)

Architecture (174); design and development methodologies or frameworks (60).

Privacy, security and safety (37).

Physical devices (174):

Sensor networks (93); robotic (49); new technologies (32).

Context awareness (304)

Environment (21); location/tracking (44); identity management (15); identity management and location (12);

Detection of specific events and situations (23); activity/interactions (52); human behavior (33);

Emotions (12); reasoning (92).

User interaction (111)

New interaction mechanisms (46); design methodologies or frameworks (48);

Personalized information (11);

Experimentation (6).

Systems (132)

AAL systems. The thematic area of architectures and frameworks was subdivided into architectures and design and development methodologies or frameworks. The thematic area of physical devices was subdivided into sensor networks, robotics and new technologies. Context-awareness articles were subclassified into environment, location/tracking, identity management and location, detection of specific events and situations, activity/interaction, human behavior, emotions and reasoning. User interaction included the subareas of new interaction mechanisms, personalized information, design methodologies or frameworks and experimentation. Table 1 shows the number of articles identified by area and subarea.

The following subsections present the analysis of the articles related to user interaction and articles reporting systems.

3.1 User interaction

A total of 111 articles were classified in the user interaction thematic area. The vast majority of these articles are related to the development of new interaction mechanisms (46) and design methodologies or frameworks to help the design process of complex interaction mechanisms (48). Additionally, 6 articles are related to the experimentation of interaction issues and 11 articles are exclusively dedicated to new ways of presenting information, namely when the output devices have strong constrains (i.e., display of mobile device [23]) or when it is required to use adequate algorithms to contextualize large amounts of data, collected over time from various locations, to convey abstract information to different user groups having different access platforms, including mobile devices [24].

The 6 articles related to experimentation either focus on specific aspects, sometimes very practical (e.g., assessment of a mobile phone as an input or output device or evaluation, within a living laboratory, if elderly users actually benefited from the use of a touch screen control and a large-scale graphic user interface for controlling telephone or video telephone communications [25]), or are related to basic research that may be important for future user interaction mechanisms (e.g., the evaluation of the impact of negative emotions on user performance [26] or the evaluation of strategies that can reduce working memory load for users of voice interactions [27]).

Considering the articles related to the development of new interaction mechanisms (46), there is a distribution by 9 different interaction typologies. Most occurrences relate to voice interaction, multimodal interaction and interaction using tangible interfaces, 12, 11 and 6 occurrences, respectively. The remaining 17 occurrences are distributed by visual-based interfaces (e.g., eye detection) ($n = 2$), virtual and augmented reality ($n = 5$, including 2 articles referring to avatars), brain computer interfaces ($n = 2$), recognition of gestures and body movements ($n = 5$, including 1 occurrence related to sign language), natural dialogue ($n = 2$) and facial recognition ($n = 1$).

In terms of explicit concerns about elderly or disabled people, 2 articles refer to multimodal interaction for disabled people, 2 report the use of voice interactions for elderly people, 1 refers to the use of a tangible interface for people with cognitive impairments, 1 presents a virtual-reality-based interaction for people with dementia, and 1 refers a multimodal interaction for people with Parkinson's disease. Thus, among the 46 articles, only 7 explicitly refer to elderly or disabled people.

The involvement of real end users in the evaluation of the prototypes is reported by 4 articles: 1 involving children, 1 involving elderly people, 1 involving people with dementia and 1 involving people with Parkinson's disease. In all four studies, the number of the end users involved was lower than ten.

Finally, explicit concerns about usability are expressed in the abstracts of 6 articles. Furthermore, the importance of user-centered design paradigm for the development of a multimodal interface is mentioned [28], a collaborative process involving 34 people with different disabilities is presented [29], specific tools to address the automatic generation of accessible graphical user interfaces in AmI environments are introduced [30], and adaptive interfaces based on the universal access paradigm are presented [31].

The 48 articles related to methodologies or frameworks aim to present comprehensive methodologies and tools to support the design and development of new-generation user interaction mechanisms for AAL systems. Those articles include an ethnographic study to understand the contextual influence on user experiments of intelligent environments [32], proposals of evaluation models for intelligent systems, development models and strategies to improve the involvement of end users. Additionally, a review of the methods already available and which are still missing to support an efficient development of AmI systems is presented [33]. The analysis shows that 7 articles consider the requirements of elderly or disabled people and 2 are concerned with the user-centered design paradigm.

Finally, with regard to universal access, 1 article presents a methodology for the evaluation of accessibility and usability of mobile applications [34], 1 article refers to the fact that the technology made available offers the possibility of introducing innovation in assistive technology [35], 1 article argues that the current notion of universal access needs to be revised in order to take into account the additional complexity of the emergence of ambient intelligence [36], and 1 article outlines issues and challenges in the context of universal access and emphasizes the need for systematic "approaches to diverse human needs, dynamic context characteristics, and technology possibilities, all of which need to be elaborated and validated in practice" [37].

3.2 Systems

A total of 132 articles were classified as reporting on systems. As AAL is related to complex interactions of a variety of technology and system components with the aim of enhancing people's everyday life, it was considered important to perform a more detailed analysis of the articles classified as systems, according to the methodology.

The target users were classified according to who will use the information provided by the system. For example, if the system provides information on patients' vital signs, this information is intended to be used by the health professional to improve the care delivered to the patient. Therefore, the user is the health professional. The user is considered to be a caregiver if the system is to be used by anyone taking care of a patient such as a family member or any non-health professional or a health professional (i.e., clinical personnel, including nurses, paramedics or physicians). Therefore, the persons who will use the information provided by the system were classified into (1) caregivers ($n = 27$), (2) clients ($n = 93$) and (3) caregivers/clients ($n = 12$).

The great majority of systems aimed at improving individuals' participation in society ($n = 84$). Of the remaining, 43 were related to the improvement in the healthcare delivery and 5 aimed at improving security.

Most systems were intended for use both indoor and outdoor in any environment (setting specified as anywhere; $n = 66$) or at home ($n = 45$). This may be related to an attempt to improve people's life in their natural environment. A very small number of systems ($n = 14$) were designed to be used in both home and care centeres. Only, 3 articles referred to systems to be used at educational settings, 3 articles report on systems to be used at work, and 1 article refers to a system to be used while driving a car.

Three stages of project status were distinguished: conceptualization, prototype and trial. As far as it was possible to identify from the information available, more than half of the systems were still in the conceptualization phase ($n = 83$), 43 systems were classified as prototype [38–80], while only 6 were tested in field trials [81–86].

Of the 45 articles describing prototypes, only 4 reported experimental studies involving end users for the prototype evaluation [53, 55, 56, 72].

Considering the field trials, 1 of the articles [86] reported the participation of 6 users of a nursing home during 1 year and 4 articles referred field trial involving elderly people (2 referred that one hundred end users could be involved [82, 83]). There is one reference [84] related to the difficulty in ensuring user participation, namely in terms of obtaining informed consent, and two stating the importance of the living laboratory methodology, supported by an appropriate organizational infrastructure [69, 83], which can ensure the participation of end users in the different stages of development and evaluation of the prototypes [83].

4 Discussion

The results of this systematic review indicate that there is a large amount of literature on AAL encompassing very diverse thematic areas. This resulted in the need to subclassify the 7 thematic areas initially defined (namely conceptual articles, architectures and frameworks, privacy, security and safety, physical devices, context awareness, user interaction and systems).

Considering the principles of AAL, it is not surprising that most systems are intended to be used by the layperson. This is in line with the AAL solutions that intend to use the AmI concept and technologies to enable people with specific demands to live longer in their natural environment and with the international health directives, which highlight the need to empower the patient on matters concerning their health through the promotion of self-care [87].

Most of the literature on AAL is technology-oriented, something that is reflected in the large number of articles on specific components (87 %) when compared to only 132 articles (13 %) related to completed systems. In addition, a considerable number of these articles on systems focus on how technology can be used in the AAL context instead of looking at the users' needs and proposing ways to solve them. The focus is still on the technology rather than on the person.

The results also show that different technologies come from different research groups with little interoperability between them. The environments where AAL can be used are very complex and can use either simple solutions or a combination of existing technologies. For this to happen, it is necessary that a bigger investment is made on the integration of existing technology and on interoperability [87]. This will not only better address existing needs, but also save time and decrease costs, namely if new organizational and services models are to be adopted [88].

Common AAL platforms must be based on selected standards to allow interoperability of applications and services [87]. This could be the basis for third-party services development and provision and could stimulate the development of products at an early stage and the establishment of value chains that put into effect the business opportunities within AAL.

In order to solve the identified problems (focus on technology and lack of interoperability), it is required that research teams are composed of professionals with different backgrounds and skills such as health or social professionals and engineers (interdisciplinary teams) and that all stakeholders, including the future users, are actively involved in all stages of AAL development and evaluation processes, including the conceptualization phase. This involvement of end users will probably also facilitate field trials of AAL systems and promote their use, currently a challenge that needs to be addressed considering the small number of articles classified as describing systems being evaluated in field trials.

With regard to the low percentage of articles referring to the involvement of end users, namely elderly and disabled people, it is clear that end users' involvement, both in the development phase and in the validation and evaluation of the results, as well as the usability and accessibility issues is not sufficiently explored.

A total of 7 articles refer to the living laboratory concept [25, 69, 83, 89–92] as a form to achieve more involvement of the users, not only in the evaluation phase, but also in the whole life cycle of the development process. User-centric development recommends close interaction between designers and users. This could be less successful when the user population is very varied and the involvement of elderly and disabled people introduces additional difficulties [14, 93]. Moreover, methods to measure the impact of the environmental factors [94] and to obtain requirements and evaluation data from elderly and disabled people are not straightforward. Finally, monitoring and interacting with retired elderly and disabled people in their home environments, rather than a workplace situation, requires additional organizational challenges [95, 96]. In this respect, infrastructures such as living laboratories could have an important role.

The adequacy of a systematic review is dependent on the keywords and the databases selected. The authors are aware that not all articles related to AAL have been reviewed. Therefore, future research should consider the addition of supplementary keywords and databases. Nevertheless, even with this limitation, the relative percentage of articles dealing with users' involvement, including elderly and disabled people, usability, accessibility and universal access constitute important evidence that AAL developers must thoroughly consider and address these issues.

Successfully designing universally accessible interfaces requires technical and cultural changes and strategic commitment: Usability and accessibility must be an objective of system development. However, the systematic review illustrates that, within AAL developments, the concept of universal access must be emphasized. The usability, accessibility and universal access research community, with years of experience in fundamental and practical research, has to strength its role within AAL, to bring an important added value to this research and development area.

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