Towards User Support in Ubiquitous Learning Systems

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Abstract—New technologies enable novel types of learning activities that differ radically from traditional approach of visiting lectures and doing homework assignments. Namely, these technologies support transforming our everyday environments into learning environments. This concept is referred to in the literature as ubiquitous learning. Enriching ubiquitous learning systems with adaptive functionality facilitates personalization of learning activities by adapting them to learners' progress and situation. In this article, we identify needs of four user roles in ubiquitous learning systems, i.e., learner, instructor, developer, and researcher. We analyze the state of the art in ubiquitous learning and find that roles other than learners have not received much attention in the literature. Finally, we propose supporting different needs identified for four user roles by adding meta-level functionality to ubiquitous learning systems. This proposal adds self-introspective capabilities to such systems to serve their users better.

Index Terms—Adaptive and intelligent educational systems, ubiquitous computing, context-aware computing

1 Introduction

Recent advances in technology facilitate significant changes in performing everyday activities. Computational resources can be embedded in human surroundings, enabling services that support users in their everyday life. Such environments are called ubiquitous environments capable of providing users with right services, at the right place and time [1]. Many fields benefit from ubiquitous computing technologies, especially from properties like context-awareness and personalization that allow systems to adapt to user goals and situations.

Ubiquitous computing has high potential in the field of education as well [2]. Information and communications technology (ICT) not only provides convenient tools for teaching and learning, but also solves a number of challenges faced by traditional learning methods. Constraints set by limited resources, like time and scale, can be tackled with e-learning [3], in which tools based on Internet technologies are offered for learning activities. Development of mobile devices has enabled learning on the go [4]. This has led to the concept of m-learning, i.e., "learning across multiple contexts, through social and content interactions, using personal electronic devices" [5]. Ubiquitous learning goes even further by integrating e-learning, m-learning, and ubiquitous environments together [6] into "ubiquitous learning environment".

The concept of Ubiquitous learning environment (and consequently Ubiquitous learning) is not clearly defined in the literature. We accept to some extent Yangs' definition: "A ubiquitous learning environment provides an interoperable, pervasive, and seamless learning architecture to connect, integrate, and share three major dimensions of learning resources: learning collaborators, learning contents, and learning services" [7]. Ubiquitous learning systems focus on the learning activity itself, not on use of tools and technologies, and aim at open, easy to access, natural, and social learning [8]. Furthermore, the integration of the physical environment into the learning process facilitates new forms of interactions, e.g. enhancing physical objects with digital content (digital augmentation) has been shown to promote active learning, to encourage collaboration among children and to enrich experience [9].

Ubiquitous learning systems have potential to support instructors as well. Due to sensing technologies of ubiquitous learning environments, they can give comprehensive information about how learners perform learning activities. Moreover, the system may offer a different kind of support depending on the teacher's selected learning strategy (e.g. inquiry-based learning, problem-based learning or project-based learning). Characteristics of ubiquitous learning may facilitate also orchestration of tasks carried out by the instructor. Orchestration is referred to as "educational practices that organize and arrange learning activities and learning environments to guide learners through learning processes" [10]. Finally, with advanced use of technologies, ubiquitous learning systems can provide significant support not only for learners and instructors, but also for other actors participating in learning activities: developers and researchers.

In ubiquitous learning environments, the physical environment is enriched with networked computational technologies, sensors and actuators. This gives great means for applications running in such environments to capture the situation, analyse it and modify their behaviour accordingly. Applications like that are called adaptive applications. Adaptive applications of a ubiquitous learning environment can adapt to different context types, like location, or student

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needs and progress (that is, integrating properties of intelligent tutoring systems [11]).

Some researchers separate ubiquitous learning and adaptive functionality, e.g. [12]. Others consider adaptive functionality as one of the core properties of ubiquitous learning [13], [14]. In this article, we use the term adaptive ubiquitous learning system to emphasize that a ubiquitous learning system has adaptive functionality, i.e., it adapts its behaviour based on context.

The purpose of this article is to study how recent adaptive ubiquitous learning systems support different user roles, reveal challenges, and suggest solutions for tackling them. We review the literature published between the years 2009 and 2014. Analysis of these works provides the foundation for our solutions. We suggest viewing adaptive ubiquitous learning systems as feedback loop systems. Such systems adapt themselves based on how they are used along with different quantitative and qualitative properties of the situation, environment (i.e., these systems are context-aware). This is related to the field of autonomic computing, and properties like self-configuration, self-optimization, self-healing, and self-protecting [15].

We suggest including mechanisms for monitoring and controlling in ubiquitous learning systems. This would enrich ubiquitous learning systems further with adaptive functionality if they do not have one. For adaptive ubiquitous learning systems, in turn, it will provide clarity of system design, customizability, and reusability benefits [16]. For this purpose, we propose a meta-level control framework [17] to be applied to ubiquitous learning systems. This framework adds a controlling and monitoring layer to such systems. Moreover, it monitors the overall interaction to gather feedback on how well the system supports its users in their tasks. With this kind of functionality, a learning system can, for example, detect that a learner constantly receives bad marks on essay related tasks and suggest the instructor to try group work for this learner. Hence, this extra controlling and monitoring layer adds introspection functionality. This improvement, in turn, facilitates supporting needs of all actors participating in learning processes.

The contribution of the article can be summarized as follows: First, we review recent adaptive ubiquitous learning systems with respect to how users are supported and identify the gaps. Second, we propose a conceptual solution to overcome some of the gaps revealed. We consider ubiquitous learning from the system architecture perspective. Hence, we do not provide details on pedagogical considerations. Furthermore, our focus is not on the learner, which has been widely considered in the literature already.

The rest of the paper is structured as follows: Background on ubiquitous learning systems is provided in Section 2 and the state of the art is analyzed in Section 3. Then, our proposal to improve support for instructors, developers, and researchers is presented in Section 4. An overview of the related work is given in Section 5. Finally, Section 6 contains discussion and concludes the article.

2 Ubiquitous Learning Systems

This section gives background information on ubiquitous learning. Since the pioneering work of Rogers et al. in the beginning of 2000 [18], ubiquitous learning has adopted several technologies, also used in other ubiquitous computing fields like digital augmentation [19]. Ubiquitous learning is different from immersive learning as learners perform learning activities in a real physical environment enriched with technology, instead of virtual worlds, not connected to any specific physical place, as immersive learning suggests [20]. Ubiquitous learning is natural evolution of e-learning and m-learning and uses diverse sensing and actuating devices of physical environment to enhance the learning experience. Some researchers focus on creating seamless transitions between formal and informal learning environments (called seamless learning) [2]. In contrast, our view is that ubiquitous learning systems support users in their learning and teaching activities by utilizing embedded and networked computational technologies, sensors and actuators [6].

A rich stream of research is related to adaptive learning and intelligent tutoring systems [11] offering individualized teaching methods that help students learn at faster pace, more effectively, and with greater understanding [12]. Hence, adaptive learning systems are capable of monitoring and interpreting the activities of their users, understanding user requirements and preferences, and acting upon gained knowledge on their users to dynamically facilitate the learning process [21]. Integrating the functionality of intelligent tutoring systems into ubiquitous learning applications facilitates achievements of highly personal learning experiences that adapt to learners' abilities, learning progress, and personal interests. Moreover, technological capabilities of ubiquitous learning environments allow adapting learning systems to the situation at hand, considering not only users but the state of environment, as well.

The information characterizing the situation can be generalized as context. In turn, applications which adapt their behavior based on context are called context-aware [22]. Context-awareness facilitates adaptation to the situation at hand and facilitates adaptive learning functionality. Context-awareness research supporting adaptive learning is very active in the fields of m-learning and e-learning [21], [23]. Ubiquitous environments are able to grasp the learners' situation in greater details by using diverse sensing and actuating technologies. Hence, context-awareness is a key feature for adaptive ubiquitous learning applications.

Since ubiquitous learning is evolution of m-learning, we extend the components presented by Ozdamli and Cavus [4] and decompose a ubiquitous learning system into three main components: User, Environment, and Content (Fig. 1).

Environment component includes the context in which the system operates and consists of physical environment, infrastructure, and tools. In ubiquitous learning, a learning activity is integrated in the environment via use of environment properties, resources and tools, whereas in m-learning, the environment is considered as either as a tool or just a location where the learning activity takes place [4]. Also, ubiquitous learning environments might utilize their existing objects as part of an application's user interface, e.g. by digital augmentation [9].

Physical environment is the physical space where the learning activity occurs, e.g. a classroom or a garden. These spaces have qualities which need to be considered, like light

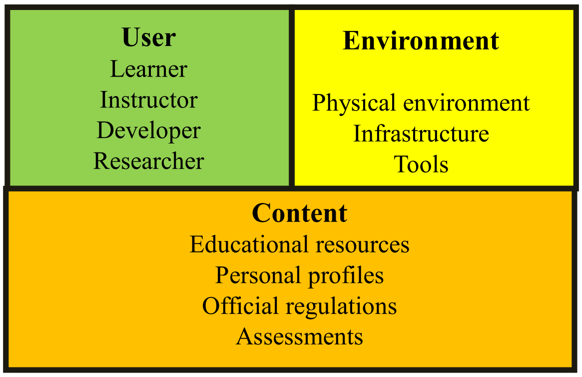

Fig. 1. Main components of a ubiquitous learning system, generalized from Ozdamli and Cavus [4].

and noise level. Infrastructure covers all the equipment and technological solutions together with software, connectivity and available appliances. Moreover, the environment includes available special learning tools and equipment, like smart boards.

Content component covers all information presented to a user. This information can be generated both at design-time and at run-time. Here, content can be categorized into educational resources, personal profiles, official regulations (like study plans), and assessments.

User component includes all main actors of the system. In our previous work, we have developed several technology enablers for ubiquitous learning [24], [25]. This work has been carried out in a multidisciplinary environment with a close collaboration among teachers, education and technology researchers, and software developers. We have followed an ethnography methodology using fast prototyping cycles, adapting Millen's Rapid Ethnographic [26] to our needs. Each implementation cycle was followed by a discussion among all researchers participating in the study to identify the problems to be solved in the next iteration. We have also used participatory design techniques to identify the requirements for a ubiquitous learning environment from the teachers' perspective. Based on all this work, we have identified the following user roles for ubiquitous learning systems: Learner, Instructor, Developer, and Researcher, not only Teachers and Learners as in [4]. This multidisciplinary research has helped us in identifying the needs of different user roles in ubiquitous learning.

To be more specific, Learner uses the learning system to learn a specific subject, whereas Instructor designs and controls learning paths and learning activities. A learning path defines the sequence of learning activities for a learner to effectively build up knowledge and skills [27]. Instructors have changed their traditional role with the incursion of technology in learning environments. The teacher has become "conductor of an orchestra" that must "conduct" students to achieve their learning goals using learning instruments available in the environment [28]. More concretely, instructors create content and arrange learning activities, monitor and evaluate learners' progress. Hence, their role is essential for useful ubiquitous learning experience. Developer is the one implementing the learning system, as well as providing run-time support. Researcher performs overall system analysis and evaluates the system and learning process against certain criteria. Researchers can represent different fields, like pedagogy, learning science, ubiquitous computing, and user experience. These different roles have quite different requirements, as seen from Table 1.

TABLE 1
Requirements Set by Four User Roles

User role	Requirement
Learner	1. Provide access to learning material
	2. Provide tools to gain knowledge (learn)
	3. Allow following the learning path and activities
	4. Allow adapting the learning path and activities
	5. Provide tools to create learning outcome, make annotations/notes to learning material
	6. Provide tools to share the learning material, notes, learning outcome
	7. Provide tools to get/give feedback from/to Instructor
	8. Provide tools to get/give feedback from/to other learners
	9. Allow collaborating with peers to perform learning activities
	10. Allow monitoring and evaluating own progress
	11. Allow applying the knowledge in real-life situations
	12. Motivate the learner during learning
Instructor	1. Provide tools to create learning material, learning path and learning activities
	2. Allow controlling and modifying the learning path and learning activities
	3. Allow monitoring learners' progress during learning activity
	4. Allow analysing the learner's progress
	5. Allow observing/evaluating results of the learning activity
	6. Allow evaluating the learner's progress
	7. Provide tools to give/get feedback to/from learners
	8. Provide tools to support learners' motivation
Developer	1. Facilitate development of system components
	2. Facilitate installation and configuration of the system
	3. Facilitate monitoring the system status (e.g. performance, HW/SW components)
	4. Allow evaluating system status
	5. Facilitate modification and reconfiguration of the system
Researcher	1. Facilitate setting up and modification of evaluation criteria
	2. Facilitate monitoring and evaluation of the system and learning process against the set criteria
	3. Allow tuning system variables and analyzing their effect
	4. Provide tools to support Instructors in creation of content and learning activities.

Current research on ubiquitous learning systems is highly focused on learners [29], [30]. After all, the learner is the most important actor since he or she is the one for whom a learning system is created. Instructors are mostly considered to create learning content and evaluate progress. Several content authoring tools have been proposed for instructors [31]. Moreover, different aspects are considered for student progress evaluation, like learning goals and learning activity performance [32]. Developers are considered as system implementers and are supported with middleware and development frameworks. Researchers are not directly supported by the reported ubiquitous learning systems, although usually researchers perform all the analysis after real-world testing.

Adaptive ubiquitous learning systems adapt their behaviour to components presented above to serve users better. Moreover, different components cannot be analyzed individually but as a whole. Learners, instructors, technology, learning activities and learning environment must interplay together in a harmonious way (orchestration) conducted generally by the instructor with the support of technology.

3 State-of-the-Art Analysis

To review how users are actually supported by recent adaptive ubiquitous learning systems, we searched relevant literature with IEEE Xplore, Scopus, and Science Direct libraries, and with the Google search engine. Key-words for the search contained both ubiquitous computing and learning terminology, for example: "ubiquitous learning system", "context-aware learning application", "pervasive learning system", and "adaptive learning application".

We set the following additional criteria: 1) Work was published between the years 2009 and 2014. This allows selection of the most recent articles. 2) Actual learning activity involves or is affected by interaction with physical environment and its objects. This criterion allows inclusion to a survey the learning applications which are not classified by authors as ubiquitous, but can be considered as such, e.g. Heimonen et al. [33].

The analysis is summarized in Table 2. For each system, we identify how users are supported according to their requirements taken from Table 1. Moreover, we also consider what context the system uses for adaptation, adaptation type and the adaptation mechanism used. The abbreviations used are explained below the table.

User support. To explore how different users are supported in reviewed projects, we identify the user roles and their requirements these systems address. As seen in Table 2, learners are well supported by the reviewed systems. Learners are able to access content, follow learning paths, and perform activities in authentic environments (Fig. 2). Actually, majority of the reviewed literature concentrates exclusively on learners and no support is provided for other kinds of users.

Some analyzed systems target instructors as well, but their role is often limited to content creation [33], [34], [35] or result evaluation [36], [37], [38] (Fig. 3). More advanced systems allow instructors to monitor learners' progress, provide explanations, and recommendations during learning sessions [39], [40], [41]. Chang et al. [39] store the trajectory track of learners, including time information and other learning activity details to help instructors to evaluate learners. Wei et al. [40] log the status of every learner throughout the learning activity, allowing instructors to understand obstacles experienced by an individual learner and provide adaptive instruction and timely feedback. Blanco-Fernández et al. [41] also log learners' actions during learning activity and allow the instructor to reflect on them afterwards during replay and debate sessions. These works demonstrate capabilities of ubiquitous learning sensing technologies for instructors. Indeed, capturing the overall situation during learning activity helps instructors to understand outcomes of learning activities at the required level of detail. Chang et al. [39] also mention a need to identify learners' strengths and weaknesses in relation to learning activities; however, no details are given whether and how this functionality is implemented in their system. Generally, Figs. 2 and 3 demonstrate lack of monitoring and analysis functionality in reviewed systems.

Developer role is important for a system that is deployed for a long time in a real environment. The reviewed systems do not focus on developers, except [41] and [42]. Laine et al. [42] provide a framework for developing ubiquitous learning games. However, no information is given whether developers are supported during system operation in monitoring the state of resources and game progress. Researchers are not supported at all in the surveyed research, although researchers are important as they perform system analyses in terms of its usefulness for learners and instructors. Only Blanco-Fernández et al. [41] present some subtasks relevant for researchers; their system supports analyses of system usage from a technical point of view.

Context. An adaptive ubiquitous learning system should sense the situation and act accordingly to support users. We explore what kind of context is considered important in the reviewed projects.

As can be seen from Table 2, location context dominates in learning applications [29], [34], [39], [41], [43]. Location context covers both location of the learner, as well as locations of target objects. Other types of learners' context are considered important as well, like learners' performance [38], [40], [43], [44], [45], which is directly calculated from tests or tasks performed by learners. Some systems utilize more general learner context like learners' interests and experience [46], and field of study [45], [47]. This context should be prefilled by a learner and included in the learner's profile. A few systems keep a record of learners' behavior for future analysis or for creation of the learner's model for adaptation [42], [43], [48], [49]. This behaviour context is retrieved in a dynamic and unobtrusive fashion when a learner uses the system. Some works consider the context of environment and infrastructure [30], [43], [45], [50]. This context is retrieved dynamically via sensors and status reports. Cahill et al. [51] present a system which does not use any context explicitly. However, learners' knowledge is encoded in advance into guiding questions which the learners have to answer with supporting evidence.

Adaptation. Adaptation functionality characterizes capabilities of an adaptive ubiquitous learning system to respond to situation changes and to provide personalization. We utilize the adaptation classification suggested by Economides [55] for context-aware ubiquitous learning systems in our analysis. Below, we give a short introduction of the categories used in this survey.

Content and course adaptation (CCA) deals with selection and construction of individualized courses and course content based on context criteria, such as learners' knowledge. Hence, this category is about structural adaptation of courses. If a system supports course (re)organization based

TABLE 2
Systems Analysis

Reference	Learner support												Instructor support								Developer support					Context	Adaptation	Adaptation model/mechanism
	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	1	2	3	4	5			
Huang et al., [34]	✓	✓	✓	-	-	-	-	-	-	-	-	-	✓	-	-	-	-	-	-	-	Not considered					Learner's location.	NSA, AF	S/Not discussed.
Chin and Chen [29]	✓	✓	✓	*	-	-	-	-	-	-	-	-	Not considered.								Not considered.					Location.	NSA	S/Manually coded.
Gómez et al., [30]	✓	✓	✓	-	✓	-	-	✓	✓	-	-	-	Not considered.								Not considered.					Learner context (interests, needs, preferences), environment context (physical parameters (noise and illumination levels), artifact digital and physical properties).	CCA, PA, ACC	S/Rule-based mechanism.
Hwang et al., [43]	✓	✓	✓	-	-	-	-	-	-	-	✓	-	Not considered.								Not considered.					Learner location and arrival time, locations of sensors, learner context (background, answers to questions, past experience, on-line records), environment context (equipment available, learning activities, temperature and humidity).	CCA, NSA, PA, AF	S/Rule-based mechanism.
Chen and Huang [38]	✓	✓	✓	-	-	-	-	-	-	-	✓	-	✓	-	-	-	-	-	-	-	Not considered.					Learner and artifact location, answers to questions, content information.	NSA, AA, AF	S/Not discussed.
Davidyuk et al., [50]	✓	✓	-	-	-	-	-	-	-	-	-	-	Not considered.								Not considered.					Learner context (current activity, e.g.), location.	NSA, ACC, AF	S/Rule-based mechanism.
Laine et al., [42]	✓	✓	✓	-	✓	✓	-	-	✓	-	-	✓	Not considered.								✓	✓	-	-	-	Location, learner actions are recorded (answers, points collected).	NSA, ACC?, AF	S/Manually coded.
El-Bishouty [46]	✓	✓	✓	-	-	-	-	-	✓	-	✓	-	Not considered.								Not considered.					Objects location, learner context (interests, experiences, actions), learner location (physical distance), social network (relation and accessibility).	CCA, ACC	S/Manually coded.
Chiou and Tseng, [48]	✓	✓	✓	✓	-	-	-	-	-	-	-	-	Not considered.								Not considered.					Learner context (learning behavior is recorded), learner location and targets location.	CCA, NSA, AF	S/Manually coded.
Wang and Wu, [49]	✓	✓	✓	✓	-	-	-	-	-	-	-	-	Not considered.								Not considered.					Learner context (learning behavior, preferences), learning objects location.	CCA, AF	D/Collaborative filtering, association rule mining.
Liu, [36]	✓	✓	✓	*	✓	-	-	-	✓	-	**	-	✓	-	-	-	✓	-	-	-	Not considered.					Learner's location, learner's performance.	NSA, AF, ACC?	S/Manually coded.
Pérez-Sanagustín et al., [35]	✓	✓	✓	-	✓	✓	-	-	✓	-	✓	-	✓	-	-	-	✓	✓	-	-	Not considered.					Location, student's familiarity with the place	NSA, ACC	S/Manually coded.

TABLE 2
(*Continued*)

Reference	Learner support												Instructor support								Developer support					Context	Adaptation	Adaptation model/mechanism
	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	1	2	3	4	5			
																										formed by collection of touched tags.		
Shih et al., [44]	✓	✓	✓	-	-	✓	-	✓	✓	✓	✓	-	Not considered.								Not considered.					Location, learner's performance in tests.	NSA, AF, ACC	?/KSAT based, no other details are given.
Wei et al., [40]	✓	✓	✓	-	-	-	-	-	✓	-	-	-	✓	✓	✓	✓	-	-	-	-	Not considered.					Learner's performance (activities are logged).	NSA, AF, ACC?	-/Not discussed.
Ku and Chang, [37]	✓	✓	✓	-	-	-	-	-	-	✓	-	-	✓	-	-	-	✓	-	-	-	Not considered.					Location, learner's profile.	NSA, AF	S?/Manually coded?
Hsu and Ho, [47]	✓	✓	✓	-	-	-	-	-	-	-	-	-	Not considered.								Not considered.					Learner's competence, courses and learning objects description.	CCA, NSA, PA	D/Fuzzy interpolation, ant-genetic algorithm.
Chu et al., [52]	✓	✓	✓	-	-	-	-	-	-	-	✓	-	Not considered.								Not considered.					Location, student performance.	NSA, AF	S/Manually coded.
Zender et al., [45]	✓	✓	✓	*	-	-	-	-	✓	-	✓	✓	Not considered.								Not considered.					Player's field of study, available playing devices, location, answers to the tasks, university events.	NSA, AF, PA, ACC?	S/Manually coded.
Heimonen et al., [33]	✓	✓	✓	-	✓	-	-	-	✓	-	✓	-	✓	-	-	-	-	-	-	-	Not considered.					Location.	NSA, ACC?	S/Manually coded.
Cahill et al., [51]	✓	✓	✓	*	✓	✓	-	-	✓	-	✓	-	✓	-	-	-	-	-	-	-	Not considered.						NSA, ACC	S/Manually coded.
Chang et al., [53]	✓	✓	-	-	-	-	-	-	-	-	-	-	Not considered.								Not considered.					Picture.	NSA	S/Manually coded.
Hung et al., [54]	✓	✓	✓	*	-	-	-	-	-	-	✓	-	Not considered.								Not considered.					Learner location.	NSA	S/Manually coded.
Blanco-Fernández et al., [41]	✓	✓	✓	-	-	-	✓	✓	✓	-	-	✓	-	✓	✓	-	✓	-	✓	✓	-	-	✓	-	✓	Learner location, actions during learning activity.	NSA, ACC	S/Not discussed.
Chang et al., [39]	✓	✓	✓	-	✓	-	-	-	-	✓	✓	-	✓	-	✓	-	-	✓	-	-	Not considered.					Location, learner's profile, learning units and activities.	NSA	S/Not discussed.

*Learner, Instructor and Developer support – numbers represent the corresponding need from Table 1. "✓" - means that support for the requirement is reported, "-" – means that support for the requirement is not reported, " * "-not clearly adaptation of learning path, but freedom in selecting the order of objects/zones to learn is reported, " ** "- location-based conversation with virtual tutor. Adaptation: (Economides,[55]) CCA- content and course adaptation, PA- presentation adaptation, NSA - navigation and sequencing adaptation, AA- assessment adaptation, AF-adaptive feedback, ACC- adaptive communication and collaboration Adaptation model: S- static, means that adaptation is encoded at the design-time, D- dynamic, means that the system evolves during time" ? " – not clearly described, but might be supported .*

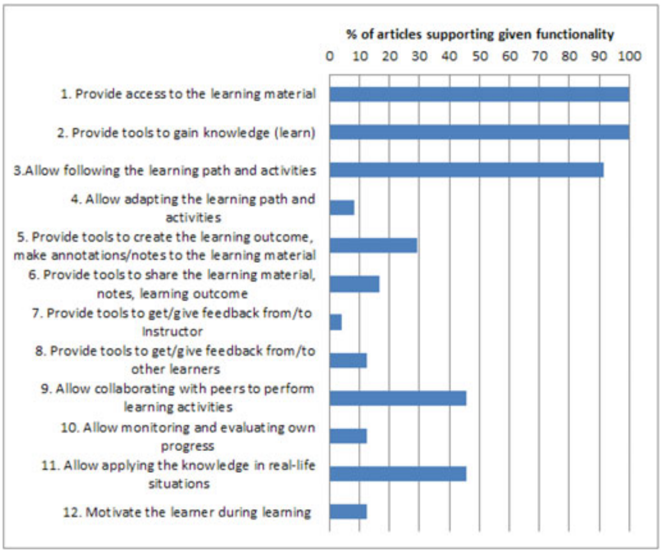

Fig. 2. Percent of reviewed articles supporting learner requirements.

on user knowledge, needs and preferences, we mark that it supports CCA.

Navigation and sequencing adaptation (NSA) rearranges the order of the material presented to a learner to create individual learning paths depending on context. Not to mix NSA with CCA, we mark that a system possesses NSA if it supports course (re)organization based on the situation at hand, like user performance, location.

Presentation adaptation (PA) indicates presenting content depending on context, such as available digital resources (e.g. mobile screen versus wall display), and competencies of learners (easier and less detailed version versus full and deep explanation).

Assessment adaptation (AA) deals with adaptation of assessments depending on context, like the learner's performance. For instance, a capable learner can be challenged with more difficult assessments.

Adaptive feedback (AF) deals with giving appropriate feedback and hints to a learner based on his actions.

Adaptive communication and collaboration (ACC) addresses communication capabilities of an application with respect to both other learners and available tools. For instance, the application can recommend other people nearby with a similar learning goal.

As seen from Table 2, all systems implement either CCA or NSA. NSA dominates in reviewed articles, as systems are mainly targeted to acquire concrete learning outcomes; hence, not much attention is paid to issues of constructing and adapting learning activities based on learning needs of students. NSA systems use location context as the main source for adaptation [29], [34]. Many systems perform NSA adaptation by fusing location context and learner's context, like activity [50]. Some works utilize learners' performance to arrange learning activities [38], [44], [45], [52]. In addition, some systems fuse environmental context to adapt content [30], [43].

To implement CCA, user needs and preferences should be analysed. For example, El-Bishouty et al. [46] infer the situation at hand and provide the required learning content based on situation information and user knowledge. Chiou and Tseng [48] consider learners' preferences for creating

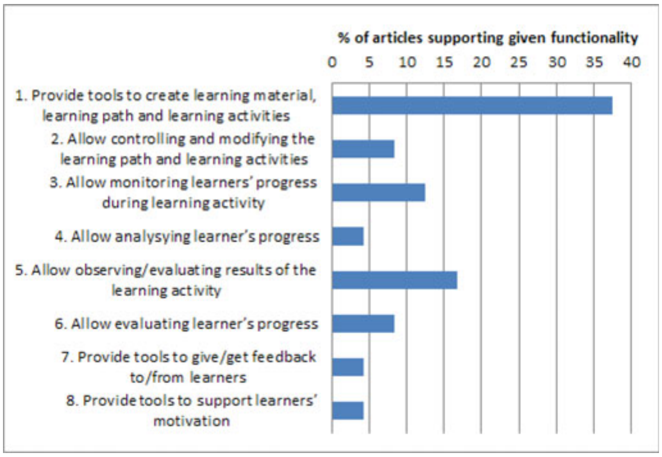

Fig. 3. Percent of reviewed articles supporting instructor requirements.

learning activities. Wang and Wu [49] analyze user needs and interests in order to provide relevant learning activities. Hsu and Ho [47] establish learning paths suitable for learners' competencies.

Few works demonstrate PA explicitly by considering physical resources of devices [30], [45], [47]. For instance, content can be played on a wall display instead of the user's mobile phone [47]. Different focus of PA is explored by Hwang et al. [43], they consider learners' knowledge and experience to select the level of detail.

AA is not very clearly described in the reviewed work. Only Cheng and Huang [38] demonstrate explicitly adaptation of questions and tasks based on learners' performance. AF helps learners to get timely and explanative feedback on activities performed. Most works provide adaptive feedback based on results of tests and tasks [34], [36], [42], [48]. However, mostly visual feedback is used, other modalities, like sound or tactile, are not used much [38], [40].

ACC is presented mostly with mechanisms to involve peers to collaborate in learning activity. El-Bishouty et al. [46] suggest peers to learners with experience in the studied topic, based on the recognized situation. Shih et al. [44] provide mechanisms to share and evaluate the solutions of other team members. Tools to arrange collaborative activities are also demonstrated [30], [50]. Sometimes, it is difficult to distinguish whether a system possesses ACC or just instruments for collaborative activities without adaptation functionality, like in [35], [40], [42], [45].

Adaptation provided by a learning application highly depends on goals and type of application. Available context plays a crucial role in adaptation support. Detailed understanding of situation of learning process and learning activity is still missing from the surveyed works, although it could help to achieve some forms of adaptation: CCA and FA adaptation can be improved by monitoring how the learner performs learning activity; PA and ACC adaptation could be improved by sensing the overall situation, e.g. in order to address learner privacy.

Adaptation model and mechanism. We consider also whether all the adaptive behavior of a learning system is encoded into the system at design-time (static adaptation model) or whether the system is capable of learning new adaptation patterns during operation (dynamic adaptation model). Most works are based on the static adaptation model approach, e.g. [29], [34], [43]. Only two systems demonstrate dynamic adaptation [47], [49]. Wang and Wu [49] propose a system which dynamically adapts the recommended learning material based on learners' personal requirements, preferences, and learning experience. Hsu and Ho [47], in their turn, evaluate knowledge deficiency that a learner must overcome and use this information to identify appropriate learning paths and objects.

An adaptation mechanism determines how the desired adaptation functionality is actually achieved by the adaptive ubiquitous learning system. Many mechanisms are implemented with the manual coding approach, meaning that adaptation is hard-coded into an application and authors do not report other details [29], [42], [52]. Benefits of manual coding are detailed control of the application and optimization of response delays. On the other hand, manual coding limits system maintenance and functionality extension. Among other adaptation approaches, the rule-based approach is common [30], [43], [50]. Rules provide advantages of modularity, expressivity, and system maintenance support [56]. Proprietary solutions are demonstrated by some systems [44], [47], [49].

To summarize our observations, most reviewed research efforts demonstrate adaptive ubiquitous learning systems, where learners are asked to complete certain tasks and tests are given after the tasks have been performed. Later on, test results or task performance are evaluated by an instructor. Only a few systems provide other forms of evaluating outcome of learning activities, such as creating a presentation about a given topic. This demonstrates the fact that full power of ubiquitous learning has not yet been explored, because the systems mostly demonstrate moving “in-class lecture methodology” to everyday environment. One great opportunity the ubiquitous technology provides to learning is capturing a learner's experience while performing a learning activity in an authentic learning environment. Such functioality supports developing more blended evaluation mechanisms.

Only a few systems provide support for instructors. Moreover, instructors have limited functionality at their use, namely content creation and result evaluation. Few works consider developers and even then they only facilitate system implementation. None of the surveyed works address researchers. This may indicate still another obstacle in realizing full potential of ubiquitous technologies in ubiquitous learning research. Researcher support means providing monitoring, altering, tuning, and analyzing services. By providing researchers support to modify and tune certain system parameters and capabilities to analyze effects of such modifications, it is possible to study and improve ubiquitous learning systems iteratively without changes in their core functionality.

Adaptative functionality allows ubiquitous learning systems to achieve personalization. Different forms of adaptation are used in the related work; however, a detailed understanding of the situation is still missing. Such an understanding would extend adaptation possibilities. Most of the related research presents a static adaptation model, meaning that adaptation is defined in advance. This approach may not work well for long learning scenarios, where user preferences, interests, and background knowledge may develop during system usage.

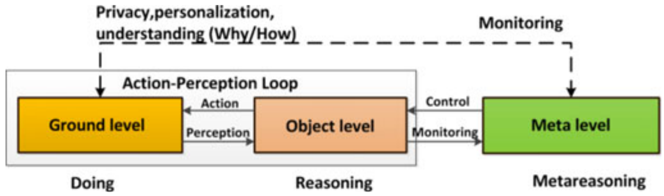

Fig. 4. Metareasoning concept visualization, modified from Cox and Raja [57] and Gilman and Riekki [17].

4 Meta-Level Framework Applied to Ubiquitous Learning Systems

4.1 Meta-Level Control Introduction

Ubiquitous applications can be represented as Action-Perception loops (Fig. 4). Such a system senses environment and user (Ground level) and infers actions to perform as a response to changes in the environment and user behaviour (Object level). These actions can change the environment and trigger new system actions.

Meta-level adds self-introspective monitoring and control over the reasoning process, this is called metareasoning [57], [58]. Metareasoning, in its turn, allows evaluating reasoning actions and modifying them as necessary. Hence, the role of meta-level is to improve quality of decision-making by spending some effort to decide what and how much reasoning to do as opposed to what actions to do [57].

In addition, as quality of reasoning process needs to be evaluated in terms of user satisfaction (how well reasoning tasks support users), an extra monitoring link is needed from Meta-level to Ground-level [17] (dashed arrow of Fig. 4). This link also adds significant explanation support on system behaviour for users [59]. Such system design results in feedback loop system properties. Namely, the system modifies itself based on its real use, performance criteria, and user and environment context.

Implementing monitoring and control functionality at a separate level (meta-level) provides clear design as each layer is only responsible for certain types of tasks. This, in its turn, improves modularization and facilitates system maintenance. Reusability is another advantage. With well-defined interfaces, meta-level components can be used by several systems in ubiquitous environment. Another benefit is customization. Meta-level has a broad view on a particular situation; hence, tailored decisions can be made about objet-level tasks.

4.2 Reference Architecture for Meta-Level Functionality of Ubiquitous Learning System

In our previous research, we outlined necessary components to implement meta-level functionality to smart spaces, as well as discussed the challenges to have a plug-in solution for it [17]. This high-level architecture can be applied to ubiquitous learning systems as well, with or without adaptive functionality. We suggest reference architecture for meta-level control for ubiquitous learning applications, see Fig. 5. Meta-level framework improves adaptive functionality or enables it if a ubiquitous learning system does not have one.

Ground level is presented with Actuators and Perceptors. Perceptors sense the environment (e.g. noise level) and user (e.g. learning stage) and gather user commands to the system (e.g. via graphical user interface). Actuators make changes in environment (e.g. turning on the light) and deliver information to users (e.g. show a message). Object level forms the functionality of ubiquitous learning applications. Namely, it implements adaptation functionality (like in Economides [55]) if it exists, composition of application components and their deployment, and task execution. Adaptation encodes context-based changes of learning activities, learning paths, and content presentation. Application component composition and allocation defines how to make ensembles from available parts of learning applications and on which resources (devices of learning environment) these parts should be deployed. Task execution is responsible for real execution of the application.

Meta-level tasks monitor and control execution of object-level tasks. All the components introduced in our previous research participate in forming the meta-level of a ubiquitous learning application [17]. Trigger component gathers events of environment and delivers them to Control component, which acts according to event types. Based on the incoming event, Control component can alter execution of an object-level task. For example, it may command to use a different algorithm for adaptation task. Control component consults Quality models when it makes control decisions. Quality models present configurations of object-level tasks and strategies for different contexts. For example, they contain information on how the selected sequence of learning activities support the student. Performance of Object-level tasks is monitored against preset criteria by Monitor component. An example of such criteria can be student performance. This information, as well as information about user satisfaction, is utilized by Learning component to construct Quality models. In addition, Control component estimates which user tasks can be postponed and which should be executed immediately. For instance, certain learning activity fits better to current student context. Waiting queue holds the tasks which cannot be processed at the moment, but can be processed when the context changes, e.g. a certain device becomes available. Content and Resource repository contain information about all learning content and resources available in the learning environment. Feedback collector gathers feedback from the user. This feedback can be collected from a user of interest (by manual input via user interface or sensors) or inferred (e.g. by getting a certain result from learning activity). Explanation component gives user cause-effect explanations regarding why the system behaves in a certain way.

4.3 Meta-Level Framework to Support Four User Roles in Ubiquitous Learning Applications

Applying meta-level concepts can improve ubiquitous learning applications and facilitates the orchestration of learning. Meta-layer functionality can help to support all the users involved and fulfill some of their requirements (Table 1). Moreover, the system can support a large amount of features listed in Table 2. Let us now examine how the proposed reference architecture supports different user roles in a ubiquitous learning application. Please refer to Fig. 5 for components.

Learner. Meta-level functionality can enrich a ubiquitous learning system with individualization. For instance, when the system prepares learning activity for a Learner, involving different devices of the learning space, an allocation algorithm is applied to deploy different tasks of learning activity to the devices of learning space (Component Composition and Allocation), e.g. use of wall display and mobile phone as remote controller. Then, the system monitors how user performs this learning activity (Task execution). The system collects all information available during performing the learning activity (Perceptors). User satisfaction and self-assessment can be requested from Feedback collector component. All this information is then supplied to Learning component, which is able to analyse it together with available context. For example, a student had got not very high scores and had commented that he did not like that his answers were observable to others in the learning space. The Learning component fuses and analyses the available information and history information about this student. In the given example, the analyses revealed that student performed well previously in similar context and deployment, the only difference was that he was alone in the room. All this information is encoded into Quality models repository for future use. Hence, Control component would advise Quality models next time the similar context is observed for this particular Learner and would activate a PA rule (Adaptation) to transfer content from a wall display to a personal device when a user is not anymore alone in the learning environment. Moreover, adaptation functionality can be personalized. This is achieved with Learning component collecting information on which learning strategies work best for a given user in different contexts. Hence, Control component could alter parameters of CCA or NSA adaptation algorithms (Adaptation). Knowing what works best is also very beneficial for Learner; here, Explanation component is handy as it can give in-depth information, especially if the component implements analytics. Therefore, meta-level functionality can potentially provide benefits for learners' requirements 3, 4, 7, and 10 of Table 1. The rest of requirements can be achived with Ground and Object levels.

Instructor. Meta-level functionality could add significant support for instructors, which is largely missing from the related work. The framework proposed in this article facilitates guiding role of instructor in multiple ways. It facilitates the learning assessment by monitoring learners' progress. While performing learning activities, meta-level provides information on what works best for a certain

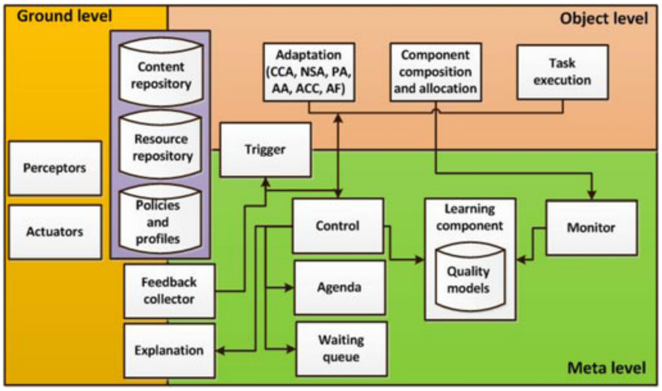

Fig. 5. Reference architecture for adding meta-level functionality to ubiquitous learning systems (modified from Gilman and Riekki [17]).

student and what does not work at all. This is facilitated by Monitoring, Learning, and Feedback collector components, similarly as for the case presented for Learner. Explanation component for Instructors could be enriched with capabilities to analyze all information available in Quality models [60]. Analysis results could be used by instructors to reconfigure, for example, CCA and NSA algorithms to produce course structure and material that suits the learner better (Adaptation). More thorough feedback can be generated for the learner, as instructors would have advanced information about performance.

Modular structure of meta-level framework provides another advantage. Depending on the learning strategy (e.g. inquire-based learning, problem-based learning or project-based learning), the support required by the instructor from the system is different. Actually, the whole system must adapt to the strategy decided by the instructor, and it is here where the flexibility provided by the meta-level framework provides a unique advantage with respect to other systems. The Meta level can modify dynamically object level tasks to adjust them to requirements for the chosen learning strategy, without modifying Ground level tasks. While other systems only work for one concrete learning strategy, a system using a meta-level framework can adapt to different learning strategies.

Generally, meta-level functionality can potentially bring benefits for instructors' requirements 2, 3, 4, 5, 6, and 7 of Table 1. The rest of requirements can be achived with Ground and Object levels.

Developer. Meta-level functionality can facilitate administration and maintenance tasks of such complex systems as ubiquitous learning applications. GUI tools could be used to define rules for adaptation algorithms, for example, for PA adaptation rules can dictate which algorithms to use in case of device failures (Adaptation). Another useful aspect is controlling applications' setup based on how the applications are used during learning activities. This is achieved with Monitor, Learning, and Control components. For example, some RFID tags might not be used by students because of a difficulty to reach them. This information is retrieved by Learning component from data supplied by Monitor, collecting the necessary context about running application or task (Task execution). Based on this information, Control component may command task redeployment (Component composition and allocation), so the content of these poorly accessed tags could be associated with other more popular tags in the system. Hence, meta-level functionality could improve support for developers' requirements 3, 4, and 5 from Table 1. The rest of requirements can be achieved with Ground and Object levels.

Researcher. Meta-level monitoring and control would facilitate recognition of interesting patterns from performing learning activities. Perceptors and Monitor component gather information about performing learning activities. Learning component fuses and analyses this information. Explanation component provides details about patterns revealed. In fact, Researcher also requires additional analytics functionality from Explanation component. Control component could provide some altering and tuning functionality to the system, for example, to change the algorithm for learning path sequencing to observe how this change affects learners' performance. Hence, meta-level functionality could provide benefits to fulfill all researchers' requirements from Table 1.

Generally, a meta-level framework can improve adaptation. Perceptors of the framework sense a rich set of context and other components then operate with retrieved information to achieve the desired functionality. CCA and NSA adaptation can be improved based on monitoring of real performance of the learner. System repository can contain several algorithms to construct learning paths, involving many different parameters. Meta-level may select adaptation algorithm and parameters for a learning path for a certain learner and situation, either automatically or together with the instructor. PA adaptation can be improved by monitoring real usage of the system and controlling adaptation mechanisms based on real system performance, as well as user preferences. AA adaptation can be improved by monitoring the overall student performance. The system can support different assessment algorithms, and based on learner performance, meta-level may select a suitable one either automatically or by consulting the instructor. AF and ACC can be significantly improved. As meta-level monitors real usage of the system and performance of users, causal relations may be inferred. Hence, the system would be able to provide more thorough feedback to users about their progress. Moreover, the search of students with similar problems in performing learning activities could be facilitated. Also, meta-level functionality facilitates development of dynamic adaptation mechanisms in ubiquitous learning systems. This is because of rich capabilities in monitoring different aspects of the system and mechanisms to use diverse algorithms.

However, the level of autonomy should be considered carefully. Users want to be in control of applications to understand how the system makes decisions, and to affect this as required [59]. The same applies for ubiquitous learning applications. Instructors have important contribution to make in design of education technology and they should be able to have control over the system to facilitate the learning process [61]. However, more intelligent hints and explanations are required to instructors, as the amount of students can be very high and thorough analysis of each student's performance could require considerable effort. The same tools should be given to researchers, so that they could explore specific features of learning system and learning process and effects from their modifications. Support for the developer could be done in a more autonomous manner. One approach would be to provide sets of rules describing the actions to take for different situations.

5 Related Work

This section presents the research related to the review given in Section 3 and to our proposal on adding an extra layer to monitor and control adaptation.

Several reviews and surveys have been published about mobile and ubiquitous learning. Ozdamli and Cavus [4] determine the main components for mobile learning and present roles of learners and teachers. Benefits and challenges of mobile learning to learners and teachers are reviewed in [62] and emerging trends in mobile and ubiquitous learning are explored in [23], [63], [64].

Lots of work has been reported about adapting learning applications to recognized progress and situation of a learner [65]. However, only a few works can be found that cover also monitoring and controlling this adaptation. For instance, Saccol et al. [66] provide a framework consisting of a set of tools, supporting learners and teachers/coaches/instructors. One of their tools (Diary) provides information for monitoring the educational or instructional process, allowing their improvements and redesigns. Li et al. [67] developed a system allowing learners to log their learning experiences with photos, audios, videos, location and other sensor data, and to share and reuse them with others. The goal of such a system is to support learners in recording their learning experiences and recall them via the context, finding out habits of individuals and support the learning in accordance with these habits. Moreover, this system uses context information to decide whether to continue generating recommendations, as well as the learner's response to improve the learning habit detection method.

Authors of these proposals are mainly concentrated on technology, namely how to easily integrate different context sensing solutions and services of the environment into personalized learning applications developed. However, no instruments are reported to access quality of solutions provided by the system, for example how well the proposed learning activity corresponds to user needs.

Such issues are addressed by self-adaptive systems, systems which are able to monitor and tune their performance when required [68]. Researchers of self-adaptive systems propose different frameworks and solutions to achieve self-healing, self-configuration, self-optimization, and self-protection properties. For instance, Ahmed et al. [69] propose a solution to achieve a self-healing service with a ubiquitous computing middleware. Trumler et al. [70] propose a middleware solution to self-organize the services that build the application.

The work presented in this article aims to connect ubiquitous learning research with self-adaptive computing research. Namely, we add introspection capabilities to adaptive ubiquitous learning systems. Adaptive ubiquitous learning systems having self-optimization and self-configuration capabilities could provide more tailored user support by monitoring own performance, as well as tuning own parameters.

6 Conclusion

The state-of-the-art analysis revealed that different user roles in ubiquitous learning applications are not yet well supported. Mostly, the same learning activities are offered to learners as used in a classroom, but outside the classroom. Support for instructors is limited to tools to create content and to evaluate student performance. Support for developers mostly includes development tools, and researchers are not considered at all.

Also ubiquitous technologies are not fully utilized to achieve adaptive functionality in the reviewed works. Many works address location of student, as well as those of objects as the only context captured by the system. Capturing the learner's learning process and detailed learning situation, not only progress, would greatly help to understand what helps students to learn more efficiently. This observation also comes from the fact that many presented works demonstrate static adaptation behavior, meaning that adaptation logic is encoded in advance. However, learning is a highly dynamic activity and changes rapidly. Hence, we consider that dynamic adaptation, where the system is able to tailor itself to its users' needs in a dynamic fashion, would enhance user experience.

A majority of analysed systems were implemented and tested with real users. As such, this is a positive sign, but in order to make thorough system evaluation, longer deployments are necessary. Such deployments require tools to support and modify the system during run-time. Moreover, in order to study the system, its effects on the learning process and learning outcomes, tools to alter the system and to analyze the effects are required.

The meta-level framework suggested here attempts to overcome these challenges. Monitoring the overall learning situation could provide insights into the real system use and facilitate discovering patterns leading to system optimization. Developers could reconfigure the system based on real use of devices. Instructors could learn which method works best for different students. Researchers would be able to obtain detailed data from field trials and modify the system easily. Learners would get full potential from personalization. Hence, the proposed framework aims to support all user roles in ubiquitous learning systems.

Separating the tasks of ubiquitous learning system to Object and Meta level provifdes maintenance advantages for the system, as each layer encapsulates only the tasks it is responsible for. Moreover, the system can be tailored to different environments and users without changes in core Object-level tasks. This, in its turn, can be achieved by setting the rules Meta level uses for controlling object-level tasks. Also Meta-level layer can be shared between different systems in ubiquitous environment, improving reusability.

Ubiquitous learning is not a very established research domain yet. Researchers are working to integrate the best learning practices and ubiquitous technology. More research needs to be done together, by education researchers and researchers of ubiquitous computing. Recent works report first attempts to go beyond classroom learning, to place learners into real-life situations to practice skills and knowledge to be learnt. More work still needs to be done to propose blended, unobtrusive, and long-life learning solutions.

This article concentrated on user support in adaptive ubiquitous learning systems. We identified main components of ubiquitous learning systems. Specifically, we focused on different user roles of such systems, namely learners, instructors, developers and researchers. We identified requirements for each of the identified user roles. To see how these requirements are supported by current research, we conducted a review of recent adaptive ubiquitous learning systems. This analysis revealed that current research is mainly focused on satisfying the needs of learners. Instructors lack support in on-line monitoring and analysis of student performance, as well as tools to modify learning activity and learning path on the fly. Developers lack maintenance support; only development support is provided. Finally, researchers are not considered at all in recent research. To overcome these gaps, we have presented a meta-level framework which potentially could overcome some of the presented challenges. We described concept, reference framework, as well as its benefits for ubiquitous learning systems and their users. As for the future work, we seek for possibilities to evaluate the theoretical concepts presented in this article in real ubiquitous learning systems.

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