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A survey on pervasive education

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A B S T R A C T

Researchers and developers worldwide have put their efforts into the design, development and use of information and communication technology to support teaching and learning. This research is driven by pedagogical as well as technological disciplines. The most challenging ideas are currently found in the application of mobile, ubiquitous, pervasive, contextualized and seamless technologies for education, which we shall refer to as pervasive education. This article provides a comprehensive overview of the existing work in this field and categorizes it with respect to educational settings. Using this approach, best practice solutions for certain educational settings and open questions for pervasive education are highlighted in order to inspire interested developers and educators. The work is assigned to different fields, identified by the main pervasive technologies used and the educational settings. Based on these assignments we identify areas within pervasive education that are currently disregarded or deemed challenging so that further research and development in these fields are stimulated in a trans-disciplinary approach.

1. Introduction

Mobile information and communication technologies have become commonplace in recent years. The evolution of smartphones in particular has allowed users to utilize applications whenever and wherever they want. This has had a huge impact on the way people communicate with each other and their environment, and how they use and exchange information. In addition, adaption to individuals, places and situations can now be realized and different scenarios are seamlessly converging [1]. Technological progress in the form of cheap sensors and new communication technologies like sensor networks and the internet have led to an increase in the quality of services in a variety of areas including agriculture, transportation, medicine and logistics. Multimedia, mobility and cloud-based services converge to pervasive media.

In education technological developments have had a strong impact on the behavior of learners and teachers as well as on learning and teaching scenarios. For instance, the availability of digital content and a constant internet connection have led to a reduction in the relevance of traditional textbooks and the emergence of new kinds of cooperation such as in worldwide communities of practice. Additional examples will be presented in the survey below. As organizational issues are increasingly taken into account, this article considers the perspectives of learners, teachers and educational organizations in the term education. Therefore, the targeted use of pervasive media in education can be described as pervasive education. For instance, the Horizon Report claims that mobile applications, augmented reality and gesture-based interaction will be

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an extremely promising prospect in terms of e-learning over the next few years [2]. Other studies conclude that mobile technologies are both essential and challenging for e-learning, in terms of access to learning, context-specific learning and cross-contextual learning [3,4]. These technologies allow new opportunities for learning and teaching to be generated beyond the borders of the classroom [5]. The classroom of the future will be a distributed instance that combines on-site with virtual elements. This includes several services (information, communication, collaboration, etc.), which are orchestrated in a user- and context-dependent way and are based on pedagogical models and methodology [6]. The design and development of such educational arrangements not only require input from the field of computer science, but contributions from non-technical disciplines as well.

It is not uncommon for the cooperation between pedagogies, psychology, social sciences, etc. on one hand and technology and information sciences on the other to be still somewhat dysfunctional. The reasons for this are manifold: each discipline's vocabulary and methodology is different, as are their underlying cultural characteristics. Images of isolated learners in front of their PC, rigid machines restricting the student's (and the teacher's) creativity and overly complexity of computer systems that regularly fail remain ever-present. This may be the result of early technophobia in the literature and society and concerns should be carefully considered and sensitively handled. However, the huge potential of today's technologies has to be made accessible to education. Technology enhanced teaching and learning requires further development simply *because of* the high importance of education to us all.

Everyday use of computers has led to changes in our behavior and perception, often resulting in an increased reliance on technology. Consider how often you use a navigation system during a road trip (while losing orientation in unfamiliar areas), how often you contact friends and colleagues using your mobile phone (without knowing a single number) or how often you consult the Web for information (and how lost you would be without an Internet connection). A common pattern that emerges from these examples is that we are often ill prepared for upcoming situations and rely on technology to help us cope. This may lead to a reduction in practical skills. Facts may seem easy to acquire but the key to success are skills like the ability to evaluate the quality of information, to use the acquired information and to control the knowledge acquisition. For this reason, the focus of education in general, and e-learning in particular should extend from pure factual knowledge acquisition to encompass relevant practical skills. In other words: to focus on a competence-based approach.

This does not only affect content delivery but also monitoring and assessment. While factual knowledge can be easily tested in quizzes, practical skills need to be tested with respect to specific activities, e.g. by measuring the effects of a learner's activity within their environment. Since the learning process is highly individual, pervasive sensing in educational scenarios has to focus on the current user (or learner respectively) and should take into account learning goals and previous knowledge, while the surrounding physical environment can be reduced to a necessary minimum. This makes education a very attractive area for the application of pervasive computing. In addition, the spectrum of typical activities is limited and hence complex behavioral models are not required (e.g. in contrast to elaborated surveillance or emergency management scenarios).

The benefit of pervasive computing technology for education lies in its ability to overcome the limitations of traditional blended learning, i.e. to no longer sequentially restrict the learners to pre-defined times, locations, interaction and tools. Instead, pervasive education aims to seamlessly connect real-life with virtual artifacts and activities [7], tightly interweaving the paradigms (and tools) of face-to-face and online teaching and learning, in both formal and informal forms. As a result, the targeted combination of different learning activities should lead to a more intense and relevant experience. Education can now be embedded into authentic settings [8]. Artifacts, activities and cognitive processes can be contextualized in order to foster effective knowledge acquisition, individual internalization and the long-lasting applicability of knowledge and skills [9,10].

These technological opportunities remain untapped unless an adaptation of pedagogical concepts takes place. An increasingly prominent example of these new concepts is pervasive educational gaming. Here, activities in the real world are tightly coupled with effects in the digital world and vice versa [11]. This helps to raise the educational capability of e-learning applications from the simple acquisition of factual knowledge to developing complex practical skills (according to Bloom's taxonomy [12]). The aim is to create a more engaging, effective and sustainable educational offering in comparison to traditional arrangements.

This article provides a qualitative overview of the existing research and development in the emerging field of pervasive education. Beyond the existing overviews in this area [13], which take into account only a subset of pervasive learning, the available solutions are analyzed and categorized according to relevant criteria both from a technical as well as an educational perspective. Our overall objective is to explain and relate various different terms used in pervasive education and to present the existing exemplary work in order to inspire interested developers and educators. On a qualitative basis, we will identify fields within pervasive education that are of importance for future research. Furthermore, areas currently disregarded or deemed challenging are highlighted in order to stimulate further research in this area — not only by individual researchers and teachers, but also by institutions and sponsors.

The article is organized as follows: Section 2 provides the theoretical background to the field and considers the disciplines involved. Section 3 presents a comprehensive survey of examples in the field of pervasive education. These examples are categorized according to different scenarios and technologies used in the scenarios. The article concludes with findings resulting from this qualitative grouping of examples and provides an indication on the direction future research in this area is likely to take.

2. Foundations and definitions

2.1. History and background

The development of mobile information and communication technologies has long been subject of research in the area of distributed systems and mobile computing and networking [14] as well as in several fields of applications. Ubiquitous Computing often synonymously called Pervasive Computing is a research direction, based on the vision by Mark Weiser [15].

Since circa 2001, diverse research has been carried out in Pervasive Computing. The major forums for research in this area include the ACM International Conference on Pervasive Computing (*UbiComp*, since 1999) and the International Conference on Pervasive Computing (*Pervasive*, since 2003), who merged to a combined UbiComp conference in 2013, as well as the IEEE International Conference on Pervasive Computing and Communications (*PerCom*, since 2003).

Since then, the application of mobile information and communication technologies for learning and teaching purposes has been considered in research. Indications of this evolution can be seen in the number of different conferences and workshops. Among several other events targeting computers in education, we would like to mention the following examples in particular: the World Conference on Mobile and Contextual Learning (*mLearn*, since 2002, formerly called European Workshop on . . .), the International Conference on Wireless, Mobile and Ubiquitous Technology in Education (*WMUTE*, since 2002, formerly called Workshop on Wireless and Mobile Technologies in Education), the IADIS conference series on Mobile Learning (since 2005), and the International Workshop on PervasivE Learning (*PerEL*, since 2005), held in conjunction with IEEE PerCom.

Accordingly, a large variety of journals and special issues have been published in this area of research.

Other communities that address various issues of pervasive learning and teaching are Learning Analytics [16,17] and Educational Data Mining [18]. These research communities are also interested in learning from the perspective of teachers and institutions. Therefore, their broadened focus is of certain value for pervasive education.

2.2. Definitions

The terms used to describe the developments and trends in pervasive education are as diverse as the research areas mentioned above. Therefore, the basic terms shall be defined here as follows. *Mobile Learning* focuses on the mobility of a learner who uses information and communication technologies [19,4]. It is notable that this definition does not assume the usage of a mobile device. It also includes the use of fixed devices, e.g. kiosk systems that can be used by the learner while on the move. Vavoula and Sharples [20] specify the learner mobility in detail by distinguishing between three dimensions of mobility, in particular space, different areas of life and time.

While the term Mobile Learning emphasizes the learner's movements, the term *Ubiquitous Learning* emphasizes that ubiquitous computing technology supports the learner [21–23].

Pervasive Learning focuses on the detection of information in the context of the learner, as well as on the adaptation of pedagogical offers/strategies according to this context [24]. The role of immersion and respective invisibility of devices and applications is a clear characteristic of pervasive learning mentioned in [25,26], which again requires ubiquitous computing technology. It should be noted that the differentiation between pervasive and ubiquitous learning is not always unambiguous. In [27], the two aspects of context and ubiquitous computing technology are combined using the term context-aware u-learning and ask to support learners ''in the right way, in the right place, and at the right time, based on the personal and environmental contexts in the real world, as well as the profile and learning portfolio of the learner'' [27]. Nevertheless, there is a broad consensus that context, context awareness and adaptivity can be seen as the core concepts of ubiquitous as well as pervasive learning.

Finally, we should mention the terms *Seamless* and *Contextualized Learning*. These concepts are ''marked by a continuity of the learning experience across different environments'' [28], which can be seen as a subset of pervasive learning [8]. Three dimensions of the changing environment can be identified [29]: first, places like classrooms, outdoors, or the home, second, the scale of the number of learners, from learning alone up to an online community and finally the learning activity or pedagogical model.

In the following paragraphs, we use the term pervasiveness as a fundamental concept and include the aspects of the learner's movement, context adaptive support and the usage of ubiquitous computing technology. Instead of only focusing on pervasive learning we refer here to pervasive education. The aim is to clarify that in addition to learning itself, teaching and organizational issues are taken into account, since they are part of the educational environment as a whole.

2.3. Technical issues of pervasiveness

As explained before, pervasive learning uses ubiquitous computing technologies in order to support different educational tasks. Ubiquitous computing deals with *devices* like pads, tablets, interactive desks, smart phones or even smaller devices; with *interfaces* for communication between humans; with *network protocols* and with *context aware applications*, which are based on information sensed from the physical and the computational environment [30,31].

First, the aspect of *context awareness* in educational *applications* shall be considered. Definitions of context are manifold [32,33]. In [31] the authors circumscribe the term context by using five W-Questions: who, what, where, when, and why? By answering these questions different context dimensions are described:

Location (*Where*) describes the user's physical position. It can be detected based on GPS or other wireless technologies. Detecting a user's location is an easy task nowadays, however, there are still open research questions in regard to indoor localization. Context aware applications utilizing information about location are manifold and include information/navigation, tracking, network-related issues, emergency assistance, entertainment, and education [34].

Another dimension of context is *individual objects* in the environment of the user. They describe a partial aspect of (*What*) and are often detected through the use of optical mechanisms (such as barcodes) or wireless technology (including RFID-tags) attached to an object. Examples for using the knowledge of an object the learner is faced with can be found for example in [35,22].

A *persons' identity* (*Who*) covers not only the single user but also any other users operating in the same environment that may be part of the educational setting. To identify people, beyond the use of tags representing a particular person, face or voice recognition is an extremely challenging option. Examples of learning systems adapting to a single learner are diverse and are e.g. commonly utilized in intelligent tutoring systems (ITS) [36,37].

It is very difficult to automatically detect the *learner's activity* (*What*). To detect the reason for an individual activity (*Why*) is even more challenging. However, there are approaches in pervasive education research that are restricted to general activities and not directly related to learning. For example, in [38] different factors such as noise level, the type of room used and time of day have been identified. These aspects influence a learner's preferences and can be used assuming their activity.

Additional aspects, regarded in adaptation, are the capabilities of the devices and the network the students are using.

Having detected the learner's context, the applications have to be designed in a context-aware manner. A number of terms characterizing this context awareness are commonly used, including personalization, adaptivity and adaptability. *Personalization* describes the ability of the application to adapt to a particular user (especially that user's knowledge or experiences) or to specific user preferences (e.g. in terms of learning style or layout of learning interfaces). In order to achieve this, the application has to know the identity and profile of a user. *Adaptivity* describes the application's ability to automatically adapt to the user, their preferences and resp. the user's context [39,40]. Adaptivity may be a form of personalization but may also be independent of the user, e.g. learning content is selected based on the user's current location. *Adaptability* is the opportunity for the user to adapt the application manually and to tailor it to their current needs [41]. Adaptivity and adaptability do not necessarily have to be in opposition as they are the two ends of a continuum [42]. Adaptivity in the form of personalization can be found in intelligent tutoring systems, or more generally in adaptive courseware, and is illustrated in many examples described in Section 3 as *situated learning* or as *mobile application*. Adaptability is commonly found in Personal Learning Environments. An illustration of the combination of both adaptivity and adaptability is educational recommender systems. Here recommendations are generated automatically based on context (adaptivity), however, the learner has a choice to select or reject a particular recommendation (adaptability).

In addition to the context awareness of applications, a key characteristic of ubiquitous computing is the use of innovative *devices and user interfaces*. In education, there are a number of efforts encouraging the use of the learner's own device such as a smartphone for learning. 1:1 learning based on the 'bring your own device' philosophy [43] is being used in institutional settings. In addition, we see the research carried out with regard to user interfaces for smart classrooms and other areas that go far beyond touchable whiteboards. Examples include multi-touch, pen-based and tangible interaction [44,45], such as interactive tables [46] and paper-based interfaces [47].

A high degree of *immersion*, which is also a potential characteristic of pervasive applications, can be achieved by augmented reality applications. The user's real view of the physical environment is augmented by virtually available information or objects. Augmentation is available on handheld, head-mounted or on spatial displays [48]. Examples of augmented or mixed reality in learning are illustrated in [49,50].

2.4. Activities in pervasive education

Activities relating to education and educational institutions are characterized by their diversity. The most obvious areas are learning and teaching. In addition organizational tasks such as course enrollment, examinations, management and even socialization [51] have to be considered, particularly in educational institutions. Besides the vague categorization into learning, teaching and organizational issues, a much more subtle analysis regarding pedagogical concepts can be carried out. Traditionally, the focus has been on offering functionality to the learner and teacher, e.g. by means of a Learning Management System, without reflecting in detail on how this functionality is used. In instructional design [52], and even more so in latest design-based research [53], the learning processes itself has developed into a central consideration. Technology-based suggestions on how to proceed in the planning, execution and evaluation of learning are currently being developed.

Ubiquitous computing technologies enable new learning settings. In addition to the traditional means of learning such as in the classroom, new opportunities have been developed, including individual learning at home, outdoor learning and workplace learning, even going as far as learning in artificial immersive environments. In the following section, we will present a survey of pervasive education examples that are classified with regard to these pedagogical settings.

3. Examples of pervasive education

Several attempts have been made to classify educational scenarios, e.g. concerning individual learning processes [54], the number of learners acting together [55], the synchronicity in space and time [56], the level of interactivity [57], the degree of control by the teacher [58] and the aspects of virtualization [59]. [13] defines ten different features that characterize mobile assisted seamless learning through the analysis of research on 1:1 technology enhanced learning. Furthermore a large variety of didactical strategies are being made available, for instance, those collected by [60].

3.1. Settings of pervasive education

Since we consider context awareness as a central benefit of pervasive learning and aim to inspire educators, we distinguish between different educational settings (or contexts) where the learning task may take place. From a technical perspective, a categorization into these settings correlates with the different contexts classified in [61], while also incorporating a didactical perspective:

1. the *formalized setting* is where the learner is in an organizational context that is part of an educational institution, e.g. a lecture hall or the affiliation to a particular class or course;
2. the *physical setting*. A main demand of situated learning theory [10] is that the knowledge or ability should be acquired in an authentic learning context comparable to the context where the knowledge or ability is to be used in the future [62]. This may be achieved in an actual environment, e.g. by classifying a plant during a field trip or by learning how to order a dish in a restaurant using a foreign language in a foreign country. In these cases, the location or more precisely the physical objects and people at this location, are relevant to the learning content or process. Situated learning may also take place in a recreated setting, e.g. in a laboratory at an educational institution. In this case, objects and people related to the learning tasks are brought together in an actual physical environment. We combine these two possibilities to achieve situated learning in a physical setting;
3. the *immersive artificial setting*. Situated learning can take place in an immersive artificial environment that simulates a context consisting of objects and people. It can be experienced in complex simulations, serious electronic games and virtual worlds;
4. the *collaborative setting* is where the learner is part of a community of learners independent of their physical or organizational environment. In these contexts, activities promote learning through social interaction between learners [63]. They exist where learners collaborate in actual locations, as well as in virtual environments such as chat-rooms and virtual classrooms. In addition, social networks, online communities and the blogosphere where individuals actively engage in common topics are collaborative settings even if there is no direct interaction between the participating learners;
5. the *loose setting* (in [64] referred to as independent setting) is where the learner executes a learning activity that is in no way related to his environment. Examples for this include learning on a bus or at the swimming pool. The learner is regarded as isolated learner and the mobile device used provides access to learning resources independent of time and location.

Finally, it should be noted that a specific educational offer can take place in different settings simultaneously.

As mentioned above, our analysis is not only concerned with learning and teaching, but also with the question of how organizational tasks (which are part of the educational environment and process) can be supported by pervasive technologies. This is reflected in [65] where an additional category is defined as:

6. *learning and teaching organization*, which summarizes "all activities that assist in the coordination of learners and teachers and resources for learning activities" [65].

The aim of this survey is to compile existing examples of pervasive education and to classify them according to their settings and technological potential as described in Section 2.3. Selected examples are presented below for each particular setting. However, it should be noted that this classification is not necessarily exclusive and a number of different settings may be acceptable for some instances.

3.2. Formalized settings

This section comprises a number of examples that enrich teaching and learning in educational institutions with the use of pervasive computing mechanisms.

3.2.1. Augmented courseware

Digital presentation slides and course manuscripts are one of the simplest forms of E-Learning. They represent a direct transfer of traditional courseware to the digital world; however, the inherent potential of multimedia technology often remains untapped.

Frameworks for implementing augmented reality scenarios can be used to enrich this kind of material with 3D or even interactive animations [66]. For instance, when a student holds the printout of his "Multimedia Technology" manuscript in front of his computer's camera, the monitor will not only capture a mirror image of his hands holding a paper, but might also add a 3D model of, e.g. the printing technology described in the document. Depending on the orientation and distance of the paper, the system can adjust the printer's perspective and add or remove the model's outer parts accordingly. Therefore, the student can explore the subject in a very individual and descriptive way.

Another issue of augmentation concerns combining the course material with other tools, e.g. connecting lecture recordings to knowledge management in wikis, discussions [67,68] or collaborative tools [69].

3.2.2. Smart teaching and learning labs

Information Technology is largely present in classrooms by means of simple projectors, Hi-Fi audio/video equipment, or interactive whiteboards [70]. Recently, interactive classroom response systems (so called clickers) [71,72] have gained popularity to activate students especially in large on-site courses.

This can be enriched with pro-active, intelligent support as known from meeting assistance [73–75]. Based on the recognition of speech and images as well as the locations of people and objects, a protocol of all activities can be created, including a structure (ontology) of terms and arguments used.

In addition, related topics or learning material can be suggested. This has been realized, for example, in civil engineering education [76]. Paper cards with information regarding an area of architecture can be arranged on a sensitive table and inherent links (e.g. the same architect or style) as well as other related items (e.g. buildings or architects) are displayed automatically.

A similar approach is used for tangible image query [77], where colored bricks are arranged on a sensitive table in order to define a search pattern. In addition, first attempts have been made to provide conceptual frameworks for the development of learning scenarios using haptic interfaces [46,78]. This includes devices and tools for visually impaired learners [79], both for the individual learning processes as well as for online cooperation.

Since these new developments require a complex infrastructure, they have so far been restricted to rigid classroom settings.

3.3. Physical settings

This section is dedicated to authentic physical environments that are enriched with or embedded into an educational setting.

3.3.1. Situated learning in physical settings

When simple learning tasks or complex simulations, enriched with contextual elements, are embedded into the learner's given environment, a new quality of education is achieved. Following the approach of problem-based learning and combining it with context-aware technology, learning offers can be directly embedded into the learner's current situation [80,81]. We distinguish between two types of situated learning, depending on whether a mobile device is used or not.

Fixed devices like interactive tabletops [82,83] are widely used in museums. Kiosk systems can be found at touristic attractions [84]. They offer additional information about the exhibits, e.g. how they have been integrated into real environments, and are available in various presentation forms including videos, animations and simulations.

The use of mobile devices allows for situated learning at an authentic location. Quite often the location as context (or at least spatial context), which may change rapidly, is used for selecting the content or tasks presented [1]. The literature provides several examples, where mobile applications for teaching and learning are able to adjust to the user's current location [85,50] or to objects within their environment [86]. In addition, most of the pervasive educational games referred to in Section 3.4.1 make use of these mechanisms. Latest developments target not only the mobile learner but also provide support for teachers to design location-based content [87]. Educational areas include children [88], students [89] and professionals [90].

An intuitive example illustrating situated learning with use of mobile devices is MathApp for primary school children [91]. This application takes into account the position of the learner and the nearby buildings and sets tasks of varying difficulty accordingly. These might include questions relating to the height of a building, its number of windows or other geometrical shapes. This way, counting and calculating is applied to a real-life scenario and the practical applicability of skills is emphasized.

To provide another example, the English manor Chawton House (known through its connection to the writer Jane Austen) has been equipped with an infrastructure to enrich literacy field trips with location-sensitive devices. A learning application [88] was designed that allows children to be put into the shoes of historic writers, transforming what they see and explore into a story that can be transferred back into the classroom.

A didactical concept behind several situated learning settings using mobile devices is referred to as micro-learning. This term describes the presentation of small learning units that fit on limited screens and are to be worked through in a short time period [92]. In order to realize seamless learning in different environments, ranging from formalized to collaborative settings (using multiple devices, differing in size, user interfaces, computational power or operating systems) the need to support interoperability and adaptation arises. This is one of the central technical questions addressed in mobile and ubiquitous learning technology research today [93].

3.3.2. Augmented reality

Real-life environments can be enriched with virtual aspects in order to offer an educational setting best suited for the intended learning process. This is comparable to introducing simulations into traditional educational settings. It is characterized by reducing the parameters to a didactically necessary amount, while offering interactive features that allow the learner to explore a particular topic. This approach is referred to as self-directed learning.

Examples mentioned in 2.3 of using augmented or mixed reality in learning are [49,50]. They are usually based on wearable devices that put a visual overlay on real-life objects. As in situated learning, augmented reality focuses on a learner's authentic experience. However, it uses artificial elements to enrich the physical environment for a didactically enhanced scenario.

The augmentation of real-life objects through various means of audio output instead of visual output is also possible. This is shown in [94] for early childhood education.

3.4. Immersive artificial settings

Since authentic physical environments are not always accessible for the purpose of learning, artificial settings promise to be beneficial in terms of education.

3.4.1. Pervasive educational games

Game-based learning [95], also referred to as serious gaming, is of increasing importance to current research and developments. It supports didactical settings through a playful and motivating strategy that is based on pre-defined rules of operation, yet still affiliated with somewhat open-ended results. Along with mobile and context-aware learning, the concept of 'gamification' achieves new significance.

Pervasive educational games combine the approach of situated learning with narrative elements, competition and often some kind of fantasy [96,97]. The context of the user is considered within the game play. This may not only refer to a location, but also to the progress of study, nearby friends, activities to be carried out, etc. For instance, the game RouteMe [98] transfers routing mechanisms in mobile ad-hoc networks to the scenario of people walking around in a park. As they meet, a temporary connection is established and messages can be transmitted. More connections and messages mean less battery power and therefore, students are forced to walk around for collecting batteries and alter the topology of the network. In higher levels of the game, more and more decisions about the routing protocol (e.g. concerning network discovery, path selection and packet priorities) have to be carried out by the students without assistance. As a result, they experience the specifics of decentralized routing in a substantial manner.

Several other educational games make use of contextual information, for example [99–101]. All of them rely on the position of the users as a key feature, while only very few consider additional information such as the status in library systems or learning platforms [11].

3.4.2. Virtual reality

Through the pursuit of augmented reality as described above, emphasis is shifted from the real world to virtual scenarios, so called virtual realities. In contrast to fictitious settings such as game-based approaches, the aim of virtual worlds is to be as realistic as possible, for the purpose of an authentic experience.

We can distinguish between two forms of virtual reality. Online 3D worlds (sometimes called cyberspace) are a networked software solution, hosted and often rendered on a central server. Learners and teachers get access to, and interact with, the world, objects and other users via a client tool [102]. In contrast to augmented scenarios, users are represented by avatars; hence, blurring the boundaries of race, gender, etc. It has been suggested that this may lead to a more inclusive form of learning [103].

In contrast to these software solutions, complex 3D hardware infrastructures can be used to create an artificial environment, so called caves. In addition to optical and acoustical feedback, they include tactile impressions but are limited to the physical boundary of the local installation. Therefore, intuitive 3D interaction is possible, e.g. through gestures [104,105].

One benefit of virtual learning scenarios is that they are not bound to physical reality and can therefore utilize optimized spatial knowledge representation. Learning tasks are often characterized by a more intense experience and their strong relationship to social settings [106].

3.4.3. Tele-tutoring

As a result of the consolidation of face-to-face and online settings by means of pervasive computing and communication, interactions between teacher and learner (e.g. through tele-tutoring, mentoring, coaching etc.) seamlessly converge with the instructions itself. Consequently, the boundaries between on-site and virtual activities in blended learning scenarios may become obsolete [7] and mentoring or tele-tutoring in pervasive education can utilize the same mechanisms as instruction.

Social presence in distance learning arrangements is traditionally achieved through optical mechanisms (e.g. by transmitting a video of the actual teacher or by depicting them as avatar) or through textual/iconic mechanisms (e.g. awareness features in a social network). However, these mechanisms do not directly correspond with activities on-site. In particular, interactions between user and system as well as bi-directional communication with other users (both on-site and in virtual counterparts) change significantly through pervasive computing. For instance, media streams in classrooms and distance learning platforms are able to seamlessly integrate. The same applies to communication features, such as message exchange between on-site and virtual learners across used tools and technologies [107]. Another example is the ability to connect a teacher's avatar in a virtual learning environment to the person in the actual classroom. The avatar follows the teacher's movements and gestures [21,108]. As a result, pointing gestures can be automatically recognized and are capable of emphasizing their target not only on the virtual canvas in synchronous settings but in lecture recordings for asynchronous use as well.

This opens up new possibilities for massive open online courses (MOOCs) [109], where learners are more or less completely disconnected from the teacher and the activities on-site [110]. Pervasive education could help to create a connection between online learners and the classroom in order to reduce the significant drop-out rates currently observed [111].

3.5. Collaborative settings

The following section is concerned with the individual learning process that can be promoted through synchronous or asynchronous social interactions within a group or network.

3.5.1. Recommender systems and awareness tools

In collaborative social settings, which are based on social networks and Web 2.0 applications, collaboration is mainly asynchronous. Many learners collaborate on a massive amount of online resources, comments or ratings. A typical mechanism for adaptivity and adaptability in social web applications is social navigation, which is also applied in the context of learning applications. It means that a user's navigation is guided based on the activities of others [112]. Social navigation can be supported by recommender systems, which mainly use information about the behavior of other users in order to calculate recommendations. Recommender systems try to suggest resources or experts based on the current task of a learner. In this regard approaches based on collaborative filtering [113,114] are worth mentioning. These approaches do not rely on a learner or domain model.

Social navigation and cooperation are also affected by awareness tools. Through graphical representation these tools inform learners about the number of learning partners online at a given time or visualize how knowledge is distributed within a team [115,116]. Based on the presented awareness information, learners are able to adapt their behavior.

3.5.2. Virtual collaboration

In addition to the basic mechanisms mentioned above, there are settings characterized by smaller groups and synchronous collaboration. These are often subject to studies, especially in the area of computer supported collaborative learning. In this area, web-based systems at fixed locations are often used. While they cannot be characterized as pervasive in general, a few examples may be considered as pervasive, especially where remote collaboration is supported by shared displays [117,118], tabletops [119] or shared tangible objects [120]. This can be compared to equipment for smart lecture rooms. In addition, there is some connection to pervasive teletutoring systems, however, it is lacking the focus on centralized instruction or mentoring by a teacher.

3.6. Loose settings

In loose settings, the learning activity is not related to the environment. Learners operating in these loose settings use learning materials varying in design, coding, difficulty, length etc. The choice or coding of the learning material offered to the learner may be influenced by information regarding their environment [25] or the capabilities and conditions of the user's device [55]. Presentation and interaction capabilities of mobile devices are still limited and not all traditional learning platforms and tools can be seamlessly utilized in mobile devices [121]. There is a need for technical adaptation in terms of transcoding content to different formats and sizes [122] or to select content in a suitable format. [55] present an abstract approach how to model and use different kinds of context information including environmental and device specific parameters to select learning content existing in different formats. Instead of selection of the existing content [38,122] introduce approaches to adapt the content depending on the device and network condition.

In addition, wireless network connectivity may not always be guaranteed so there is a strong demand for asynchronous operation modes with the occasional synchronization of data [123]. Finally, a user on the move may not be able to fully pay attention to the mobile application due to distractions nearby such as colleagues, ongoing events, traffic conditions, obstacles, etc. [92].

Besides these technical aspects, in loose settings the learner's activity may be information relevant for adaptation. In [38], information concerning the type of location (e.g. library, café, home) and the category of location (e.g. public, private, in transit) is considered as relevant for the selection of a learning activity. Since factors like the frequency of interruptions or the degree of concentration may be directly linked to location, it is used to select appropriate content related to pedagogical interactions [124]. In [119], the values of different smartphone sensors are used in order to decide on the ideal format (video, audio recording, written text) for the presentation of a particular learning object. Similar in [42], the limitations introduced by the end-user devices and the delivery networks are considered in the selection of content modules which are presented to the learner. Especially in terms of short-term activities in loose settings the concept of "microlearning, which deals with relatively small learning units" [115] is considered relevant.

3.7. Learning and teaching organization

In the previous subsections we have introduced different approaches to support the learning and teaching process in a narrow sense, i.e. knowledge or skills are acquired or imparted respectively. As referred to in Section 3.1, we want to present pervasive applications that are related to organizational tasks in education, e.g. the coordination of enrollment, dates, resources for learning activities (such as rooms) and examinations.

3.7.1. Guidance tools

The assistance functions include applications that can guide participants through an entire campus. [125] illustrates a system that allows students to attach virtual notes to physical spaces and to share them with other students. This way, a social map and a campus tour can be constructed. Similarly ActiveCampus Explorer [126] supplies its users with relevant information about activities, departments, labs, etc. within their immediate surroundings. A more comprehensive example is the RUB Mobile App [127]. This application combines different functions to support students. These include access to personal lecture timetable and online libraries as well as an interactive campus map that allows lecture halls to be augmented to live camera views. However, this adaptation is still based on location information. Infocility [128] uses near field communication (NFC) tags to link the user to information regarding buildings, rooms and consultation hours of university staff.

3.7.2. Personal learning environments

A current trend is to merge a variety of university services with a number of external services used in the learner's personal life within a modular, personal(ized) platform: a personal learning environment [129,130]. In such PLEs the learners themselves trigger personalization. Based on the identity of the user, services can effectively be tailored to the user [131,132].

A pre-requisite for this flexible integration is the provision of decoupled components or services as a basis [133,134], which are bound at run-time, depending on the current situation. This can be realized by means of a flexible portal, which is composed of several portlets, i.e. interfaces to different services related to the system [135]. In the case of education, this could include features of a learning or campus management system, news, email, calendar, etc.

Middleware from the area of pervasive computing is used to connect a number of services being offered with a number of contextual conditions to be considered [136,137]. However, a systematical application in the area of education, which could realize the visions of a pervasive university [138] and life-long learning, is still missing.

4. Clustering of examples

In combining the examples, concepts and terms described in the previous sections, we are now able to provide an overview of which technological approaches to pervasive education are used in which educational setting.

4.1. Categories used for clustering

In order to group the pervasive education examples elaborated on previously we use two categories in accordance to the main technological characteristics of pervasive applications mentioned in Section 2.3. The first summarizes applications that are context aware, while the second contains examples of immersive applications and infrastructures. In addition, a number of examples will fall into both. The first category contains a number of subcategories relating the different kinds of context.

The results of these classifications are presented in Table 1.

4.2. Analysis

The qualitative overview presented in Table 1 allows – beyond the inspiration of interested researchers and educators – the identification of areas that are of importance for further research.

It is clearly apparent that examples of pervasive education are not evenly distributed across the matrix. While the emphasis of physical and collaborative settings (as well as learning and teaching organization) seems to focus on context-awareness, formalized and artificial settings appear to benefit mainly from immersive applications and infrastructures. While this is straight-forward in terms of immersive artificial settings, further consideration in other fields is required:

- in formalized settings, context-aware applications are not prominent. One may assume that the context is pre-defined here because it does not change in a formalized setting and therefore does not need to be considered. Instead, learning

Table 1
Clustering of examples presented in this survey.

	Formalized setting	Physical setting	Immersive, artificial setting	Collaborative setting	Loose settings	Organization of learning and teaching
	Context-aware applications					
Learner, Identity				Recommender [113,114]		Personal learning environments [129,131,130,132]
Activity			Pervasive Ed. games [11]	Awareness tools [115,116] Recommender [113,114]		
Environment, Physical location		Situated mobile learning [91,85,50,88]	Pervasive Ed. games [99,101,98]		Selection of microlearning objects [119,38]	Guidance and information tools [125,41,127]
Object	Augmented objects in classrooms [35,22]	Situated mobile learning [94,86] Augmented objects in classrooms [35,22]	Pervasive Ed. games [100]			Guidance and information tools [128]
Device and network					Adaptation to network/deviceconditions [42,55,121,38,122]	
	Immersive applications and infrastructures					
Software solutions	Augmented courseware [67,69,68]	Augmented reality [94,50]	Pervasive Ed. games [99,100,96,11,97,98] Virtual reality [103,102] Tele-tutoring [107]	Virtual collaboration [117–119]		
Hardware solutions	Smart teaching and learning labs [70,76,46,44,71,72,45,78,47]		Virtual reality [108]			

objects and people within a setting may change if formalized settings are dissolved partially (for example during group work) and hence should be taken into account, heading towards the ideas of collaborative settings;
- in physical settings, context-awareness is usually limited to environmental conditions. Location and objects are more easily detected by information technology than activity. Since the consideration of learner context (identity and activity) may help to foster individual learning processes, the detection of a learner's activity is an extremely relevant area for research. Furthermore, the degree of immersion may increase as the capabilities of mobile devices evolve, i.e. through holographic output or precise 3D gesture input;
- in collaborative settings, the emphasis is on learner context, especially where learners use tools that support distance collaboration. In contrast to physical settings, activities can be detected much easier. However, a considerable amount of research and development still has to be carried out. In the future, environmental context should be considered in more detail. Gradually, it will be possible for learners to be mobile in collaborative settings. While immersion mainly focuses on online applications, socialized on-site learning could immensely benefit from smart spaces as used in formalized settings;
- in artificial settings, particular attention is paid to immersion. As the examples show, many of these developments include context-awareness. Therefore, this could be considered the most highly developed category. A reason for this may be the large degree of freedom in artificial settings. Since these settings are extremely different from "traditional" learning settings, there appears to be a lack of innovative pedagogic concepts utilizing the existing technological means;
- the cluster concerned with organization of teaching and learning focuses on organizational tasks and their simplification. Hence, context-awareness is of a certain benefit. Consideration of individual activities, however, which would allow personalization, is still lacking. Whether immersive applications or infrastructures may help in organization of learning and teaching has to be explored in more detail.

In addition to the analysis of Table 1, a more in-depth analysis of the examples of pervasive education discussed in Section 3 reveals additional research directions in terms of context-aware educational applications:

- although the mechanisms exist in other areas of technologically enhanced learning, only few adaptive educational offers provide more than content selection when adapting to current context. Group formation, adaptation of learning object ordering, characteristics of learning objects, and layout should be facilitated in pervasive education as well;
- in relation to learner specific context based on identity or activity, the information used is limited. Most applications focus on demographic criteria such as age, gender, field of study and academic level only. As indicated in Table 1 there has been little progress in terms of advanced attributes such as learning styles, previous and current activities or general learning goals. Learning Analytics (including the interpretation of data collected with regard to the learner and the modeling of the information resulting from this interpretation) is partially related to these issues and is gaining increasing relevance;
- environmental context focuses predominantly on location. However, further effort should be made in terms of objects and people within the vicinity.

Furthermore, learners and teachers will often rapidly switch between these settings and use meanwhile different devices or carry devices between different scenarios. Features of collaborative settings will increasingly merge into physical and artificial settings and combine their respective pros and cons by integrating their mechanisms of context-awareness, adaptivity, and immersion.

This offers a manifold didactical potential and assists in overcoming the separation between learning and the application of acquired knowledge, which is increasingly gaining significance in a rapidly evolving environment. In order to exploit this potential innovative and specific didactical scenarios have to be developed and evaluated.

New challenges regarding the heterogeneity of the tools and network connections will have to be addressed from a technical perspective.

5. Conclusion and future research directions

While comprehensive work has been carried out in various areas of pervasive education, our analysis shows that there is still a tremendous demand for further research and development. Empty or sparsely populated fields within the matrix presented in Table 1 highlight disregarded or challenging aspects of pervasive education. As technological progress advances, all types of educational settings should benefit from the variety of pervasive technologies available.

In this respect, proximity within the matrix may be of significance in order to identify the related work for research or development from the perspective of both technology (rows) and educational setting (lines). Furthermore, different settings should be considered in combination, for example in seamless learning [139].

Pervasive education shows great potential for future teaching and learning. Considering traditional degrees of virtualization in E-Learning, we conclude that pervasive education will result in a fusion of traditionally isolated educational settings. On one hand, on-site settings enriched with information technology allow for much tighter integration of online activities, while on the other hand, virtual settings are sent back into the classroom and integrated with face-to-face activities. As a result, we expect significant results from pervasive education research and development to find its way to normal operation in educational institutions in the near future.

Evidence from several reports and studies worldwide indicates that the majority of challenges and innovations in E-Learning (i.e. current hot topics) are related to pervasive education in some way [3,140,2,141]. Computer-supported teaching and learning may generally evolve towards context-awareness, adaptivity, and immersion.

As a result, we would like to encourage fellow scientists to dedicate research to pervasive education, in interdisciplinary teams where possible.

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