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Augmented Reality and Mobile Learning:
The State of the Art

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ABSTRACT

In this paper, the authors examine the state of the art in augmented reality (AR) for mobile learning. Previous work in the field of mobile learning has included AR as a component of a wider toolkit but little has been done to discuss the phenomenon in detail or to examine in a balanced fashion its potential for learning, identifying both positive and negative aspects. The authors seek to provide a working definition of AR and to examine how it can be embedded within situated learning in outdoor settings. The authors classify it according to key aspects (device/technology, mode of interaction/learning design, type of media, personal or shared experiences, whether the experience is portable or static, and the learning activities/outcomes). The authors discuss the technical and pedagogical challenges presented by AR, before looking at ways in which it can be used for learning. Finally, the paper looks ahead to AR technologies that may be employed in the future.

Keywords: Augmented Reality (AR), Education, Mobile Learning, State of the Art, Situated Learning, Taxonomy, Technology Enhanced Reality

INTRODUCTION

Augmented reality (AR) is a growing phenomenon on mobile devices, associated with the increase in mobile computing in recent years and the international ubiquity of Internet access.

The NMC Horizon Report for 2011 identified augmented reality as the topic rated most highly by its Advisory Board, with time to widespread adoption set at 2-3 years (Johnson et al., 2011). What was once seen as a mere gimmick with few applications outside training, marketing/

PR, sport and entertainment, is now becoming mainstream, with increasing opportunities for it to be used for educational purposes.

This paper examines the state of the art in the application of augmented reality for education, with a particular focus on the mobile learning that occurs in specific locations and outdoor settings. One of the most compelling affordances of AR is its resonance with immediate surroundings and the ways in which information can be overlaid on these surroundings, enabling us to learn about and annotate our environment.

We begin with a definition of augmented reality, before exploring the pedagogic theories that underpin its use. We offer a framework in the form of a suggested taxonomy that can be used to classify AR in mobile learning, before examining criticisms and limitations. Finally, we suggest how AR can be embedded within mobile learning. We make two important contributions to the field: a *discussion of underlying pedagogies* associated with the use of AR; and a *taxonomy* that classifies different aspects of mobile AR for learning in outdoor situations.

DEFINING TECHNOLOGY ENHANCED REALITIES: VIRTUAL, MIXED AND AUGMENTED

Milgram et al. (1994) provide a helpful representation of how reality and virtuality are connected (see Figure 1). This shows a continuum encompassing all real and virtual objects and environments. Mixed reality is an area in the middle, where the two extremes meet, and is considered a blend of the virtual and the real.

Azuma (1997) defined AR as "*3-D virtual objects [...] integrated into a 3-D real environment in real time*", reflecting early research into the use of AR as a primarily graphical display. We consider this definition too narrow and prefer a working definition of AR that includes the fusion of any digital information with physical world settings, i.e. being able to augment one's immediate surroundings with electronic data or information, in a variety of formats including visual/graphic media, text, audio, video and haptic overlays. Indeed, in a later paper, Azuma et al. (2001) updated his definition, reducing the emphasis on graphical objects and identifying the three essential properties of AR as: the combination of virtual and real objects in a real environment; a system that aligns/registers virtual and real objects with each other; and that runs interactively in real time. Their paper also defines 'mediated reality' or 'diminished reality', where some real objects are electronically stripped out, so users are better able to focus on other aspects of their environment.

A critical aspect of AR is the *dialogue* between the media and the context in which it is used, i.e. how the media responds to and changes that context. It is not enough to state that AR consists of availability or presence of digital media within a particular location, as this could encompass passers-by playing music on their mp3 players as they travel through that environment. Rather, we need to take into account the *explicit intention* of the digital media

Figure 1. Representation of the reality-virtuality (RV) continuum, re-drawn from Milgram et al., 1994
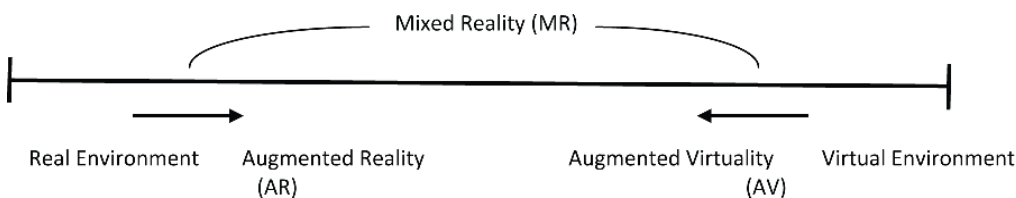
deployment, to supplement or augment our surroundings through additional information being made available (e.g. visually, auditory or through haptic interfaces) that has contextual relevance to that specific place.

Whilst it is clear that virtual, as well as physical, environments can be augmented, this falls under the category of 'augmented virtuality' as shown in Figure 1 and as such is outside the scope of this paper. Much interesting work has been done in the area of virtual worlds and education; however we are more concerned with how learning takes place in an augmented world. We focus on the use of augmented reality for mobile learning, in all senses of the word 'mobile', where the learner is not constrained to a desktop computer at a fixed location and the learning itself may be dynamic and across contexts. Fixed or static AR provided via large screen displays in public spaces or desktop computers (e.g. work by Luckin & Stanton Fraser, 2011) can generally only be used in one place. Mobile AR adds new elements. Importantly, it fosters the mobility of users, increases the physical places where learning can occur, serves as bridge between these places, and enables connections between formal and informal learning. It also serves as a mechanism for more personal or individual experiences with AR, as shown in Table 1, than are possible with a large static display. Spatial mobility is a powerful component (Cowan & Butler, 2013), which can be combined with temporal mobility allowing learners to take advantage of AR resources at times and places convenient and relevant to them. Mobile AR enables us to integrate experience and meaning within specific contexts.

Munnerley et al. (2012) refer to two main forms of AR: *artefact-based* and *geolocated*. Artefact-based AR uses physical markers or objects that are scanned by a camera and then carry out an action, for example displaying an animation or video. Markers have typically been QR (quick response) codes or bar codes; however recent technological advances have enabled the use of any kind of image defined within the AR technology (e.g. the 'Aurasma'

mobile phone app [http://www.aurasma.com] used primarily for marketing). Geolocated AR uses locational sensing, typically through Global Positioning Systems (GPS), and overlays digital information on points of interest (POIs) including physical places and map references. Users who have the appropriate equipment, typically a GPS-enabled smartphone or tablet computer, can view these POIs.

As we focus upon mobile learning in this paper, we refer primarily to geolocated AR examples, particularly to those located outdoors. GPS requires line of sight for satellite communication and so cannot be used indoors with any great accuracy; current technical limitations in accurate indoor tracking/positioning mean that a learner's location is usually best achieved through use of outdoor GPS positioning (there are some promising attempts in tracking a person's indoor location, but currently no mature products). Visits to outdoor locations such as historic buildings/sites and fieldwork activities provide excellent opportunities for mobile learning to take place, enabling both formal and informal learning experiences. The benefit of using geolocated ("marker-less") AR over artefact-based (or "marker-based") AR is that learning resources can be delivered electronically with little or no specialist equipment or additional resources (such as QR codes stuck to signposts) needed, apart from a GPS- and- Internet-enabled smartphone or tablet computer. In addition, geolocated AR resources can be updated much more quickly and easily than physical, tangible objects, since most are delivered through an online network. Hence, they may have greater reach and impact than artefact-based AR, in terms of the numbers and variety of people who may choose to engage with these technologies. For these reasons, we have chosen to focus upon geolocated mobile AR in this paper.

In the past, technological limitations often confined AR devices and their users to a fixed location. Nevertheless, developers have always aimed to make AR portable. When Sutherland began work on a 3D headset display in the 1960s, he noted that his intention was "*to present the*

Table 1. A suggested taxonomy of AR used in mobile learning projects, showing how it can be employed to categorise different aspects of the research

Project (in Date Order)	Device or Technology	Mode of Interaction / Learning Design	Method of Sensory Feedback	Personal / Shared Experience	Fixed/Static or Portable Experience	Learning Activities or Outcomes
Zapp (Meek, et al., 2013)	Smartphone	Exploration Illustration Understanding Reflection	Visual overlay: label/text	Both personal and shared (small groups)	Portable	Interpreting geological features of a rural landscape through situated inquiry and collaboration.
Out There, In Here (Adams et al., 2011)	Laptops, tablet devices, smartphones	Exploration Illustration Understanding Reflection Collaboration	Mixed: visual, auditory, text	Shared (small groups)	Portable	Collaborative inquiry-based learning to enable sharing of data, development of hypotheses, access to information/resources etc. between in-field students and those in a lab.
CONTSENS (Cook, 2010)	PDAs (Personal Digital Assistants), mobile phones	Illustration Understanding Reflection Collaboration	Mixed: visual (3D wireframe model), video	Both personal and shared between 2 users	Portable	Archaeological and architectural surveying of abbey ruins; providing different visual perspectives on the mobile devices.
Augmenting the Visitor Experience (Priestnall et al., 2010)	PDAs, mobile phones, tablet devices, head-up display (HUD)	Exploration Understanding Reflection Collaboration	Mixed: visual, audio, text, video	Both personal and shared between 2-3 users	Both static and portable	Comparing different technologies/techniques to provide information about the landscape to the casual visitor; student-generated criteria focused on usability and sustainability.
History Unwired (Epstein & Vergani, 2006)	Smartphones, PDAs (Pocket PC) + headphones	Exploration Understanding Reflection Performance (by the authors)	Mixed: audio, video	Both personal and shared	Portable	Informal learning about the Castello region of Venice, via a walking tour using local citizens to depict local experiences of art and craft, history and folklore, public and private spaces.
Mudlarking in Deptford (Futurelab, 2006)	PDAs + headphones	Exploration Understanding Reflection Collaboration	Mixed: text, audio, visual	Shared (small groups + pairs)	Portable	Students acted as co-designers to create local tour guides on mobile devices, using multimedia relating to the local area and their observations.

user with a perspective image which changes as he moves" (Sutherland, 1968). Azuma (1997) looked back on a decade of literature dealing with the medical, manufacturing, visualisation, path planning, entertainment and military applications of AR. His review suggested various learning opportunities implicit in this research, including opportunities for medical students to develop their understanding based on an X-ray view of the body, and for trainee architects to see the underlying infrastructure of buildings. He identified factors that would be key to the mobility or portability of this technology; as well as the need for trackers or sensors that could support the accurate alignment of physical

and virtual realities at a distance by providing greater input variety and bandwidth, higher accuracy and longer range.

The developments Azuma reported in 1997 focused mainly on adding visual information. By the beginning of the 21st century, researchers were working on augmented reality for hearing, touch and smell (Azuma, et al., 2001). Milgram and Kishino (1994) wrote of the possibilities for *auditory* augmented reality, mixing computer-generated signals with those from the immediate environment; *haptic* augmented reality, incorporating artificially generated sensations of touch and pressure; and *vestibular* augmented reality, synthesising information about the forces of

acceleration acting on its user. Possibilities for mobile applications were also increasing, as researchers worked to make use of situational awareness and geolocated information retrieval. For example, Columbia University's Mobile Augmented Reality System (MARS) combined a mobile computer and headset with a compass, inclinometer and GPS, allowing users to see representations of historic buildings in their original locations (Höllerer et al., 1999).

Other developments included a point-to-select method for GPS and sensor-equipped mobile devices developed by Robinson et al. (2008). This allowed users to highlight locations of interest during a journey and then to view a report about these locations. Kanjo et al. (2008) developed 'MobGeoSen' software components, using sensors in mobile devices to monitor the local environment or record an individual's activities. Benford et al. (2004) evaluated systems for location-based multi-player games, seeking to understand how *in situ* users share location information at a distance by comparing self-reporting and GPS readings. Finally, Coulton et al.'s (2010) recent work combines geocaching (an activity resembling a GPS-guided treasure hunt) with augmented reality.

Mobile learning researchers have long understood the importance of locational context and of objects found in that context, to the process of meaning-making (Clough, 2010; Leinhardt et al., 2002). In recent years the capabilities of location-aware technologies have dramatically increased. Combining GPS and digital compass technologies allows people holding a device to compute their orientation and position. Recent advancements in GPS and networks have enabled location accuracy to within 5-10 metres for single-point receivers (Ordnance Survey, 2012); carrier positioning accuracy (or 'survey grade GPS') improves this to less than 1cm. Larger, thinner and lighter touch-sensitive screens and advances in cameras and sensors increase the potential for creating and viewing information anytime and anywhere. Combining these technologies has led to the emergence of mobile applications that utilise location sensing to provide users with relevant geo-referenced information. Smartphone apps, including Wikitude and Layar, orient users to information about their surrounding area (e.g. approximate distance and direction to a point of interest). What these systems need now are appropriate representations and guidance to provide or enhance *situated* meaning-making.

THE ROLES OF PLACE AND SPACE IN LEARNING WITH AUGMENTED REALITY

When considering augmented reality, we need to take into account the environment that is being augmented, in order to understand what spatial components can be augmented and why we might want to do this. Dourish (2006) presents our environment as a duality analogous to the "house/home" comparison. He distinguishes between "space" (the physicality of our surroundings and their structures, which may enable or constrain our movements or interactions) and "place" (the social, cultural and historical contexts we associate with such settings, acquired through our interactions with them), (Dourish, 2006). We can also consider the "affordances" of such spaces, a term employed to describe perceived properties which facilitate particular actions, e.g. a chair affords sitting; a pen affords writing. Bligh and Crook provide an excellent overview of how spatiality impacts upon technology-enhanced learning, discussing at length the notion of "learning spaces" in terms of the design and evaluation of learning activities (Bligh & Crook, 2014). They talk about the need to consider carefully the spatiality of learning and environments in which learning takes place, together with the interfaces that learners use to interact with this space and access learning resources. Together with FitzGerald (2012b), they note that the ways in which we theorise about the learning/space relationship are unclear and fragmented, drawing upon theories from educational, human-computer interaction (HCI) and architectural/design disciplines. In addition, despite the prevalence of spatial metaphors in learning-related vocabulary, learning theories

commonly neglect spatial context (Bligh & Crook, 2014; Boys, 2011).

Bligh and Crook (2014) identify several affordances of spaces for learning:

- **Impeding:** Students may be inhibited by the space around them – which maybe could more accurately be described as a "disaffordance". Obstacles must be taken into account, or overcome, for satisfactory learning to take place. AR such as the Zapp application (Meek et al., 2013; Sharples et al., 2012) (see also Table 1) can help address this by providing opportunities for learners to "see" beyond their usual field of view;
- **Containing:** The layout of a space may restrict/challenge, or support/enhance, learning interactions. AR for learning can take this into account by considering how the space around learners may influence the ways in which they interact with AR – for example, seating could be used to encourage engagement with group tasks, or a specific object could be used as an electronic marker for an action or learning task;
- **Stimulating:** Spaces can be used to stimulate learners' thinking and to encourage physical exploration (discussed more in the next section, in relation to embodiment) and reflection. Studies including the 'Speckled Computing' project (Leach & Benyon, 2009) and 'Urban Mediator' (see http://tinyurl.com/TPM-Notts) have used resources placed in the environment to encourage exploration, discovery, engagement, and reflection. AR digital information overlaid on physical reality has the potential to do the same, but we must avoid cognitive overload by ensuring that the environment is not overly stimulating for learners;
- **Associative:** Harrison and Tatar (2008) observed that experience of place is dependent upon 'semantic tangles' of people, events and loci/space and on physically embodied constructs of learning, including the development of abstractions, metaphors and analogies. This is important when considering the kinds of space/place in which mobile learning might occur and the aspects of that space that could/should be augmented. In order to provide an in-depth experience, we may need to augment the learners as well as their environments;
- **Constitutive:** We form part of the physical environment in which we are located. Theories of embodiment and distributed cognition (discussed in the next section) help us to make sense of the ways in which we constitute and are constituted by the environment and of our ability to use external tools to help us perform cognitive tasks. This is akin to the vision presented by Douglas Engelbart of the augmentation of human intellect (Engelbart, 1988). AR provides a way of extending our cognition and blurring the boundaries between internal and external, as incorporeal digital information and mental models are interwoven with real-world physicality;
- **Socially constitutive:** Social space is both produced by and can afford social interaction by groups and communities. Learning spaces can be socially constructed and maintained; shaped by the interactions that people experience within them. A social space/place may be intentionally designed as such or may emerge organically. AR can be used to foster social interaction and collaboration between learners, both within the physical space (enhancing the social affordance) and beyond it (expanding it), as shown by Morrison *et al*. (2009) and Dunleavy et al. (2009).

Additional work on the influence that space has upon learning includes the 'augmented contexts for development' (ACD) that Cook (2010) describes as an extension of Vygotsky's Zone of Proximal Development. Augmented contexts for development consider a learner's environment as a frame for learning interactions and thus part of the wider learning design. Luckin's research into ecologies of resources (Luckin, 2008; Luckin, 2010) considers environment

as a material resource that can be utilised as part of a collaborative learning experience. Vavoula and Sharples discuss 'micro sites for learning' where learners create personal learning experiences from available physical and social resources; these resources include the physical setting, which may be conventional and static, or unpredictable and changing, depending on the formality of the learning experience (Vavoula & Sharples, 2009). Formally managed learning is likely to have a fixed, stable physical environment such as a classroom, while personal mobile learning is likely to be dynamic and include different places and spaces.

More radical thinking into how we extend cognition beyond the internal has been carried out by researchers looking at 'externalism', which considers the mind to be a product of external events, and 'enactivism', where actions taking place in the external world influence internal cognition (FitzGerald, 2012b). However, these are ambiguous and controversial viewpoints, providing only vague definitions of what is meant by 'external', and are thus of limited use when we want to establish a common ground – and semantics – upon which to bring together different interdisciplinary perspectives.

Nevertheless, it is also crucial to consider how AR used in particular environments translates to specific learning activities and tasks. Specht et al. (2011) give examples of how the affordances mentioned above, and learner interactions, translate into educational patterns. These patterns are constructed from the specific contexts of a learner (identity, location, environment, relationship and time, borrowed from Zimmermann et al., 2007) and different educational objectives (illustration, exploration, understanding, reflection, collaboration and performance). For example, 'augmented books' encompass both understanding and reflection, whilst also referencing the context of identity (both that of the learner, and the objects that they are interacting with). We have referenced these educational patterns in our taxonomy (see Table 1), to describe the learning activities taking place in each case study.

THE PEDAGOGY: THEORISING ABOUT LEARNING IN AUGMENTED REALITIES

In order to gain insights into the learning affordances of mobile AR, we need to compare it with mobile learning and pedagogical theories relating to non-augmented, 'normal', reality. But what is 'normal reality' mobile learning before we augment it and what does augmenting that reality provide? A focus on learning through interaction with 'reality' directs us to situated theories of learning and a careful attention to context. Developers, educators and e-learning designers often lack clarity regarding the impact that a student's situation has on their interpretation of e-learning.

Vygotsky argued that human consciousness is associated with the use of tools and artefacts, which mediate contact with the world. These tools produce quantitative improvements in terms of the speed and efficiency of human development; they also produce qualitative transformation because mediated contact with the world provides humans with the means to control and organise their behaviour rather than be buffeted by external stimuli (Vygotsky, 1978).

Bowker and Star (2000) took the concept of 'situated' learning further by suggesting we must also consider issues of space and time in any learning process. Latour (1999) had emphasised our need to create order in these processes. Our 'reality' is continually mediated and reinterpreted by our practices and meaning-making exercises. At a first glance, the shift from low-tech to mobile-tech and to AR may seem merely quantitative: augmenting/adding to reality has always been a part of outdoor education, whether it is through informative signposts at a site, costumed re-enactments of historical

events, or straightforward on-site tuition by a teacher or parent. We change our perspectives, understanding and meaning-making of reality by augmenting it with additional information. Technology merely offers systems and resources that can enhance our situated learning by augmenting our realities more effectively. Yet we need to consider how new technologies might offer the potential for qualitative changes in our relationship with reality: imagine a learner leaving a 'video note' for peers at an historical point of interest; viewing a geographical site as it would have looked during an Ice Age; or collecting audio-visual notes of observations. Such experiences transform reality into a multimodal social text, as described by Bezemer and Kress (2008).

Embodied cognition can also provide a complementary framework, because AR affects the ways in which we interact with the physical world. The bodily experiences – including cultural, contextual and social factors – which we engage with when we use AR help us to construct meanings from our reality. Cognition itself is embodied (Núñez et al., 1999; Radford, 2005), providing a foundation for social situatedness.

Munnerley, et al. (2012) refer to both cognitive dissonance and variation theory when theorising how we learn with augmented reality. Cognitive dissonance is described as "*the idea that people have a strong motivational drive to reduce the dissonance resulting from simultaneously holding conflicting cognitions by altering those existing cognitions or adding new ones to create consistency*" (Munnerley, et al., 2012, p.43). The goal of the learner is to align multiple perspectives to form a coherent understanding. It is easy to see how this applies to augmented reality, particularly to the provision of information to learners in a range of multimodal formats. Differing perspectives can also be provided by informational overlays, such as those in the 'To the Castle!' project (FitzGerald et al., 2013), which provided geolocated audio recordings of sometimes conflicting historical accounts of Nottingham's 1831 Reform Riot. Variation

theory proposes that the process of experiencing something different and being mindful of this difference – i.e. an awareness of a variation – facilitates learning (Pang & Marton, 2005; Runesson, 2006). Augmented reality certainly helps us perceive our surroundings in a diversity of ways. Learners may need to be supported to recognise these differences and to integrate these cognitive dissonances effectively. Variation theory is further explored by Åkerlind, whose work on phenomenography presents the world constituted as a relation between the two perspectives 'outside/external' and 'inside/internal' (Åkerlind, 2005). An alternative interpretation is that, because reality is subjective and perception is linked to cognition, our understanding of objects and places changes once we have interacted with them (Jones, 2011).

CLASSIFYING AUGMENTED REALITY: A SUGGESTED TAXONOMY

This section of the paper aims to produce an initial taxonomy of projects that have used AR in mobile learning scenarios; a wider taxonomy could include purpose/usage as a category, with education as one example among many. For the purposes of this paper we focus on education, specifically mobile learning, examining the different dimensions inherent in AR before exploring some of these in more detail. Table 1 shows the dimensions of AR utilised by six mobile learning projects that included augmented reality as a key component.

Table 1 shows that AR has mainly been used as a portable experience that lends itself to both personal and shared interactions. There were no incidences of larger, static displays or of displays targeted at larger group experiences, attributes which are exemplified in AR experiences such as video mapping (for example, work by the Macula project, including 'old town' [http://vimeo.com/15749093], which celebrated the 600-year anniversary of Prague's astronomi-

cal tower clock). This suggests that use of AR in mobile learning is currently geared towards individual and small-group experiences.

Common modes of interaction or learning activities include exploration, understanding and reflection, with some case studies also including illustrations, collaboration and performance. The exploratory modes is also typified in AR games such as Environmental Detectives (Klopfer & Squire, 2008) and Locatory (Specht, et al., 2011). In this table we have focused on non-gaming examples because we consider this to be a separate research area in its own right, however a good reference to the educational potential for AR games can be found in Schmitz et al. (2012).

The media used have primarily been visual (still images), video, audio and text, although the 'Augmenting the Visitor Experience' project also used printed acetates showing an annotated outline of the landscape at fixed viewpoints. Whilst this is not strictly AR, it nevertheless presents an interesting vision for the future, as the transparency of the acetate allows information to be overlaid while the user can perceive the landscape behind the augmentation. Google exploits a similar approach with its 'Google Glass' product, discussed later in this paper.

The nature of the technology used for engaging with AR has changed over time; early projects tended to use PDAs and mobile phones; more recent projects utilise smartphones and tablet devices. This is exciting because smartphones contain an increasingly sophisticated array of sensors, enabling AR to become more personally meaningful and situated. Experiences that formerly required the loan of specialist equipment are now likely to be accessible by students or the general public, thus providing a more sustainable technology for everyday learning.

CRITICISMS AND LIMITATIONS OF AUGMENTED REALITY

Although AR has evolved considerably, there remain challenges associated with its use in educational situations. These can be broadly divided into technical, pedagogical and social challenges.

Technical Challenges

Top-of-the-range geolocation systems are very precise and very expensive: cheaper tools are only accurate to several metres. Their accuracy can be further degraded by local environmental conditions, including 'urban canyons' where tall buildings shadow and reflect signals. In practice, this means they are likely to be accurate within ten metres: acceptable when standing on top of a mountain and surveying a large area, but problematic when distinguishing one side of a street from another (Gaved et al., 2010). Lack of accuracy may produce registration errors, leading an AR device or app to present learners with information about a nearby location rather than with information about their actual location.

AR typically requires some form of Internet access. Devices using phone networks are susceptible to varying quality of signal: while basic phone and 2G networks may be reliable in urban areas of developed countries, other locations experience less reliable signal quality. Additionally, 3G/4G and other higher data rate services cannot be assured. Alternative strategies, such as setting up a local network, may be necessary if tools require reliable network access (Davies et al., 2010). In either case, there is likely a cost issue – possibly to the learner if using 3G/4G, or to the experience provider if using a local network.

In common with other mobile technological tools, students and tutors have to ensure connection is paid for, batteries have sufficient charge to complete the activity, and the network is accessible. Other concerns include ensuring the screen can be read in bright sunlight and that the device can function in the rain or after being dropped.

Pedagogical Challenges

In common with other technological additions to learning and teaching, AR presents pedagogical

issues. There is a concern that planning may be influenced by the strengths and weaknesses of the tool rather than driven by pedagogy. The novelty of the technology may detract from the learning experience, with students (or teachers/learning designers) focused on shiny devices rather than learning objectives. If the technology is more engaging than the surrounding environment, students may fail to learn from their experience of the location. It is always important to consider whether technology might remove learners from the immediate experience of the location rather than augmenting it.

Technology may guide how and where learning occurs and may require extra resources in terms of technical support. It is important the learning is not constrained by a device's limitations. For example, students should be able to stand in the best place to understand the context, rather than a shady area where they can see the screen; they should be able to devote their time to learning rather than to changing batteries.

From a teaching perspective, it is critical to consider learning objectives and goals before considering how best to achieve these. AR may not be the most effective tool; other, cheaper, more robust techniques may be more appropriate to the learning activity. Providing learners with an immediate overlay of information has the potential to reduce observation skills by offering excessive scaffolding and reinforcement. It may be preferable to offer a staged approach with AR offered as an add-on once students have acquired a certain level of proficiency in interpreting their environment.

From a cognitive perspective, overlaying digital information on the physical environment may enrich a learner's surroundings too much; provoking cognitive overload by delivering more information than can reasonably be processed. Another danger is that the proffered information may not be contextually relevant and so learners may waste time and effort in identifying relevant resources. This is particularly important when user-generated content is used to provide augmented reality. In an attempt to encourage the creation of high-quality, relevant content, FitzGerald (2012a) discusses the problem of *curation* of content and provides an authoring framework to support consideration of the aspects of user-generated content that are most pertinent to location-based learning.

Social Challenges

In addition to technical and pedagogical challenges, we must also consider social elements of geolocated augmented reality. One of the most sensitive issues relates to knowledge of a user's location. This is a basic requirement of geolocated AR, but may be off-putting for users who are not aware exactly what data is being collected or who are wary of being tracked or targeted by companies which provide personalised marketing (Hamilton, 2012). This can be a particular problem when using location-aware apps such as FourSquare or social networking tools, such as Twitter or Facebook, which are capable of broadcasting users' location to others. 'Please Rob Me' (http://pleaserobme.com) raises awareness of the dangers associated with sharing location inappropriately.

Despite these concerns, most commonly used geolocated AR apps do not currently require users to create accounts and do not usually publicly broadcast or map the locations of their users. Therefore, these concerns should not deter learners from engaging with AR.

Hamilton (2012) suggests that AR may widen the digital divide between learners. AR is most commonly used on smartphones and other mobile devices that are reasonably up to date and therefore prohibitively expensive for some learners. The tensions between innovative technologies such as AR and changing or maintaining practices for communities of users have been raised by (Adams et al., 2013), who use the phrase 'catwalk technology' as a metaphor for high-tech innovation akin to high fashion, and its relationship to ready-to-wear clothing and technologies.

There is also the common fear that the use of technology will inhibit "healthy" social interactions – we see this as predominantly unwarranted moral panic that is likely neither justified nor based on a strong base of evidence.

Indeed, in four of the six projects listed in Table 1, collaboration was a key component of the learning design.

EMBEDDING AUGMENTED REALITY IN MOBILE LEARNING: PRESENT AND FUTURE

It is clear that integrating AR with mobile learning involves both opportunities and challenges; however, we remain convinced that there are compelling reasons for doing so. Using AR for educational purposes can appeal to students at a personal level, promoting both engagement and motivation (Klopfer & Squire, 2008; Luckin & Stanton Fraser, 2011). A recent study of the use of AR in a static environment showed that it supported particular learning activities, such as problem solving, in a highly interactive and memorable fashion (Luckin & Stanton Fraser, 2011). The study identified other positive aspects of AR, including ease of use by young children, fun factor, flexibility across age groups and subject domains, ease of use in reference to installation/mobility of hardware, and the immersive and engaging nature of 3D AR visualisations.

Further evaluations of AR have shown that AR has had a positive effect upon learning or processes directly related to learning. For instance, the work done by Luckin & Stanton-Fraser found improvements in memorability and engagement, both key to effective learning (Luckin & Stanton Fraser, 2011), whilst Di Serio et al. found statistically significant improvements in motivation for middle-school students (Di Serio et al., 2012). Cowan and Butler (2013) also showed statistically significant improvements, investigating student performance in geography pupils after they had engaged with AR for a year, although they admit that due to the small sample size (n=16), these results must be treated cautiously and may not be replicable. Improved spatial skills have been reported by Martin-Gutierrez et al. (2010) and Schmalstieg & Wagner (2007). Some learners have also described AR learning content as having added value (as reported in Specht, et al., 2011), although this could be due to the novelty effect.

Several projects have focused on the use of AR to encourage problem solving and independent research. Squire (2010, pp. 2565-2566) notes that:

From a classroom management perspective, the narrative elements of the unit enabled teachers to create a dramatically different classroom culture, one that was built around students performing as scientists. ... Most noteworthy to teachers was how the technology-enhanced curriculum enacted students' identities as problem solvers and knowledge builders rather than as compliant consumers of information....

As mentioned earlier, Cook (2010) also examined the use of AR to support collaborative problem solving. He suggests that mobile devices and their surrounding physical environment enable learners to generate their own contexts for development, which can be interpreted or assisted through AR. Analysis of a video blog recorded by students on a field trip showed that students used physical and digital representations to interact synchronously and inform one other, leading to the development of co-constructed knowledge. Mobile devices acted as contextual sensors, enabling visualisations to be portrayed to the learners in a situated manner.

AR can be used to support learning through haptic interfaces, offering new possibilities for visually impaired users. The 'Haptic Lotus' is a handheld plastic flower containing sensors that respond to its position in a gallery by moving its petals. This haptic feedback was used to encourage exploration of the environment and to provide reassurance for users (van der Linden et al., 2012). Mehigan (2009) discusses the use of sensors in smartphones – particularly accelerometers – to develop opportunities for mobile learning for vision-impaired students and to reduce the digital divide between sighted

and blind students. Audio may also be a valuable AR tool here: for example, a sound-rendering system can transform visual data about objects and places into audible information, overcoming a major difficulty experienced by visually impaired learners. Integrating visual labels and audio tracks within environments offers many teaching opportunities and may be particularly helpful for those who are unable to visualise abstract or hidden parts of systems (Lin et al., 2012). Sprake also views haptic referencing as a means of connecting more fully with our local surroundings (Sprake, 2012).

Augmented reality has progressed from a specialist, relatively expensive technology to one that is commonly used, due to technological advances in mobile computing and sensor integration and to smartphone apps such as Layar and Wikitude. Large corporations are currently working on AR technology, including Google Goggles (landmarks in photos are identified and overlaid with relevant information) and Google Project Glass, a 'heads-up display' that overlays contextual information on glasses – see http://www.google.com/glass (Eddy, 2012). EyeTap is another device worn in front of the eye; it records what its wearer is seeing and superimposes computer-generated imagery (see http://eyetap.org).

One use of AR builds on the campus map to provide navigation for newcomers (the 'augmented campus', see e.g. Genco et al., 2005), and links with friendship circles in order to arrange meet-up times and locations. This extends prior experiences of the use of mobile devices for use of 'dead time' (Pettit & Kukulska-Hulme, 2007). While this has previously been managed through plan views and mapping tied with social networks, overlays are increasingly used to convey this information, as can be seen by the recent advent of Blackboard Mobile Central AR features (Blackboard, 2012).

Munnerley, et al. (2012) discuss several ways in which AR can be used in educational contexts. They suggest the application of AR within formal education should be embedded within a broader framework that takes into account how learning occurs, employing it to support reflection, collaboration, questioning and critical thinking. AR can add richness to learners' surroundings by enabling access to physically inaccessible places, providing different perspectives or views, adding sensor-based information (e.g. infra-red; microscopic) that prompts learners to question the constraints of their unaided view, offering multiple perspectives and supporting the creation of shared narratives.

SUMMARY

This paper presents an overview of the current state of augmented reality for mobile learning. We have discussed the theoretical underpinnings of AR in relation to situated learning and created a suggested taxonomy of AR mobile learning projects as a way of analysing trends, examining the learning design in each and exploring the potential for further development. We have also discussed the limitations and challenges inherent in the application of AR for mobile learning experiences, as well as suggesting how AR can be used to enhance learning.

The use of AR in education, and particularly in mobile learning, is still in its infancy and it remains to be seen how useful it will be in creating effective learning experiences. The overview of learning activities in Table 1 shows that AR can be used successfully for situated and constructivist learning, particular when collaboration and student inquiry are key. AR has also been shown to support informal learning experiences, as seen in the 'History Unwired' case study.

We intend to revisit this work in the next few years to report on new innovations and how learners and educators have made use of them. What is already clear is that we have the opportunity to provide immersive, compelling and engaging learning experiences using augmented reality, which are situated in real-world contexts and can provide a unique and personal way of making sense of the world around us.

We believe AR will prove to be a powerful tool, provided we can harness it appropriately, and we look forward to seeing how other academics and practitioners advance this research field.

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