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A Framework for Mixed Reality Free-Choice, Self-Determined Learning

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In this article, we present a theoretical framework for mixed reality (MR/XR) self-determined learning to enhance ecological literacy in free-choice educational settings. The framework emerged from a research study in New Zealand which aimed to explore how learning experiences which incorporate mobile technologies within free-choice learning settings can be designed to enhance learner development of marine ecological literacy. An understanding of how mobile technology can be integrated into the teaching and learning of sustainability education that incorporates free-choice learning contexts, such as visitor centres, is of strategic importance to both education outside the classroom and adult learning. Following a design-based research methodology, the framework is presented in the form of a set of design principles and guidelines, informed by key theories in ecological literacy and free-choice learning, heutagogy, bring your own device and self-determined learning. We briefly describe how the framework provided the foundation for an educational intervention. This paper aims to assist researchers and developers of MR/XR immersive learning environments to consider design principles and processes that can enhance learning outcomes within free-choice settings, such as museums and visitor centres.

Keywords: immersive learning; BYOD; heutagogy; free-choice learning; mixed reality; ecological literacy

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Introduction

There is growing evidence that educational technology has the potential to enhance learning, increase knowledge and promote transformative changes in the attitudes and behaviour of both individuals and the broader community (Aguayo and Eames 2017a; Becta 2009; Hennessy *et al.* 2019; Somekh 2007). Within educational technology, today's mobile learning technologies (e.g. smartphones, tablets) have multiple potentially positive impacts for teaching and learning. In particular, they facilitate

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learning practically anywhere in collaboration with anyone (Cochrane *et al*. 2013; Pachler, Bachmair, and Cook 2010). They also promote innovative (Parsons 2013), inclusive (Traxler 2010) and transformative (Lindsay 2016) types of learning that challenge traditional teaching and learning approaches (Cochrane 2014; Merchant 2012). The content can be shaped to fit individual characteristics and needs (Aguayo 2016) through self-determined and real-life learning, and within user/learner-generated content and contexts, an approach known as *heutagogy* (Hase and Kenyon 2013; Luckin *et al.* 2010; Narayan and Herrington 2014).

Recent mobile learning research has emphasised new patterns of connected social learning, and research into the transformative possibilities of digital tools (Cook and Santos 2016). We recognise that learning in the 21st century can occur practically anywhere at any time, in school and out, between students, teachers, non-formal educators and parents/adult learners. Twenty-first century learning outcomes also focus on enhancing access to knowledge and promoting organic and distributed social learning throughout the community, with an awareness that learning can be influenced by technological innovations and affordances (learning possibilities offered by technological tools) (Aguayo and Eames 2017b; Bull, Petts, and Evans 2008; Pachler, Bachmair, and Cook 2010). We also recognise that the sociocultural context provided by educational settings and those within them can build on, disrupt and challenge the personal constructs learners bring to those settings (Aguayo 2016; Rennie and Johnston 2004). A heutagogical approach mediated by mobile technologies could then act to create connections and reinforce learning between classroom and outside classroom experiences.

Here, we present a theoretical framework, primarily targeted at researchers and digital learning developers, to inform the development of mixed reality (MR/XR) immersive learning environments, based on self-determined learning and bring your own device (BYOD) approaches. The framework aims to ultimately enhance ecological literacy (ecoliteracy) learning outcomes, knowledge acquisition and attitudes and behaviour change across educational sectors within free-choice educational settings, such as museums and visitor centres. It has been developed as an outcome from a study exploring how purposeful educational design using mobile learning might enable integration of classroom and outside of classroom teaching and learning (Eames and Aguayo 2019). The context for the case study was marine conservation in New Zealand with a goal to enhance the ecoliteracy of primary school students and their parents, and by extension to promote sustainable communities.

Following a design-based research (DBR) methodology (Amiel and Reeves 2008), the framework was guided by a set of design principles and guidelines, informed by key theories in ecological literacy and free-choice learning, heutagogy, BYOD and self-determined learning and MR/XR design.

Literature review

The following sections explore the literature surrounding the foundational theoretical frameworks and contexts that underpin the case study project.

Ecological literacy and free choice learning

An ecologically literate citizenry is key to addressing the complex global challenges and social transformations taking place worldwide (Hackmann and St Clair 2012;

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United Nations Educational, Scientific and Cultural Organization [UNESCO] 2006). For example, in New Zealand, our marine environment is under threat from over-fishing, food web changes, pollution, land use changes and climate change (Royal Society of New Zealand 2016). Education is a means to create a more ecoliterate citizenry (Orr 2004; United Nations 2012). Ecoliteracy requires more than just knowledge development (Hollweg *et al.* 2011; Kollmuss and Agyeman 2002); it also includes experiences that can lead to learning and attitudinal development, and both knowledge and attitudes are intrinsically linked to the action required to bring about change for sustainability (Jensen and Schnack 1997).

Significant life events research has indicated the importance of time spent in nature in influencing pro-environmental behaviour in later life (Liddicoat and Krasny 2013), and place-based research has illustrated the importance of (re)-connecting people to places to support the adoption of sustainable ways of living (Gruenewald 2003; Penetito 2009; Smith 2007). However, as noted by Ballantyne and Packer (2011), research also indicates that although visitors often leave a 'free-choice' learning setting with enhanced knowledge and an intention to adopt more environmentally-friendly behaviour, only a small number of visitors actually do so. Ballantyne and Packer (2005, 2011) stress the need for further research to:

- develop empirically based principles for the design of learning experiences in non-formal settings that optimise learning for sustainability
- develop ways of complementing and reinforcing the free-choice learning experience with post-visit action resources.

Outside the classroom, educational settings, such as zoos, aquariums, museums and visitor centres, offer unique learning experiences for relevant, context-based education (Ballantyne and Packer 2011; Boyer and Roth 2005), which can complement learning within formal (i.e. school) contexts (Falk 2005). The learning may be governed by individuals' or groups' needs and motivations (Brookfield 1986; Falk and Dierking 2002).

Contexts such as nature-based visitor centres can offer the opportunity to complement and reinforce outdoor experiences by promoting reflection and meaning-making processes around socio-ecological issues (Ballantyne and Packer 2005, 2011). This education outside the classroom (EOTC) can then be aligned with formal curriculum guidelines. For example, in the case of this study, it can meet the objectives of *The New Zealand Curriculum* (Ministry of Education 2007) around science and sustainability within the local environment, which can lead to the development of student ecoliteracy (Ministry of Education 2016; Warner, Eames, and Irving 2014).

Recent studies into the use of post-visit action resources have illustrated that the use of mobile technologies can stimulate students to remain engaged with an inquiry begun through a museum visit (Delen and Krajcik 2017) and nature tourism visitors to remain engaged through social media with the State Park they visited (e.g. Wheaton *et al.* 2015). These studies recommend further research into the use of digital technologies for educating and supporting visitors during their experiences and to encourage sustained commitment to pro-environmental behaviour.

Heutagogy, BYOD and self-determined learning

BYOD is situated within and informed by the wider body of mobile learning research and practice that is now informed by almost two decades of research

(Aguayo, Cochrane and Narayan 2017; Cochrane 2013; Lai 2019; Parsons 2014b; Sharples 2000). Research in mobile learning has moved from an initial focus upon devices to enabling informal learning (Laurillard 2007) and the mobility of the learner (Cook and Santos 2016). Mobile learning provides a catalyst (Kukulska-Hulme 2010) for redefining learning experiences (Puentedura 2011) towards self-determined learning – or heutagogy (Hase 2014; Hase and Kenyon 2001, 2007). Key research methodologies for the design and evaluation of mobile learning include activity theory (Eames and Aguayo 2019; Frohberg, Goth and Schwabe 2009; Uden 2007) and DBR (Bannan, Cook and Pachler 2015).

A seismic change in user adoption of mobile learning occurred in 2013 when the number of mobile devices connected to the Internet exceeded the number of fixed computers connected to the Internet (Gagno 2013), and subsequent rapid adoption of mobile learning in schools (Pegrum, Oakley, and Faulkner 2013). Mobile device adoption and ownership now typically exceeds 100% per capita in most developed countries (International Telecommunication Union 2017). Most secondary schools in New Zealand now support a BYOD strategy as a fundamental ICT ecosystem (Parsons 2014a, 2017; Parsons and MacCallum 2018).

Mobile devices can mediate potentially transformative learning experiences when learning experiences are designed to take advantage of the unique affordances of mobile devices (Cook and Santos 2016) with their built-in environmental sensors that enable augmented and virtual reality (VR), built-in accessibility features (text-to-speech, speech-to-text, 2D and 3D scanning, haptic feedback, etc.) and user-generated content via their multimedia creation capabilities (high-resolution cameras, text input, audio recording, image and video editing, geotagging and geolocation). Ubiquitous connectivity, via 4G/5G and WiFi, facilitate communication, collaboration and user-generated content sharing that can effectively bridge the formal and informal learning environments. In particular, mobile devices have been utilised in museum and art gallery contexts to enhance informal (free-choice) learning (Sharples 2010; Sharples *et al.* 2007).

Free-choice learning settings are ideal places for BYOD interventions, given the range of visitors bringing with them their own mobile devices. One of the main benefits of focusing on BYOD is the reduced cost invested in technology, as such cost is transferred to the users (Emery 2012). In education, it has become increasingly clear that mobile learning intervention should focus on BYOD strategies to reduce the cost involved with sophisticated digital infrastructure (Johnson *et al.* 2016; Traxler 2010). One drawback, however, lies in that technology-enhanced learning interventions dependent on BYOD strategies are required to cater for a range of mobile device models, operating systems and capabilities and digital literacy of users, which calls for special attention during the design and development stages of BYOD interventions (Aguayo 2017).

Effective and transferable mobile learning design is device platform-independent, and most often utilises web-based platforms or repurposes social media applications that have been parallel-developed for the two dominant mobile device ecosystems: iOS and Android. Mobile devices are particularly suited to enabling augmented and VR learning experiences (Cochrane 2016; Cochrane, Smart, and Narayan 2018), enabling the design of learning experiences that give the user agency and self-determination of informal learning. Such learning environments encourage user exploration and learner-generated content and contexts (Aguayo, Cochrane, and Narayan 2017).

Key considerations for the design of BYOD to enable self-determined learning within EOTC environments include:

- provision of robust connectivity via WiFi and charging outlets for devices,
- provision of large-screen mirroring for sharing BYOD content,
- moving beyond static content delivery,
- capturing user experiences via personal eportfolios (e.g. Instagram, Pebblepad, YouTube, Google Streetview, Cardboard Camera, Google Local Guides),
- exploring location-based games on site for linking and navigating key activities,
- using QR codes to link to content, geolocations and presentations (online via Google Slides or Slideshare),
- augmenting content via simple AR platforms such as HP Reveal,
- utilising mobile friendly surveys and polls (SurveyMonkey, Polleverywhere),
- exploring the use of proximity-based technologies such as iBeacons for interactive push of content to users
- showcasing user-generated movies of experience (e.g. iOS Clips, VideoStar, Vimeo),
- using set-up exhibits for BYOD – e.g. microscope adaptors for users own device, WiFi temperature gauges, pilot and stream video from Drone/Robot to own devices, audio narration via devices as moving through centre exhibits.

One key idea informing the study reported here is that combining heutagogy, BYOD and self-determined learning with the affordances provided by MR/XR-immersive environments could significantly enhance free-choice learning outcomes. The next section examines this.

Mixed reality and immersive self-determined learning

Digital innovation in education is constantly advancing with new technologies, theories, affordances and types of user-experiences being developed on a daily basis worldwide. Digital innovations within immersive technologies, such as augmented reality (AR), VR and MR/XR, have demonstrated promising prospects in the field of educational technology and technology-enhanced learning (see, e.g., Akçayır and Akçayır 2017; Fotaris *et al.* 2017; Goff *et al.* 2018; Jowsey and Aguayo 2017; Lai, Chen and Lee 2019; Pellas *et al.* 2018).

Up until recently, immersive digital affordances, like AR and VR, have commonly been addressed and considered in isolation in educational practice. Yet, in the past 5–10 years, this has started to shift towards an integration of immersive digital affordances around a particular context and/or setting, with the aim of creating a 'continuum' of digital experiences based on the combination of different technologies, tools, platforms and affordances. This concept of a 'digital continuum' was initially proposed during the mid-1990s by Milgram and Kishino (1994), and is what today is referred to as the original approach to 'MR/XR' or 'mixed realities' (MR) in educational practice – at least to most mainstream practitioners given the ongoing re-definition of the concept. The underlying notion, which we draw upon here, is that an MR/XR digital continuum goes from the 'real environment' (RE) end, where no digital immersion exists, all the way to the fully digitally immersive VR end, where digital immersion is at its full, as represented in Figure 1.

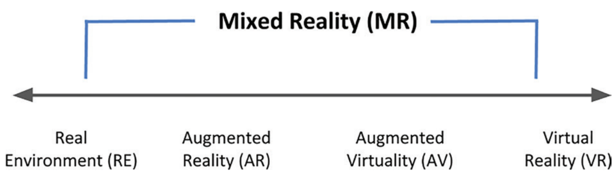

Figure 1. Milgram and Kishino's mixed reality continuum (*adapted from* Milgram and Kishino 1994).

Today, state-of-the-art MR/XR literature currently expands the original digital continuum view – based on Milgram and Kishino (1994), to now consider MR/XR environments to include a multi-variety of dimensions, technological tools and platforms, and embodied user engagement modes, creating interconnected learning ecosystems (see, e.g. Chen and Fragomeni 2018; Parveau and Adda 2018; Mann *et al.* 2018; Speicher, Hall, and Nebeling 2019). This new approach is being referred to as 'XR', where the 'X' means 'anything' reality, accounting for the existing technologies and denoting the imminently yet-to-come emerging digital affordances. In this view, multidimensional MR/XR immersive environments are approached and understood as a dynamic 'medium', offering targeted and flexible user experiences leading to user-centric learning processes.

The conceptualisation of MR/XR immersive environments is currently a very fluid space, where definitions and re-definitions of what is understood by MR/XR are being provided on an ongoing basis. This continuous evolution of the MR/XR concept represents a challenge to educators, designers and practitioners (Aguayo 2017). Attempting to set a definitive meaning and purpose of MR/XR-immersive environments within educational practice escapes the purpose of this article, primarily given its dynamic nature when approached from the educational technology field.

MR/XR approached as an immersive continuum can offer ideal conditions to suit self-determined learning in free-choice educational settings, by offering a range of learning affordances, instances and environments in the form of a *learning ecosystem* (Eames and Aguayo 2019). Such an approach therefore can make available a range of 'entry points' to experiencing educational digital affordances, not only suiting the range of existing cognitive frameworks, digital literacies and users' socio-technological characteristics and needs (Aguayo 2014), but also facilitating BYOD and self-directed learning (Eames and Aguayo 2019).

In the case of this study, we sought to design a framework for using an MR/XR approach in the classroom, outside the classroom and between the two settings, to enhance teaching and learning in a connected and interrelated way between formal and non-formal spaces. We were also interested in how these tools may reinforce learning and promote inter-agency between generations as students and their parents co-constructed knowledge around their collective experiences in these free-choice settings. Finally, exploring how non-technology-mediated learning activities, such as snorkelling in a marine reserve, could be integrated and fused with different degrees of technology-mediated learning experiences, either at an EOTC setting such as a marine discovery centre, and/or within the classroom and at home.

Therefore, our take on a technology-enhanced learning continuum provided in the form of a MR/XR-immersive environment was simultaneously approached from a spatial, temporal and inter-generational perspective. We did so inspired on the original view of MR/XR proposed by Milgram and Kishino (1994).

Methodology and research design

The study informing the development of the theoretical framework was based on a marine reserves learning experience at a primary/elementary school which connected with a marine science and conservation visitor centre in New Zealand. Our partnership brought together a 'BYOD' school classroom teacher and a class of her senior students (aged 8–12 years), educators from the marine reserve visitor centre, a marine scientist, a learning design/technology team and researchers experienced in science and sustainability education. This partnership constituted the REEF – the Research into Ecoliteracy Enhancement Forum. Our aim was to co-create and trial a mobile learning intervention that could enhance ecoliteracy for students and their parents. The study addressed the following question:

> How can mobile learning be designed with EOTC to enhance the ecological literacy of students and their parents?

This 2-year study used a DBR methodology (Amiel and Reeves 2008; The Design-Based Research Collective 2003) to produce design principles for the development of self-determined MR/XR learning environments following a BYOD approach (see Figure 2). The DBR methodology allowed us to incorporate the unpredictable, dynamic and innovative nature of learning technologies along with the emergence of new and emerging technological options such as MR/XR (Cochrane *et al.* 2017; McKenney and Reeves 2018), while accounting for learning processes based on a marine reserves unit incorporating an outside the classroom visit. The study involved one primary school class learning about marine reserves, which included a visit to the Goat Island Marine Reserve in North Auckland and the associated Goat

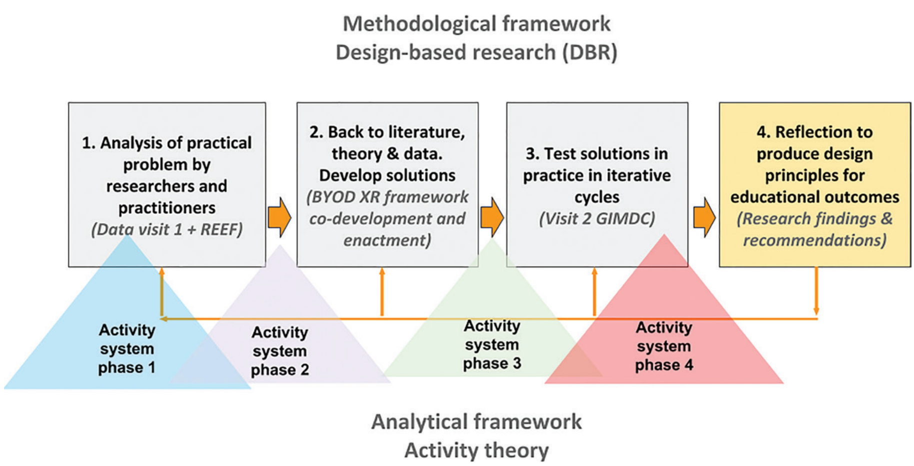

Figure 2. Research phases represented in relation to design-based research and activity theory (*adapted from* Eames and Aguayo 2019).

Island Marine Discovery Centre (the 'Discovery Centre') hosted by the University of Auckland. The study included four phases.

Phase 1 in early 2017 involved the teacher planning and implementing a marine reserves unit to her class of 20 students (age range 8–12). The unit included a visit to the Goat Island Marine Reserve (including a class snorkelling session in the real marine environment) and a visit to the Discovery Centre. Data collection included student questionnaires exploring ecoliteracy, and attitudes towards, and use of, mobile learning technology (if any) during the unit; observations (either in person or video) of the Discovery Centre educator, teacher, student and parent behaviour during the visit; post-visit focus groups with students and interview with the Discovery Centre educators; and post-unit focus groups with students and interviews with the teacher and parent helpers. Data analysis and review by the REEF team provided a baseline to inform the development of the mobile learning framework. Note that this baseline data are not reported here as we focus on the process of the development of the theoretical framework in this paper.

In phase 2, the REEF team then worked collaboratively face to face, and online using a Google+ community, to design the mobile learning framework. This framework drew on the data evidence from the marine reserves unit and a number of theoretical positions:

1. theories from environmental and sustainability education, which recognise the importance of constructivist and place-based knowledge and attitudes, motivation to act for a sustainable future and post-visit learning reinforcement;
2. theories of mobile learning, which recognise the inclusive and transformative potential of mobile devices and their affordances within self-determined learning environments (i.e. student-generated contents and contexts, or heutagogy), the strategic importance of BYOD settings and use of freely available and/or low-cost development of mobile learning technologies, and the emergence of collective and distributed learning through mobile-based technologies.

Data were gathered through observations at two face-to-face meetings, and the online posts, and were thematically analysed to examine how the REEF worked together to co-construct the framework, and to explore the elements of the framework.

Once the first version of the framework was available from phase 2, phase 3 involved the design of an MR/XR intervention for the same unit to be taught by the same teacher with her 2018 class, including a visit to the marine reserve and Discovery Centre. Following the DBR methodology, this design and development involved a continuous loop between: (1) collaborative refinement of practical problems, (2) development of solutions informed by existing theory and technological innovation, (3) iterative cycles of testing and implementing solutions in practice and (4) reflection to produce design principles and enhance solution implementation (Amiel and Reeves 2008) (see Figure 2). This process involved user-informed design that drew on the ideas of the students, the needs of the teacher and the Discovery Centre educators and the infrastructure available at the visit setting. During this process, the REEF team also identified four main areas informing the framework: (1) mobile learning considerations and opportunities, (2) teaching and learning principles (pedagogy and heutagogy), (3) marine science and conservation (the context) and (4) development of ecological literacy (learning objectives).

In phase 4 in early 2018, the teacher planned and implemented a marine reserves unit again to her class of 28 students (age range 8–12), this time incorporating an XR-based intervention (see below for details). As this was a multi-age class, approximately 50% of the students had been in the same class the year before and had experienced the marine reserves unit. The unit again included a visit to the Goat Island Marine Reserve (including a class snorkelling session again) and a visit to the Discovery Centre. Data collection again included pre-unit and post-unit student questionnaires exploring ecoliteracy, and attitudes towards, and use of, mobile learning technology during the visit and the wider unit; observations (either in person or video) of the Discovery Centre educator, teacher, student and parent behaviour during the visit; post-visit focus groups with students and interview with the Discovery Centre educators; and post-unit focus groups with students and interviews with the teacher and parent helpers. Data analysis and review by the REEF team responded to the outcomes of the XR intervention.

Data analysis was structured around a sociocultural activity theory analytical framework, as described by Engeström (1987) and Krasny and Roth (2010), and as previously used by the researchers (Aguayo 2014, 2016) in the context of using digital learning technologies for community education for sustainability. This involved the identification and description of the overarching elements constituting the activity systems in the study. Our analysis of the design of the framework examined system elements such as the roles REEF team members played, how digital affordances, heutagogy and theories of mobile learning and sustainability education influenced design thinking, and how the context shaped the framework. Each phase of the study was recognised as a novel activity system, which, in turn, interacted with the following activity system. Figure 3 represents the activity system for phase 2, dealing with the co-development of the framework by the REEF team. This activity system provided the framework which then became the tool for designing the mobile learning intervention in phase 3.

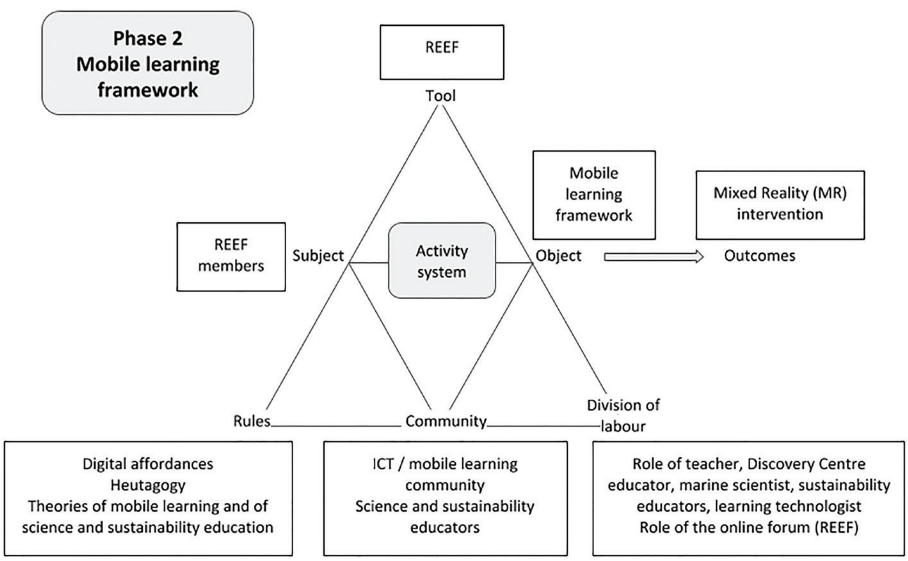

Figure 3. Mobile learning framework co-development activity system (phase 2).

Ethical procedures were approved by a university human research ethics committee, and these included the gaining of informed consent from all participants, consideration of anonymity where possible and/or desired by participants, and a conscious attempt to do no harm through our research.

Design principles of a self-determined mixed reality learning framework

The work of the REEF team during phase 2 led to a set of key messages, or design principles, for each one of the four main areas of the framework. These key messages summarise an extended list of principles and ideas discussed by the REEF, yet they cover the key aspects to be considered when using mobile learning to enhance the development of marine ecological literacy within an EOTC context. Table 1 shows these key messages.

These key messages and design principles are generic in many ways but flexible and adaptable enough to be locally developed according to the specific characteristics and conditions of each educational context. In this project, Auckland University of Technology's AppLab, led by Dr Aguayo and with support from Conical Studios, enacted the framework, developing a set of mobile learning digital experiences using an XR approach. In this context, and as described earlier in relation to the original definition from Milgram and Kishino (1994), MR/XR is understood as the merging of real and virtual worlds with different degrees of immersion within a digital continuum. The different elements of the XR intervention at the Goat Island Marine Discovery Centre are shown in Figure 4.

The digital elements of the XR intervention were themed around 'Pipi's World', including an app based on Pipi the snapper (see Figure 5), a young female character that was inspired by the original designs from the school students in a co-creative design process, following an Art+Science approach (Jowsey and Aguayo 2017). Pipi's World offered users different engaging digital learning experiences through AR via the mobile app (freely available on Google Play or App Store). There was also a computer-generated VR experience accessible through different types of high-end VR headsets; an 'analogue' and 'haptic' kelp forest created using felt materials centred around 'recycling' as a theme (i.e. Smith 2018), including QR codes; and a range of other complementary experiences accessible through different entry points (e.g. QR codes, 360 aerial, underwater and land-based virtual tour of the marine reserve, online VR viewer using low-end headsets, complementary array of apps and other already existing content). The narrative was centred around Pipi the snapper who could show users her world – the Goat Island Marine Reserve, the positive impacts of marine conservation inside the reserve over time and the fishing pressures she and other marine life get exposed to outside the boundaries of the reserve.

In applying the framework to develop the XR intervention, the set of design principles presented in Table 1 provided the parameters informing the digital development, in terms of mobile learning affordances, heutagogical considerations, learning context considerations and addressing specific targeted learning outcomes. Such parameters were clear enough to guide the ongoing decision-making processes that normally occur when designing digital learning affordances, in this case a digital continuum in the form of an XR intervention.

For instance, prioritising self-guided BYOD opportunities over affordances demanding sophisticated hardware; using a co-creation approach to meet the target audience's characteristics and needs through user-informed design; focusing the

Table 1. A framework for complementary mixed reality (XR) and free-choice learning education.

(1). Mobile learning considerations

i. Mobile, immersive and real experiences should support and complement each other through a mixed reality approach (following current digital trends)
ii. Mobile learning implementation and use (in free-choice education) must focus on bring your own device (BYOD), in part to manage the cost of technology.
iii. Mobile learning opportunities should emphasise self-determined learning (heutagogy), so that the learning experience can unfold in unique ways for each learner based on their own motivations and needs.
iv. User-informed design and co-creation should guide the design of mobile learning opportunities to promote meaningful learning.
v. Mobile learning opportunities should be authentic to the context, integrated within and across learning areas and scaffolded for a clear learning pathway.
vi. Mobile learning opportunities require access to technology (e.g. WIFI connectivity and IT infrastructure) and staff who are well prepared in the use of the technology and the pedagogy/heutagogy that can maximise learning.
vii. Learners need prior training and exposure in the use of mobile learning resources (e.g. virtual reality) in order to be able to focus maximally on the learning intentions of their use.

(2). Pedagogy/heutagogy (teaching and learning principles)

i. Focus should be placed in self-determined (heutagogical) learning, where the learning is guided by learners' motivations and needs.
ii. The placement of the outside-the-classroom visit within a teaching unit is pedagogically important.
iii. The structure of the outside-the-classroom visit is pedagogically and logistically important.
iv. Pre-visit resources can help to sensitise learners and initiate connections to place (the visit site).
v. Use of the mobile learning resources (virtual/immersive environments) should be designed to complement and not detract from sensory (embodied/haptic) experiences in the real environment.
vi. The visit should allow freedom to experience but also have some focus to scaffold learning, and to promote interactions between learners (social learning).
vii. Opportunities for learners to interact with both real and virtual/immersive learning environments increase learner autonomy and engagement.
viii. Learning needs to be reinforced post-visit to deepen knowledge, clarify attitudes and support next learning steps.

(3). The learning context (in this case: Marine science and conservation)

The key concepts in the context that underpin the unit of teaching which includes mobile learning and education outside the classroom, for example (in this case):
i. Marine reserves conserve the marine environment through protection, research and education.
ii. Marine reserves protect biodiversity (e.g. range of species within the reserve).
iii. Marine reserves provide social and/or cultural benefits (e.g. cultural practices).
iv. Biodiversity is crucial for interdependence (e.g. food webs snapper/kina).
v. Pollution threatens marine environments (e.g. sedimentation runoff, plastics).
vi. Global warming is threatening marine environments (e.g. ocean temperature change and acidification).

Table 1. (*Continued*)

(4). Learning objectives (in this case: Development of ecological literacy)
What you intend students/adult learners to be able to know and do in response to the teaching and learning through mobile learning and education outside the classroom/free-choice education. i. To develop ecological literacy about marine reserves, learners need to: a. Gain knowledge of marine ecology and the impact of marine reserves (environmentally, socioculturally and economically) through authentic inquiry, system thinking and meaningful experiences b. Demonstrate holistic thinking that views marine reserves as systems that connect the natural environment with society and its culture and economy c. Reflect on their own and others' attitudes and values towards marine reserves d. Be motivated and able to think critically, plan and take action in respect of marine reserves.

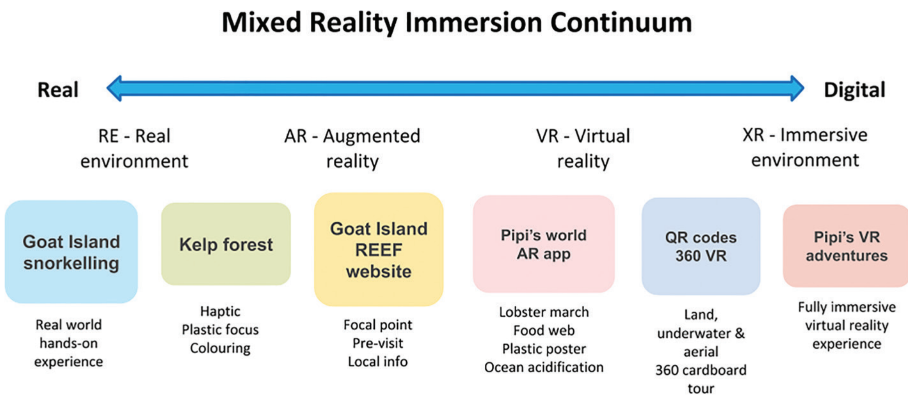

Figure 4. The XR approach developed following the mobile learning framework.

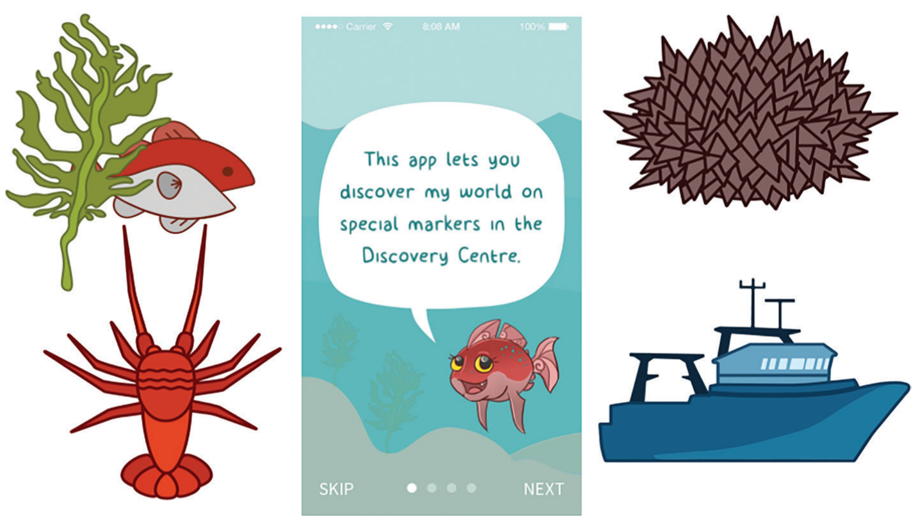

Figure 5. Graphic elements portraying aspects of Pipi's World Augmented Reality app, including Pipi the snapper.

narrative and storytelling on those themes that were deemed more important by the REEF, like lobster population decline, plastic pollution and ocean acidification; or considering the merging between the formal environment existing in the classroom and the non-formal nature of the EOTC occurring at the Discovery Centre, to name some examples. This process permitted focusing certain design decisions and milestones over a wider range of creative ideas and options that emerged during the digital development period. Some consultation with the REEF also occurred during this period, in particular around specific issues such as, for example, the final aspect of Pipi the fish.

From the perspective of the DBR methodology, the first mobile learning framework draft and its XR enactment by the digital development team represent the development of solutions within the theoretical framework stage (phase 2 in Figure 2), and the testing phase with the class at the Discovery Centre represents the testing of solutions in practice stage (phase 3 in Figure 2), respectively. The project team provided ongoing feedback on the iterative development of the XR intervention, with input from the teacher and the Discovery Centre educators during the testing of solutions in the DBR model. The set of refined key messages and design principles from Table 1 represent the final DBR process of 'reflection to produce design principles for educational outcomes' (phase 4 in Figure 2).

Discussion and conclusion

The first mobile learning framework (DBR methodology phase 2) enabled the development of a collection of XR digital experiences in a collaborative, co-creative, dynamic and iterative way. The refined framework (Table 1) that emerged following the DBR methodology (phase 4) can be seen as general guidelines and/or design principles intended to be flexible and adaptable to local conditions and emerging technologies. The collaborative and co-creation design and development process (e.g. in developing and subsequently refining the Pipi the snapper character) appears to have increased the meaningfulness of learning experiences (Eames and Aguayo 2019; Facer and Williamson 2004). The focus of the DBR approach on dynamic and iterative design and development led us to incorporate an XR approach which, for various reasons, was not even imagined at the outset of the 2-year project. Such digital dynamism and rapid adaptation to new technologies may be a key strength in the potential of mobile learning (Aguayo, Cochrane, and Narayan 2017; Pachler, Bachmair, and Cook 2010).

A focus on facilitated collaborative work to guide the agenda of the REEF team (both face-to-face and online), in addition to the iterative nature of DBR, provided a fertile ground leading to the co-development of the framework by the REEF team. DBR as a digital design methodology (DBR methodology phase 3) further assisted the digital development team to enact the mobile learning framework, allowing for flexible and adaptive prototyping and decision-making processes, following the parameters set by the framework from the REEF team, and inspired by the artwork developed by the students. This process also included ongoing back and forth feedback between the REEF team and the digital team, and between the digital team and 'end-user' participants following a co-design framework (Aguayo 2014; Facer and Williamson 2004).

The XR intervention in the marine reserves unit appeared to heighten student engagement and learning at the Discovery Centre (data which will be reported elsewhere), and promote post-visit learning (Ballantyne and Packer 2005). All elements of the XR intervention appeared to contribute together. However, it is noteworthy that the activities that engaged students the most are located at either end of the MR immersion continuum, leading to speculation that the continuum might actually exist as a circle rather than a line, in which VR becomes juxtaposed with immersion in the real world. Moreover, according to Aguayo (2017), the concept of 'real reality' (RR) becomes relevant here, as the 'analogue' end of the continuum ought to *actively* complement and facilitate the process of learning through engagement with real-world experiences – in opposition to an educationally passive engagement with the real world, as in the 'RE' view of the original XR continuum from Milgram and Kishino (1994). This has implications for deeper connections between virtual and real worlds that can engender learning as a whole, and that learning can be socially shared and provide a bridge between outside the classroom, the classroom and the home, as well as inter-generation agency.

Adopting a heutagogical approach appeared to assist in engaging the students in learning both at the Discovery Centre and back in the classroom, but presented challenges to the parent helpers and Discovery Centre educators, indicating a need for better preparation for these roles under this approach. The educators did find it challenging being in a slightly different role and some parents found it less satisfying, but most enjoyed seeing the students so engaged. A post-visit reinforcement strategy emerged, not using social media as initially envisaged, but through re-engagement with the XR resources in the classroom. The ongoing availability of the AR markers, 360 VR and QR codes for the students, with access to mobile devices and the freely available Pipi's World app, facilitated seamless and time-independent integration of the experiences had during the EOTC visit with subsequent classroom work.

Evidence suggests that the XR intervention assisted some knowledge and attitude development. Students felt that they learnt on the trip, and that both the snorkelling and mobile activities helped them learn. This was supported by the student-driven learning process at the Discovery Centre. The enactment of the mobile learning framework facilitated learning, provided students with many opportunities, and enabled them to engage in both individual and social learning. We also refer to early findings of the study (reported elsewhere) indicating that: (1) meaningful XR learning interventions have the potential to promote social learning between learners; (2) XR learning interventions ought to complement fully immersive digital learning experiences with analogue and non-technology-based learning opportunities and (3) flexible XR learning interventions have the potential to integrate and reinforce learning opportunities between free-choice learning settings and formal educational settings, while connecting teachers, students, educators, parents and the wider community in promoting more sustainable communities.

In conclusion, the adoption of an XR intervention incorporating an EOTC visit, in which mobile-less immersion in an RE combined with mobile-enhanced immersion in the Discovery Centre, complemented by a heutagogical approach with post-visit reinforcement for teaching and learning, appears to have had educational impact. This suggests some implications for practice:

- XR can provide a continuum from real to digitally immersive experiences. Offering a range of experiences along this continuum can provide effective opportunities for diverse learners. Attention to the local context in designing these experiences is achieved through co-creation of content with partners in ways that are meaningful to the target audience.

- XR can also provide a continuum between EOTC activities and classroom activities, reinforcing the learning from outside the classroom into the classroom. A cross-sector and intergenerational heutagogical learning approach is recommended to assist this.
- Educators and students are as yet quite naive in their use of digital tools such as VR, and there needs to be support for the development of skills to enable them to be used most effectively for teaching and learning. Skills in adopting a heutagogical approach when using these tools also need development.

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