

## **XR Maths – Designing a Collaborative Extended Realities lab for Teaching Mathematics**

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**Abstract:** Serious games, games-based learning, and simulation-based learning have been used to teach Mathematics at various educational levels. In this paper we shall present a design process and the first steps towards an extended realities (XR) collaborative lab for teaching of mathematics at HE level, which is currently under implementation.

Designing for XR applications is a complex task that requires knowledge from multiple disciplines in terms of interaction design, user experience, programming, and content creation. This complexity increases when the XR application is for educational purposes. XR education applications require additional competencies for defining learning objectives, designing activities that ensure that the objectives are achieved, and know-how regarding the integration of the application in the curriculum, whilst, at the same time, overcoming external barriers such as student access to technology and institutional support.

The design process proposed in this paper aims to give guidance to designers of XR applications that are integrated in an education context. The design process is then applied in the design of XR Maths, a XR mathematics collaborative lab which aims to help students understand and familiarise themselves with mathematical concepts and improve the learning experience offering an additional teaching tool to lecturers. The purpose is to complement, and not replace, frontal teaching of Mathematics in different disciplines across different programs, supporting lecturers rather than being their substitute.

To gather students' views and initial requirements regarding the use of XR for teaching mathematics, a survey and follow-up interviews were conducted between July and September 2020. The sample targeted were first year students enrolled in six different programmes at the University of the West of Scotland that involved mathematics modules. Lecturers in mathematics were also consulted to understand how the subject is taught to students from various programmes.

In this paper, we propose a process for designing XR application for education and initial findings regarding the user and functional requirements for the XR Maths lab as well as the limitations and barriers that need to be overcome for the success of such platform are presented.

**Keywords:** Extended Realities, Design Process, Mathematics

## 1. Introduction

Extended realities (XR) is a relatively young subject and although some of its children technologies such as VR, have been around since the '60s (Heilig, 1957), they have only recently started to be widely adopted thanks to the introduction in the consumer market of XR technologies. The youth of XR as an academic subject introduces additional challenges in understanding and integrating it in education contexts. As a teaching medium XR has great potential to support educators in the development of innovative teaching practices that exploit serious-games, game-based learning, and simulation-based learning to teach abstract subjects (Hamilton et al., 2021b) such as Mathematics.

Designing for XR applications is a complex task that requires knowledge from multiple disciplines in terms of interaction design, user experience, programming, and content creation. This complexity increases when the XR application is for educational purposes, which require additional competencies for defining learning objectives, designing activities that ensure that the objectives are achieved, and know-how regarding the integration of the application within the curriculum.

Recent literature reviews (Radianti et al. 2019, Hamilton et al., 2021b, and Hamilton et al., 2021) show that the design of XR education applications is still not well understood as applications are often not developed around learning objectives (Radianti et al. 2019), do not address specific learning needs (Hamilton et al., 2021b), do not mention pedagogies (Hamilton et al., 2021b), or are used as short interventions instead of being systematically integrated in the teaching of the subject during the course (Hamilton et al., 2021).

In addition, other barriers compound to make the designing and adoption of XR applications in education contexts difficult, such as students access to the technology (Hamilton et al., 2021), maintaining and running cloud based XR services, and user barriers related to physical constraints, motion sickness, and arms fatigue, which limit how long the XR application can be continuously used in a session, typically estimated to be about 20 minutes in the education literature (Hamilton et al., 2021).

This paper contributes to the field of XR in education contexts by presenting a design process aimed at overcoming the issues and barriers identified in this section. Furthermore, initial findings regarding the user and functional requirements for XR Maths lab, a collaborative application to support teaching mathematics currently under implementation, are discussed.

## 2. Related Work

There is little literature on effective design processes for XR applications in education, with most papers focusing on user interfaces and interactions design (Hamilton et al., 2021b; Scurati et al., 2020; Vi et al. 2019), instead of a model for fulfilling learning objectives and in-class integration.

Scurati et al.'s (2021) design framework is based on behaviourism (Skinner, 1989) and is developed for VR applications that aim to change user's behaviour. The model is based on three spheres of behaviour: emotional, relational and practical, which are linked to one another by design elements, such as aim, experience, user, level of immersion, and representation (Scurati et al., 2020). Although Scurati et al. (2021) framework is one of the most well-developed in the literature, it focuses on VR applications targeted for behavioural changes and do not provide a template for education XR applications that do not aim at behavioural change.

By contrast Liszio and Masuch (2016) propose a design approach based on cognitivism (Shuell, 1986; Dede, 2008) and social play, prioritising interaction, and conversation with other players in the virtual environment. Notably, Liszio and Masuch (2016) observe that there are multiple design techniques that are useful for VR experiences, taking the view that different techniques are necessary to fulfil different design objectives.

Harley et al. (2019) research through design take a generative view to design for mobile VR, basing their approach on Gaver (2012). This generative approach is developed as a research tool for understanding the mobile VR design space. However, this approach can be adapted to education contexts and used to start discussion with students, lecturers, and stakeholders to determine where and how the experience will take

place and how it will fit within the curricula. As shown by Makransky et al. (2020) generative approaches can be taken to the classroom as part of the learning process, enhancing the learning in VR.

For an XR application to be successful in an educational context, the design and development problems and barriers described in this section need to be addressed. This requires a systematic approach that starts from the identification of the students needs in relation to a subject understanding and develops into a strategy for integrating the use of the XR technology as a key technology in teaching the subject.

### 3. A Design process for Extended Realities in Education

In this section a design process for XR applications in education contexts is described. The process is student centred and aims at identifying student needs to develop learning objectives, choice of technology, interactions, mechanics, and visual elements. To keep the explanation simple in this section with the term designer it is meant a designer's team comprising as a minimum of an education expert, a user researcher, a graphic designer, and an XR interaction designer, some of these professional figures may be represented by the same person. It is recognised that the expertise required to design an XR application using the proposed process requires expertise from different fields.

#### 3.1 The Design Process - Overview

Figure 1 shows a high-level diagram of the design process. The process is composed by four phases: pre-design, design, development, and evaluation. The design process is centred on students and lecturers, which are involved at every stage of the process embedding their needs and feedback within the interim and final outputs of the process.

The aim of the pre-design phase is to address the issues highlighted in the previous section where XR applications are not always linked to learning goals, based on a learning theory, or consistently integrated within the teaching. The *design* phase follows an iterative and generative design paradigm, where artefacts are built to explore the design space (Harley et al., 2019; Graver, 2012), the generative process proposed allows to embed different design techniques in this stage, for instance those discussed by Liszio and Masuch (20016).

The *development* phase is based on an agile methodology (Fowler, 2001) the development looks back at the previous stages to ensure that the software being generated matches the pre-design and design outputs produced as well as testing the feasibility of previous stages outputs. Finally, the *evaluation* phase aims to do an overarching assessment of the output XR application in terms of embedding the pre-design outputs, the designer intent and the software validity as a teaching tool. Initial pre-design outputs are improved, the design revisited, and the software adjusted accordingly with the results of the evaluation.

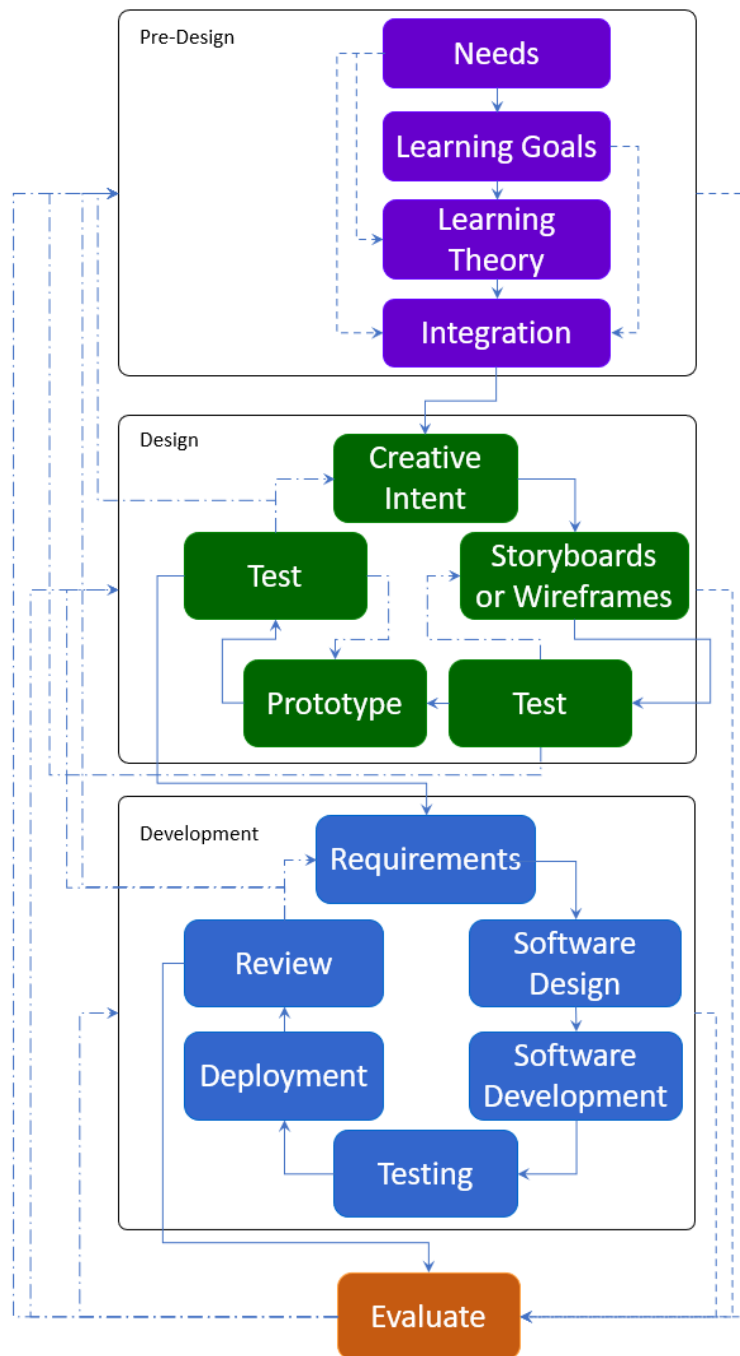
##### 3.1.1 Pre-Design Phase

The pre-design phase starts by identifying the students *needs* regarding the learning of the software. In this stage views about learning difficulties are gathered from both students and lecturers using user research methods (Nunnally and Farkas, 2016). This process helps understand whether there is a disconnection between what students and lecturers see as problematic withing the programme. If such disconnection exists, the designer can then address the issue with the lecturers and, upon agreement, look to integrate a solution in the XR application.

Once the needs are known the designer and the lecturers agree on what *learning goals* should the XR application aim for. In this stage learning goals is used loosely and intentionally differentiated from the term learning objective, as the XR application may not necessarily be needed to achieve a learning objective as indicated in a course descriptor but it may simply needed as a support tool to help understanding.

Once the designer has identified students and lecturers needs, and agreed upon learning goals for the XR application *learning theories* such as behaviourism (Shuell, 1986; Skinner, 1989), cognitivism (Shuell, 1986; Dede, 2008), constructivism (Fosnot, 2003), experientialism (Kolb and Kolb, 2012), and connectivism (Simens, 2014), are discussed with the lecturers. Learning theories describe learning models that can be used by the designer to identify the best type of experience to provide to the students through the XR application (Radianti

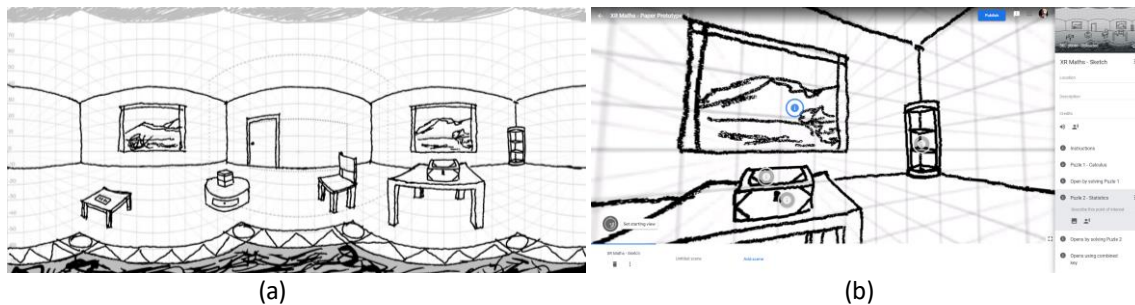
et al., 2019). The discussion between designer and lecturer regarding the learning goals and theories is then used as the basis to determine the *integration* of the XR application in the teaching, indicating how and when the application will be used.



**Figure 1** Proposed design process

### 3.1.2 Design Phase

Once the pre-design phase is concluded the designer moves to the design phase. As mentioned in 2.1 this stage is generative aiming to create design artefacts that help the designer understand the design space in which they are working. In this paper a design artefact is intended as anything that has been created by the designer to explore the design space, this includes, for instance, text, sketches, physical objects, as well as paper and software constructs. Figure 2 shows an example of design artefact.



**Figure 2** Example of design artefact. (a) paper wireframe of the environment on a 360 template (b) same wireframe sketch uploaded on a 360 software application with added interaction points.

The design phase starts with the designer establishing the *creative intent* for the XR application. The creative intent is a statement that embodies what the XR application will be and how it will be experienced, including moods and emotions that the experience will solicit in its users (Prosperi, 2016). The creative intent is used as the basis for the generation of paper-based artefacts such as *storyboards and wireframes* which are used to iteratively *test* with students and lecturers to ensure that the pre-design outputs are being embedded into the design. The use of paper-based artefacts enables fast iterations and exploration of ideas. Once the storyboards and wireframes are finalised, they are translated into software or physical *prototypes* that are again used to iteratively *test* the creative intent with students and lecturers ensuring the design embeds their needs, the learning goals, learning theories, and fits with the agreed incorporation plan. During the test stages of this phase the designer can uncover additional needs from students and lecturers, and adjust the outputs of the pre-design phase, for instance by modifying or setting new learning goals with the lecturers if required. The prototyping stage gives the designer an idea of the possibilities and the viability of ideas generated at the previous stage. At the end of this phase the designer will have a clear idea of how the application will take shape with artefacts that demonstrate the vision to the developers.

### 3.1.3 Development Phase

The development phase is an agile software methodology that is chosen by the developer's team. During the first stage the designer works with the developers to define user and functional *requirements* for the application. This stage determines what the software will be, and the design artefacts produced during the design phase are used to describe to the developers' team how the application will look like. The developer team will then produce the *software design and implements* it. At this stage *testing* with students and lecturers is performed. During testing the designer and development team should work together to ensure that the designer creative intent and student's and lecturers needs, learning objectives and learning theories are correctly translated into the XR application, the testing stage is also a moment of reflection for the designer that can be used to improve the original design and feed it into the next cycle of the agile software development. Once separate elements of the software are tested the application is *deployed and reviewed* with students and lecturers, to ensure that the pre-design outputs are embedded into it. If needed the software development cycle can restart with adjustments to the design.

### 3.1.4 Evaluation Phase

The evaluation phase is guided by the outputs generated in the pre-design phase and feeds from the design elements and the XR application to identify appropriate research questions and methodologies that are best suited to evaluate the XR application in the education context.

## 4. Designing XR Maths

One of the earliest examples of using virtual reality to teach mathematics was Winn and Bricken's (1992) 'Experiential Algebra' application, which consisted of a VR application that allowed students to directly manipulate algebraic formulae by manipulating three-dimensional objects. More recent VR programmes, such as 'CalcFlow' (Nanome inc., 2017), attempt to introduce linear algebra concepts through visualisation, letting the user manipulate formulae and displaying the corresponding three-dimensional vectors and graphs. Although such applications provide interesting functionalities the focus is on the symbolic language of maths rather than building the student's intuition.

The formal abstract language that characterises Mathematics is often an obstacle to students that approach the subject at University level (Winn and Bricken, 1992). However, the formal language used in Mathematics is just a tool to communicate and develop abstract concepts, as such, the understanding of the concepts and properties of mathematical objects described by the language is of greater importance than the language itself.

Many approaches have been developed using XR to make it easier for students to understand concepts and familiarise themselves with the formal language. The highly visual characteristics of XR lend themselves to be exploited to create strategies that help students develop their spatial imagination (Lai et al., 2016; Host'ovecky, Huraj, and Pribilova, 2019). Lai et al. (2016) argue that spatial imagination is a learned skill that can be developed through practice, and that in particular geometric imagination is of great importance for the understanding of Mathematics. This observation is at the basis of XR maths applications such as Construct3D (Kauffman, Schmalstieg and Wagner, 2000), Geometry Explorer (Lai et al. 2016), and Sommerauer and Muller's (2014) mathematics exhibition.

In the remainder of this paper the pre-design stages of the design process proposed in section 2 are applied to the design of 'XR Maths' are discussed. Students across different programmes were consulted during the 'need' stage of the design process. The XR Maths lab application is still being designed, and the case study will present a general overview of the first steps taken during the design of the application.

## **4.1 Pre-design Stage**

### *4.1.1 Needs*

Existing information regarding all mathematics and statistics modules delivered across the University was collected before starting this phase. The University modules database was explored to identify mathematics modules across schools, resulting in 15 modules that were part of more than one programme. The teaching material for these modules was then reviewed to identify which topics were taught to students in which programmes and at what level.

Further ranking of modules based on the number of programmes they serve identified 10 Level 7 (first year of University in the Scottish system) modules as the target for the study. A questionnaire that aimed at identifying which topics should the XR application focus on was developed based on the teaching material. After obtaining University ethical approval, students email addresses were obtained from the modules virtual learning environment (VLE) pages and an invite list of 296 level 7 students was created.

The questionnaire was open for two weeks with students invited to take part via email, with a reminder email sent one week after the first invite. Students that completed the questionnaire were redirected to a separate form that invited them to sign up to a follow up interview based on the descriptive analysis of the questionnaire responses. Contacts obtained from the sign-up process were stored in separate database from the questionnaire responses to guarantee anonymity. The interviews lasted for approximately 20 minutes. Slides were used as prompts to investigate some of the themes identified from the analysis of the open question's responses of the questionnaire.

Of the 296 students invited to complete the questionnaire 59 students completed the questionnaire with 62% male, 26% female, and 2% non-binary gender. The age split mirroring the statistics of the University population, with 71% of responders falling between 18-24, 21% between 25-34, 5% between 35-44, 2% between 45-54, and 2% over 55.

Each respondent was asked in an open question for a topic, or topics, which they found difficult to understand, and which had been challenging.

The main areas which were raised under "understanding" were Calculus (15%), Vectors and Matrices (14%), Logarithms (10%) and Discrete Mathematics (10%).

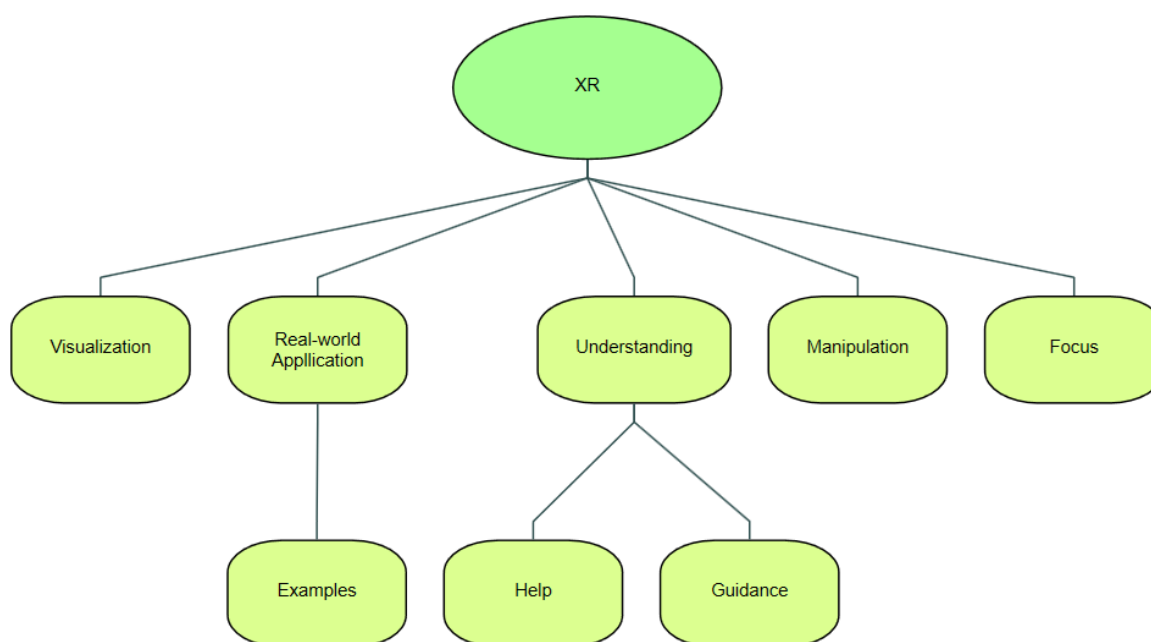
The main areas which were raised under "challenging" were Calculus (24%), Statistics and Probability (14%), and Matrices (12%).

These open questions highlighted the following themes: forgetting about pre-requisite concepts, confidence, group work, understanding the language, and need for support.

The questionnaire shows that 90% of the students had used online resources to assist their learning. In terms of devices being used to access these resources, 71% use a desktop or laptop, 54% use a smartphone, and 24% use a Tablet.

Of the responders, 52% had used a VR headset (the vast majority for gaming), 32% own a VR headset, and 40% had used an AR app (the vast majority for gaming). This highlights that the technologies are not yet widespread across the student population. Those with access to a VR headset claim to spend, on average, around 2.6 hours per week using the device, and AR users spend around 1.7 hours per week using the device.

Further, 72% of responders thought that VR could be useful in learning mathematics, and 68% thought that AR could be useful in learning mathematics. Analysis of the open question asking to explain the choice highlighted the following themes (see figure 3): visualization of abstract objects, real-world applications, improve understanding of a topic, manipulation of mathematical objects, increase focus on the concepts. The 'example' sub-theme was identified for 'real-world application' where students propose to have examples, not just explanations, of how maths work in the real world. The 'help' and 'guidance' sub-themes were identified for the 'understanding' theme, where students suggest that XR can help their understanding and provide guidance on how to solve problems.



**Figure 3** Themes emerged from the open questions in the questionnaire

Students with a negative perception of the use of AR or VR just didn't think it would help, expressing concerns on the application being distracting, motion sickness, and detachment from the classroom.

Of the 59 participants that completed the questionnaire only 20 signed up to the follow up interview and only 5 of those responded to the invite to be interviewed. From the interviews emerged that group study is a key element in the learning of mathematics as students often commented that it was good to be able to ask questions to fellow students:

*"Yeah, I would say the more productive of any, any of the aspects of the course where group work as far as classes go. Because, because as I've kinda... same as before, they don't really have confidence and, and once they start coming to and be able to talk to people, and once you're setting a group, and you can be able to get on, it helps to be able to ask questions, so some that you don't understand, or some that, some you don't understand, you can just turn around and ask the person next to you Do you understand that? And likewise, they can come in see, well, you know, I don't I don't I don't get that part, can you help me with this? "*  
 (Participant 3)

This collaborative aspect will need to be in XR applications as, as participant 3 observes, some students may not be more comfortable in asking a fellow student for help than the lecturer.

From the interview also emerged that some topics were presented without explaining from where the mathematical object comes from, students commented that they prefer to understand the origin of the object, as Participant 5 points out:

*“I understand derivatives their uses, and how we get them. integrals are the same. But matrices, I just, I don't know where they come from. Just they just seem to, like, come out nowhere. Know, I mean, just, like, they just give it give it to us. And we like learn about it. And I don't like it.”* (Participant 5)

The results from the questionnaire and interviews can be translated in the following initial general requirements for the application:

- R1. The application must be collaborative allowing students to work in groups to solve problems and support each other, helping them to build confidence in their abilities.
- R2. Scenarios must be implemented explaining the origin of the mathematical concepts to consolidate the student understanding about that concepts, where it comes from, its meaning and use.
- R3. The application must allow manipulation of formulae, assisting students in solving problems.
- R4. The application must allow students to visualise and interact with the mathematical object to help them understand how the objects work and what they mean.
- R5. The application must be multiplatform. As highlighted in the questionnaire VR hardware is not widespread in the target student population, mobile and desktop options must be available.
- R6. The calculus, vectors and matrices, logarithms, statistics and probability, and discrete mathematics must be topics covered within the application as highlighted by the questionnaire.

#### 4.1.2 Learning Goals, Learning Theory, and Integration

A new module ‘Applied Maths for Games and User Research’ that is currently under development has been chosen as the candidate for integrating the application into it. The module aims to teach linear algebra applied to computer games and introduce statistics to students. The module learning outcomes are:

- L1. Demonstrate understanding of linear algebra and statistical concepts
- L2. Demonstrate mathematical reasoning in solving problems applied to computer games and game user research
- L3. Demonstrate the ability of applying critical reasoning to interpret and visualise data

Discussions with the lecturer identified that the application should be structured as ‘episodes’ to allow the instructor to use each ‘episode’ as a weekly pre-class and post-class collaborative activities to help student reflect about the material. The learning goals set for each episode are subordinated to the main learning outcomes of the module and designed to help the students achieve them, an example is given in figure 4.

Episode 3 - Vectors in coordinates	
<b>Problem</b>	<i>P1. Can you create a vector of length 1. P2. Using the vector of length one can you determine how long is the vector presented to you? P3. Can you create 3 vectors of length one that are independent from each other? P4. Using the vectors you created can you measure the length of the vector presented in each of those directions? P5. What happens to the coordinates if you change the basis?</i>
<b>LG</b>	Understand where coordinates come from Understand the link between vectors and their algebraic representation Understand how vectors can be represented in algebraic form
<b>FR</b>	Students must be able to set a measuring unit via a unitary vector Students must be able to assemble a vector basis Students must be able to use the basis to visualise coordinates attached to a vector Students must be able to modify the basis to see how the change affects the vector and its coordinates

**Figure 4** Example of learning goals (LG) and functional requirements (FR) for episode three.

The design of each episode is still in progress and only the first five episodes have been fully defined.



Generative learning (Cognition and Technology Group, 1991) underpins each of the episodes, which is implemented through problem solving. In each episode a series of problems, see figure 4, will guide the student in the development of the understanding. The student will be presented with a set of mathematical tools appropriate for the episode, and they will need to use the tools to solve the problem to advance to next problem or unlock the next episode.

## 5. Conclusions

XR has high potential to engage students with complex abstract material. However, XR applications in education do not follow a coherent approach that considers student needs, learning objectives, pedagogy and it is limited to short interventions. In this paper a design process for XR learning experiences that aims to address those issues was proposed. The process comprises of four phases, pre-design, design, development, and evaluation, with the central two phases based on well known and tested processes, namely generative design, and agile development. The pre-design phase of the process was discussed in the context of designing an XR application for teaching mathematics at University level, showing how it can be used to plan the integration of XR into the module design. The main limitation of the proposed design process is that the design team would need to have a wide range of expertise, covering education, graphic design, interaction design and research methods. Moreover, maintaining engagement with students and lecturers during the design and development process can be challenging.

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