Investigating Design Strategies for Classroom-based Augmented Reality Learning Experiences

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by

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Dedicated to

My Family

(Mr. Ramendranath Sarkar, Mrs. Shibani Sarkar, and Dr. Prathama Sarkar)

Approval Sheet

This thesis entitled **"Investigating Design Strategies for Classroom-based Augmented Reality Learning Experiences"** by Pratiti Sarkar is approved for the degree of Doctor of Philosophy.

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Abstract

The Indian schools in Tier 2 and Tier 3 cities involve technology-driven classrooms. However, learning the subjects such as (but not limited to) Mathematics, Science, and History that include abstract concepts often becomes challenging for students due to the requirement of visualising skills, a lack of learner-content control, and frequent disengagement. This leads to the requirement of a student-centered techno-pedagogical tool. Recent works have indicated Augmented Reality (AR) to be one of the emerging technologies for student-centered learning that superimposes computer-generated virtual objects onto the real world in real-time. Moreover, the ubiquity of mobile phones has led to increased integration of AR and mobile learning. In the context of Indian schools, this technology is still being explored and is yet to be added to the benefits of classroom teaching. Hence, there is a need to identify the ways by which AR technology can be designed and used in Indian schools to provide an interactive, immersive, and enhanced learning experience. To create such a classroom-based Augmented Reality Learning Experience (ARLE), the potential design strategies have to be identified and applied.

This dissertation advances our understanding of these problems in two ways: (1) to characterize the design strategies of an ARLE incorporating the three dimensions of learning i.e. content, incentive, and interaction (Illeris, 2003), and (2) to apply the identified design strategies in creating an ARLE. We have used Design Based Research (DBR) as the overarching research approach to design and iterate on the potential solution. DBR is a research methodology that aims at the development of educational interventions or learning environments through iterative cycles of analysis and exploration, design and development, and evaluation and reflection. We carried out seven research studies (N = 235) using a mixed-method approach in two cycles of DBR.

To address the first research goal i.e. to understand the required design strategies for a classroom-based ARLE, along with a literature review, three studies were conducted to iteratively identify the design strategies. Initially, the expectations from students, teachers, and parents of having an ARLE in the classroom were outlined (Study 1). Furthermore, the suitable AR interaction mediums that can be used for collaborative AR problem-solving in the classrooms were identified (Study 2). This was followed by conducting a workshop with the designers of an ARLE to identify the design strategies classified under the three dimensions of learning (content, incentive, and interaction), that meet the user expectations and incorporate the AR interaction mediums (Study 3). The identified design strategies guided us in designing an ARLE, named *ScholAR* in two iterations.

With the help of *ScholAR*, the 7th-grade learners could explore the AR content, perform the AR learning activities and answer the reflective questions with and without AR. This was done for the topics related to 3D geometry such as *'Lines and Angles'* and *'Visualising Solid Shapes'*. The primary objective of these AR learning experiences was to provide the learners with an authentic context and involve embodiment while addressing the three dimensions of learning. Thus, the learners could gain (a) cognitive learning while exploring the concepts and solving the problems in AR (content), (b) affective learning while getting immersed in the process through embodiment (incentive), and (c) social learning while collaborating with peers and teachers to solve the problems in AR (interaction). Such learning experiences are critical for embedding concepts and practices into pedagogy and aiding learners' key learning processes while performing the AR learning activities. Moreover, the DBR approach helped in identifying the features of the activities like instructional slider and prompt, embodied controls for multi-perspective view through physical navigation, 3D object manipulation, and annotation in the augmented space.

The first iteration of *ScholAR* for the module of *Lines and Angles* was evaluated in a lab setup (Study 4) where students either used *ScholAR* in dyads or individually. The *Visualising Solid Shapes* module was evaluated in a classroom (Study 5) with students belonging to either the group performing the AR learning activities or the group learning the same topic using the available physical objects. In both the studies we examined how the design strategies were used in *ScholAR* for problem-solving; impacting cognitive, affecting, and social learning. We reflected upon the effective design strategies and the corresponding design changes required. The evaluation of the revised design and the effective design strategies was done with dyads for both *Lines and Angles* (Study 6) and *Visualising Solid Shapes* (Study 7). Thus, in constantly refining our design to support 3D visualisation for problem-solving, we refined our understanding of the design strategies that led to the Co-ASAR (**Co**gnitive, **A**ffective, and **S**ocial learning using **A**ugmented **R**eality) framework.

The major contributions of the thesis include a set of design strategies catering to the dimensions of learning in a classroom-based ARLE, the design of an ARLE for problem-solving supporting 3D visualisation, and a framework for designing a classroom-based ARLE to attain cognitive, affective, and social learning.

Keywords: Augmented Reality Learning Experience, Design Strategies, Dimensions of Learning, 3D visualisation, Problem-solving, Design-based Research

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List of Abbreviations

AR	Augmented Reality
ARLE	Augmented Reality Learning Experience
DBR	Design Based Research
DQ	Design Question
EDR	Education Design Research
ICT	Information and Communication Technologies
LQ	Literature Question
RQ	Research Question
UI	User Interface
UX	User Experience

Chapter 1

Introduction

1.1. Motivation

Over the years, technology has become increasingly influential in a variety of fields, including education. In this sector, numerous technologies have been implemented within and outside classrooms. The embrace of technology in the classrooms of Tier 1 to 3 schools in India has challenged the conventional teaching style of textbooks and blackboards (Singh, 2020). Blackboards are being replaced in school classrooms with a variety of technology tools such as interactive whiteboards (Takawale & Kulkarni, 2016; Menon, 2015) and accompanying modules that include images, videos, audios, and animations that may be displayed on screens (Goswami, 2014; Bharadwaj, 2007). These tools tend to provide an improved learning experience to the students. However, in all such instances, the instruction medium remains to be instructor-mediated (Cuban et al., 2001). In our preliminary visits to schools, it was commonly observed that the instructors tend to control the interactivity of these techno-pedagogical tools. After showing the related examples or demonstrations using the technology mediums, the students are asked to solve textbook problems. This causes hindrance for the students from thinking and solving problems beyond the textbook ones.

Moreover, in subjects such as Science, Mathematics, Astronomy, and History, to name a few, there are various abstract concepts that students need to visualise. Such abstract concepts must be represented in a manner to delve into deeper understanding. In doing so, the students must have the ability to visualise and conceptualise spatially. This ability is based on their exposure to prior experiences that they can relate to and further build up their imagination skills (Schunk, 2012). However, due to differences in personal experiences, this ability of spatial thinking may vary from person to person (Fox, 2001). Though the technology mediums have been developed to provide such visualisation aid in the classroom, the control and use of it depend on the instructor. Also, in the process of teaching such concepts using techno-pedagogical tools, it cannot be instantly assured whether the students were engaged throughout and have learned those abstract concepts while passively interacting with the displayed content. This leads to the requirement of creating content and supporting controls and interactions that involve the active engagement of the students, resulting in enhanced learning outcomes.

Learning has been characterised by Illeris (2003) in terms of both the learning outcome and the mental and interaction processes that go along with it. Highlighting the three dimensions of learning, i.e. content, incentive, and interaction, the interconnection of the learner, the content, and the incentives have been illustrated. A key approach to attaining this interconnection has been the use of student-centered technology in the classrooms (Sandholtz, 1997; Singh, 2011) to encourage active engagement, divergent reasoning, problem-solving, and critical thinking (Hannafin & Land, 1997). For this reason, the motivation of this research began with understanding the scope of using student-centered technology in the classrooms involving content with learning activities for active engagement and a learner's interaction with the content, instructor, and peer learner.

There are a few student-centered technology approaches that have been adopted at school levels. In the Flipped Classroom approach, students have access to online video lectures prior to in-class sessions. This prepares them to participate in more interactive and higher-order activities like problem-solving, discussions, and debates (Mohanty & Parida, 2016; Bhagat et. al, 2016; Bergmann & Sams, 2012). This approach involves more of outside classroom events and individual levels of comprehension due to the self-pace of learning. Clickers or similar Personal Response Systems (PRS) are frequently employed as technology assistance to gather votes from the students (Ryan, 2013). When the majority of the class chooses the appropriate option as their answer, the instructor knows the exercise was a success (Majumdar & Iyer, 2015). It is found to be most effective with peer instruction (Hall & Saunders, 1997). This approach involves peer discussions and is limited to answering multiple choice questions. Computer simulations and games can help promote modern, inquiry-based methods to scientific education by replicating real-world circumstances with fully interactive guided experiences. This can help students envision, investigate, and generate explanations for events that would be impossible to see and handle otherwise (Siddiqui & Khatoon, 2013; Nedungadi et al., 2015). While all these student-centered technologies reflect on self-directed independent learning, we intend to provide an enhanced collaborative environment for consistent engagement and learning in the classrooms. Hence, we further looked into student-centered technologies that can be explored collaboratively.

Immersive technology, which is defined to be able to enhance the realistic experience of the virtual components and create a sense of immersion for the users (Soliman et al., 2017), if introduced in classrooms, can improve the learning skills of the students and keep them motivated. One such emerging immersive technology is Augmented Reality (AR) which superimposes computer-generated virtual objects onto the real world in real-time (Azuma et al., 2001). Over the years, various benefits of using this technology in educational environments have been reported, including an increase in student-centered learning, collaborative learning, and interactivity, to name a few (Diegmann et al., 2015), which stands essential for our objective. Moreover, the ubiquity of mobile phones has led to increased integration of the use of AR and mobile learning (Kim, 2013; Alhassan, 2016). However, in the context of Indian schools, this technology is still being explored and is yet to be added to the benefits of classroom teaching. Hence, the further motivation lies in identifying the ways in which AR technology can be designed and used in Indian schools while incorporating the three dimensions of learning to provide an interactive, immersive, and enhanced learning experience in classrooms. To create such a learning experience for the students in the classroom, the design strategies have to be identified and kept in mind while designing Augmented Reality Learning Experiences (ARLEs).

Thus, narrowing the motivation of the research work led to the following broad research goal:

> ***To develop an understanding of the required design strategies to create ARLEs for classrooms, identify their applicability to attain the dimensions of learning, and use this understanding to design AR learning activities for students to be performed in the classroom.***

1.2. Research Goal

As the Indian schools are gradually accepting and equipped with Information and Communication Technologies (ICTs), the research attempts to incorporate a student-centric emerging technology into the classrooms. One such technology is Augmented Reality (AR). In the Indian context, AR technology is being explored gradually, especially in the domain of education and training. Thus, to incorporate the same in the school classrooms, it is required to begin with understanding the design process to make appropriate design decisions and follow strategies to create a classroom-based learning experience. By realizing the appropriate design considerations at the macro and micro-level use in the classroom, the interactivities can be defined. This is to provide interactive and immersive learning experiences to the students directed towards attaining cognitive, affective, and social learning while integrating the three dimensions of learning. Thus, the research objective of this work is two-fold:

> ***Develop an understanding of the design strategies involved in designing an interactive ARLE for classrooms. Based on that, create a classroom-based ARLE to support cognitive, affective, and social learning.***

1.3. Research Methodology

As described in previous sections, the research goals of this thesis are to understand the design process and strategies to create an ARLE. Additionally, design an ARLE supporting the identified design strategies. These two goals aligned with the methodology of design-based research (DBR).

DBR is a methodology that guides the development of learning theories, improvement of instructional design, and possibilities of a new design (McKenney and Reeves 2014). This methodology consists of an iterative cycle of analysis and exploration, design and development, evaluation, and reflection. We have followed the DBR methodology proposed by McKenney and Reeves (2014), where the different stages are mentioned. The first stage is the analysis and exploration of the problem, the context, and the participants. It includes analysis of the existing solutions to address the problem along with exploratory study with novice or experts to understand the requirements. The stage of design and development follows it, where the designers or researchers create a preliminary learning design that is evaluated by various qualitative and quantitative methods. It is followed by the evaluation and reflection stage, where reflection is done on the designed solution identified for the given context. We have adopted the DBR methodology in our research work to first identify the design strategies required to design an ARLE and secondly to understand the effective design strategies which lead to cognitive, affective, and social learning. Our research questions (RQs) and design questions (DQs), as described in Table 1.1 emerged from the two research goals and our literature review. In the first cycle of DBR, the potential design strategies leading to effective learning have been identified. In the second cycle of DBR, the effective design strategies leading to cognitive, affective, and social learning have been elaborated.

Table 1.1. List of Research Questions (RQs) and sub-RQs

DBR Phase	**Research Question**	
DBR CYCLE 1: Understanding the design strategies of interactive ARLEs for classrooms		
Problem Analysis and Exploration	Broad RQ 1	What are the potential design strategies required to create classroom-based ARLEs?
	RQ 1a	What are the expectations of the users if ARLEs are used in classrooms?
	RQ 1b	What are the suitable AR interaction mediums while collaboratively solving problems in classrooms?
	RQ 1c	What are the design strategies adopted by the designers of a classroom-based ARLE to meet the user expectations while using the suitable AR interaction medium?
Design and Development	Broad RQ 2	How do the potential design strategies of creating an ARLE incorporate the dimensions of learning?
	DQ 1	What should be the design features of an AR app named *ScholAR*, incorporating the design strategies that lead to cognitive, affective and social learning?

Evaluation and Reflection	RQ 2a	What is the effect of the designed module on *'Lines and Angles'* of *ScholAR* on the students' cognitive, affective, and social learning?
	RQ 2b	What is the effect of the designed module on *'Visualising Solid Shapes'* of *ScholAR* on the students' cognitive, affective and social learning?
DBR CYCLE 2: Defining the design strategies for creating effective interactive classroom ARLEs		
Problem Analysis, Design and Development	DQ 2	What should be the improved design features of *ScholAR* modules, incorporating the design strategies that lead to cognitive, affective, and social learning?
Evaluation and Reflection	Broad RQ 3	What are the effective design strategies for the modules of *ScholAR* that lead to cognitive, affective, and social learning?
	RQ 3a	What is the effect of the designed module on *'Lines and Angles'* of *ScholAR 2.0* on the students' social learning?
	RQ 3b	What is the effect of the designed module on *'Visualising Solid Shapes'* of *ScholAR 2.0* on the students' cognitive, affective, and social learning?

1.4. Solution Overview

As mentioned, the design-based research (DBR) methodology (Barab & Squire, 2004) was followed, and two cycles of the same were conducted. The overview of our solution approach is shown in Fig. 1.1.

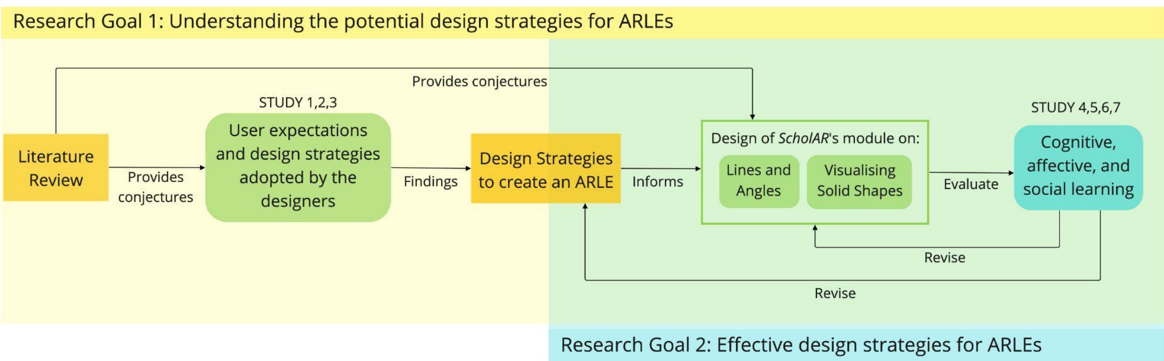


Fig. 1.1: Research goals of this thesis

1.4.1. Defining Design Strategies

Our first research goal was to understand the design strategies that can guide us toward designing an ARLE for classrooms. To identify these, we initiated by understanding the user expectations from an ARLE-based classroom (Study 1). This was followed by understanding the suitable AR interaction mediums for the students (Study 2). We found that *Tap and View* and *Draw and Annotate* were the comfortable interaction mediums for the students to interact with. The results from the first two studies became the directives for the next study in which the designers in groups comprising an AR developer, an interface designer, an education researcher, and a middle-school Math teacher brainstormed on the creation of an ARLE for the classrooms (Study 3). Through inductive analysis, the design strategies adopted by the groups were outlined based on the three dimensions of learning i.e., content, incentive, and interaction, as shown in Table 1.2.

Table 1.2. Classification of the potential design strategies based on the three dimensions of learning

Design Strategies		
Augmented Content for Cognitive Learning	Incentivizing AR Learning Activities for Affective Learning	Interactions and Interactivity in AR for Social Learning
Contextual Content Representation	Ensuring Immersion	Promoting collaboration
Enabling Exploration	Motivating through real-time feedback	Embodied interactions
Content Manipulation	Multi-level challenging problems	Instructional scaffolding

The next research goal was to understand the impact of the design strategies on students' learning outcomes in terms of internal (cognitive and affective learning) and external (social learning) interaction processes. Based on the design strategies obtained from literature and study conducted with designers of ARLEs, we were able to design ***ScholAR***, a **markerless AR application**.

1.4.2. *ScholAR* Pedagogy

Fig. 1.2 describes the framework of the *ScholAR* pedagogy, where, with the fading effect of the instructor's support, the learners could explore the AR content, perform the AR learning activities and answer the reflective questions with and without AR. This framework has been proposed for the different topics of a chapter that are covered over multiple days in a week or two in the classroom.

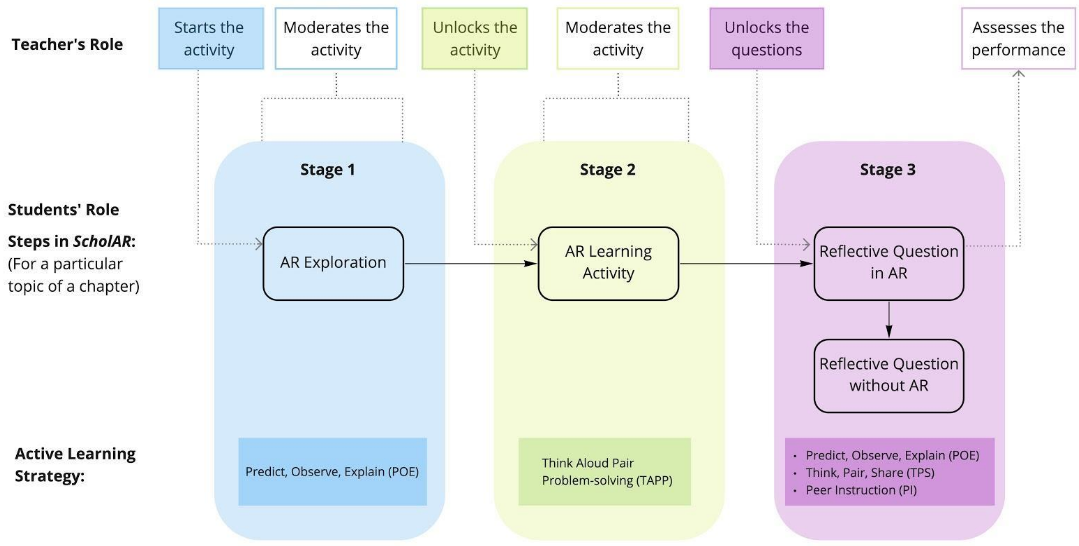


Fig. 1.2. The *ScholAR* pedagogy

The pedagogy has been broadly divided into three stages:

1. **Exploration:** In this stage, the teacher has the authority to start the activity. On broadcasting the activity, the students explore the virtual 3D object and the related concepts by moving around it and manipulating the concerning values or parameters. During the entire process, while the students explore themselves, the teacher moderates it to clear any doubts or confusion arising.
2. **Learning Activity:** This stage involves performing the AR learning activity. This learning activity is a non-evaluative one that the students perform when the teacher unlocks it for everyone in the class. During the process, the teacher acts as a facilitator to help students when they are stuck.
3. **Reflective Questions:** The final stage involves two forms of reflective questions:
   a. **Reflective Question in AR:** This includes a reflective question that is shown in the AR environment. The 3D object is supposed to be observed while answering the displayed question. On submitting the answer, the system gives feedback about the correct and wrong answers.
   b. **Reflective Question without AR:** The students answer the question collaboratively as shown on the screen, having multiple options to choose from. It is devoid of the AR space, and the 2D representation of the 3D object is shown. There is no facilitation of the teacher involved in this stage. On submitting the answer, the system shows the correct answer. In the end, the combined score of both reflective activities is shown.

1.4.3. *ScholAR* Learning Environment

The *ScholAR* application is a tablet/mobile-based Augmented Reality Learning Experience (ARLE) that involves two modules on *Lines and Angles* and *Visualising Solid Shapes*. Based on the design strategies obtained in initial studies, the design features of both the modules were defined, designed and developed.

The module of *Lines and Angles* consisted of multi-level AR learning activities, as shown in Fig. 1.3. On scanning the environment using the tablet/mobile device, a 3D house gets augmented in the real world. The three different activities catering to varied concepts are targeted towards recalling, visualising, identifying the example of a type of angle asked in the activity, and marking it on an augmented 3D object (3D house in our study) by annotating it in the AR view. The immersiveness is enhanced with the involvement of physical movement inside and outside the augmented 3D house.

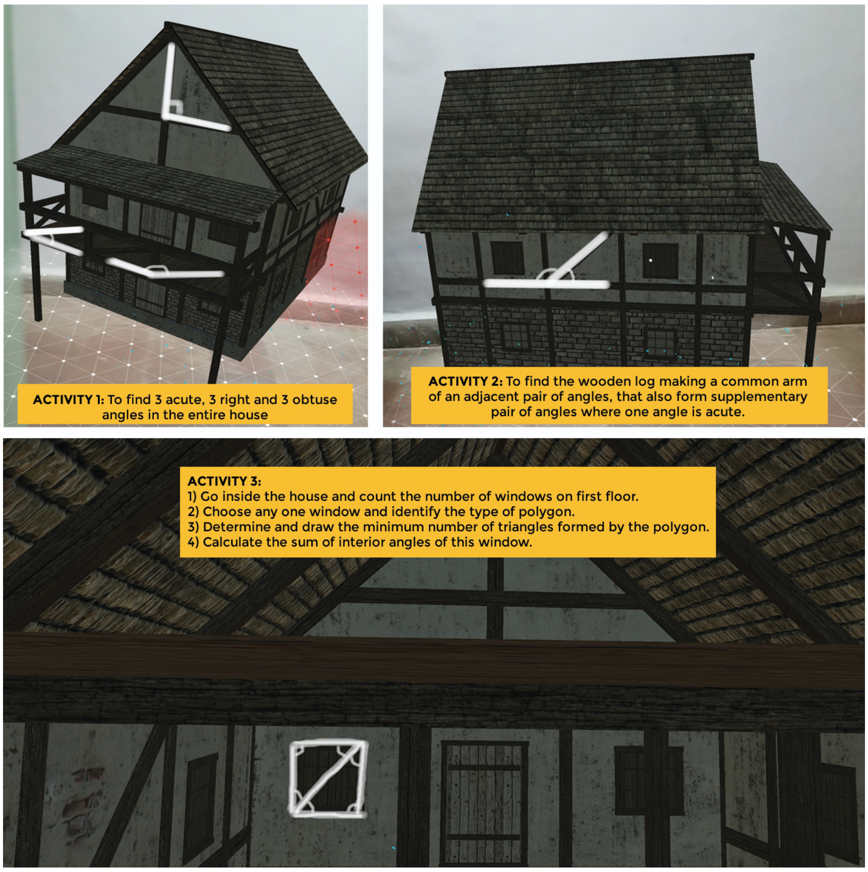


Fig. 1.3. Types of questions for the AR learning activities designed in *Lines and Angles* module

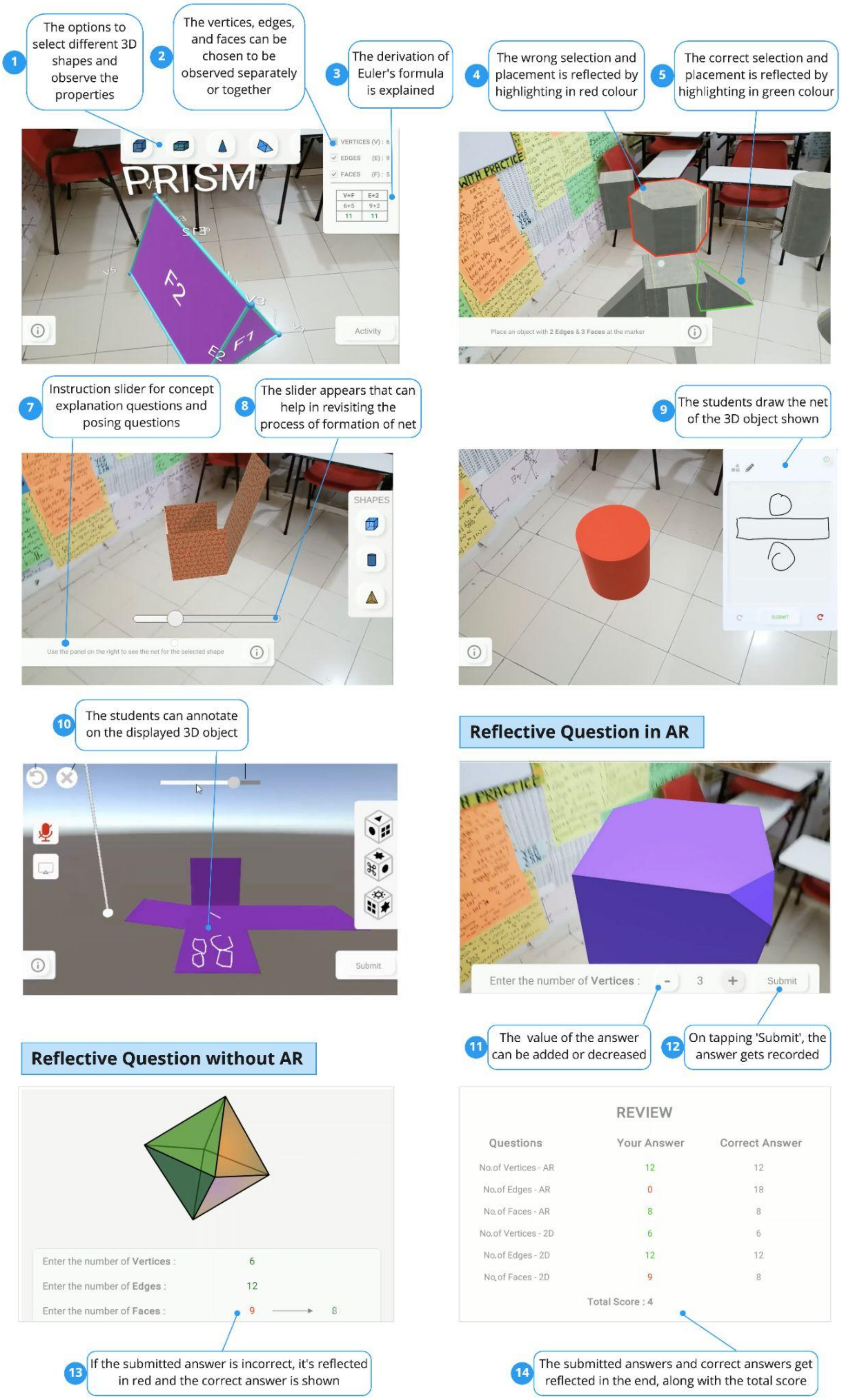


Fig. 1.4. Types of questions for the AR learning activities designed in *Visualising Solid Shapes* module

The module on *Visualising Solid Shapes* also consisted of multi-level AR learning activities, which is an operationalization of the *ScholAR* pedagogy. Fig. 1.4 shows the compilation of the snippets of the main features of this module's activities, corresponding to the stages of Exploration, Learning Activity and Reflective Questions (in and without AR). On scanning the environment using the tablet/mobile device, the 3D objects for the corresponding activity get augmented on the real world. The key features involved annotated information, information slider, animation slider, scribble pad, annotation on the 3D object, system feedback on the marked response, and score display. Detailed screenshots of the activities are presented in Chapter 7.

The teacher-side of the application is supported on Windows laptops or PCs. Once the students join, the teacher can see their screens at the same time, their progress through individual and overall progress bars, and the log of the actions that they are doing throughout. The first log indicates the directory in which the log files and the screenshots are saved. If a teacher/experimenter wants to communicate with a student, they can tap on the student's screen. A **blue pointer** appears to help the teacher point at a student's screen and explain to that student, as shown in Fig. 1.5.

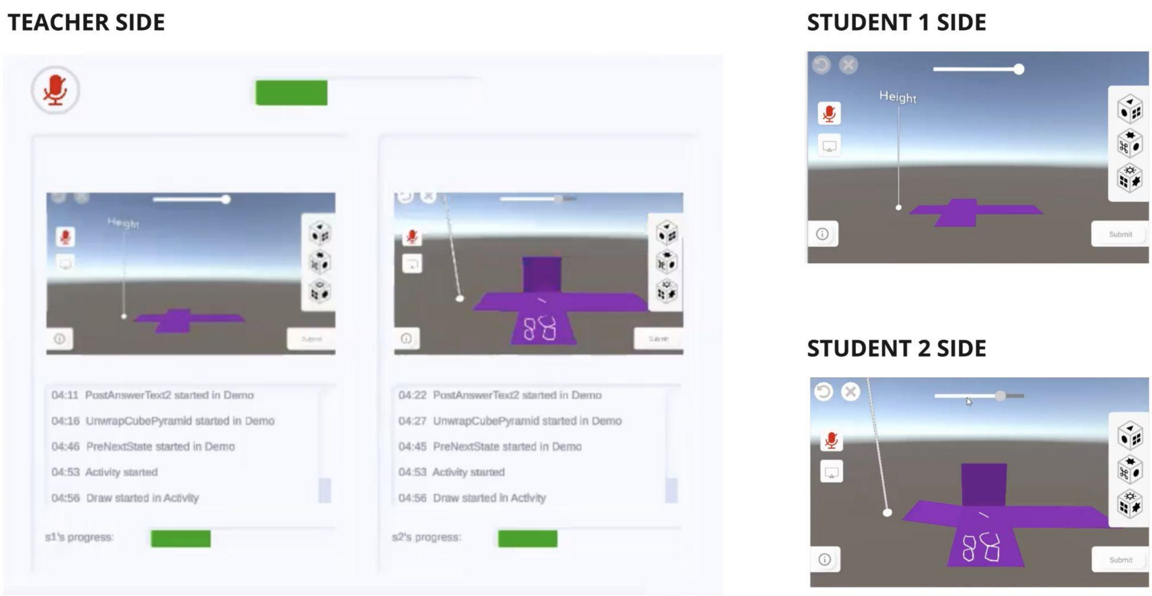


Fig. 1.5. The teacher side of the application

1.4.4. Evaluating *ScholAR*

Study 4 and 5 were conducted in the first iteration of DBR, where the modules on *Lines and Angles* and *Visualising Solid Shapes* were designed based on the obtained design strategies. To evaluate the impact of the considered design strategies, the primary focus was to assess cognitive learning through the evaluation of pretests and posttests. To align with the other dimensions of learning, the secondary focus was on the evaluation of affective and social learning. Based on the feedback obtained from the teachers and students, a few design changes were made to the two modules of *ScholAR*. The effect of the design strategies in creating *ScholAR* was further evaluated in Study 6 for *Lines and Angles* and Study 7 for *Visualising Solid Shapes*. Thus, in constantly revising our design to support learners' cognitive, affective, and social learning, we refined our understanding of the effective design strategies and the ways to incorporate the dimensions of learning. A summary of the studies done in this thesis is shown in Fig. 1.6.

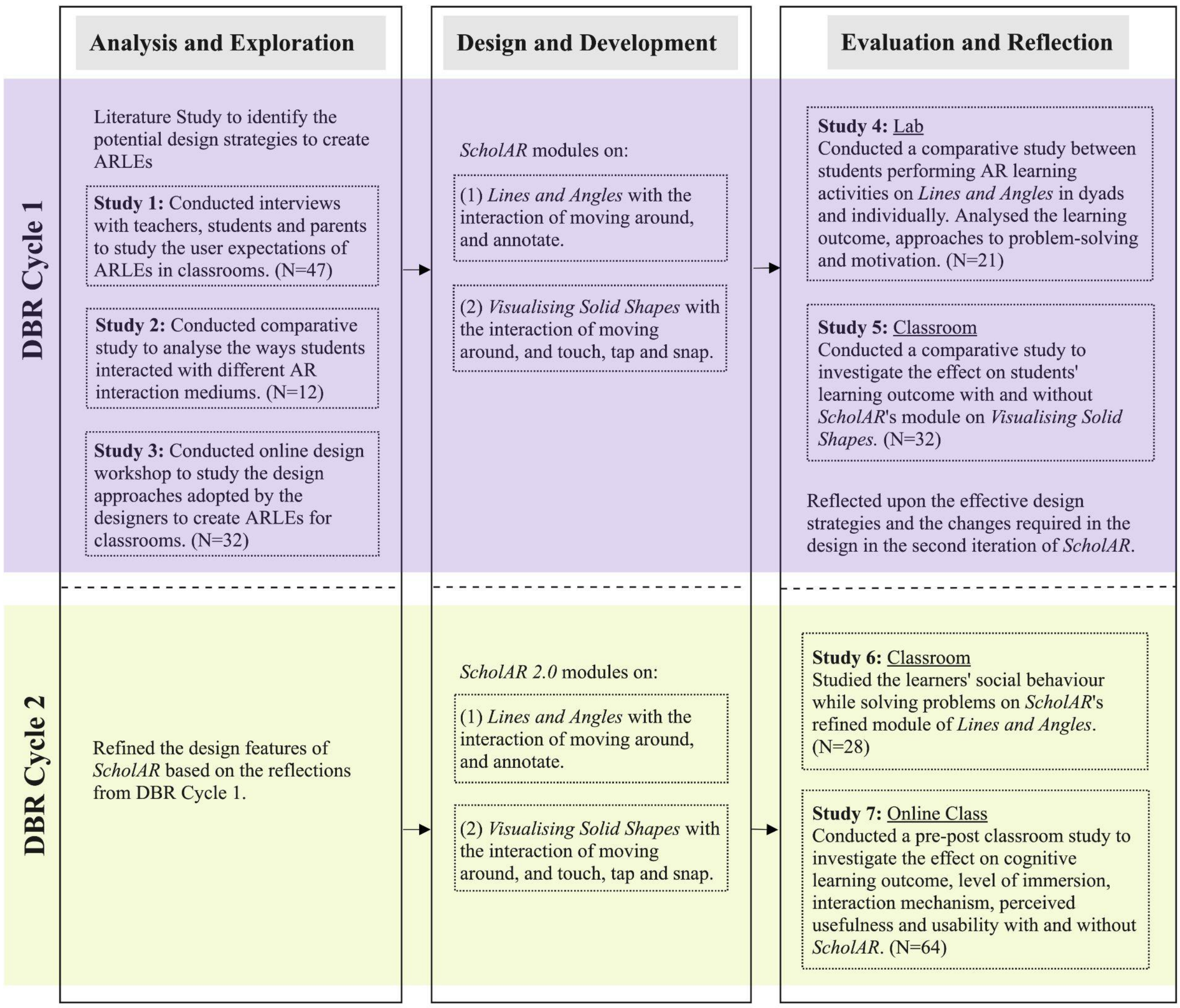


Fig. 1.6. Design-based research as applied in this research

1.5. Scope of this work

The research work has been scoped along the dimensions of the target audience, context, technology, and topic, as explained below:

Target Audience

According to Piaget's Theory of Cognitive Development (Wadsworth, 1996), children of age 11-15 years reach the formal operational stage where they are able to think logically, conceptualise the abstract invisible processes and perform operations mentally. Also, in the study of Minimally Invasive Education (Mitra et al. 2005), the researchers claimed that the students of age 10-14 years are able to explore technology all on their own. The middle school students are the ones essentially falling in the age groups mentioned in the two studies. Hence, for this research work, an AR technology-enhanced learning intervention named *ScholAR* has been developed for middle-grade (6th to 8th grade) students.

Context

ScholAR's modules have been designed to be used by the students in classrooms, while the teacher acts as a facilitator. It is intended to be used as a supplementary learning material in the classroom, designed as per the academic curriculum. In the research, we are considering that technology is explored by the students while working collaboratively.

Technology

The technology-enhanced learning environment has been created with the support of Augmented Reality (AR) technology. The development has been done using Unity game engine and Google ARCore SDK. The AR implementation is *markerless*, which gets triggered by scanning the surrounding environment, without using any fiducial marker (Brito & Stoyanova, 2018). It is designed for Android-based tablets and mobile phones that support Google ARCore.

Topic of Learning Content

Not every topic area necessarily calls for the use of AR. This is primarily because the advantages of visualisation are crucial in certain disciplines of Science, Technology, Engineering, Arts and Mathematics (S.T.E.A.M) education, where spatial arrangement or dynamic changes are significant. The topic of 3D Geometry in Mathematics at the middle-grade level has been explored as it was considered the most suitable one for AR exploration from the literature as well as teacher interviews. A module on 2D Geometry - Lines and Angles, with its application in the 3D space, was also explored during the research.

1.6. Contributions of the Thesis

This research work contributes to the existing knowledge of the design and development of technology-enhanced learning environments, more specifically involving the integration of design strategies to create an Augmented Reality Learning Experience (ARLE) to help the learners in contextually and collaboratively solving problems. The contributions are based on an analysis of the results of studies conducted as part of this research work.

1.6.1. Theoretical Understanding of Design Strategies

In this section, the key contributions of the thesis to theory have been highlighted. We posit that this can help the education researchers, designers, and developers in the design space while conceptualizing and designing an ARLE for classrooms. The contributions include:

1. A list of the characteristics of the user expectations from a classroom-based ARLE.
2. A detailed characterization of the design process and the set of design strategies while conceptualizing the design of an ARLE.
3. Based on the design strategies adopted by the designers and validated by the researchers, the CoASAR framework for designing an ARLE has been proposed.

1.6.2. *ScholAR* Pedagogy and Learning Environment

In this section, the key contributions of the thesis to pedagogy and learning design have been highlighted. We posit that this can help the education researchers, designers, and developers in the learning space while designing an ARLE for classrooms. The contributions include:

1. A pedagogical design framework for the AR learning environment that indicates the phases of applying the design strategies.
2. The AR learning activities in *ScholAR* that help the learners to solve contextual problems while attaining cognitive, affective, and social learning.
3. *ScholAR* is an instantiation of an AR learning environment with the pedagogical framework that enables the learners to solve multi-level problems and attain cognitive, affective, and social learning.

1.7. Structure of the Thesis

The organization of the thesis is as follows:

- Chapter 2 describes the related work in the literature. We analyzed the current trends of technology in K-12 education and the rationale for implementing an ARLE for the classrooms. We then looked into the existing design principles and strategies for creating such ARLEs. This was followed by studying the impact of the design strategies on the dimensions of learning. Our theoretical basis thus emerged from this literature review.

- Chapter 3 describes the research methodology adopted for this research. We begin by discussing the candidate research methodologies. We then highlight the chosen methodology (DBR) to answer our research questions and ethical considerations.

- Chapters 4 and 5 describe the first cycle of DBR. Chapter 4 highlights the problem analysis and exploration in which we conducted a literature review and three studies to identify the potential design strategies. Chapter 5 describes the design and evaluation phases of DBR for which two studies were conducted for evaluating the designed modules on 'Lines and Angles' and 'Visualising Solid Shapes' of *ScholAR*, and the overall reflections have been reported.

- Chapters 6 and 7 describe the second cycle of DBR. Chapter 6 highlights the second iteration of problem analysis and exploration and the design and evaluation of the module on 'Lines and Angles' of *ScholAR 2.0*. Chapter 7 specifies the design and evaluation of the module on 'Visualising Solid Shapes' of *ScholAR 2.0*.

- Chapter 8 summarise the results and reflections of all our studies and discuss the claims, limitations, and generalizability of this research.

- Chapter 9 describes the contributions and future work of this thesis.

Chapter 2

Literature Review

This chapter provides a review of the literature related to the emergence of AR mobile applications in learning environments. From the literature review, the gaps have been synthesised in existing research to position this work. In order to develop conjectures regarding the process of designing such AR Learning Experiences (ARLEs), the literature related to the existing design principles of handheld AR and the dimensions of learning were reviewed. The synthesis led to a set of conjectures that have been investigated in this thesis.

The literature search began with understanding and reviewing the potential use of the emerging technology of AR towards student-centered learning and the current trends adopted (Section 2.1). This was followed by gaining an understanding of the different facets of learning that included theories, models, dimensions, and content classification for learning (Section 2.2). Further, we investigated the existing design approaches, principles, and frameworks for creating such ARLEs (Section 2.3). While targeting the dimensions of learning as suggested by Illeris (2003), the design strategies were investigated for integrating cognition, emotional intelligence, and social embodied interactions in the ARLEs to enhance the content, incentive, and interaction dimensions respectively (Section 2.4). Finally, the synthesis of the literature directed us in presenting a set of conjectures that have been studied in this thesis (Section 2.5). The organization of this chapter is shown in Fig. 2.1 and elaborated below.

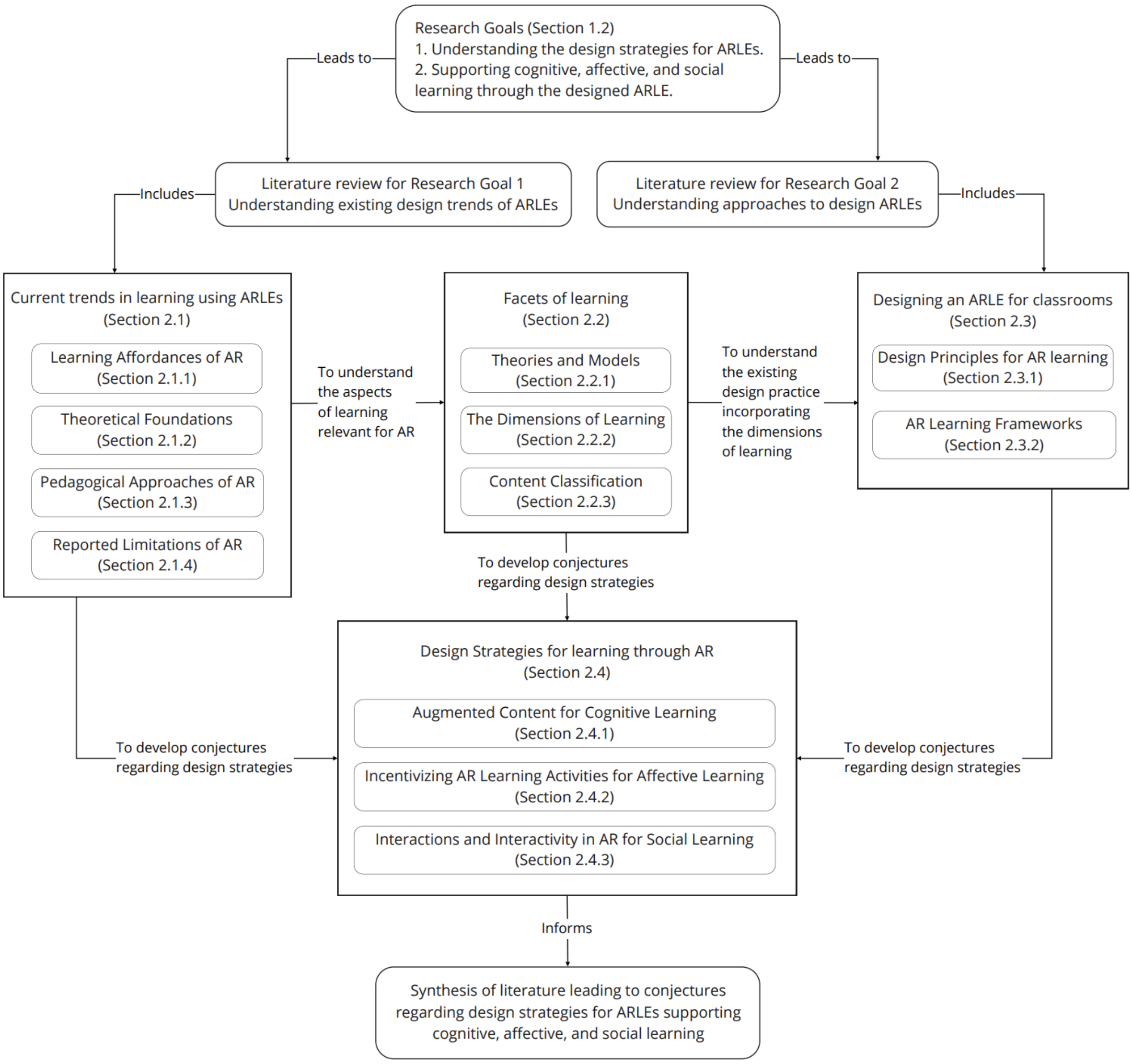


Fig. 2.1 Organization of Literature Review

The initial step of the literature survey was towards understanding the design requirements of ARLEs. The guiding literature questions (LQs) for this search were:

LQ1: Why AR can be a potential technology for student-centered learning? (Section 2.1)

LQ2: What are the current trends in learning using ARLEs? (Section 2.1)

LQ3: What are the relevant facets of learning for classroom-based learning? (Section 2.2)

LQ4: What are the existing design principles for creating an ARLE? (Section 2.3)

The answers to these questions gave an understanding of the context of AR in education. This helped us in identifying the gaps in the literature and defining the scope of our research objectives.

2.1. The Potential of Augmented Reality in Education

The advent of technology is evident enough in many sectors. Education being one of these sectors, various technologies across the world have been introduced to bring a positive impact on the ways of teaching and learning. In many Indian schools, the traditional method of blackboard teaching is now getting supported/replaced with several digital means. Several schools are providing digital devices like tablets, laptops, desktops, etc., to the students to help them learn advanced concepts through online modules (Bharadwaj, 2007; Nedungadi et al., 2014; Kundu & Bej, 2020). It also helps parents and teachers to monitor the students' performances regularly. Several mobile applications are also being used as a means of practice modules (Singh, 2010; Kumar, 2011; Mehdipour & Zerehkafi, 2013).

In one of the studies, it was observed by the researchers that children of age 8-14 years are capable of understanding a technology themselves, irrespective of them belonging to rural or urban areas, hence promoting it as Minimally Invasive Education (Mitra et al. 2005). On similar lines, smart classroom technologies are providing smarter ways of using the content in the physical environment, engaging the students, and assessing their performances (Saini & Goel, 2019). Though there are issues with managing the hardware and software, the schools are yet encouraged to use the different technology mediums (Saini & Goel, 2019). Thus, rapid acceptance of technology is now being observed in and reported by many schools in India, where the students are being encouraged to enhance their learning skills by going beyond the traditional method of teaching using blackboards and textbooks. As the technology is widely accepted in classroom scenarios, the existence and the role of the emerging technologies as a solution to having a potential technology for student-centered learning is being widely researched (Kovács et al., 2015).

Augmented Reality (AR) is one of the emerging technologies that is being widely used in schools and colleges in various parts of the world. AR evolved from the concept of Virtual Reality (VR), which was explored in the 1960s. The term Augmented Reality first came into use in 1992 when virtual graphics were developed to help the aircraft workers in their assembly work and showed them in their real environment display in real-time (Thomas & David, 1992). With time, more applications and definitions of AR were stated. However, the concept of 'Milgram Reality-Virtuality Continuum' (Fig. 2.2) is what came to be widely accepted (Milgram & Kishino, 1994). As can be seen in the figure, the left side of the range belonged to the real environment and the right side of the range belonged to the virtual environment. Blending the two environments together is what is called Mixed Reality (MR). AR and Augmented Virtuality (AV) are both combinations of real and virtual environments. In AR, virtual information is overlayed over the real world, whereas in AV, real elements are brought into a predominantly virtual environment.

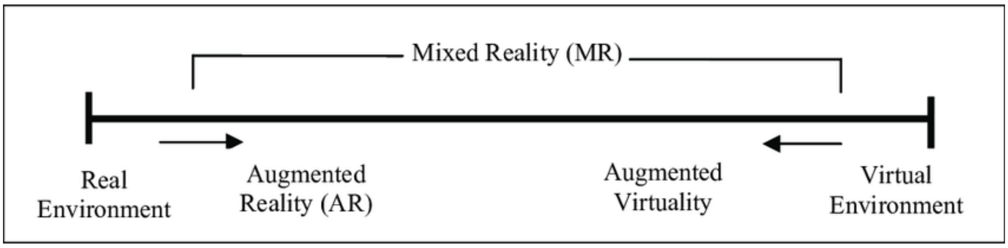


Fig 2.2 Milgram Reality-Virtuality Continuum

Thus, AR is defined as a technology that superimposes computer-generated virtual data (graphics, videos, animations, audios, etc.) onto the real world in real-time (Azuma et al., 2001).

Further, this technology can be broadly made use of through three types of displays (Zhou et al., 2008):

1. *Head-Mounted Displays (HMDs):* These displays require the users to wear the display device on their head where the images are projected onto a small display in front of the eyes (Kiyokawa, 2007).
2. *Hand-held Displays:* These displays involve the use of mobile devices like tablets and smartphones where the camera of the device first scans the environment to map the spatial information and tracks back in real-time to superimpose the related virtual data onto the real surrounding (Wagner & Schmalstieg, 2006).
3. *Screen-based Spatial Displays:* These displays involve the video-based display of the real-time event from the screen of the monitor onto a surface (Bimber & Raskar, 2005).

There are three types of AR implementations: Marker-based, location-based, and Markerless. The *marker-based* AR implementations scan the marker through the device's camera and reflect the matched content from the database onto the real world

(Edwards-Stewart et al., 2016). *Location-based* AR implementations use the device's GPS and compass, internet connection, and image recognition techniques to track features defined prior to superimposing the virtual graphics on the real world (Edwards-Stewart et al., 2016). *Markerless AR* implementations get triggered by scanning the surrounding environment, without using any fiducial marker (Brito & Stoyanova, 2018).

Due to the different advantages of AR like overlaying vector graphics, display of virtual instructions, annotations, visualisation of concepts, the x-ray vision of human body parts, etc., researchers have suggested various domains of application of AR, including education and learning, medical, manufacturing and repair, entertainment, etc. (Azuma et al. 2001; Lee, 2012; Yuen, 2011).

To understand the significance of Augmented Reality in K-12 Education, it was required to go through the previous works of the researchers in this field. For this purpose, online libraries and databases like Scopus, IEEE Xplore, ACM Digital Library, Springer, Computers and Education, British Journal of Educational Technology, ResearchGate, International Journal of Technology and Design, and Google Scholar, consisting of conference and journal papers were searched to get the corpus of literature review. The relevant papers were searched using the keywords: ("Augmented Reality" AND "education" OR "learning" OR "school" OR "K-12" OR "STEM" OR "STEAM" OR "learning experience" OR "pedagogy"). Out of the huge collection of the list of papers, the duplicate ones were removed. The titles and abstracts of these papers were then read and based on the inclusion and exclusion criteria (Table 2.1) considered to be appropriate for this study, the papers were further sorted.

Table 2.1 Inclusion and Exclusion criteria

Inclusion Criteria	**Exclusion Criteria**
● Papers published in last 12 years i.e. 2008-2020 ● Empirical Work ● Research based on school students ● Downloadable full-text available ● Review Papers	● Research based on Higher education ● Research based on students with special needs ● Mentioning the term "Mixed Reality" or "Virtual Reality" ● More emphasis on technicalities of the developed intervention

There were many papers that did not clearly state the target group or gave the hint of focusing more on the technicalities of the intervention in their titles or abstracts. Therefore, after applying the inclusion and exclusion criteria, the remaining papers were downloaded specifically to glance into the Methods sections. In the end, the papers with empirical work on AR for K-12 education were obtained to be reviewed. In addition to these papers, 10 review papers were also considered to validate the relevance of the list of papers collected as well as to get familiarised with the work across different target groups other than K-12. A summary of the findings of the review papers considered is given in Table 2.2.

Table 2.2. Summary of findings of a few review papers

Author(s), Year	**No. of studies reviewed**	**Summary of Findings**
Cheng & Tsai, 2013	12	The papers have been reviewed and categorised on the basis of the type of AR implementation in Science Learning, i.e. Image-based and Location-based. The authors suggested that image-based AR is mostly implemented when targeting the affordances of learning that include spatial ability, conceptual skills, and practical skills. Location-based AR mostly supports inquiry-based learning.
Santos et al., 2013	87	On analyzing the studies conducted in K-12 education, the authors suggested that the design strategies to create AR learning applications must enable exploration, promote collaboration, and ensure immersion. The authors concluded that AR has mainly three advantages: real-world annotation, contextual visualisation, and vision-haptic visualisation. Moreover, these advantages of AR are supported by the existing theories like multimedia learning theory, experiential learning, and animate vision theory.
Bacca et al., 2014	32	The authors investigated and reported the uses, advantages, limitations, effectiveness, challenges, and features of

		augmented reality in educational settings. The major use of AR included explaining a topic and providing additional information. Learning gains, motivation, interaction, and collaboration are the reported advantages of AR. Thus, AR is effective in leading to better learning performance, learning motivation, student engagement, and positive attitudes.
Radu, 2014	26	The author has reported the positive and negative effects of using AR in education and the factors that are responsible for such effects. Based on these factors, the author has suggested a heuristic questionnaire to evaluate the learning potential of an AR application.
Diegmann et al., 2015	25	The authors reported 14 benefits of AR in the educational environment and categorised them into 6 groups (State of Mind, Teaching Concepts, Presentations, Learning Type, Content Understanding, Reduced Cost). These benefits were then mapped with the five directions of AR suggested by Yuen et al. (2011) namely Discovery-based Learning, Objects Modeling, AR Books, Skills Training, and AR Gaming, to suggest the possible benefit for a specific direction.
Akçayır & Akçayır, 2017	68	The authors reported enhancing learning achievement to be one of the key advantages of AR, among other advantages. Usability issues and technical problems in using AR applications were among the key limitations of using AR.
Chen et al., 2017	55	The authors analyzed the current state-of-the-art research in AR in the domain of education. One of the key findings of the authors was that more empirical studies were carried out in Science, Social Science, and Engineering.

Ibáñez & Delgado-Kloos, 2018	28	For the studies conducted in STEM education using AR, the authors concluded that most AR applications were designed with exploration or simulation activities, focusing on the conceptual understanding of the students.
da Silva et al., 2019	45	The authors discussed the guidelines for AR educational evaluation. They suggested that evaluating with the use of multiple metrics, both quantitative and qualitative, to have longitudinal studies, and to have the involvement of teachers in the evaluation in more active ways as possible.
Garzón et al., 2020	46	This study analyzed the impact of the pedagogical approaches of AR applications on the learning outcomes of the students. The authors concluded the medium impact of AR on students' learning gains. Moreover, Situated Learning is the most common pedagogical approach, whereas Collaborative Learning shows the greatest impact on students' learning.

Along with the review papers, the data from more empirical papers were coded on the basis of the themes of learning affordances, theoretical foundations, pedagogical approaches, and limitations of AR. These themes have been summarised in the below sub-sections:

2.1.1. Learning Affordances of AR

This section reports some of the major learning affordances using AR experiences:

Increased Understanding of Content

In most of the surveyed papers, it was reported that for the topics on which the designed AR intervention focused, the AR experience proved to be more effective in teaching the topic to the students as compared to other mediums like books, web-based desktop or mobile/tablet experiences. In a comparative study between three mediums of teaching, i.e. 2D picture books, 3D physical objects, and 3D virtual objects using AR, the AR experience gave the elementary students the hands-on experience to explore and learn about bacteria as compared to the other mediums (Hung et al., 2017). The introduction of a completely new concept of the

Water cycle also proved to be better understood by the 2nd-grade students using the AR application (Bratitsis et al., 2017).

Increased Spatial Ability

Few studies reported that the activities in AR helped in increasing their spatial ability skills, where they could visualise the characteristics of the 3D virtual objects shown during the exploration of the topic using the AR intervention (Hung et al., 2017). With the help of an AR hand-held device to view the AR scene of the book made to teach electromagnetic concepts, the authors claim that AR can be very effective in understanding spatial 3D concepts (Dünser et al., 2012). In another study, a high correlation was found between spatial ability and learning achievement using marker-based AR, where, on scanning the markers through a webcam, the desktop screen would display the corresponding 3D images to teach solid geometry to junior high-school students (Lin et al., 2015).

Increased Memory Retention

Many studies claimed that learning with the AR experience helped the students in the retention of the knowledge for a longer duration as compared to any other medium of learning. AR motion-sensing using Kinect was used to demonstrate the concepts of magnetic fields and lines (Cai et al., 2017). Inquiry-based and role-play strategies were incorporated into doing so. Through the study, researchers found that the students memorised the content for a longer duration using the AR motion-sensing as the scaffold to the teaching method. Another study was concerned with the retention of the number of characteristics of a bacteria which was performed with 5th-grade students (Hung et al., 2017).

Increased Learning Motivation and Attitude

In one of the research works (Sirakaya & Kiliç Çakmak, 2018), the comparison was made between two AR applications, where one was AR competitive game-based application and the other one was without a game, where the authors claimed that AR game based application improved the learners' attitude in the field trip and kept them motivated in performing the tasks. Another study comparing two AR applications with and without Concept Maps to learn the concept of the food chain, claimed to have improved learning outcomes, motivation, and attitude in learning (Chen et al., 2016). Thus, both the studies suggested that a certain scaffold to AR can enhance the motivation in the students to master the course content.

Increased Learning Achievement

Studies have also claimed that there is an increase in student learning and achievement in the educational environment using AR experience (Sirakaya & Kiliç Çakmak, 2018). Enhancement of certain capabilities like problem-solving skills (Karagozlu, 2018), collaborative learning (Bratitsis et al., 2017; Enyedy et al., 2015), and spatial abilities (Lin et al., 2015) have been the stated reason for the increased learning achievement. However, some researchers have also suggested that the novelty and the awe-factor of the features of AR may be responsible for better focus and performance (Cheng & Tsai, 2013; Bacca et al., 2014; Akçayır & Akçayır, 2017). Thus, it is required that the studies using AR experiences in learning should be conducted for a longer duration to understand the cognitive gains over the period.

2.1.2. Theoretical Foundations

The AR interventions in the studies were based on certain theoretical foundations such as:

Conceptual Blending Theory - The theory suggests that AR users need to transit smoothly between the virtual and real environments, creating a conceptual blend between the multiple sources with different conceptual spaces (Enyedy et al., 2015).

Spatial Cognition Theory - This theory suggests that AR users have the skill of forming mental images of objects or situations and are able to mentally transform them (Dünser et al., 2012).

Experiential Learning Theory - This theory suggests that gaining personal experience from AR activities can enhance learning achievement. The experience can be attained at any of the four stages of learning: 1) concrete experience, 2) observation and reflection, 3) forming abstract concepts and generalizations, and 4) testing in new situations. (Hung et al., 2017; Huang et al., 2016).

Embodied Cognition Theory - The theory suggests that when the manipulation through rotation of virtual objects in AR involves the aspect of the human body, the learners can relate to and perform the activities better (Klautke et al., 2018).

Motivation Theory - This theory suggests that by increasing students' attention and satisfaction in using the AR application, students get motivated in learning. (Sirakaya & Kiliç Çakmak, 2018; Chen et al., 2016).

Flow Theory - This theory suggests that with AR activities students can immerse themselves in a flow state, creating a balance between the challenges and skills gained through AR activities (Ibáñez et al., 2014).

2.1.3. Pedagogical Approaches of AR

The following pedagogical approaches were commonly incorporated in the studies (Garzón et al., 2020):

Situated Learning - The pedagogical approach involves the construction of knowledge by interacting with social situations. This is obtained by creating contextual learning environments in which the students learn by doing (Brown et al., 1988). In one of the works, an educational AR system was developed based on situated learning theory and applied AR to a library's learning environment (Chen & Tsai, 2012).

Inquiry-based Learning - This is also known as Discovery learning where the students search a problem, pose questions and then search for their answers, using strategies of group discussion and guided learning. The students thus learn through exploration, experience, and discussion (Pedaste et al., 2015). A study explored whether an online unit on socioscientific issues (SSI) enhanced by AR and incorporating inquiry-based learning pedagogy can improve students' understanding of the science content involved (Chang et al., 2013).

Cognitive Theory of Multimedia Learning - This follows the multimedia principles where students learn more deeply from words and pictures than words alone (Mayer, 2002). With CTML as the pedagogical approach, learners' visual behaviors were tracked, compared, and summarised in text-graph-based, AR-based, and physical model-based learning environments (Wang et al., 2018).

Collaborative Learning - In this approach, the learning mechanism is triggered through interactions among people. Collaborative environments involve strategies regarding group size, learning goals, communication, assignments, and assessment (Dillenbourg, 1999). For example, the effect of a mobile collaborative AR simulation system on learners' knowledge construction behaviors and learning performances while solving problems related to the elastic collision was reported. (Lin et al, 2013).

Problem-based Learning - With this student-centered learning approach, the students learn and gain knowledge and skills by investigating and answering complex problems while working for an extended period (Blumenfeld et al., 1991). In the context of AR learning, the effects of PBL on learning achievement and attitude towards physics subjects as a part of science education were investigated (Fidan & Tuncel, 2019).

2.1.4. Reported Limitations of AR

Some of the key limitations that have been observed or reported in the papers include:

- The studies reported have been conducted for a short duration and require the lengthening of the timeframe of research (Hung et al., 2017).
- The students need to be trained before using the AR intervention (Cai et al., 2017; Huang et al., 2016).
- The training of using the AR interventions can be extended to the teachers and developed in a way to help them design the activities.
- Usability issues like slow working or less intuitive interface (Lin et al., 2015; Gopalan et al., 2015).

Synthesis

This section of the literature review looked into the ways in which AR has evolved in the field of education. From the review, it was observed that marker-based and location-based AR implementations have been majorly reported. The design and impact of *markerless* AR applications on learning achievement seem to be a less explored one in educational research. Moreover, over the course of time, AR applications have been supported by theoretical and pedagogical approaches to leverage the affordances of AR. Thus, within the scope of our research, we intend to incorporate a few of the stated affordances with theoretical foundations for the design of markerless handheld AR implementation for learning experiences. However, to design the AR application for educational purposes, it was required to understand the facets of learning. Hence, the next section reviews the facets of learning relevant for AR implementation.

2.2. Facets of Learning

Learning experience is defined as "a wide variety of experiences across different contexts and settings which transform the perceptions of the learner, facilitate conceptual understanding, yield emotional qualities, and nurture the acquisition of knowledge, skills and attitudes" (IBE UNESCO, 2013). There are different lenses of learning that have been showcased through various theories that include behaviorism, cognitivism, and constructivism (Ertmer and Newby, 1993). This section discusses the theories and models, types of content, the dimensions of learning and their application in AR.

2.2.1. Theories and Models

In the instructor-mediated teaching-learning practice, the teachers or the instructors play an important role. The teacher gains complete control over the learning process by becoming the main source of information and the students then become the passive recipients of the material (Peyton, More, & Young, 2010). On the other hand, student-centered learning is the process of learning in which the power of gaining the experience resides with the students (Estes, 2004). Students are responsible for their own learning by autonomously pursuing learning goals. In the process, the philosophy entails a learning collaboration where everyone including the teachers becomes practical learners.

To build the student-centered ICT, it is required to establish a psychological foundation based on learning theories. The process of learning in the literature has been broadly classified under the theories of behaviorism, cognitivism, and constructivism (Schunk, 2012). *Behaviorism* assumes that knowledge is built based on the responses to external stimuli (Skinner, 1989). In this, the learning requires drill and practice through repetition where the teacher plays a key role in transferring the correct behavior response. *Cognitivism* involves the construction of new knowledge based on prior experience and knowledge. Learning is viewed as an active, constructive, and goal-oriented process, encouraging discovery and assimilation or accommodation of knowledge (Shuell, 1986). Learning is influenced by building connections between the stimulus received and the internal information. The instructors build the knowledge through thinking activities. *Constructivism* involves an active and constructive learning process, where the learning is subjective to a learner's mental representation of the new information linked to individual prior knowledge (Fosnot, 2013). The learners socially engage in different activities facilitated by the instructor to obtain the active process of learning.

Recently, experiential learning and connectivism have also been considered essential learning theories (Kathleen Dunaway, 2011). *Experiential learning* finds its base in the constructivist theory, where the learning is drawn from the learner's personal experience. In this, the teacher acts as a facilitator to motivate the learners through various stages of the learning cycle (Kolb & Kolb, 2012). *Connectivism* considers the digital age and assumes that people process information by forming connections (Siemens, 2014). Fig. 2.3. Outlines the learning theories and methods that form the basis of student-centered learning (Bishop & Verleger, 2013). As can be seen, the theories of constructivism and experiential learning form the foundation for student-centered learning.

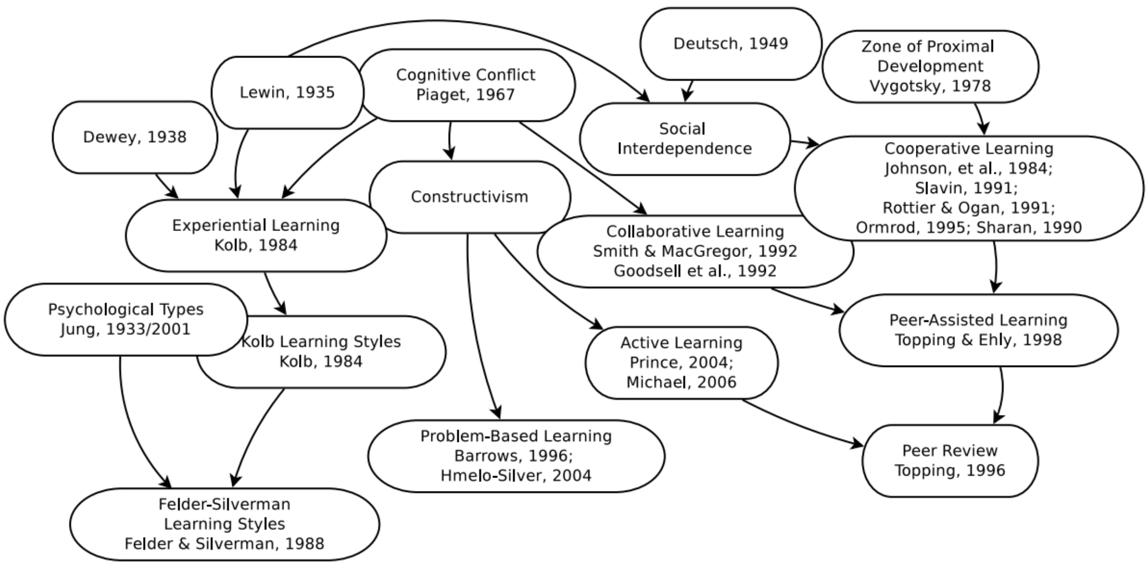


Fig. 2.3. Defining the origins of student-centered learning theories and methods (Bishop & Verleger, 2013)

Constructivism learning theory states that knowledge is actively constructed by people, and reality is determined by the experience of the learner (Paige, 1996). In constructivism, knowledge is an active process of construction (Schunk, 2012). Learners thus build their new knowledge upon their prior knowledge. Moreover, learning is an active process and not a passive one in which the learners are considered empty vessels to be filled with knowledge. Instead, through the active process, the learners learn through active engagement with the environment (Yilmaz, 2008). Constructivism also considers the ability to learn from the social environment (Palincsar, 1988). However, in the entire process, based on prior knowledge and experiences, each individual learner has a distinctive point of view (Fox, 2011). The same teaching method and resources may be interpreted differently by every other learner.

Going a level deeper, *Experiential learning* emphasises learning to be a process of gaining and constructing knowledge through reflection on prior experiences. Kolb (2014) has defined learning as “the process whereby knowledge is created through the transformation of experience”. As per Kolb’s Theory of Experiential Learning (Kolb, 1984), the knowledge is constructed in a cyclical manner involving the transformation of experience in each stage. With the benefit of active participation of students, classroom-based experiential learning is thus being highly adopted and implemented in the forms of games, simulations, role-playing, presentations, group works, etc. (Fuha, & Paulb, 2015). Dewey (1938), Kolb (1984), and Piaget (2005) have explored experiential learning through constructivism. Among the pioneers of constructivism, Jean Piaget in his Constructivism Theory states that people generate knowledge and form meanings based upon their experiences (Ackermann, 2001). The theory also focuses on how learning actually happens for children. It has been stated that the children by the age of 10-14 years, majorly belonging to the group of middle school students, reach the stage of formal operation where they gain the ability to think logically and can conceptualise the things not seen in the actual surroundings (Ojose, 2008). Thus, at this age, the students can be guided towards building up their creative and imaginary skills.

Situated learning theory postulates that much of learning takes place in the specific context in which it is learned (Lave, 1988; Lave & Wenger, 1991; Greeno et al., 1992). In the process, the learners learn by doing and by the interactions with the people, places, objects, etc., situated in the context (Brown et al., 1988). Thus, in classrooms, the learners comprehend meaningful learning based on the creation of a personalised sense of the situation and incorporating the same into the prior knowledge (Harley, 1991). As AR is considered to be a flexible space that contains learning opportunities for the learners to grasp at their will, it aligns with the student-centered way of learning by confronting the reality and the context it is set in (Munnerley et al., 2012). Thus, the strategies discovered through our studies can support the situated learning approach while aligning with the student-centered learning method.

Moreover, *Embodied cognition* theory involves the act of enacting knowledge and concepts with our bodies and is considered a tremendous force for learning (Abrahamson & Lindgren, 2014). The interactions of the body with its physical surroundings are fundamental to human cognition (Gallagher, 2005; Wilson, 2002). The introduction of new technologies and interfaces, especially AR, that accept natural physical movement like gestures, touch, and body placement as input into interactive digital worlds is strengthening the trend in embodied learning (Lindgren & Johnson-Glenberg, 2013). It has been suggested in the research on embodied cognition that AR apps can be designed in a way that can let students physically enact abstract concepts and that these experiences have the potential to influence student understanding (Radu, 2014). Furthermore, Radu & Antle (2017) proposed five embodied interaction methods using handheld AR, which were tested with elementary school children: (1) Perspective change through movement, (2) Exploration through physical action, (3) Reenactment through physical action, (4) Interaction with abstract concepts, and (5) Embodying new entities. Thus, the designs of ARLEs can be majorly supported with bodily engagement while learning to promote conceptual understanding.

2.2.2. The Dimensions of Learning

It is imperative for teachers to know how learners learn in order to be able to bring in the teaching practices that can have the best desired effect (Sungkur et al., 2016). Emphasizing upon learners attaining constructive meaning, the process of learning has been classified based on three dimensions proposed by Illeris (2003): content, incentive, and interaction (Fig. 2.4). The content and the incentive dimensions are concerned with the individual acquisition process, and the interaction dimension is concerned with the interaction process between the individual and the environment.

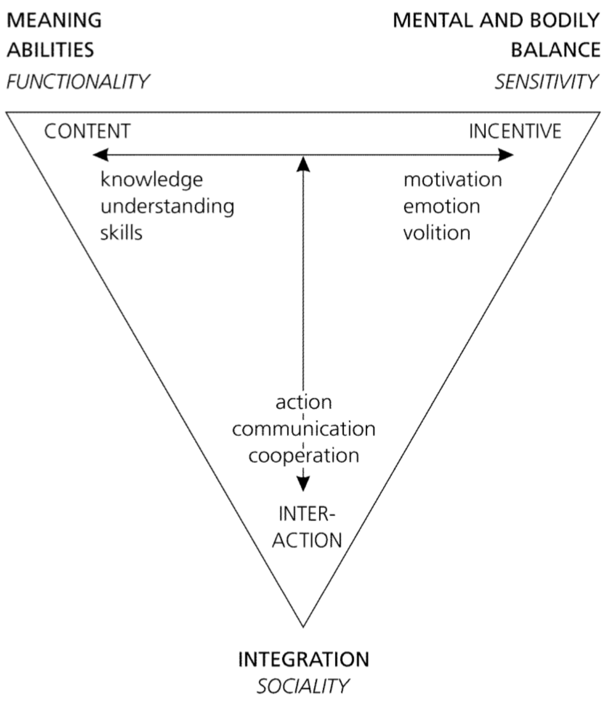


Fig. 2.4 The Three Dimensions of Learning (Illeris, 2003)

These three dimensions broadly fall under two types of learning processes - internal interaction and external interaction. The former involves the psychological process of acquisition and elaboration; the latter involves the process between the learner and the social, cultural, and material environment. The *'content'* dimension is concerned with what has been learned and the cognition involved. In the process, the learners establish the meaning and the ability to deal with real-life challenges and develop their overall *functionality*. The *'incentive'* dimension is concerned with the mental energy for cognition to happen. It incorporates motives, emotions, and the volition for learning through a continuous process of mental balance and personal *sensitivity*. These two dimensions guide the internal interaction. The *'interaction'* dimension builds up the *sociality* of a learner i.e. the individual's interaction with the social and material environment. Through perception, transmission, experience, imitation, activity, participation, etc., impulses for the learning process are initiated. Hence, it is the dimension of external interaction involving participation, communication, and cooperation. Thus, the holistic approach to learning involves these three dimensions, where it is required to operationalise them into the design practice of creating ARLEs.

2.2.3. Content Classification

To understand the influence of the type of content on the approach of designing an ARLE, we studied the work on the classification of content. One of the classifications of content is based on cognitive, skill, and affect (Kraiger et al., 1993). Further, the category of cognitive learning outcomes includes declarative (factual), procedural and strategic content. Another classification puts forth a matrix involving cognitive levels (Remember, Understand, Apply, Analyze, Evaluate, and Create) based on Bloom's taxonomy on one axis and knowledge dimensions (Factual, Conceptual, Procedural, and Metacognitive) on the other axis (Anderson & Krathwohl, 2001). Thus, the content is created based on the learning objective represented in each cell, as shown in Fig. 2.5.

	Remember	Understand	Apply	Analyze	Evaluate	Create
Factual Knowledge	*Objective 1*					
Conceptual Knowledge					*Objective 2*	
Procedural Knowledge		*Objective 3*				
Metacognitive Knowledge				*Objective 4*		

Fig. 2.5 Content Classification (Anderson & Krathwohl, 2001)

Comparing the two mentioned classifications, Kraiger's model does not involve conceptual knowledge. On the other hand, Anderson's matrix lacked the consideration of skill, affect, and strategy. For our research purpose, considering the age group of our targeted learners and their cognition ability, Anderson's matrix seems relevant where we have considered the first three knowledge dimensions based on the current curriculum.

Synthesis

This section of the literature review highlighted the theories, models, dimensions, and content classification of learning. These facets have been discussed with the intent of their incorporation into ARLEs. Studies have indicated that situated learning and embodiment play a crucial role in ARLE implementations, where contextual learning with natural physical movements guides in understanding abstract concepts (Radu & Antle, 2017). Moreover, with the holistic approach to attaining cognitive, affective, and social learning, it is required to operationalise the three dimensions of learning (content, incentive, and interaction) into the design of ARLEs. Further, for our target group, to create the content and assess the learning for attaining the three dimensions of learning, the first three levels of Anderson's matrix are considered to be appropriate. However, to incorporate these facets of learning into the design, it's required to first understand the appropriate design practice of ARLEs for classrooms. Hence, the next section reviews the design principles, guidelines, strategies, and frameworks existing in the literature for designing ARLEs.

2.3. Designing an ARLE for Classrooms

In the research work of Giunta et al. (2018) and according to the model of Pähl et al. (2007), the following design stages of the AR application development process have been identified: Task, Design Specification, Concept, Preliminary Layout, Definitive Layout, and Product Documentation. It was discovered that the Concept, Preliminary Layout, and Definitive Layout phases of the design process are studied the most, while the Task, Product Documentation, and Design Specification stages are being investigated the least. This gave us a direction towards the need to outline the design processes and approaches required for novice designers and highlight the necessary design strategies to define the tasks while conceptualizing and designing an ARLE from start to end.

2.3.1. Design Principles for AR learning

To use any SDK or authoring tool to create educational AR applications, one must first evaluate the design principles for AR learning environments. The design principles involve a set of guidelines for creating designs that are both satisfying and simple to use. For instance, Santos et al. (2015) proposed a few design guidelines for educational handheld AR apps which were derived from existing guidelines in diverse areas such as tourism, navigation, and games. The guidelines included presenting context-aware content, providing content controls, preempting technical difficulties, preserving intuitive icons and menus, promoting social interactions, and paying attention to manipulability. These parameters were then used to create the FlipPin application, which was used to teach new vocabulary in a real-world setting. In another research, to ensure a pleasant user experience for the learners, it was proposed that ARLEs be created in a way that gives a sense of challenge and fantasy and enhances their curiosity (Dunleavy, 2014). Though these guidelines become imperative for individual learners learning using an AR application, our aim is to understand the design requirements for a holistic AR learning environment in a classroom.

In order to offer justification for the design, comply with the decisions, and achieve the set goal by applying the strategies, it is critical to reflect on acceptable design strategies while applying the design principles (Hubka, 1983). Various research on ARLEs in classrooms has been synthesised to provide design strategies such as enabling exploration, promoting collaboration, and ensuring immersion (Santos et al., 2013). In terms of content, another study recommends using design strategies such as creating ARLEs that are contextual, gamified, and student-driven (Miller & Dousay, 2015). Additionally, when creating AR experiences, the simulations and stories were divided into four categories: location, story, roles, and experience mechanics (Dunleavy & Dede, 2014). Deciding on one of the factors can help in defining the basic structure of the AR applications. Though these design strategies focus on the role of students in using the ARLEs, in a classroom environment the control of and synchronization with the teachers is also essential. Hence, considering the role of teachers in the classrooms and reducing their orchestration load, five principles, i.e. integration, awareness, empowerment, flexibility, and minimalism, have been proposed for the design of ARLEs (Cuendet et al., 2013).

Due to the lack of educators' grasp of technology and AR developers' understanding of education, Billinghurst & Duenser (2012) argue that education and sound learning theory must be incorporated into design decisions. Hence, we argue to define the design strategies for AR learning applications while incorporating the dimensions of learning.

2.3.2. AR Learning Frameworks

There are but a few AR Design frameworks developed to guide towards deciding the relevant factors for creating educational AR content that can help in defining the basic structure of an ARLE. Additionally, there is a paucity of specifying the requirements for bringing together cognitive, affective, and social learning.

Along the lines of experiential learning and to provide a concrete learning experience, Chen & Wang (2008) proposed a framework (Fig. 2.6) that presented the integration of four knowledge domains - cognitive science, tangible AR technology, learning theories (experiential and collaborative) and design process. As per the framework, the stimulus is delivered to learners via the processing continuum, which encompasses a wide range of learning styles, from constructive to analytical. Visually from reflecting observation, and tactilely from concrete feedback, the initial mental image/model is perceived and developed. Designers progress through each cycle of the spiral design process by presenting, testing, and re-imagining solutions to a set of connected challenges. This continual combined feedback from visual and tactile channels then reinforces abstract concepts. The existing abstract concept is then converged with active experimentation by designers. The previously researched problems are then revisited to examine the earlier decisions made during this design activity. The output involves the knowledge gathered by tangible AR systems' expressive, playful, reflective, situational, and interactive learning activities. Though this framework seemed quite relevant for this work as it highlighted the design process involved in bringing the experiential learning through AR, the focus primarily lies on the cognitive and embodied learning aspects, and lacks the influence on social and affective learning for the learners.

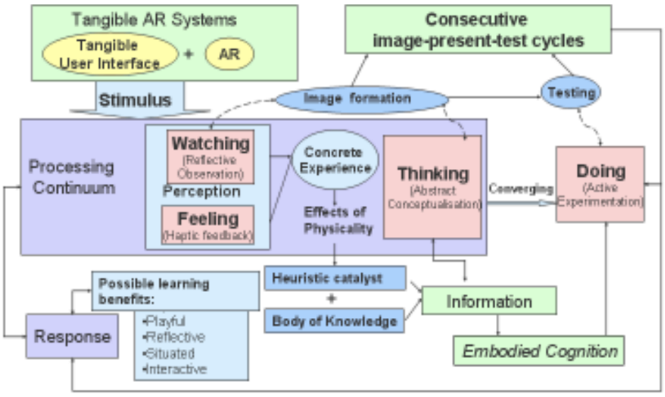


Fig. 2.6. Framework for applying tangible AR concepts and technology to architectural design learning (Chen & Wang, 2008)

Sommerauer & Müller (2018) analyzed the existing works and suggested a conceptual AR design framework for learning, as shown in Fig. 2.7. It was proposed based on the learning theories at different stages. The core of a learning activity, represented as learning content, is the transmission of information and knowledge. As per the framework, the learning content should be prepared at the content layer using Mayer's cognitive theory of multimedia learning (CTML) and any subset of the twelve multimedia design principles (Mayer, 2002). The motivational layer involves a communication interface to collect and exchange information and takes into account elements of game-based learning, simulation-based learning, and experiential learning, particularly in terms of engagement, navigation, and communication inside and across learning activities. Though this framework seemed to be appropriate in defining the design methods for an ARLE and highlighted the cognitive mechanism involved, it lacked highlighting learning through various levels of interactions to bring in social learning.

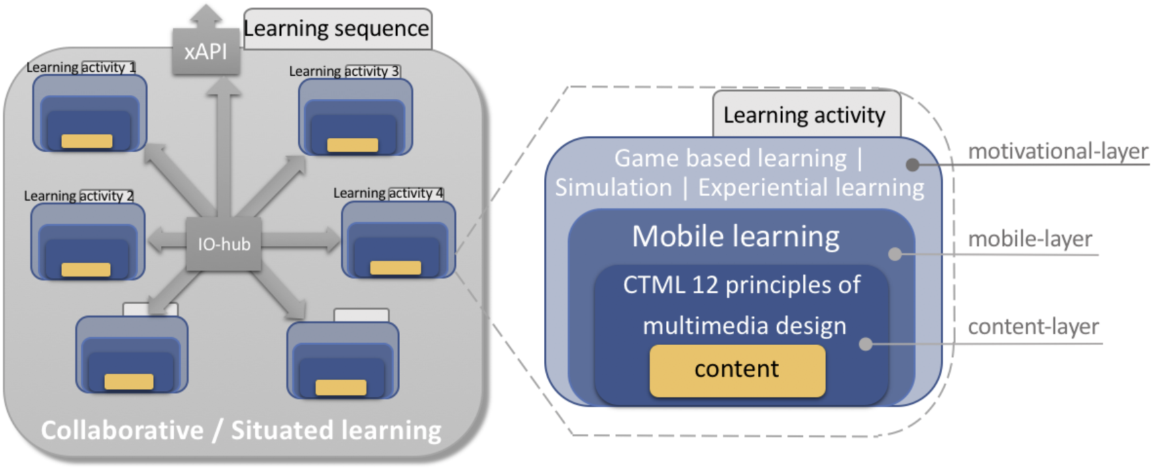


Fig. 2.7. Graphical representation of the conceptual AR design framework for learning (Sommerauer & Müller, 2018)

The framework proposed by Acosta et al. (2019) is based on three theoretical foundations: motivational design (Keller, 2010), universal design for learning (UDL; Meyer et al., 2014; Rose & Meyer, 2002) and co-creation (Sanders & Stappers, 2008). The framework is further divided into three sections. The first section focuses on externally managed information and services that are accessed by mobile or web-based applications (i.e., outside the AR application). Supporting applications either receive or send data to the AR application. The second section involves four layers: User interface and interaction layer, AR activities/experiences layer, Student support layer, and Assessment layer. The first layer manages authentication, the user interface (UI), and the interaction mechanisms required to show the information to students. The second layer involves scaffolding, i.e. a strategy for helping students so that they can complete a learning activity, augmented information, and real-time feedback that the system provides in response to a student's interaction with the AR application. The third layer supports students' learning through 1) videos with the learning content to provide an alternative way of presenting information, 2) ask your teacher module by which students can send questions to their teacher as and when their doubts arise during the AR learning experience, 3) FAQs which involve questions typically asked by students for a particular learning task, and 4) Progress Monitor (PMO) which is a module that keeps track of student activity in the application and how they interact with it. It's used in tandem with the Monitoring (MON) module that records a student's interactions with the framework's four layers and transmits this information to the PMO for reporting. The fourth layer is that of Assessment, which manages the assessment process in the AR application. The third section of the framework depicts the input of data from a number of devices that can be used to record data from the real world and overlay it on top of the digital data. The AR experience is aided by the data from these devices. While this framework consolidates the design requirements of an ARLE and its impact on cognitive and affective (motivational) learning, its influence on social learning has not been discussed.

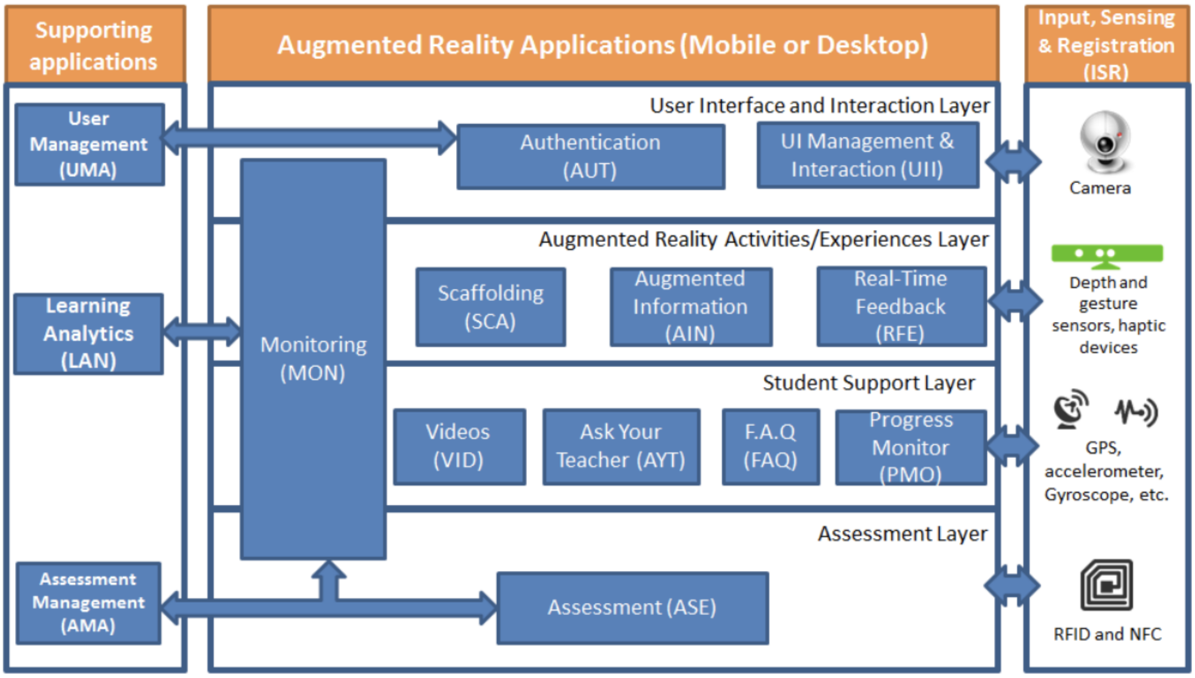


Fig. 2.8. Framework for designing and developing motivational AR applications (Acosta et al., 2019)

Synthesis

The works in the literature emphasise generic implications for the design process. Also, professionals and practitioners find AR/VR guidelines to be scattered across the internet (Ashtari et al., 2020). The literature on the design process that provides relevant design strategies for creating classroom-based ARLEs seems to be sparse. Moreover, considering the design of ARLEs based on the three dimensions of learning, there are individual frameworks catering to each of these dimensions. Thus, we intend to add to the knowledge body of the ARLE design process by providing empirical insights on the approaches that can be adapted to create an ARLE for the classroom, that holistically caters to the three dimensions of learning.

2.4. Intersection - Design Strategies for Learning through AR

The literature survey indicated that there is sparse and scattered literature available on the ways to design ARLEs while considering the holistic approach towards the dimensions of learning. Further, most of the work comes in the form of guidelines and recommendations. However, looking through the lens of the three dimensions of learning, i.e. content, incentive, and interaction (Illeris, 2003), it becomes imperative to obtain the design strategies for attaining and operationalizing the underlying learning mechanisms.

In order to begin our investigation into the required design strategies, there is the need to develop a set of conjectures regarding the process and approaches of designing a classroom-based ARLE and its effect on cognitive, affective, and social learning. This will guide the research questions and research methods of this thesis. Hence, we examined the related work on designing ARLEs for classrooms through the lens of content, incentive, and interaction dimensions of learning. Following were our guiding questions for the literature review:

LQ5: What are the design strategies for creating augmented content in ARLEs to attain cognitive learning?
LQ6: What are the design strategies to incentivise the learners to attain affective learning through ARLEs?
LQ7: What are the design strategies leading to interactivity in AR to attain social learning?

2.4.1. Augmented Content for Cognitive Learning

Contextual teaching and learning has been defined as *"a conception of teaching and learning that helps teachers relate subject matter content to real-world situations; and motivates students to make connections between knowledge and its applications to their lives as family members, citizens, and workers and engage in the hard work that learning requires"* (Berns & Erickson, 2001). To attain meaningful learning, the learners are able to relate the content with the context in which it can be used. In the process, the learning goals are achieved while reconstructing the prior knowledge. Thus, the ability to relate the concepts with real-life situations provides an indication of merging the content learned in the context with the actual situations and building upon the existing knowledge (Harwell, 1999). Such contextual learning approaches have been found to be having an influence on student motivation

(Wolters, 2011; Ekowati, 2015; Naziah et al., 2020) and engagement (Lam et al., 2012; Mentari & Syarifuddin, 2020).

In the attempt of learning in a contextualised environment, it may be difficult to access learning materials outside school hours. Hence, virtual manipulatives have been considered to be a handy solution to this process (Moyer et al., 2002; Bujak et al., 2013). In the cases of ARLEs, the network of knowledge gets enhanced with meaningful cues that can be found in the real environment (Santos et al., 2013). AR can improve learning experiences by making the unseen visible and facilitating exploration while allowing students to manipulate virtual 3D objects (Wu et al., 2013). As the linkage of augmented information to a physical space or object facilitates "the development of process skills such as critical thinking, problem-solving, and communication utilised through interdependent collaborative activities", the use of AR has been considerably involved in creating contextual learning experiences (Dede et al., 2009). Using AR, students can engage with and view 3D representations that would otherwise be invisible or difficult to exhibit in a classroom setting. The capacity to modify and examine these 3D models in diverse ways has been found to provide students with a better understanding of concepts when they are shown (Yuen, Yaoyuneyong & Johnson, 2011). It has been previously argued that the ability to access and collaborate around contextually relevant virtual content and engage with it leads to improved learning experiences using AR (Bujak et al., 2013). Furthermore, learning and comprehension can enhance by superimposing animation or video within these models. Students can see how pieces are connected and move objects from various angles, which is not possible in a 2D interface or with videos or photos, allowing them to engage with the virtual 3D objects and give a genuine learning experience (Kaufmann & Schmalstieg, 2003).

Thus, from the literature, we were able to summarise a few of the proposed design strategies for augmented content creation in ARLEs that can help the learners to attain cognitive learning:

- **Contextual Content Representation:** With the ability to superimpose 3D objects on the real environment that can be viewed from different perspectives which are otherwise difficult to view, the learners tend to gain contextual learning experience.
- **Enabling exploration:** By showcasing different kinds of scenarios in an AR learning activity, can help learners explore the taught concept in the relevant context. This would enable the learner to understand the concepts while viewing the 3D object and its related scenes.

- **Content manipulation:** While the content in the AR environment is being displayed, the manipulation of the same by the students gives them the authority towards learning. Thus, the AR learning activities can involve components with the access of their manipulation.

2.4.2. Incentivizing AR Learning Activities for Affective Learning

The *'incentive'* dimension is concerned with the mental energy for cognition to happen, which can be attained by being engrossed in the activities. This leads to a natural human state called *immersion* which emerges as people engage in an engrossing activity (Weibel et al., 2010). Georgiou & Kyza (2017a) investigated immersion in the context of location-based AR and discovered empirical evidence that immersion is a three-stage continuum of cognitive and emotional involvement, consisting of engagement, engrossment, and final immersion. The first level, engagement, is based on interest and usability; to proceed to this level, students must first enjoy the activity and grow comfortable using the AR app. Students may be able to get to the second level of immersion, i.e. engrossment, if they are engaged in the activity and believe the AR application is user-friendly. The decisive factors at this level include focused attention and emotional connection. In the final stage, students feel the 'presence', a sense of being surrounded by the blended environment, and 'flow', a sense of being totally absorbed in the activity.

Moreover, to keep the learners motivated throughout the learning process, real-time feedback on the response to a question imposed in the AR environment is provided to the learners. Multiple ways have been adopted for the same. For example, in an AR system designed for 2nd-grade students to explore concepts like means of transportation, types of animals, and similar semantic categories, the game offered audio feedback in the form of an applause-like sound if one correctly identified a category from the given options. The game played a "wrong-buzzer" sound if the answer was incorrect (Freitas & Campos, 2008). In UNED-ARLE, while answering MCQ questions in AR, the correct answer is represented with a tick mark, and a new AR button appears. The wrong answer is represented with a cross. The next question to be answered is shown via a blue arrow (Cubillo et al., 2015). Further, while teaching the topic of Periodic Tables in Chemistry in AR, scaffolds in the form of hints are provided if students are unable to provide the correct answers and can proceed to the next question only if the correct answer is provided (Abd Majid & Abd Majid, 2018). The use of a defined gesture such as 'jumping', 'stretching', and 'boxing' to correctly answer a question in the AR system has also been explored (Hsiao & Rashvand, 2011). Further, to make it engaging it was suggested that it's vital to allow learners to access and process the content of the activities of the AR experience and then challenge the learners with higher-level difficulties (Dunleavy, 2014).

From the literature, we were able to summarise a few of the proposed design strategies for incentivizing AR learning activities that can help the learners to attain affective learning:

- **Ensuring immersion:** In the learning process, the immersion can be ensured by building on interest, usability, attention, and emotional connection, leading to creating a sense of the presence of the 3D object in the real-world (presence) and the sense of being absorbed in the world where the activity is taking place (flow).
- **Real-time feedback:** For every action that is done by the learner while performing an activity in the AR world, the real-time feedback by the system and/or the teacher can keep the learners motivated in the learning process.
- **Multi-level challenging problems:** While showcasing the related concepts with the help of the superimposed graphics, the practice and engaging behaviour of the learners can be set by putting up multiple related smaller problems. Once the students have learned a concept in AR, they can be given problem-solving questions that challenge their learning ability.

2.4.3. Interactions and Interactivity in AR for Social Learning

The term interactivity is a widely used one, having different meanings and use depending on the context (McMillan, 2002). In general terms, interactivity is defined as the process in which two or more people or things work together and influence each others' actions. In terms of communication, Rafaeli (1988) described interactivity to be related to the degree of sequential communication exchanges. In the context of Human-Computer Interaction (HCI), the term interactivity has been defined as the response in the form of output, to a user's action of providing input for technology in use. The sequence of actions then forms an interaction (Sims, 1997). This interaction depends on some sort of 'flow' in the form of material, energy, or information between systems (Barker, 1994). Thus, it has been recommended that the understanding of interactivity can lead to creating environments that facilitate interaction (McMillan, 2002). The researchers have gained this understanding by operationalizing interactivity with the consideration of various dimensions of evaluation.

Interactivity in learning has been considered "a necessary and fundamental mechanism for knowledge acquisition and the development of both cognitive and physical skills" (Barker, 1994; Sims, 1997). Interactivity has also been defined to consist of a variety of learning activities that include interactions between students, interactions of the students with the instructors, and interactions of the students with the teaching material itself. Thus, broadly classifying interactivity into learner-learner interaction, learner-instructor interaction, and learner-content interaction (Moore, 1989). Researchers have argued that interactivity can lead to learning through the activation of cognitive processes (Moreno & Mayer, 2005), activating the knowledge stored in the long-term memory and triggering the brain to integrate it with the incoming information.

In the context of AR applications, interactivity has been mostly referred to as the implementation of tasks that involve the users interacting with the virtual elements on the screen. The manipulations could involve changing the position, shape, and/or other graphical features of the virtual content. These manipulations were possible using fingers or motions of handheld devices by shaking and tilting them (Kesim & Ozarslan, 2012). Santos et al. (2013) summarised the various embodied interactions described in the literature. For example, while holding a MagicCup (i.e. a cup-shaped handheld compact AR input device with a tracker), a user holds it upside down and controls the virtual objects with interactions such as 'cover', 'put', 'slide', 'rotate', 'shake' and 'incline' (Billinghurst et al., 2009). In the context of learning, Aristo - an AR platform explored gesture interaction consisting of two gestures: *page flipping* and *point-and-click* to interact with the virtual content (Zheng et al., 2017). In the AR storybooks, the learners used handheld paddles to interact with the content, facilitating engagement and recall of story events (Dünser, 2008). While creating augmented books, interactivity was considered to be central to content engagement (Billinghurst & Duenser, 2012). In another study, the learners could move around the magnets and see how the magnetic field changed (Matsutomo et al., 2012). Thus, interactivity has been stated to be enhancing the learning experience with the ability to actively explore and manipulate the virtual content (Dünser & Hornecker, 2007). The interactivity in these cases has been described on the basis of learner-content interaction.

One of the studies reported the facilitation of interaction among students and the environment context using the AR experience of EcoMOBILE (Kamarainen et al., 2013). In another study, a Classroom Augmented Interactive Video (CAIV) approach was proposed that incorporated AR with video interactions and the characteristics of classroom-based instruction. Based on the authority to initiate an action, the interactions were categorised as teacher's interactions, students' interactions, and classroom interactions (Kazanidis et al., 2018). As the benefit of AR experiences includes face-to-face collaboration along with access to virtual content, it helps the learners to have their personalised perspective and control the content as well as collaborate with their peers (Bujak et al., 2013). Hence, interactive AR needs to incorporate these abilities for an effective learning experience.

Thus, from the literature, we were able to summarise a few of the key proposed design strategies for bringing in interactivity in ARLEs that can help the learners to attain social learning:

- **Promoting collaboration:** The group composition and the interactions defined in the learning activities in AR can lead to doing actions with the peers that can further lead to collaborative discussions and learner-learner interactions that help exchange knowledge by diving into the authority of controlling together.
- **Instructional scaffolding:** While designing an ARLE, it becomes essential to specify the roles and controls of the instructors and the students in a classroom while interacting with the ARLE, leading to appropriate instructor-learner interactions.
- **Embodied interactions:** The embodied interactions, such as moving around the virtual objects or making the virtual objects move, make it engaging for the students while being able to define the actions to manipulate the virtual object. Manipulation of the same by the students gives them the authority towards learning and brings forth the learner-content interaction.

Synthesis

A common observation throughout the review of the literature has been the lack of a critical approach concerning the benefits of augmented content, challenging and motivating problems, and interactions and interactivity to AR learning. Consequently, there has been a lack of systematic research to evaluate the holistic effect on the learning dimensions in AR environments. Though the different related works stated to have created interactive and immersive ARLEs, the reason for the holistic influence of the interactive nature on learning has been less explored, which will be argued in this research.

2.5. Conjectures Emerging from Theory

In this chapter, the literature was reviewed related to AR technology in education, the dimensions of learning to be targeted, and the design principles to create ARLEs. With the review, we were able to identify certain design strategies to create ARLEs. Thus, the literature study guided us in putting forth the following conjectures regarding our research goals of understanding the design strategies to create ARLEs and supporting the dimensions of learning.

2.5.1. Conjecture 1

The designers of ARLEs focus on contextual 3D content representation and manipulation, exploration and challenges through multi-level problem solving, and immersion through embodied and collaborative interactions to support cognitive, affective, and social learning to learners.

This is a conjecture regarding the research goal of understanding the approaches and strategies adopted by the designers of ARLEs to help learners learn by problem-solving. In this work, we will detail the design strategies taken by the designers in the entire process while aligning with the objectives of incorporating the three dimensions of learning. This conjecture is examined in Chapter 4.

2.5.2. Conjecture 2

An Augmented Reality learning environment (ARLE) created using the design strategies of incorporating augmented content, providing motives for learning, and integrating embodied, immersive and social interactions would holistically support the learners with cognitive, affective, and social learning.

This is a conjecture regarding the research goal of designing an ARLE to support problem-solving. In this, we will design modules of ARLEs based on the outlined design strategies. Additionally, we will evaluate how problem-solving activities lead to cognitive, affective, and social learning. This conjecture is examined in Chapters 5, 6, and 7.

2.6. Summary

Though the use of technology has been seen to be prevalent in the classrooms, they are mostly instructor-mediated. Thus, as a solution to the student-centered approach for the use of technology in classrooms, the potential technology of Augmented Reality (AR) was studied and analyzed, with its influence on the different facets of learning. This was followed by understanding the relevant design strategies to incorporate the three dimensions of learning, i.e. content, incentive, and interaction, to bring in cognitive, affective, and social learning respectively. Based on the literature in these areas, we established two conjectures about our research goals of understanding the design strategies for creating an ARLE and aiding the three dimensions of learning. The methods we used to systematically investigate these conjectures are described in the following chapter.

Chapter 3

Research Methodology

This chapter highlights the suitable research methodology considered for our research, its characteristics, and how it is applied in our research. As described in Chapter 1, the objective of the research is two folds, i.e. (1) to iteratively define the design strategies to create interactive ARLEs and (2) characterise the content, incentive, and interaction dimensions of learning in the designed ARLE. Chapter 2 guided us towards the three conjectures regarding the two research objectives to be examined in this thesis. Hence, we needed to identify the appropriate research methodology that could align with the research goals.

3.1. Selecting Suitable Research Methodology

The derived conjectures in Chapter 2 directed us towards defining the sub-goals of the research work (as shown in Fig. 3.1):

1. Understand the expectations of learners, teachers, and parents for the design of a classroom-based ARLE.
2. Understand the design approaches and strategies taken by the designers of classroom-based ARLEs.

3. Using the design strategies to design an AR-based application for supporting content, incentive, and interaction dimensions of learning.
4. Evaluate how the features in the designed ARLE promote cognitive, affective, and social learning.
5. Refine our understanding of the effective design strategies for ARLEs.

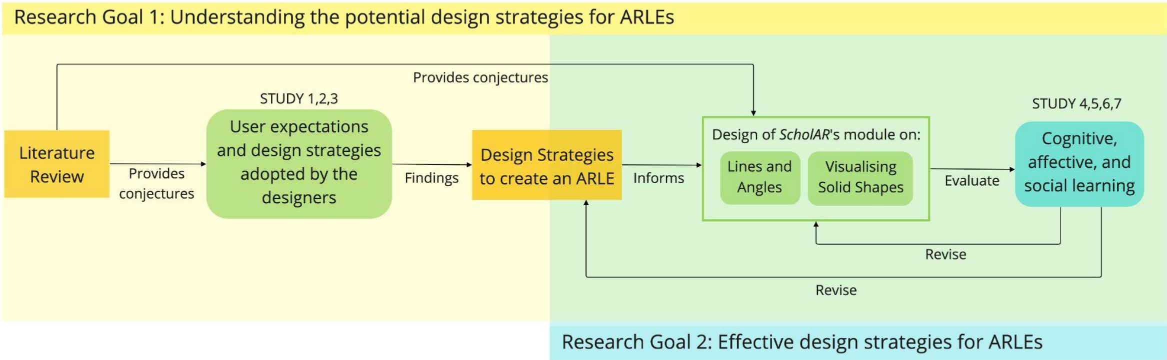


Fig. 3.1: Research goals of this thesis

Any research plan involves the intersection of philosophy, strategies of inquiry, and specific methods (Creswell, 2013). Considering the aspect of research philosophy, this research follows a pragmatic worldview. The emphasis of the pragmatists is on the research problem, oriented towards real-world practice, and they use all approaches available to understand the problem (Rossman & Wilson, 1985; Creswell, 2002; Creswell 2013). Next, we identify the strategies of inquiry, i.e. candidate research methodologies, and select the suitable one that aligns with the pragmatic worldview and our research goals.

Our strategy of inquiry required an overarching methodology that supported iterative research designs with qualitative and quantitative methods to evaluate the research outcomes. We began by looking into the Mixed Methods research (Creswell, 2013), which involves both qualitative and quantitative methods to conduct research. In the advanced version of Multiphase Mixed Methods, each phase has one study that informs the next study in the next phase. And each study uses qualitative, quantitative, or mixed methods to conduct the study. As this methodology seemed to be generic without indicating the nature of the studies to be conducted and the aspects to be defined by following a particular research process, we sought to determine a specific methodology.

As one fold of the research goals involves investigating the design decisions, strategies, and methods in the design process of the ARLEs, we began by looking into the methodology for design research. Design Research Methodology (DRM) caters to formulating measurable criteria of success, understanding the design and development of design products and processes, reflecting on the design and development of design support, and evaluating those (Blessing & Chakrabarti, 2009). DRM partially suits our requirements, as one of our objectives is to understand the effective underlying design process. However, in addition to the design process and approaches, our research goal also includes designing a techno-pedagogical environment.

Therefore, going deeper into creating a technology-enhanced learning environment (TELE) as an intervention, we looked into the research methods falling under the broader term of Education Design Research (EDR) (Plomp and Nieveen, 2010). The broad motive of EDR is to design and develop an intervention solving complex, real-world, educational problems, by developing or validating theories. Moreover, it advances the knowledge of the researchers about the characteristics of the interventions and the processes to design and develop them. EDR broadly includes three types of research methodologies - Design based research (DBR), Design and Development research (DDR), and Design-based Implementation research (DBIR).

The DBIR methodology involves the holistic view of educational systems by designing effective, scalable, and sustainable educational policies and programs (Penuel et al., 2011; Fishman et al., 2013). It involves the stakeholders at different educational system levels, such as administrators and policy-makers. None of the motives of the methodology aligned with our research goals; hence this methodology was not applicable to our research.

The DDR methodology has been defined as "the systematic study of design, development and evaluation processes with the aim of establishing an empirical basis for the creation of instructional and non-instructional products and tools and new or enhanced models that govern their development" (Richey & Klein, 2014). This methodology is partially aligned with our requirements, as one of our objectives is to design and develop a techno-pedagogical environment. However, our research goal also includes designing pedagogy and contributing to the underlying principles of design and learning.

The DBR methodology caters to involving the stakeholders and the real-world context in the design and evaluation of interventions (Barab & Squire, 2004; Cobb et al., 2003). It can guide the TELE designers toward the generation of practical knowledge that can be shared among the broad design community (Wang & Hannafin, 2005). It has been defined as "a systematic but flexible methodology aimed to improve educational practices through iterative analysis, design, development, and implementation, based on collaboration among researchers and practitioners in real-world settings, and leading to contextually-sensitive design principles and theories" (Wang & Hannafin, 2005). As DBR involves the iterative design of a learning experience to understand the reasons for the successful or failed working of certain features, this methodology seemed appropriate to align with our research goal.

3.2. Design Based Research (DBR) Methodology

As explained in the previous chapter, the research goal is to understand the design strategies for ARLEs and create those to support learning through cognition, incentive, and interaction. Aligning to the research goals, the design-based research (DBR) methodology was adopted for this research. DBR is a flexible and pragmatic one as the aim of this methodology is not restrictive to designing, developing, and evaluating the techno-pedagogical solution, but also to identifying the underlying design principles or local learning theories (Barab & Squire, 2004; Gravemeijer and Cobb, 2006; Plomp and Nieveen, 2010). Thus, it is grounded in theory and real-world context (Wang & Hannafin, 2005). The designers are involved in the design processes, working together with the learners. This makes this methodology an interactive one. It is also iterative in nature where each iteration of DBR has three phases namely Analysis/Exploration, Design/Construction, and Evaluation/Reflection (McKenney & Reeves, 2014). It has been considered for the "refinement of problems, solutions, methods, and design principles." (Reeves, 2006). Thus, the changes can be incorporated whenever necessary. The credibility of the research is enhanced through mixed research methods that depend on the specific phase of the research as new needs and problems emerge and the focus of the research evolves, which makes this methodology integrative. Thus, overall, DBR caters to our research objectives as described in Table 3.1.

Table 3.1. Suitability of our research goal to adopt DBR methodology

Criteria for suitability of DBR	**Our research context**
DBR is contextualised as the identified design principles, and theories are connected to the context and the design process.	The aim of our research is to create a contextual techno-pedagogical environment.
DBR is theory-driven and grounded in relevant research, theory, and practice.	The purpose is to develop or validate theories about learning through interactivity.
The knowledge claim of DBR is in the form of design principles.	The lens of design strategies for designing interactive ARLEs is being considered.
Designers are involved in the design processes while they work together with the learners to refine the design.	The process of research involves working closely with the potential stakeholders, i.e. learners, teachers, and designers.
The DBR phases involve design processes that are conducted and studied in real-world settings.	The outcomes are expected to be connected with the authentic real-world settings and the corresponding development processes.

For this research, the DBR structure suggested by Reeves (2006) has been followed. This structure involves multiple iterations of research. As shown in Fig. 3.2. DBR has four phases: Problem Analysis and Exploration, Design and Development of the solution, Evaluation, and Reflection which have been explained below.

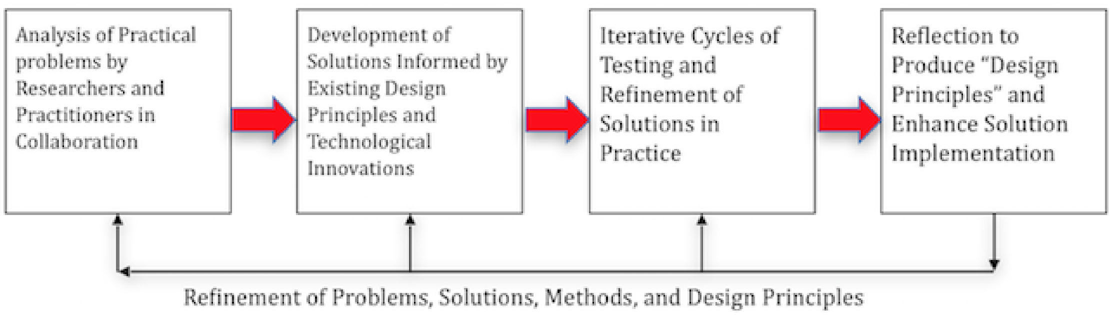


Fig. 3.2: DBR Phases (Reeves, 2006). Figure reproduced from Plomp and Nieveen (2010)

- The first phase of DBR involves *problem analysis and exploration* where the researchers conduct literature analysis to address the problem by analyzing the existing solutions, to understand the specifics of the context through pilot/exploratory studies, and the needs of the participants.
- The second phase of DBR involves *solution design and development*. The insights from the existing design principles, theoretical underpinnings, and empirical findings are then used to design and develop the solution or the learning environment.
- In the third phase of DBR, i.e. *evaluation*, various qualitative, quantitative, or mixed methods are used to evaluate the design and refine the solution.
- The fourth phase of DBR includes *reflection,* where the researchers reflect upon the findings based on the design and evaluation results in the previous phases. This helps to produce the design principles and enhance the implementation of the solution design.

In this research, the third and fourth phases of DBR have been discussed together.

3.3. Applying DBR in the Research

In this research work, we are undergoing two iterations of DBR. The goal of the first iteration of DBR is to understand the potential design strategies to come up with the design of an interactive ARLE for a classroom. In the second iteration of DBR, the goal is to refine the design strategies to characterise the cognitive, affective, and social learning of students through the designed ARLE.

3.3.1. Research Questions

The two iterations of DBR are being used to answer the research questions mentioned in Table 3.2. In the table, RQ stands for Research Questions that have been answered through empirical studies. LQ stands for Literature Questions that have been answered through literature analysis. DQ stands for Design Questions which relate to finding specific operationalization of theories or practices to design and/or develop artifacts or methods.

Table 3.2. List of Research Questions (RQs) and sub-RQs

DBR Phase	Research Question		Analysis Method
DBR CYCLE 1: Understanding the design strategies of interactive ARLEs for classrooms			
Problem Analysis and Exploration	Broad RQ 1	What are the potential design strategies required to create classroom-based ARLEs?	
	RQ 1a	What are the expectations of the users if ARLEs are used in classrooms?	**Study 1** (Thematic Analysis of the responses obtained from the teachers, students, and parents)
	RQ 1b	What are the suitable AR interaction mediums while collaboratively solving problems in classrooms?	**Study 2** (Interaction Analysis of the behaviour of groups)
	RQ 1c	What are the design strategies adopted by the designers of a classroom-based ARLE to meet the user expectations while using the suitable AR interaction medium?	**Study 3** (Inductive thematic analysis of the ways used by the designers to conceptualise the design of an ARLE)
Design and Development	Broad RQ 2	How do the potential design strategies of creating an ARLE incorporate the dimensions of learning?	
	DQ 1	What should be the design features of an AR app named *ScholAR*, incorporating the design strategies that lead to cognitive, affective and social learning?	Designed and developed interactive modules of *ScholAR* on *Lines and Angles* and *Visualising Solid Shapes*.

Evaluation and Reflection	RQ 2a	What is the effect of the designed module on *'Lines and Angles'* of *ScholAR* on the students' cognitive, affective, and social learning?	**Study 4** (Thematic analysis and motivation analysis based on the Instructional Materials Motivation Survey (IMMS) to analyze the differences between individual and dyads performance)
	RQ 2b	What is the effect of the designed module on *'Visualising Solid Shapes'* of *ScholAR* on the students' cognitive, affective and social learning?	**Study 5** (Quantitative and qualitative analysis of the differences between experimental and control groups)
DBR CYCLE 2: Defining the design strategies for creating effective interactive classroom ARLEs			
Problem Analysis, Design and Development	DQ 2	What should be the improved design features of *ScholAR* modules, incorporating the design strategies that lead to cognitive, affective, and social learning?	Re-designed and developed *ScholAR*'s modules on *Lines and Angles* and *Visualising Solid Shapes* based on the reflections from literature analysis and studies 3 to 6.
Evaluation and Reflection	Broad RQ 3	What are the effective design strategies for the modules of *ScholAR* that lead to cognitive, affective, and social learning?	
	RQ 3a	What is the effect of the designed module on *'Lines and Angles'* of *ScholAR 2.0* on the students' social learning?	**Study 6** (Lag sequential analysis of the interaction patterns)
	RQ3b	What is the effect of the designed module on *'Visualising Solid Shapes'* of	**Study 7** Quantitative and qualitative

		ScholAR 2.0 on the students' cognitive, affective, and social learning?	analysis of the difference between experimental and control groups

3.3.2. DBR Cycles in the Research

The details of the studies conducted in the two cycles of DBR are shown in Fig 3.3.

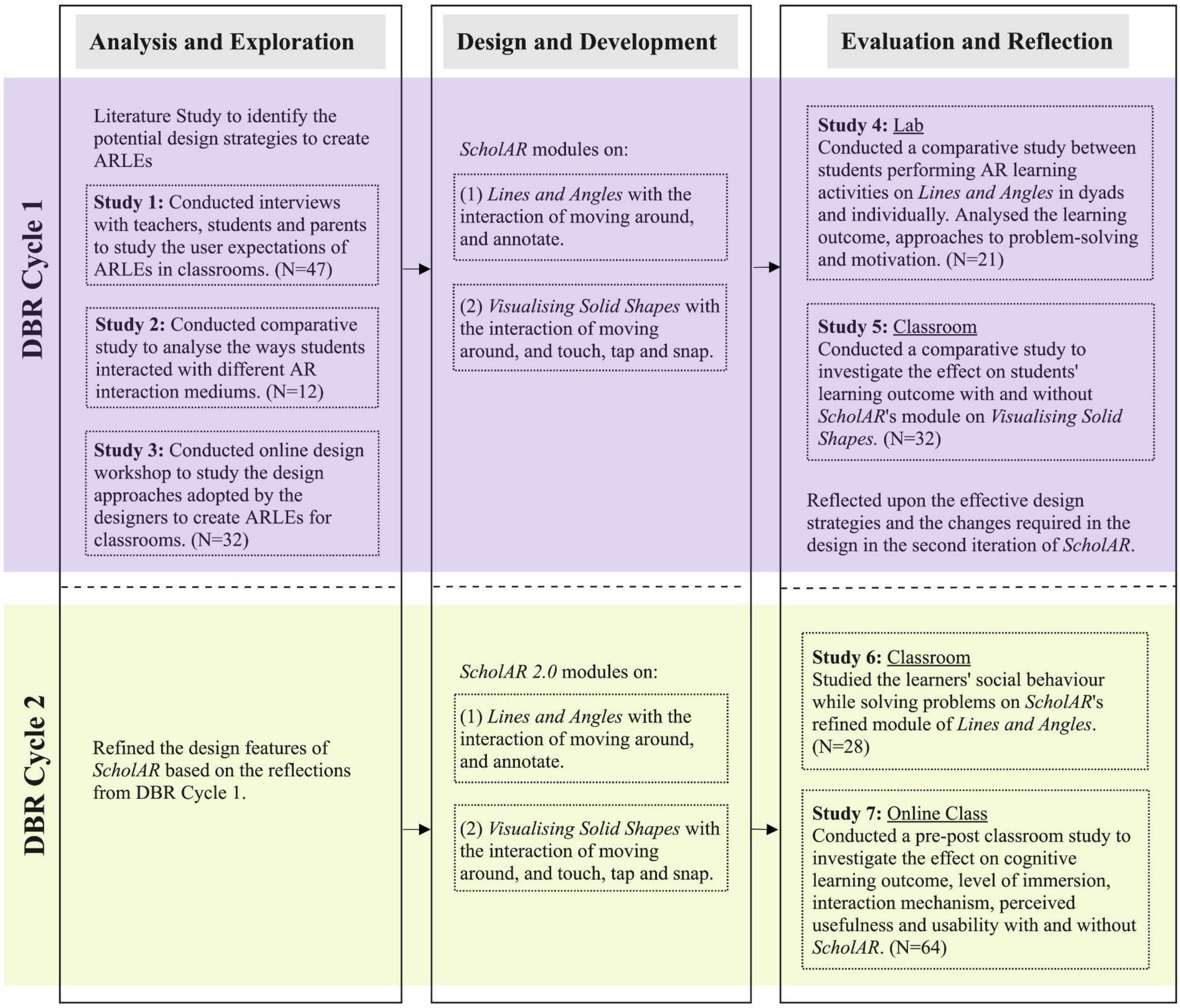


Fig. 3.3: Overview of the iterations of Design Based Research (DBR) in this thesis

The details of each phase of DBR are as follows:

DBR Cycle 1: Understanding the design strategies of interactive ARLEs for classrooms

The primary objective of the first iteration of DBR was to understand what are the possible design strategies for creating interactive ARLEs for classrooms, characterised by content, incentive, and interaction dimensions of learning. Further, apply those design strategies to create the initial version of a handheld and markerless AR application and evaluate its impact on learners' cognitive, affective, and social learning.

a) **Analysis and Exploration:** The research was guided towards having a technology-enhanced learning environment promoting a student-centered learning experience in the classroom. To begin with, it was required to understand the expectations of the key stakeholders from having an AR learning experience in the classrooms. Thus, to answer RQ1a, teachers and students of a school and parents who had the AR experience at a mall were interviewed (Study 1). Thematic analysis of their responses was done to obtain the characteristic user expectations.

    Thematic Analysis has been defined by Braun & Clarke (1996) as a versatile and broadly applicable qualitative analysis method for providing a comprehensive description of data by "identifying, analyzing, and reporting patterns (themes) within data". It is used to organise, describe, and provide interpretations about various aspects of the research goal based on data. However, it differs from grounded theory in which on the basis of data, a plausible hypothesis of the event under investigation is produced. Data collection and analysis are interleaved in the research process to generate theories. On the contrary, thematic analysis unveils the patterns in the data. The details of the thematic analysis applied in study 1 are provided in Section 4.1.2.

    The further objective was to understand the suitable AR interaction mediums in the classroom environment. We conducted an exploratory study with students in groups to answer RQ1b. We were interested to understand and analyze the ways in which the students interacted with the different AR interaction mediums. Additionally, we wanted to understand how the students interacted with each other in a group while solving varied mathematical problems using the handheld AR app (Study 2).

    Interaction Analysis guides in empirically investigating human-human and human-environment interactions (Jordan & Henderson, 1995). It examines human actions like talk, gestures, and the use of artifacts and technologies in order to uncover common practices, issues, and possible solutions. It is founded on ethnography and assumes that knowledge and practice are situated in the interactions among members of a community and their engagement with the environment. Another assumption is that analysis and theories are based on reliable observations captured on videotapes and then analyzed to draw conclusions. Thus, this method was chosen as our analysis method as it aligned with our research goal of understanding the group behaviour and solution approaches using the AR interaction mediums. This study has been described in detail in Section 4.2 which gave us a direction toward the possible interactions that can be designed and implemented in an interactive ARLE for the classroom.

From studies 1 and 2, we were able to gather an understanding of what aspects need to be considered while designing a classroom-based ARLE. To answer RQ1c and understand how the aspects can be incorporated into the design, we conducted a workshop with the designers of an ARLE, i.e. in groups consisting of an interaction designer, an education researcher, an AR developer, and a middle-grade Math teacher (Study 3). The groups designed ARLEs for 7th-grade Mathematics topics. The design strategies adopted in the process were analyzed using inductive thematic analysis (Thomas, 2006), which has been described in Section 4.3.3.

b) **Design and Development:** While designing the modules of our handheld and markerless AR application named *ScholAR,* the design strategies were adopted from the existing literature and Study 3. The interactions were based on the results of Study 2. The design of the modules was targeted at the user expectations obtained from Study 1. Thus, two modules of *ScholAR* were created. The first module was on the topic of 2D Geometry - *Lines and Angles* based on the syllabus of 7th grade. The interactions involved in the design were touch, slide, annotate, and movement. The second module of *ScholAR* was on the topic of 3D Geometry - *Visualising Solid Shapes* based on the syllabus of 7th grade, where the interactions were based on touch, tap, and movement. The conjecture mapping framework (Sandoval, 2014) was employed to generate a set of design and theoretical conjectures regarding how the design of *ScholAR* leads to the three dimensions of learning.

c) **Evaluation and Reflection:** The testing of the module on Lines and Angles was done in a lab setting to answer RQ2a. The lab study was a comparative one between students performing the activities in dyads and individually. This helped to closely observe the interactivity of the students. Pre and posttests were conducted to evaluate the cognitive learning outcome of the participants. These assessment instruments were designed to address the requirements of 7th-grade Mathematics curriculum and focused on 'understand' and 'apply' cognitive levels and 'conceptual' and 'procedural' types of knowledge within the chosen topic (Study 5). Also, a motivation questionnaire developed from the Instructional Materials Motivation Survey (IMMS) (Song and Keller, 2001) was provided to understand the motivation of the two groups, in order to study the affective learning in the students. The usability of the application was further evaluated using the System Usability Scale (SUS) questionnaire (Brooke, 1996). The details of the results and analysis have been discussed in Section 5.4.

To address RQ2b and evaluate the effectiveness of *ScholAR*'s module on Visualising Solid Shapes, a comparative study was conducted to investigate the cognitive learning outcomes of students with and without *ScholAR* (Study 6). Similar to the evaluation for Lines and Angles, the cognitive learning outcomes were evaluated using posttest papers comprising questions that focused on 'understand' and 'apply' cognitive levels and 'conceptual' and 'procedural' types of knowledge. The interactivity of the students while performing AR learning activities was observed and reported along with the perception of learning, usefulness, and limitations of the application as per the students and the teacher, which have been discussed in detail in Section 5.6. The results from studies 5 and 6 in DBR cycle 1 reflected upon the effective design strategies and features in the design of *ScholAR*'s interactive learning activities to promote the learning acquisition process.

DBR Cycle 2: Defining the design approaches for creating effective interactive classroom ARLEs

The objective of the second iteration of DBR was to refine the design features of the *ScholAR* app based on the reflections from the first iteration of DBR. The effectiveness of interactive learning was then evaluated for the revised version of DBR2.

a) **Analysis and Exploration:** The objective was to dig deeper into the design approaches and strategies to create interactive ARLEs for classrooms. The results obtained from the literature study and empirical studies in cycle 1 of DBR helped in identifying the features or actions that required amendments in the design of *ScholAR 2.0*'s modules on Lines and Angles and Visualising Solid Shapes.

b) **Design and Development:** While refining the *ScholAR 2.0*'s modules on Lines and Angles and Visualising Solid Shapes, the design was refined by supporting the theoretical underpinnings and the reflections from the previous studies. The design at the micro (application) and macro-level (classroom use) was defined to come up with the framework of the solution. It was conjectured that *ScholAR 2.0* would better support the three dimensions of learning.

c) **Evaluation and Reflection:** The testing of the revised module on Lines and Angles was done in a classroom setting which was conducted with dyads. To answer RQ3a and analyze the interaction process, their learning and interactivity behaviours were coded and analyzed using Lag Sequential Analysis while interacting with *ScholAR 2.0* (Study 6). The process has been described in detail in Section 6.1.2 onwards.

Lag Sequential Analysis is the computation of the conditional probability of one event occurring before or after another (Gunter et al., 1993). Conditional probabilities are determined by adding the frequency of one coded event (the condition) and then the proportions of all other occurrences that occur before or after it. It guides in detecting the significant sequential relationship between each categorised behavior (Bakeman & Gottman, 1997). This method has been extensively used to gather descriptive data of social interactions in classroom learning (Gunter et al., 1993), digital learning (Hou, 2010; Sung et al., 2010) as well as AR learning (Lin et al., 2013; Chiang et al., 2014; Wang et al., 2014). Hence, this method was considered for analysis as it aligned with the research goal of understanding the influence of the designed module on social interactions.

Scholar 2.0's module on Visualising Solid Shapes was tested in an online classroom setup due to the pandemic. A comparative study was done where similar activities were created and tested for the then commonly used method of teaching i.e. on laptops/desktops (Study 7). The cognitive learning outcome was analyzed using the pre and posttest papers. This along with the usefulness and usability of the application, have been reported. We wanted to understand how the interactions with the two comparative mediums facilitated the participants in solving the problems and the various ways in which the features of *ScholAR 2.0* were used to solve those. As described above, interaction analysis followed by the thematic analysis was appropriate for addressing RQ3b, which has been discussed in section 7.6.4.

3.4. Ethical Considerations

As human participants, especially children were involved in the different stages of the research, ethical clearance was taken from the Institute Ethics Committee. The following aspects were followed as part of the ethical considerations:

Briefing and Informed Consent

The participants included in this research were teachers, interaction designers, education researchers, AR developers, and majorly the students. These participants were given a consent form (Appendix A) that documented the research objectives and the details of the study. To conduct the studies on the school premises or online, due consent was taken from the school principal. For the school students, the consent of their participation was taken from them using Assent forms, and their parents' using Consent forms. They were assured that no risk is involved and the participation of the students in the study would have no bearing on their grades and academic performance. The participants were offered clarification from the researchers whenever required. They were assured voluntary participation and could discontinue from the study at any point of time. Once the participants had clarity regarding the above points, they were asked for their consent by signing the provided form. The participants were provided with certificates at the end of every session.

Anonymity and Confidentiality

The anonymity of all the participants was maintained throughout. All the data was appropriately collected, preprocessed, and stored for this. No one apart from the primary and secondary researchers on the project had access to the computer data and written artifacts of the participants. The necessary permissions to publish the insights from the studies were taken from the participants.

Conducting Online Studies during the Pandemic

A year and a half of the research work was carried out during the COVID-19 pandemic. This made us decide upon conducting the studies online due to the uncertainty of the tenure for it to reach the endemic stage. It resulted in several constraints for this thesis work. The *Visualising Solid Shapes* module of the *ScholAR 2.0* application and a comparative non-AR desktop application had to be redesigned to conduct Study 7 online. Multiple discussions and demonstrations had to be carried out with school principals, teachers, and parents to explain the actual execution of the study. This further brought in the constraint of recruiting students of 7th grade who had ARCore supported mobile phones at home and/or a Windows laptop and good internet connectivity. Additionally, multiple supporting volunteers were required to conduct and control the parallel sessions. Moreover, the study with a set of students had to be broken down across multiple days to reduce internet fatigue and synchronise with the academic timetable. The participation of the students was voluntary, and they were provided the Certificate of Participation in the workshop after the end of the study.

3.5. Summary

In this chapter, we advocated our choice of Design Based Research (DBR) as an underlying research methodology and detailed the two DBR iterations (DBR1 and DBR2) used in this thesis. The studies and the research methods in each of the iterations have been briefly discussed. DBR1 has been elaborately discussed in Chapters 4 and 5, and DBR2 in Chapters 6 and 7. The next chapter begins by explaining the problem analysis phase of DBR 1 that includes Study 1, 2, and 3, followed by the design and development of the initial version of the handheld AR application, i.e. *ScholAR*.

Chapter 4

DBR 1 Problem Analysis: Understanding Design Strategies

As described in Chapter 3, the first phase of DBR includes Problem Analysis and Exploration which is conducted to understand the problem and the context. This phase includes the literature review (covered in Chapter 2) and preliminary level exploratory studies. We began by doing field visits as part of primary research and established the theoretical foundation for the observations and insights through literature. As the AR technology in the classrooms as a solution for student-centered learning is being proposed, we initiated the research by investigating the expectations of the key stakeholders from this technology. This was followed by understanding the AR interaction mediums suitable for implementation in the classroom scenario. Further, the design strategies adopted by designers of ARLEs were analyzed to meet the user expectations and the AR interaction mediums requirements.

To begin with, the broad research question to be addressed was:
Broad RQ1: *What are the potential design strategies required to create classroom-based ARLEs?*

4.1. STUDY 1: User Expectations

Augmented Reality (AR) in the classrooms can help students to visualise abstract concepts that are otherwise difficult to understand (Bacca et al., 2014). However, for the acceptance of such a technology, it is required to design the AR services in schools as per the expectations of the key stakeholders for a satisfactory user experience. The broad goal was to understand the outlook of students towards technology and the expectations of the three user groups (students, teachers, and parents) from an AR experience in an Indian school education setting. Further, the possible characteristic expectations for attaining a dimension of learning were obtained and categorised.

The following research question was addressed in this study:
RQ1a: *What are the expectations of the users if ARLEs are used in classrooms?*

4.1.1. Methods and Materials

Participants and Recruitment

The exploratory study was conducted in 2 metropolitan cities of India - Mumbai, and Delhi, in three phases with 47 participants belonging to three different user groups of 6 parents, 7 teachers, and 34 students. A semi-structured interview was conducted with randomly selected 34 students of a private school in Delhi from grades 4 to 9, who were regularly taught in the classroom using smartboards. Four students from grade 4 and six students each from grade 5 to 9 were interviewed in groups. Thus, the students belonged to the age range of 9-14 years (M=11.64, SD=0.43). Their individual responses to the interview questions were recorded. For this study, convenience sampling was done in selecting the parents and teachers for the study, and students were randomly selected by the teachers.

Procedure

6 parents who were there in the R-city mall in Mumbai along with their children, experiencing the AR display put up there (Fig. 4.1), were interviewed. 7 teachers teaching 6 to 10-grade students of the same school were interviewed. They had been using the smart class solution i.e. interactive smartboards in the classroom, along with the regular textbook teaching. Also, they were using smartphones out of which three at times referred to other educational applications complementing their teaching style.

For all the 47 participants, the audio and video recordings of the individual responses to the interview questions (Appendix E.2) were obtained. They were asked about their familiarity with *Pokémon GO* (Paavilainen et al., 2017) and were explained about the AR technology while showing a demo of the same using an existing mobile application. Based on their understanding of AR, they were then encouraged to 'think aloud' about their expectations of using AR in the classroom as per the suggested scenarios. They were allowed to give highly futuristic responses.

Fig. 4.1 People experiencing the AR display put up on the screen at a mall in Mumbai

4.1.2. Data Sources and Analysis

The audio-video recordings were transcribed to obtain the user stories. The user stories from all three user groups were jotted down on sticky notes. Using *thematic analysis,* the user stories were grouped further at multiple levels and brought down to certain themes (Fig. 4.2.). Inter-rater validity was performed by two researchers on the themes generated. One of the researchers was part of the main interview process. On obtaining the transcripts, the two researchers independently coded them to ensure the validity of the codes. There was 83% agreement of codes (Cohen's kappa = 0.61) between the two raters. Based on the mapping, certain inferences were obtained which suggested some characteristics of expectations pertaining to AR experience in classrooms. These characteristic expectations were then mapped with the three dimensions of learning suggested by Illeris (2003) - (1) *Content* – focuses on what is learned to develop one's functionality. (2) *Incentive* - focuses on maintaining the mental balance to develop one's sensitivity towards learning. (3) *Interaction* – focuses on the interaction of content and incentive to help in one's integration into society.

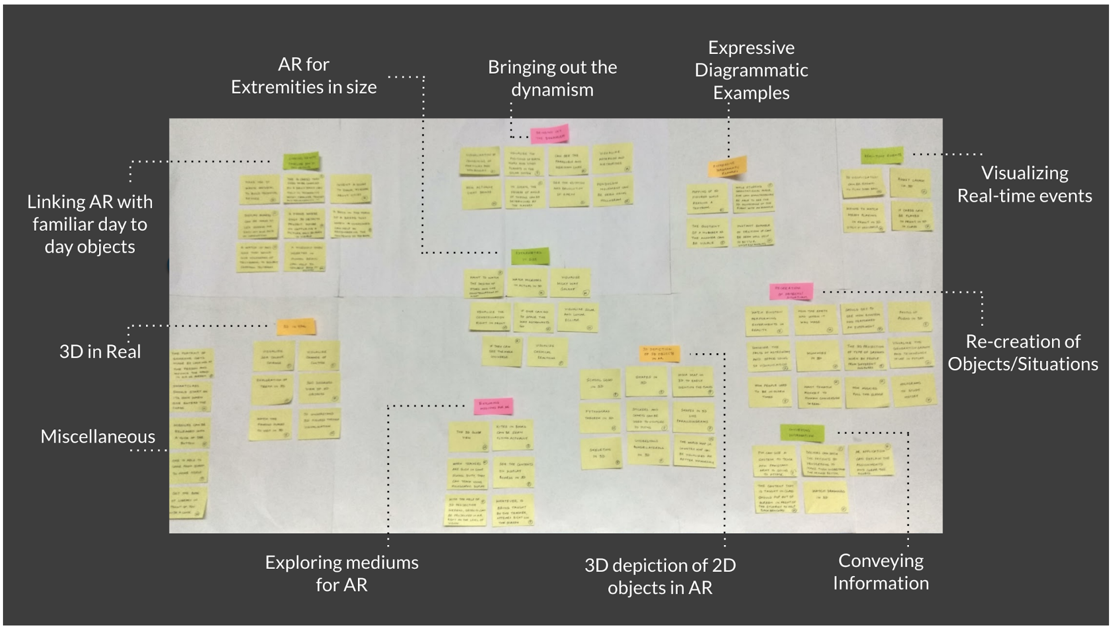


Fig. 4.2. Thematic Analysis of the user stories

4.1.3. Expectations of the Users

Many students knew about the popular AR-based game – *Pokémon GO* (Paavilainen et al., 2017). However, only 4 students knew the technology it used i.e. AR and could describe it a bit. For the RQ, the themes obtained from these user stories were classified under the three dimensions of learning. Based on those themes, 12 characteristics of expectations were obtained as shown in Table 4.1. The suggested characteristics of expectations under the *'Content'* dimension focus on designing the functionality of the AR services to help the students understand clearly what is taught to them. The suggested characteristics of expectations under the *'Incentive'* dimension focus on designing the AR services targeting the emotional intelligence quotient to help the students to bring in the sensitivity of cognition and keep them motivated in the learning process. The suggested characteristics of expectations under the *'Interaction'* dimension focus on designing the AR services with factors that integrate the functionality of AR services with the related incentive. This would ultimately help the students to initiate the process of learning with the AR services. Thus, it is suggested that in order to provide the users with a satisfactory experience in terms of learning using the AR services, the combination of these characteristics of expectations must be kept in mind by the designers while designing an AR service for schools.

Table 4.1. summarised characteristics of expected AR Experience in schools based on the themes generated under the three dimensions of learning.

<table>
<tr><th>Themes</th><th>Instances of User Statements</th><th>Characteristics of Expected AR Experience</th></tr>
<tr><td colspan="3">Dimension of Learning: Content (Functionality)</td></tr>
<tr><td>Exploring Mediums for AR</td><td>“see the contents on display board in 3D”, “scan the globe to see the cultures across countries”</td><td rowspan="3">Visual Cues: Enabling indication of AR elements in the mediums

Familiarity: Relating with prior knowledge of the associated content

Situational Re-generation: Explaining the working of past events and situations

Exploratory: Sense of experimenting with the AR components</td></tr>
<tr><td>Linking with familiar day-to-day events</td><td>“exploration of teeth in 3D”, “watch famous places to visit in 3D”</td></tr>
<tr><td>3D Depiction of 2D graphics</td><td>“country or world map can be visualised for memorizing easily”</td></tr>
<tr><td colspan="3">Dimension of Learning: Incentive (Sensitivity)</td></tr>
<tr><td>Bringing out the Dynamism</td><td>“Visualising combining of particles and molecules”, “see parallel and meridian lines”</td><td rowspan="3">Immersive: Feeling of being engrossed in the interaction of elements and learning

Developing Interest: Finding it engaging while the content is explained

Intuitive Engagement: Sense of efficiently understanding in one go

Motivational Instances: Feeling of excitement while experimenting with innovative mediums</td></tr>
<tr><td>Re-constructing objects/situations</td><td>“watch Einstein performing experiments in real”, “how the earth was made”</td></tr>
<tr><td>Expressive Diagrammatic Examples and Feedback</td><td>“while studying gravitational force, one is able to see the occurrence of the event with an example”</td></tr>
<tr><td colspan="3">Dimension of Learning: Interaction (Integration)</td></tr>
<tr><td>Consistent real-time information</td><td>“content taught in class should pop in front of students to help backbenchers learn together”</td><td rowspan="3">Controlling the dynamism: Controlling the interactive motion of contents

Interactive content: Sense of interactivity with the elements of AR

Information delivery: Instructor and/or system prompting related details and information with the 3D graphics

Responsive: Paying attention to the AR interactions and reacting in a suitable way</td></tr>
<tr><td>Reactions to Actions</td><td>“degree of angle rotation can be seen while moving an object”, “popping of 3D figures while reading a textbook”</td></tr>
<tr><td>Control extremities in sizes</td><td>“visualise the constellation right in front of me and zoom in and out”, “watch and control the sizes of the microbes”</td></tr>
</table>

4.1.4. Implications

In the solution space of this research, we are proposing the use of Augmented Reality (AR) technology in classrooms to provide interactive student-centered learning. While involving the key stakeholders in the process, it was required to understand their expectations from incorporating this technology into the classrooms. Thus, the teachers, students, and parents were interviewed and key themes of their expectations were defined which were categorised as per the three dimensions of learning. The combination of these characteristic expectations can guide us in creating interactive ARLEs for the classrooms. Additionally, the expectations of implementing AR was majorly raised around Mathematics subject by the participants as certain topics involving 3D visualisation are difficult for the students to understand and cannot be explained using physical objects. Moreover, to ensure the internal and external interactions among the students while using an AR application, it is required to understand what interactions are suitable for the students and how they interact with them to gain cognition. Thus, the next study was conducted with the intention of understanding how students interact with different interaction mediums in certain topics of Mathematics (section 4.2).

4.2. STUDY 2: AR Interaction Mediums

A critical part of Science, Technology, Engineering, Arts, and Mathematics (STEAM) education involves experiential learning, where learners learn from their experiences and reflect on those with minimal help from the adults. The students can thus be made to solve a real-life problem by constructing their knowledge on top of prior experiences. This learning in classrooms can be enhanced while exploring the multiple solutions approach in the open-ended learning environments with few resources and tools as the scaffold (Biswas et al., 2016). Collaboration among students in this process can further help in exchanging knowledge and developing social skills, critical thinking, and creative problem-solving ability (Laal, M. & Ghodsi, 2012). When it comes to classroom education, AR can be useful as a teaching aid in providing affordances that are not readily available in classroom environments. Hence, to execute the AR learning experience in the classroom, it is required to understand what interactions and interactivity are suitable to be incorporated in the design of an ARLE.

Thus, the following broad research question was supposed to be addressed:

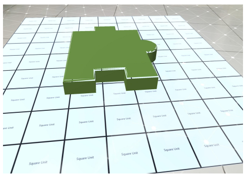
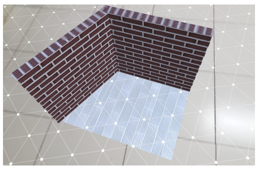
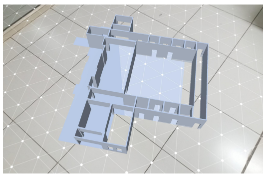
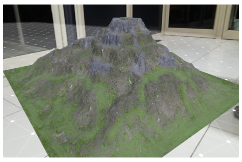
RQ1b: *What are the suitable AR interaction mediums while collaboratively solving problems in classrooms?*

This RQ was answered by first going through the literature to understand what are the existing interactions and interactivity involved in ARLEs for classrooms, which has been described in section 2.4.3. The common interactions were that of embodied interactions where the students could interact with the virtual content using fingers or by tilting or shaking the handheld devices (Kesim & Ozarslan, 2012; Santos et al., 2013). To investigate deeper into the ways students solve problems while interacting with AR and peers, we conducted a study where the students collaboratively explored different AR interaction mediums in problem-solving. Before coming up with the techno-pedagogical design of our ARLE, the interactivity of the students with three types of possible AR interaction mediums was explored. These interaction mediums included students interacting with the projected virtual object by (1) making use of finger taps and moving around the 3D virtual object on the screen, (2) drawing/annotating on the virtual object where their finger acts as a pencil on the screen, and (3) using tangible marker cubes to interact with the virtual object on the screen. The broad goal of the study was to understand the interaction of the students with the AR interaction mediums and their influence on problem-solving. They were given open-ended problems so that they are able to explore the utility of the AR interaction mediums while solving.

4.2.1. Task Design

In our study, several tasks were designed for each selected topic based on the 7th-grade Mathematics syllabus of the Maharashtra board. The tasks were designed around the 3D models and have been described in Table 4.1.

Table 4.2. Designing the Tasks: The four open-ended tasks that were given to students to solve

No.	Topic	3D Models	The Task	Learning Goals
1	Area	 Field on a 9x9 grid	To think of ways in which its area could be calculated.	To understand what a square unit is. To provoke discussion on the ways in which the area for irregular shapes could be calculated.
2	Lines and Angles	 Walls with 120° angle	To think of methods to find the internal angle between the two walls.	To understand the basis of the formation of Lines & Angles and their measurement. To leverage concepts of geometry like parallel lines and adjacent angles.
3	Symmetry & Congruence	 Floor plan	To think of ways to fill this structure (leaving no space) with objects of any shape and size.	To evaluate the ways in which different shapes of different sizes fit together. To understand how the fitting gets affected by the scale.
4	Visualising 3D Solids	 Mountain	To find ways of climbing the mountain in the fastest way possible.	To be able to relate the model to an actual mountain and develop a thorough understanding of the pyramid shape for it being a major factor in path and method planning.

4.2.2. The AR Interaction Mediums

There were three AR interaction mediums for every group to experience once:

1. **Tap and View:** It emphasised the creative use of imagination as a method of problem-solving. The students could physically move around the model and view it from different perspectives. The details of the 3D object could be seen by zooming in and out using two-finger taps near or farther on the detected plane. A three-finger tap cleared all elements on the screen.

2. **Draw and Annotate:** One could draw in the 3D space by moving the phone around and drawing anywhere on the screen with one finger. A three-finger tap completely cleared the screen, and a two-finger tap was used to place the task-related object on the detected plane.
3. **Tangible Tool:** Two tangible marker cubes were provided, which overlaid different 3D models, based on the task being performed:
    a. Task 1: a scale and a protractor
    b. Task 2: a protractor and a ladder
    c. Task 3: a round table and a cupboard
    d. Task 4: a flagpole (post) and a rope.

4.2.3. Study Design

The study was conducted with 12 students (convenience sampling) from a sub-urban Indian school of 7th grade. There were 5 male and 7 female students of age group 12-14 (M=12.42, SD=0.67), who were divided into 4 groups of 3 students each. The study was conducted a few days after their end-semester examinations, to ensure they all were familiar with the concepts covered in the AR tasks. Each group was assisted by a researcher to guide them about the tasks and observe their actions. The task and its corresponding AR interaction medium for a group were selected using the balanced Latin square design (Fig. 4.3.). Each group was also once the control group, where the task had to be done by seeing a 2D isometric image of the 3D objects, shown to other groups as 3D models in AR.

	Area	**Lines & Angles**	**Symmetry & Congruence**	**Visualising 3D Solids**
Group 1	Draw and Annotate	Tap and View	Tangible Tool	Control
Group 2	Tap and View	Control	Draw and Annotate	Tangible Tool
Group 3	Control	Tangible Tool	Tap and View	Draw and Annotate
Group 4	Tangible Tool	Draw and Annotate	Control	Tap and View

Fig. 4.3. The balanced Latin square design for the task and AR interaction mediums distribution

The interactions were captured using video recording. Fig. 4.4 shows examples of how students used the annotating and marker cube mediums. Observation logs were used to note group behaviour, involvement, and interaction with each other and the AR interface. Further, the students wrote their answers on a sheet, in the forms of writing sentences, sketches, diagrams, etc. At the end of each task, the students were interviewed about their approach to solving the problem. As the focus was to understand their thought process involved while solving the problems with and without AR, the following two open-ended questions were asked to a group:

Q1: What did they think of while solving the problem?

Q2: How did they come up to a solution?

For the analysis of the observations, interaction analysis was performed to examine the interactions of the participants with an AR interaction medium and each other to understand how it led to solving the problem.

Fig. 4.4. Students using the draw-enabled feature and tangible marker cubes

4.2.4. Findings

Using the *Tap and View* interaction medium in AR gave students the freedom to think and use it in a creative manner. The group working on the Lines & Angles task communicated by means of making angles with their hands while moving around the virtual 3D object. They initially categorised the angle between the walls differently but on collaboratively discussing among themselves and viewing the wall from different angles, they deduced that it was indeed the same angle which was obtuse. During this discussion, they communicated by means of making angles with their hands. Another example of the creative freedom students employed was calculating the area in the Area task by using objects which were around them. For example, they hypothesised that the field was 10 lunch boxes large or approximately 15 pencil boxes large. Thus through this process, they were able to visualise, associate, and dissociate the meaning of square units.

While using the *Draw and Annotate* interaction medium in AR, all students were comfortable with the ability to draw in 3D space. The group with the Area task did not draw any tools but instead used this AR interaction medium to communicate ideas among themselves. The groups performing the Symmetry & Congruence and Visualising 3D Solids task efficiently used this functionality as a tool. In Visualising 3D Solids, students drew an accurate representation of a ladder, they drew a rope and while viewing this in AR, they realised that the rope would need an anchor. The group working on the Lines & Angles task drew a triangle on the augmented wall from the top view, they then proceeded to replicate this triangle on paper in order to calculate the angle. Thus, students thought of their own ways of using the ability to draw in AR, many of which were effective and unique.

While using the *Tangible Tool* medium in AR, the marker cubes and the respective objects they represented were used as a stimulus to the solutions that students formulated and three of the groups (performing Lines & Angles, Symmetry & Congruence, and Visualising 3D Solids) went ahead to more intricate solutions, using the cubes as a stepping stone. The use of cubes was less effective in the case of the Visualising 3D Solids task. Students used the rope but did not use the flagpole in any of their solutions. In the tasks of Lines & Angles and Area, students predominantly attempted to calculate the exact values even though they were specifically asked not to in the task orientation. The cube objects represented realistic tools that could be used for measurement and this could be the reason for this. The cubes faced a problem that they had to be within view of the camera in order to be tracked and their respective objects seen. Some students found this hard to manage, usually, one student held the tablet and another student or two held the cubes. One group found a unique solution to this problem, where instead of moving the cubes, they placed both cubes on the floor beside the QR Code/3D task model and then changed their perspectives by moving the tablet around. Hence, they were able to understand the perspective views of the virtual 3D object.

There were certain differences in the approach followed by the students among the *control group* as compared to the other groups. The group performing the Visualising 3D Solids task used sketches to communicate complex ideas among themselves. They drew multiple paths on the hill and then numbered them while discussing the scenarios in which these paths could be used. Another limitation of this medium was apparent when the group performing the Area task had confusion about the shape of the field. To overcome this, they drew a top view of the field from the given isometric view and then used that. Further, they attempted to use a protractor to map the circular areas of the top view they drew but also had problems differentiating between a square unit and a cube unit as the units of area. In the

Symmetry & Congruence task, the group doing it went a step further by noting down the approximate number of items that would be required, for example, 40 mobile phones, 14 newspapers, etc. This was the only group to do so, but at the same time, it restricted them to only household scenarios and did not think further.

For the different tasks and AR interaction mediums used, the following were the observed group behaviour (Fig. 4.5):

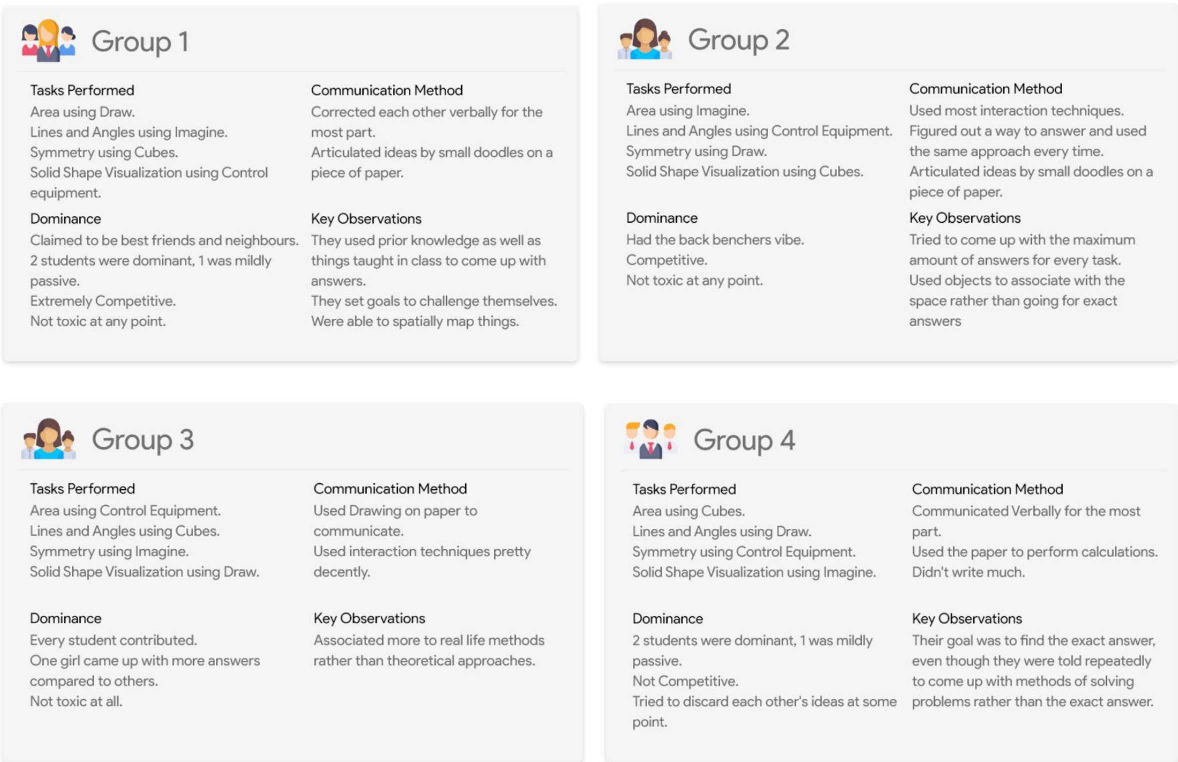


Fig. 4.5. Describing the group behaviour of students during the study

4.2.5. Discussion

The results of RQ1b indicated qualitative differences in the ways in which participants approached various tasks as well as their experiences of using AR interaction mediums. The AR interaction mediums provided to experimental groups helped in visualising the problem and generating a higher number of creative solutions. Group interactions and dynamics were essential in shaping the approaches of students. The discussions were overall positive and helped in the formation of finished solutions. However, in a group of three students, it was commonly found that two students were always dominant in the problem-solving process.

AR interaction mediums provided a stimulus to discussion. All the groups had a positive response to these. The Tangible Tool medium by its design, provided students with a prompt of two tools to stimulate their thinking ability to find solutions. However, it was observed that their thoughts were limited to the two tools. Thus, even though students liked the Tangible Tool's interactive environment, such an AR interaction medium might be more beneficial for solving problems with a defined solution or convergent thinking tasks. Another limitation pertaining to plane detection and occlusion using the Tangible Tool medium requires the improvement of the technical aspect of the application.

One of the groups, while being the control group, was not keen on doing the task on paper but wanted to use one of the AR interaction mediums. It was seen in our study that prior knowledge and experiences played a major role in the generation of ideas by students. Most of the solutions were directly inspired by either school or household scenarios along with media like TV shows and online videos. Thus, we could claim that AR interaction mediums have the potential to provide triggers to visualise and associate with prior knowledge and experiences that are otherwise not possible. Moreover, the design of AR interaction mediums ensures that students use AR not only as a visual tool but also as an immersive and interactive experience to think beyond the screen.

4.2.6. Implications

While proposing the AR technology as a solution for use in the classrooms, it was required to understand the different internal and external interactions that are suitable for the students to learn using an AR application. Keeping the scope of interactions to that of embodied interactions (Radu and Antle, 2017), three different types of interactions were explored: Tap and View, Draw and Annotate, and Tangible Tool along with a controlled scenario of giving only a 2D image to solve the problem. Through observations and analysis, it was found that the students were able to apply the learned concepts while solving problems in the AR world. The AR interaction mediums introduced worked as the triggers for visualisation and association, which guided the *elaboration* of knowledge (Santos et al., 2013). The behaviour of each group was based on their approaches to solving the problems, which was consistent across the tasks and the corresponding mediums. Moreover, the Tap and View, and Draw and Annotate mediums were the ones that the students found the most suitable. The Tangible Tool caused occlusion problems making it difficult for the students to use. Hence, for designing the ARLE for our research, the other two interaction mediums will be incorporated and investigated with other design strategies for interactivity in the classroom.

4.3. STUDY 3: Design Workshop

The initial two studies provided direction for understanding the user expectations for ARLEs and the suitable AR interaction mediums to be deployed. Further, we wanted to test the conjecture obtained in Chapter 2 that the designers of ARLEs focus on contextual 3D content representation and manipulation, exploration and challenges through multi-level problem solving, and immersion through embodied and collaborative interactions to support cognitive, affective, and social learning to learners. To further investigate the design strategies to be involved in creating an ARLE for classrooms, we conducted a design workshop with multiple groups and focused on a qualitative method of evaluation.

The study addressed the following research questions:

RQ 1c: *What are the design strategies adopted by the designers of a classroom-based ARLE to meet the user expectations while using the suitable AR interaction medium?*

4.3.1. Design Task

The goal of the research was to look at the various design strategies used by ARLE designers. To achieve this, the participants were asked to create an ARLE for classroom setting in which students could learn collaboratively by utilizing tablets to complete AR learning activities. The research included a few areas from the Mathematics curriculum for students in grades 6-8. These themes were chosen based on recommendations from Math teachers from previous research. The teachers thought that adopting AR to teach these topics would help students understand and learn more effectively. Furthermore, the chosen topics i.e. Fractions, Mensuration, Probability, and 3D Geometry, are widely covered in the AR in education literature. Each topic was randomly assigned to two groups, as shown in Table 4.3.

Table 4.3. The distribution of topics and groups

Topic	Fractions		Mensuration		Probability		3D Geometry	
Grade	6th		7th		8th		8th	
Group	G1	G8	G2	G4	G3	G5	G6	G7

Each group was given the chapter material of the designated topic. In addition, a list of user expectations obtained in study 1 for an AR experience in the classroom (Sarkar & Pillai, 2019) was presented as a starting point for discussion. Participants could presume that students in the classes have access to tablets. Each group was given the task of developing an AR-based learning activity and documenting the process of developing it for using in the classroom. The participants were required to document any assumptions other than those specified by us. It was not required of the participants to create a functional prototype and could present the conceptualised activities.

4.3.2. Methods and Materials

Participants and Procedure

As the study's goal was to construct ARLE based on the current state of Indian classrooms, participants coming from various parts of India were gathered for an online design session. Eight groups of 32 individuals participated (14 males, 18 females), where each group comprised an AR developer, an interaction designer, an education researcher, and a middle-school Math teacher. Such a group was composed to receive comments on learning issues and practices, learning sciences, and the viability of AR technology integration, design, and implementation. Teachers were found using internet mailing lists and on average had the experience of 18 years of teaching Math to middle-grade students. Through personal connections and snowball sampling, education researchers and interaction designers were recruited. Advertising on public channels was used to recruit AR developers. The latter three categories had on an average 3 years of experience of working with AR.

All participants gave their informed consent before the research and were informed that the session would be recorded while maintaining the anonymity of the data. Their information such as age, gender, job title, years of work experience, and knowledge with AR were captured. The *Zoom* video conferencing was used to connect the participants on the day of the study. Each day, two sessions were planned, each lasting around three hours. This time frame was chosen since a shorter time frame would not result in comprehensive concept development, while a longer time frame might have been too tiring for the participants. Furthermore, we opted not to break the session across multiple days in order to eliminate the possibility of individuals dropping out of the research in between sessions. To make it easier for the participants to engage with one another, an informal ice-breaker session was held at the start of the session. With the design brief, the participants were instructed to think aloud during the session and write down their thoughts and ideas on the *Miro* board so that everyone could observe, discuss, and create according to the specified brief in real time (see Appendix B). In the end, the participants had to present their ideas and briefly discuss their decisions and experiences during the session.

Data Sources

The following sources were used to collect the data for this study:

1. Video recording: In order to record the triggers of the design decisions and the approaches taken towards coming up with the design of an ARLE, the entire session of a group was recorded on *Zoom*.
2. Researcher observations: While the participants brainstormed, the researcher collected regular unstructured observations, highlighting situations that would require more explanation in the follow-up interview.
3. Participant generated artefacts: This included the final *Miro* board obtained after the brainstorming session and its documentation by the participants.
4. Retrospective think aloud: We used a semi-structured interview approach to interview the participants right after they finished the task to understand their design decisions and the strategies adopted.

Analysis

The goal of the project was to learn about the design strategies that go into creating an ARLE for a specific Math topic. *Atlas.ti* software was used to capture and analyze the whole session (Fig. 4.6). Useful codes were formed from the acquired data and affinity diagrams were developed to build themes surrounding the study issue using inductive analysis (Thomas, 2006). The group is the unit of analysis. During the design process, members in a group discussed, brainstormed, and jotted down their ideas; their decisions, approaches, and strategies were studied. To generate the initial possible codes, the researchers used open coding. In the axial coding step, the codes were further categorised through iterative talks to achieve higher-level codes. The coding method was incremental and iterative. It was halted when no new codes were discovered. After 6 of the 8 experiments, we reached saturation, resulting in the next section's findings. The codes that emerged were categorised on the basis of the three dimensions of learning (Illeris, 2003), i.e. content, incentive, and interaction, all of which are examined in further depth in the next section.

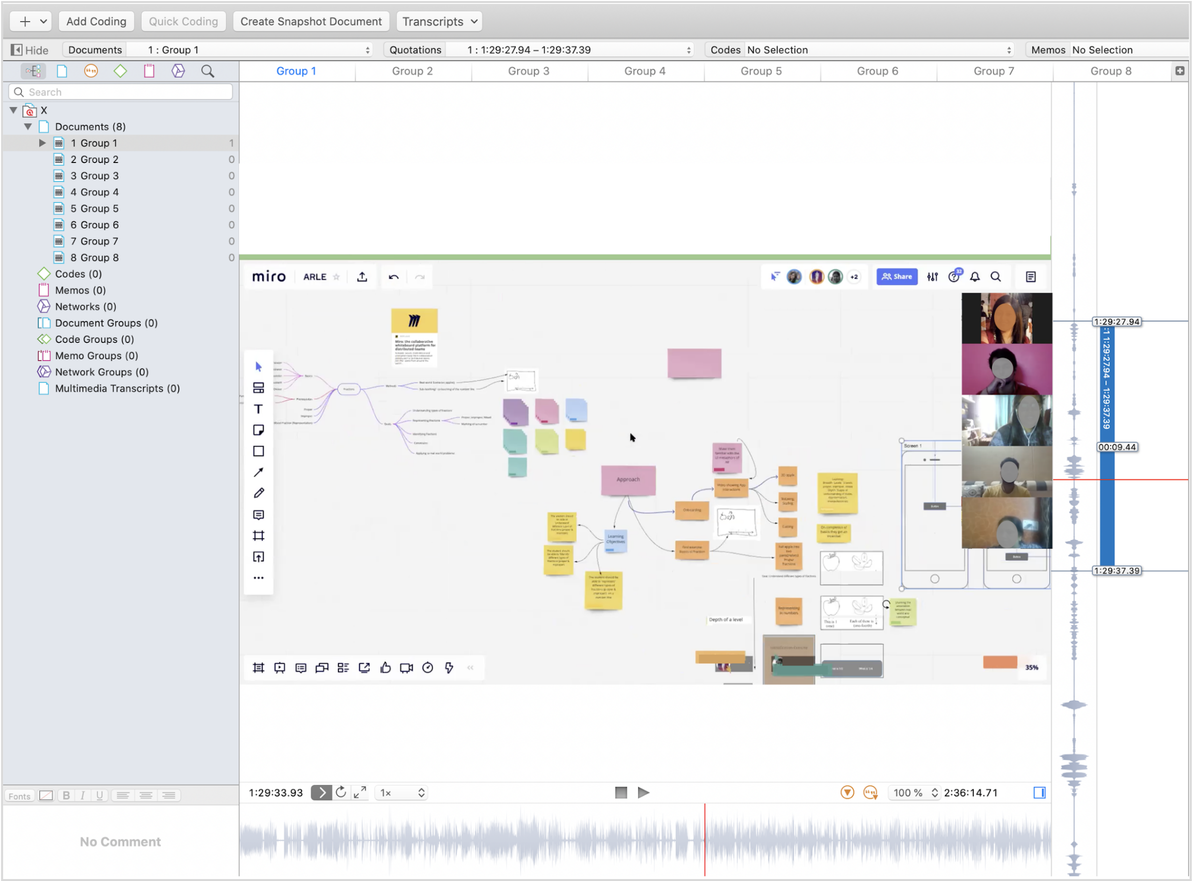


Fig. 4.6. Coding of the events using *Atlas.ti*

4.3.3. Findings

In this section, the key findings based on the observations are provided. For the different user groups, following were commonly observed:

- The Math teachers were offering insights on existing teaching approaches, learning issues, and how students might engage in AR learning activities.
- The education researchers helped to integrate the techno-pedagogical component with content creation while taking into account the students' cognitive levels.
- The interaction designers attempted to integrate the benefits of AR technology with instructional activities.
- The AR developers proposed implementation options for the entire system.

Despite the wide diversity in the approaches among the groups, we discovered that the majority of them shared several general strategies of solution design. These strategies have been categorised as per the three dimensions of learning (Illeris, 2003).

Content: Translating the Textbook Content to AR Activities

To bring the AR component to the textbook content, its appropriate analysis was done by:

1. Scrutinizing the chapter content
2. Identifying the topics that required visualisation of the abstract concepts
3. Identifying the learning objectives
4. Identifying the learning difficulties of the students

To resolve the learning difficulties pertaining to visualisation of abstract concepts, the relevant examples including real-life scenarios were shortlisted by the groups. As shown in Fig. 4.7, to convert to AR instances, three approaches were considered by the groups where the textbook examples were categorised as per:

1. The list of user expectations of AR experience (Sarkar & Pillai, 2019), explained in section 4.1.3, that was provided in the beginning of the task.
2. The dimensions of cognitive levels proposed in Bloom's taxonomy (Anderson & Krathwohl, 2001), where the functionalities of AR were created based on the complexity of the examples.
3. The types of contents, i.e. factual, conceptual, and procedural (Anderson & Krathwohl, 2001).

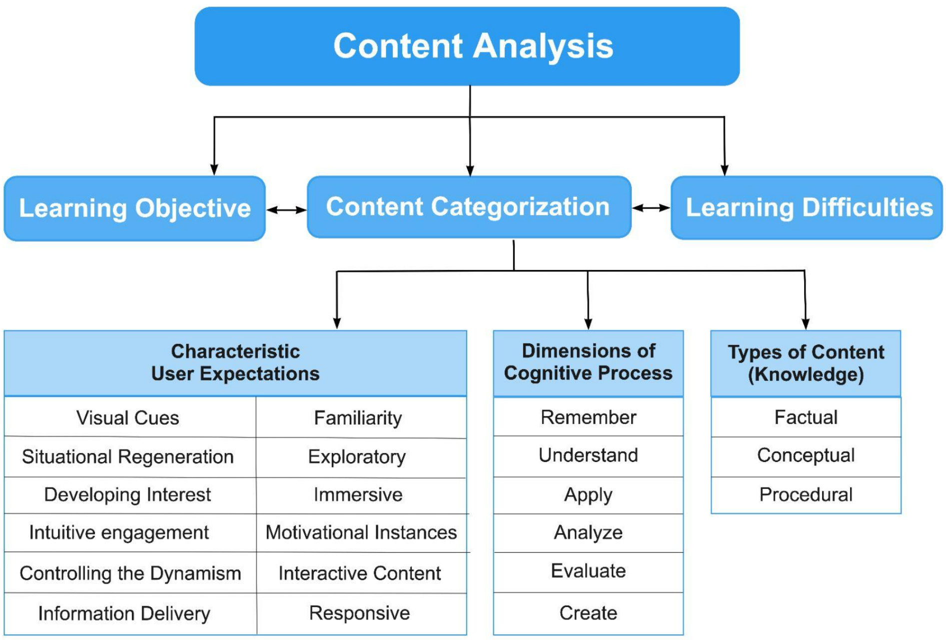


Fig. 4.7. Strategies to analyze the textbook content appropriate for AR translation

Following the identification of probable relevant examples, the arguments dominated by the AR developers were centered on combining AR's affordances with an appropriate tracking medium to achieve the defined learning objective(s). Three types of AR tracking mediums were considered by the groups:

1. **Marker-based** - considered by four groups, it involves scanning a marker i.e. an image or a physical object using the device's camera which triggers the overlaying of virtual graphics (Edwards-Stewart, 2016)
2. **Markerless** - considered by three groups, it gets triggered by scanning the surrounding environment, without using any fiducial marker (Brito & Stoyanova, 2018)
3. **Location-based** - considered by one group, it uses the device's GPS which allows placing the virtual objects in a certain location (Edwards-Stewart, 2016). As an example, the group stated: *"We can scatter the shapes as geo markers and then the students will find the shapes like a treasure hunt activity. They find people having the 3D shape of the 2D shape that's assigned to them"*.

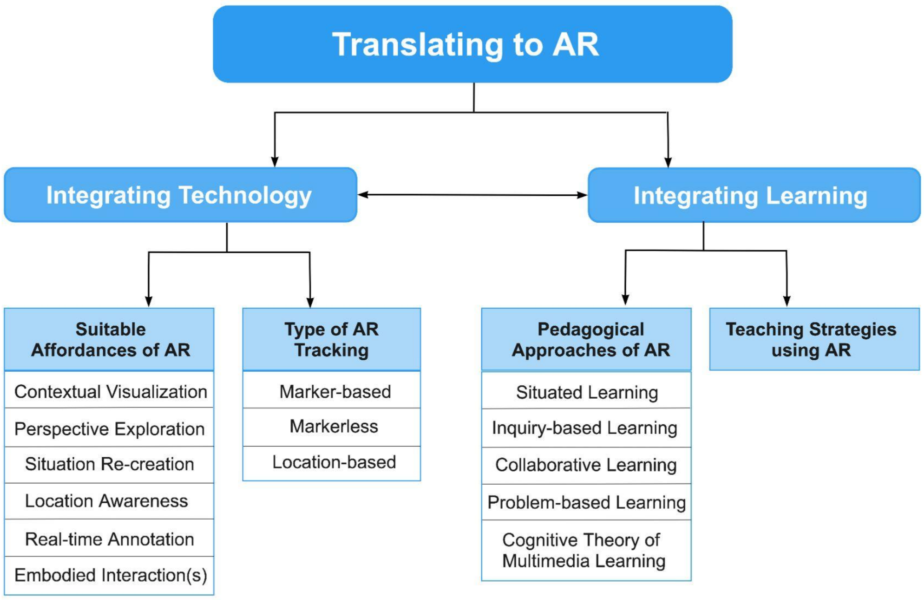


Fig. 4.8. Strategies to translate the textbook content to AR learning activities

The following affordances of AR were considered by the groups:

- **Contextual visualisation:** The discussions were around the realization of setting up the virtual content in a specific context such as a birthday celebration, where the interaction of swiping a knife for cutting of an augmented round cake in the presence of peers in the real classroom represents the concept of Fractions (Group 8).
- **Perspective Exploration:** To encourage the visualisation of a 3D object from multiple perspectives which is otherwise a challenge to explain in the class, the activities for the topics of 3D Geometry and Mensuration were created with the focus of exploring the varied 3D shapes from different perspectives.
- **Situation Re-creation:** The ideations of both the groups working on the topic of Probability were supported with the re-creation and augmentation of real-life scenarios. For example, the probability of playing cards or the falling of a mango off a tree on throwing stones were insisted to be created in AR which are otherwise not demonstrated in the classrooms to help students relate to and realise the real-life application of the concept.
- **Location-Awareness:** In the classroom, to achieve a learning objective, two groups suggested a playful and engaging learning experience like that of the popular *'Pokemon Go'* game, by finding scattered fractions in different locations of the classroom to complete a shape.
- **Real-time Annotation:** The ability to do real-time annotation on a virtual object in AR was proposed to explain the related concepts of Mensuration and 3D Geometry. The remaining topics of Fractions and Probability highlighted the system-generated annotations such as indications to move in a direction, swiping, slicing an object.
- **Embodied Interaction(s):** To provide authentic learning experience and the ability to move around and observe, three groups insisted on the affordance of full-body movement along with 3D object manipulation tasks like swiping, slicing, rotation, etc.

Further, the depth and breadth of learning were examined while merging the affordances of AR with the learning aspects. The depth was determined by how deep the concept needs to be taught using AR as per Bloom's taxonomy levels (Anderson & Krathwohl, 2001). The breadth was decided by the number of tasks assigned to each level, defined by the increasing difficulty.

While considering the pedagogical approach for AR learning, collaborative learning process was considered by all the groups. Moreover, the groups ideating on the topics of 3D Geometry and Probability considered the teaching strategy of *Predict, Observe and Explain* (POE) (Kearney, 2004), where the students are expected to predict the answer for a question, followed by performing a defined action on the virtual 3D object to verify the predicted answer. To elaborate the targeted concept, discussion takes place with the peers and the teachers. The remaining groups proposed *gamification* to keep the students motivated.

Incentive: Incorporating AR Activities in the Classroom

As shown in Fig. 4.9, to motivate the students to collaboratively perform the AR learning activities, the following design decisions regarding the design of the AR application and its learning activity for the given topic were considered:

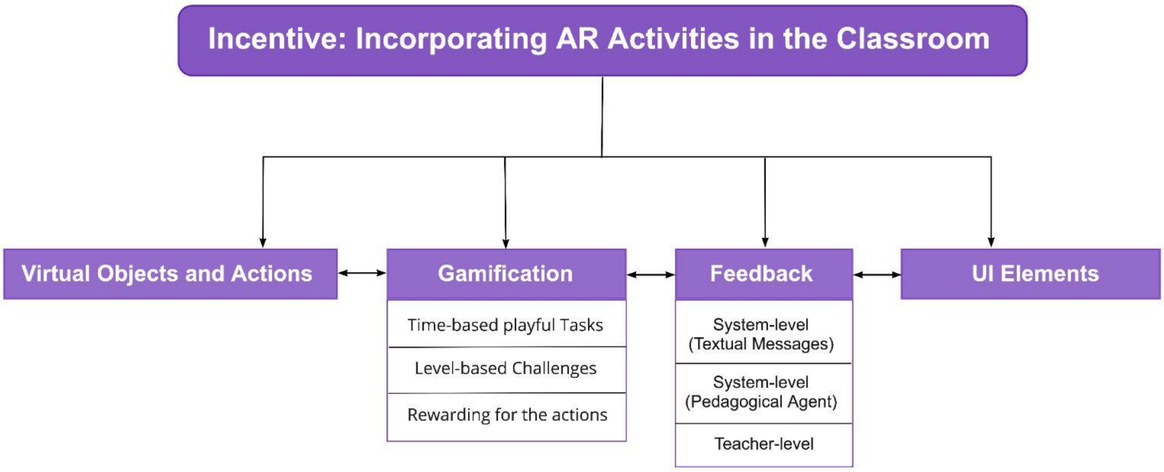


Fig. 4.9. Strategies to integrate AR-based learning in the classroom

While the groups ideated on the design of an AR learning activity, they defined specific virtual objects to be augmented and a corresponding learning process as a result of a defined action. This would help the students to understand the relevance and immerse themselves in the context being taught using AR. For example, to showcase the instance of representing fractions on a number line, Group 1 mentioned:

"...on the screen they can have the same part going on the number line, say from 0 to 1 as a slider. If there is one 3D apple, and they have a 3D knife to control it the way they would do in real-life, they cut the apple into four parts. And then they see the number line divided into 4 parts. That could create a dynamic arranging of the number line representation as they move the slider with actions on the real-life examples..."

Six groups suggested a gamification approach to keep the students motivated while learning in a competitive, interactive and fun manner. Three ways of gamification emerged in the discussions:

1. **Time-based Tasks** - Each AR learning activity needs to be completed in a stipulated time indicated with a timer.
2. **Level-based Challenges** - For the multi-level problems, the difficulty levels increase with each progressing level to enable reaching the levels of Bloom's taxonomy.
3. **Rewarding for the Actions** - For each level or time-based task, rewards in the form of points or badges may be given to raise the spirits of learning in the students.

For the actions being performed on the virtual 3D object to solve the tasks, the feedback on the same were suggested to be provided in two ways:

1. **System-level**: Any mistakes committed and the required corrections can be indicated using system-level feedback provided using textual messages, color-highlights or a virtual pedagogical agent in the AR environment.
2. **Instructor-level**: To provide a detailed explanation and reasons for the required corrections the instructors can provide feedback on the open-ended problems or for clarification of doubts.

The participating groups further discussed the UI elements required to represent the content in AR on the tablet/mobile screen. This was done by detailing the 3D virtual objects/graphics, the needful action, the task levels, and the feedback mechanism. For example, as shown in Fig. 4.10, Group 5 depicted the way to introduce the topic of Probability with the help of a virtual pedagogical agent, i.e. a 3D character of Genie.

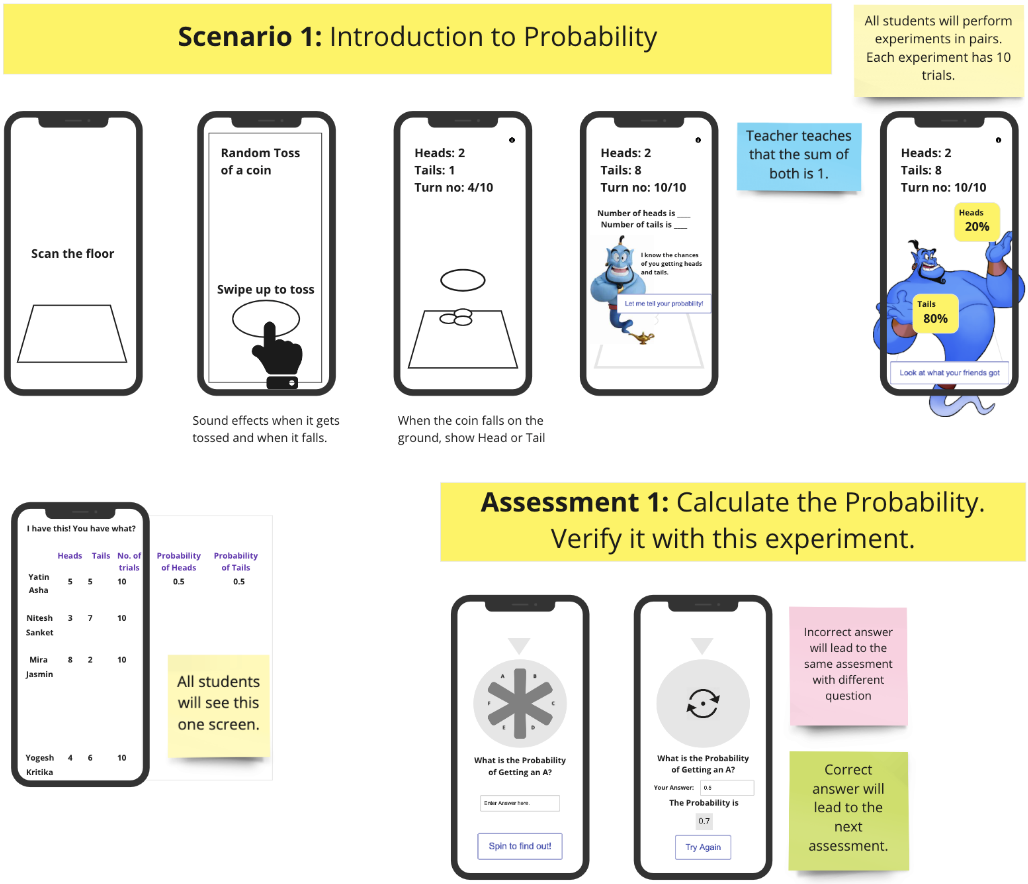


Fig. 4.10. Group 5 working on the topic of Probability designed the UI of the screen

Interaction: Content, Learner and Instructor Interactivity

In the design process of creating a classroom-based ARLE, an appropriate learning delivery mode was considered. The process involved the consideration of learner-learner, instructor-learner and content-learner interactions as shown in Fig. 4.11 and elaborated below.

Learner-Learner Interaction

Considering the pedagogical approach of collaborative learning, the groups elaborated the ways to use a tablet-based AR application in the classroom for a particular group composition of the students to bring in learner-learner interaction. In the discussion, two types of group composition emerged:

1. **Group of 4 students** - Two groups considered the formation of a group of 4 students handling one tablet per group where for multiple tasks and in turns, one student holds the device and each task is performed by one student in discussion with the remaining group members.

2. **Group of 2 students** - Remaining six groups suggested the composition of dyads where the roles of the individuals were decided. For example, group 7 suggested "*...one student cuts the shape in AR and the other one merges it back*".

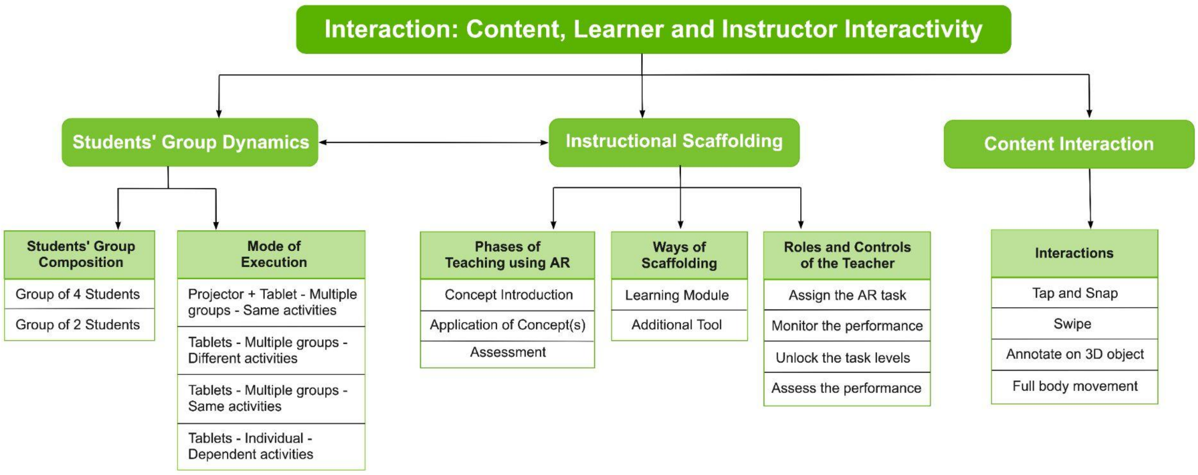


Fig. 4.11. Strategies to incorporate learner-content, learner-learner, and learner-instructor interactivity

Further, four ways of using the tablet-based AR in the classroom emerged on the basis of the types of AR learning activities.

1. **Projector screen along with the tablets; same activities** - Two groups suggested this setting where students would work in groups, each with one tablet. During and/or after an AR learning activity, the projector screen would be utilised to share the displays of all the tablets in use. Students will be able to concurrently reflect on their peers' work and approaches in this manner.
2. **Multiple groups of students; different activities** - To enable focused interaction with the group members, the different formed groups can compete to accomplish the different assigned AR learning activities of similar difficulty level.
3. **Multiple groups of students; same activities** - In this commonly proposed way, each group collaboratively uses a single tablet to perform the same AR learning activities and the instructor would be the facilitator.
4. **Individual; dependent activities** - Assuming the number of tablets to be equal to the number of students in a classroom, Group 3 suggested providing a tablet to each student where they collaborate to perform an AR learning activity in groups. The action of one student gets reflected on the next student's action in that group. For

example, through the game of snakes and ladder, Group 3 demonstrated how to reinforce probability and chance, as shown in Fig. 4.12. The students assess the chance of getting bitten by a snake or ascending the ladder while playing snakes and ladder by physically moving and climbing up and down depending on the arrangement of the virtual boxes, ladders, and snakes on their augmented displays.

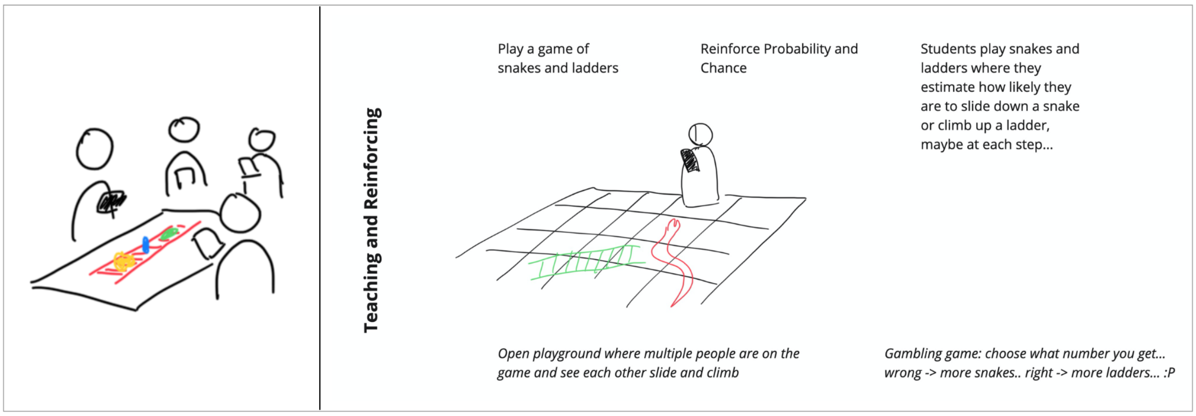


Fig. 4.12. Group 3 suggesting the way to perform their designed AR activity

Learner-Instructor Interaction

To further elaborate the learner-instructor interactions, the phases of scaffold to align the AR activity sessions with the curriculum design and the role of the instructor were defined.

The following phases of scaffolds were defined:

1. **Concept Introduction** - Suggested by three groups, AR learning activities will be used to introduce a topic using examples which are otherwise difficult to demonstrate in the classroom. As an example, Group 5 ideating on Probability proposed:

> *"When the teacher starts with this experiment, everyone has to swipe to toss the 3D coin 10 times... the first pair of students share that they have got 5 tails, 3 heads and so on… the 3D virtual Genie has magically given us this probability! While doing this they might have deducted the formula already or after this. The teacher then uses the data of those 20 groups of students and she puts it all together. This would help the students see that the probability tends to an ideal value when they talk of a large number of trials. And here the teacher tells them that because you are not going to*

toss so many times whenever you are doing anything, that is why we move from experimental probability to classical probability and we talk about the formulae".

2. **Application of Concept(s)** - The commonly proposed method involved explaining the application of the taught concept with the help of contextual tasks such as merging and cutting shapes from other shapes while teaching 3D Geometry.
3. **Assessment** - Two groups suggested the assessment of students' learning through quizzes on performing the multi-level AR learning activities. The Bloom's taxonomy levels (Anderson & Krathwohl, 2001) were used to determine the level and difficulty of the quiz questions in AR.

The participants were seen debating on two approaches to provide scaffolding at various stages of teaching:

1. Display the AR learning activities as a **learning module** that could be used for both teaching and visualisation.
2. **Additional instructional tool** on completion of a topic.

While the students performed the AR learning activities, the following instructor side AR application controls for the instructors working as the facilitators were suggested:

- **Assign:** The instructor decides the type of AR learning activity to be performed on a particular day in the classroom.
- **Monitor:** The instructor monitors the actions of the different groups of students while they perform the AR learning activities. Students may be helped or guided on getting stuck somewhere.
- **Unlock***:* If the AR learning activities have levels of tasks, the teacher can set the control of unlocking the next level for the students whenever found appropriate.
- **Assess***:* The teachers can have a dashboard to receive the statistics based on the performance of the students in the group. The results obtained can be used as a formative evaluation of the students' performance during an AR session.

Learner-Content Interaction

Considering the time duration of an activity and the intuitive nature of the interaction, four ways of interacting with the content were commonly discussed:

1. **Tap and Snap**: Group 6 working on 3D Geometry suggested: *"Say there is a knife or a cutting plane in the app itself. When we tap that, it should align at any angle. The cutting action will show the segmented part of the cube or a complex shape"* (G6).
2. **Swipe**: This interaction was suggested to initiate the animation of the augmented 3D object
3. **Annotate on 3D object**: The students would be able to mark or draw with the index finger on the screen of the tablet to annotate on the augmented virtual 3D object.
4. **Full body movement**: The ability to see the 3D object from all the sides by either rotating the marker or physically moving with the handheld device in case of markerless or location-based design solution.

To summarise, Table 4.4 shows the design strategies and their triggers considered to meet the potential user expectations identified in section 4.1.3, classified under the three dimensions of learning by Illeris (2003).

Table 4.4. summarised design strategies and their triggers corresponding to the expected AR Experience in schools based on the themes generated under the three dimensions of learning.

User Expectations	Design Strategies	Triggers to Design Strategies
Dimension of Learning: Content (Functionality)		
- Visual Cues - Familiarity - Situational Re-generation - Exploratory	Content categorization	1. Types of user expectations 2. Dimensions of cognitive process 3. Types of knowledge
	Suitable affordance of AR	1. Contextual visualisation 2. Perspective Exploration 3. Situation Re-creation 4. Location Awareness 5. Real-time Annotation 6. Embodied Interactions
	Type of AR tracking	1. Marker based 2. Markerless 3. Location Based

	Pedagogical approaches of AR	1. Situated Learning 2. Inquiry-based Learning 3. Collaborative Learning 4. Problem-based Learning 5. Cognitive Theory of Multimedia Learning
	Teaching Strategies using AR	1. Bloom's taxonomy 2. Predict, Observe, Explain 3. Peer Instruction 4. Gamified questions
Dimension of Learning: Incentive (Sensitivity)		
- Immersive - Developing Interest - Intuitive Engagement - Motivational Instances	Virtual objects and actions	Define specific virtual objects to be augmented and a corresponding learning process as a result of a defined action
	Gamification	1. Time-based playful tasks 2. Level-based challenges 3. Rewarding for the actions
	Feedback	1. System-level (textual message) 2. System-level (pedagogical agent) 3. Instructor-level
	UI Elements	Detailing virtual 3D objects, the needful actions or responses, feedback mechanism
Dimension of Learning: Interaction (Integration)		
- Controlling the dynamism - Interactive content - Information delivery - Responsive	Students' Group Composition	1. Group of 4 students 2. Group of 2 students
	Mode of Execution	1. Projector screen along with the tablets; same activities 2. Multiple groups of students; different activities 3. Multiple groups of students; same activities 4. Individual; dependent activities
	Phases of teaching using AR	1. Concept Introduction 2. Application of Concept(s) 3. Assessment

	Ways of Scaffolding	1. Learning Module 2. Additional Tool
	Roles and Controls of the Instructor	1. Assign the AR task 2. Monitor the performance 3. Unlock the task levels 4. Assess the performance
	Interactions	1. Tap and Snap 2. Swipe 3. Annotate on 3D Object 4. Full body movement

4.3.4. Discussion

In this section we discuss what our findings suggest using the lenses of the dimensions of learning suggested by Illeris (2003) for the novice designers to move toward the iterative design strategies for creating an ARLE for classrooms.

Towards Augmented Content for Cognitive Learning

Contextual Content Representation

According to our findings, scanning and categorization of material are essential for content translation. This is then linked to the intended learning goals, as well as a reflection on the learning challenges that students confront in the classroom. The context of the ARLEs must be provided by placing cases from real-life settings to aid in Visualising abstract concepts, as shown in prior studies (Cuendet, 2013; Santos et al., 2013; Miller & Dousay, 2015). As a result, design decisions for the alternate representation in AR are dependent on (1) user expectations (Sarkar & Pillai, 2019), (2) designers' past experience with AR apps, and/or (3) the affordances of AR. To avoid overpowering representations for the students, the design solutions also emphasised that the AR representation should be kept basic and minimal (Cuendet, 2013).

Enabling Exploration

To enable exploration while bringing in the contextual dimension of learning (Bujak et al., 2013), the real-life examples from the textbook and the ones referred by the teacher in the classroom are enumerated for the categorised content. This approach is in contrast to the reported approaches where the students' ways of problem-solving in the physical classroom are initially analyzed to come up with the design of ARLEs (Radu et al., 2015; Villanueva, 2020). However, such ARLEs are targeted towards a particular skill to develop. In both the approaches, on outlining the key contents, the translation to AR to enable exploration involves the ideation of the AR environment. This seems to be influenced by the choices of creating (1) a simulation, (2) a contextual representation, (3) a gamified world (Santos et al., 2013; Miller & Dousay, 2015), (4) a storytelling method, or (5) a mixed combination of these choices.

Content Manipulation

To make it an engaging user-centered experience (Normand et al., 2012) for the students, it was prominent from the analysis of the discussions that the intention was to provide them active control for the designed activities. While active control of students was encouraged by the participating groups, studies have suggested appropriate approval of students' actions from the teachers for a guided execution in the classroom (Drljević, 2017; Cuendet, 2013; Villanueva, 2020). The type of AR tracking, interaction, and complexity of the AR learning activity gets decided accordingly.

Towards Incentivizing AR Learning Activities for Affective Learning

Ensuring Immersion

The immersiveness of the application can be enabled by letting the students rotate the augmented 3D objects, physically moving around them, and/or locating them in the classroom space. This counts for appropriate virtual objects and the actions to be performed on them using the defined interactions. In earlier studies, game-based AR learning has been suggested to promote fun, challenge, and curiosity (Miller & Dousay, 2015) among the students. The participating groups had similar objectives while deciding the gamification aspect of the AR learning activities. Moreover, badges and rewards can create a sense of competitiveness and motivation while exploring the different levels within the activities (Deng et al., 2019).

Real-time Feedback

While the students interact and learn with the AR content, informative feedback is required to make the status of the system obvious (Dünser et al., 2007) and provide a response to validate their actions. It was suggested that the feedback can be provided by the virtual pedagogical agents (for instance, mimicking a popular cartoon character) in the AR space (Chen & Tsai, 2012). However, if the students have doubts or get stuck, the teachers are expected to be the facilitator in the process as suggested previously (Fan et al., 2020). Thus, it is required to determine the amount of scaffolding required from the system and teacher side.

Multi-level Challenging Problems

As reflected from the findings, learning using AR can be imparted in three possible stages: (1) to introduce the topic, (2) to reinforce the taught concepts, and/or (3) to assess the learning. Further, from our observation and as suggested by Wu et al. (2013), the tasks can be designed to promote game-based learning, problem-based learning, or learning by design. This can lead to curiosity among the students while they perform the AR learning activities (Miller & Dousay, 2015). The discussions also implied that the tasks can be strategised to incorporate multiple levels to guide the students in attaining the different stages of learning as per Bloom's taxonomy (Anderson & Krathwohl, 2001). Though the findings did not target any skills such as spatial thinking or critical thinking, we realise that learning may also be targeted at skill acquisition as suggested in prior works (Wu et al., 2013; Kaur et al., 2018, Villanueva, 2020). This aspect was not considered by the participating groups in our study for keeping it restricted to the textbook-based examples and activities.

Towards Interactions and Interactivity in AR for Social Learning

Promoting Collaboration

Collaboration of students play an important role in providing active control to the students (Santos et al., 2013). The students can see the augmented virtual objects and information along with their peers in the same space. As suggested by (Sarkar et al. 2019), this can promote peer learning while being involved in the exploratory processes and embodied learning (Radu & Antle, 2017). It also helps students in building community through collaboration and competition (Dunleavy et al., 2009). The group distribution and composition must be taken into consideration while defining the functions of the AR learning activities.

Embodied Interactions

The interactions in the AR learning activity must be intuitive for the students (Bujak et al., 2013). The cross-hair mode of interaction is a mode that has been previously studied with younger students (Radu et al., 2016). However, the study reported finger interactions to be more intuitive for the children. Thus, the tap, swipe, and annotate modes of interaction with the augmented 3D objects obtained in study 2 can be easier for the students to respond to within the restrictive duration of the activities in the classroom.

Instructional Scaffolding

Our findings on instructional scaffolding aligned with the principles of reducing orchestration load for teachers mentioned by Cuendet et al., 2003. The insights indicate that while aligning to the regular teaching practice, the teachers play a key role in the entire experience. To provide authority to the teachers while still keeping a student-centric experience and encouraging two-way communication, the teachers can (1) assign the AR tasks, (2) monitor the students' action live, (3) unlock the levels, and/or (4) assess the performance of the students. Thus, the teachers can be given the controls to initiate the process and monitor the actions and performance of the students on their own tablets. Moreover, to use the ARLE effectively in the classroom lesson plans in AR can be provided.

4.3.5. Implications

We began this study with a conjecture regarding the design strategies of the designers of ARLEs, that their focus would be on contextual 3D content representation and manipulation, exploration and challenges through multi-level problem solving, and immersion through embodied and collaborative interactions to support cognitive, affective, and social learning of learners. Our findings validate and elaborate on this conjecture. Our study was aimed at observing and reporting the design strategies and decisions adopted by the designers involved in creating an ARLE for classrooms. The findings indicated the categories and inter-dependencies in the three aspects of content, incentive, and interaction of an ARLE. In addition to the strategies identified in the conjecture, instructional scaffolding for the AR learning activtites was another key strategy that was highlighted by the designers during the workshop. Our empirical findings guided us towards defining the design strategies for the novice designers that can be considered to design a handheld ARLE for classrooms, ranging from content analysis to basic prototype design to incorporate the design strategies enabling cognitive, affective, and social learning.

4.4. Summary

This chapter describes the first phase of DBR, i.e. problem analysis and exploration. In the problem space of this research, through primary research of field visits, it was identified that even when there is the existence of technology in the classrooms, its use is majorly instructor-mediated. Though there is the claim to provide interactive visualisations of the abstract concepts, the engagement of the students in this learning process is not assured. This indicated the need for a student-centered digital learning environment where the students can get to interact themselves with it and active learning can be incorporated within the digital learning space.

In the solution space of this research, we propose the use of AR in the classroom. Using handheld devices, the students can visualise and interact with the 3D virtual objects through active participation. As AR technology is still emerging as a solution in the Indian classroom context, it was needed for us to understand the expectations of the key stakeholders i.e. teachers, students, and parents. Through thematic analysis of the interview responses, twelve key themes were derived which were classified under the three dimensions of learning: content, incentive, and interaction (Illeris, 2003). The combination of these characteristic expectations can be incorporated into the design of our ARLE.

Beyond the expectations, it was required to understand the suitable interaction mediums to bring in interactivity while learning using AR in the classroom. Therefore, three interaction mediums related to embodied interactions (Santos et al., 2013) were tested and explored with the students. *Tap and View* and *Draw and Annotate* were the suitable interaction mediums for the students to interact with. Thus, in the further phases of this research, these two interaction mediums will be incorporated into the design of our ARLE.

The potential designers of ARLEs (interaction designers, education researchers, and AR developers in this case) along with the teachers play a key role in ideating, prototyping, and evaluating the design of the ARLEs for classrooms. This chapter highlights their design decisions, strategies, and methods adopted while conceptualizing the designs of interactive ARLEs for classrooms. The study indicated major steps of approaches to create an ARLE for a given Math topic. These findings along with the previous studies and literature review, guided us towards the design strategies that can be taken to create an ARLE for the classroom. Incorporating these suggestive design strategies led to the design of our ARLE named *ScholAR,* which has been described in the next chapter.

Chapter 5

DBR 1 Design and Evaluation: Understanding the Effective ARLE Design Strategies

Augmented Reality (AR) is an emerging technology that is gaining popularity in education as it gives students an immersive and interactive experience while engaging them in rich contextual learning (Billinghurst & Duenser, 2012). There has been research that shows students' positive motivation, knowledge construction, and behaviour patterns when collaboratively interacting with AR learning environments (Lin et al., 2013; Estapa & Nadolny, 2015; Sarkar et al., 2020).

In the field of mathematics, AR is seen to be advantageous since it allows users to interact and visualise augmented 3D objects in real-world settings (Estapa & Nadolny, 2015). As a result, AR aids learners in understanding abstract topics that would otherwise be difficult to grasp (Radu, 2014). Though AR is most commonly associated with learning concepts using 3D objects, research has shown that it may also be used to help students grasp abstract concepts utilising figurative languages (Bujak et al., 2013). Teaching the concepts of Fractions using augmented interactive number lines (Palaigeorgiou et al., 2018; Kazanidis et al., 2018) and "sorting unit fractions, mixed fractions, equivalent fractions with the area model, and matching equivalent fractions" (Özdemir & Özçakir, 2019) have both used AR to visualise abstract concepts. Similarly, the topic of Probability has been taught through AR and has been shown to improve students' conceptual comprehension (Li et al., 2016), learning gains, attitude (Cai et al., 2020), and self-efficacy (Cai et al., 2019). With the ability to visualise 3D objects in AR, several studies in teaching 3D geometry to school students have been conducted. Students investigated related formulae in an interactive GeoAR book for subjects like volume and area (Kirner et al., 2012), and used nets and unit cubes to compute and compare the volume and surface area of an object in AR Geometry Tutorial Systems (ARGTS) (İbili et al., 2020). Teaching geometry to middle-school students via AR has been shown to improve students' 3D thinking capacity (İbili et al., 2020), spatial ability (Lin et al., 2015), visualisation abilities (Sarkar et al., 2018), mental-rotation ability (Kaur et al., 2018), learning performance, and attitude (Liu et al., 2012).

We thus propose that Augmented Reality (AR) is one such technology that can provide an interactive learning experience with the student-centered learning approach. In this research, an AR-based application named ***'ScholAR'*** has been developed and provided to the students, which involves several tasks for different topics of Mathematics of a particular grade. In this chapter, we describe the design and evaluation of two modules of *ScholAR* based on the Geometry chapters of NCERT Mathematics textbook of 7th grade : (1) Lines and Angles, and (2) Visualising Solid Shapes.

The broad research question to be addressed was:
Broad RQ2: *How do the potential design strategies of creating an ARLE incorporate the dimensions of learning?*

5.1. Integrating Literature and Data to Design an ARLE

The results of studies 1, 2, 3 and literature review gave the following requirements for designing an ARLE:

1. Trigger information visualisation
2. Support exploration through multi-perspective views
3. Support application of conceptual knowledge
4. Support incorporation of multi-level problems
5. Provide control of the environment
6. Trigger metacognitive process of evaluation

7. Trigger immersiveness through embodiment
8. Trigger interactions of Tap and View and/or Draw and Annotate
9. Support aspects of problem-solving that require collaboration

In this section, the pedagogical features are described based on the identified design strategies in section 4.3 and the literature review in section 2.4. Together the pedagogical features provided the first version of the *ScholAR* application. Broadly, the design strategies identified were converted to pedagogical features in *ScholAR* to meet the above-stated requirements in the following manner:

1. Contextual Content Representation: Relevant mapping of the content examples from the textbook. It involved the topics that required visualisation of the abstract concepts (Requirement 3). For Lines and Angles, the concept of types of angles, pairs of angles, and interior-exterior angles of a triangle were identified. For Visualising Solid Shapes the concept of types of 3D shapes, and vertices, edges and faces of 3D solids were identified in the first iteration of DBR.
2. Enabling Exploration: Each activity has a contextualised question that enables the students to explore the augmented 3D object from multiple perspectives while viewing the annotated information to understand its properties and related concepts (Requirement 1, 2).
3. Content Manipulation: The students interact with the virtual 3D object by annotating on it in the activities of Lines and Angles. Additionally, the students form a complex 3D shape with drag and snap features in the activity of Visualising Solid Shapes (Requirement 5).
4. Ensuring Immersion: The designed AR application provides the ability to move around a virtual 3D object augmented on the real-life environment of the classroom (Requirement 6). Embodiment in the form of full-body movement leads to the interaction with the 3D object in a way it would be done by a similar real-life object.
5. Real-time Feedback: The teachers are encouraged to guide the students wherever applicable. Moreover, the system provides feedback by highlighting the correct or incorrect answer in green or red respectively (Requirement 6).
6. Multi-level Challenging Problems: Multiple contextualised problems have been presented, the difficulty levels of which increased as per the first three levels of Bloom's taxonomy (Anderson & Krathwohl, 2001), i.e. remember, understand, and

apply (Requirement 4). The final problems involve Reflective Questions, with and without AR to see the impact of AR on learning.

7. Promoting Collaboration: The students are encouraged to perform the activities in collaboration where two or more students discuss and solve the activities together (Requirement 6, 9).
8. Embodied Interactions: The interactions of Draw and Annotate, and Tap and View identified in section 4.1 have been incorporated in Lines and Angles, and Visualising Solid Shapes respectively (Requirement 7, 8).
9. Instructional Scaffolding: The instructor has the ability to assign the AR task to the groups, monitor the student's performance, and assess the performance of the student groups. Additionally, the instructors can explain, guide or clear the doubts wherever applicable (Requirement 3). The instructor scaffolding tends to fade with the increasing level of the activities.

5.2. Conjecture Mapping

In DBR, conjecture mapping (Sandoval, 2014) is the technique of identifying the salient features of a learning environment design and mapping out how they are expected to interact in order to produce the desired forms of learning. It is a way of describing the predicted learning pathways of a student working in a designed learning environment. Thus, conjecture mapping explicates the implicit conjectures in a learning environment design about how learning is expected to happen. A conjecture map has

- a *high level conjecture* about how to support learning in some context which leads to
- the *embodiment* of the specific design, namely the tools & materials, the task structures, the participant structures, and the discursive practices which are expected to generate
- the *mediating processes*, including the observable interactions and participant artifacts, that produce
- the desired *outcomes*

The researchers' ideas about how the elements of the embodiment together generate the mediating processes are called *design conjectures*, while the ideas of how the mediating processes together produce the desired outcomes are called *theoretical conjectures*. The conjecture map relevant to our context is shown below in Fig. 5.1.

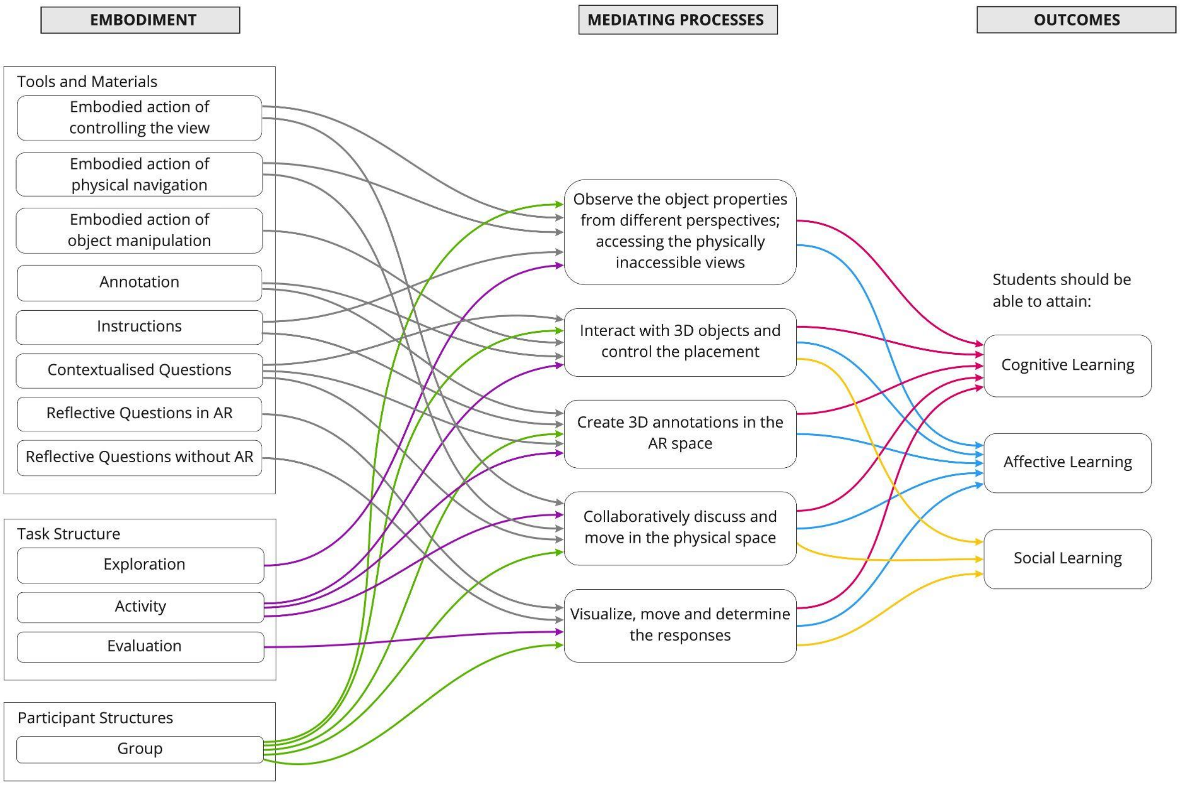


Fig. 5.1 Conjecture map of *ScholAR*

The design conjectures of *ScholAR* are as follows:

1. If the students in groups use the embodied actions of controlling the view, physical navigation, 3D animation, and the instructions to explore, they will be able to observe the object properties from different perspectives which will enable accessing the physically inaccessible views.

2. If the students in groups use the embodied actions of object manipulation, annotation, and contextualised questions to perform the activity, they will be able to interact with 3D objects through active control.

3. If the students in groups use the annotation, the instructions, and contextualised questions to perform the activity, they will be able to create 3D annotations in the AR space.

4. If the students in groups use the embodied actions of controlling the view, object manipulation, physical navigation, and contextualised questions to perform the activity, they will be able to collaboratively discuss and move in the physical space.

5. If the students in groups use the reflective questions in AR and without AR to do the evaluation, they will be able to visualise and determine the responses.

Based on the literature review, a conjecture was proposed related to the design of a classroom-based ARLE (Conjecture 2 in section 2.5.2). Based on our initial studies and the resulting design of *ScholAR*, we propose theoretical conjectures that guide the design of *ScholAR* and how it supports cognitive, affective, and social learning, which have been evaluated in studies 4 and 5.

Conjecture 1:
If the students are able to observe the object properties from different perspectives, interact with 3D objects through active control, create 3D annotations in the AR space, collaboratively discuss and move in the physical space, visualise and determine the responses, then the students will be able to attain cognitive learning.

Conjecture 2:
If the students are able to observe the object properties from different perspectives, interact with 3D objects through active control, create 3D annotations in the AR space, collaboratively discuss and move in the physical space, then the students will be able to attain affective learning.

Conjecture 3:
If the students are able to interact with 3D objects through active control, collaboratively discuss and move in the physical space, and visualise and determine the responses, then the students will be able to attain social learning.

5.3. Design of *ScholAR*: Lines and Angles module

We created an AR simulation of *ScholAR* to incorporate the AR interaction medium of Draw and Annotate. In the process, we explore its implementation in 2D Geometry where the students can realise the application of the related concepts in real-life instances.

5.3.1. Theoretical Foundations of the Intervention

At the middle school level, 2D Geometry topics such as Lines and Angles are presented in a formal environment (6th to 8th grade). Learning the fundamental ideas of Trigonometry is one of its most important applications in subsequent years of STEM education (Biber et al., 2013). Traditionally, memorizing the definitions and diagrams of varied angle types has been used to teach the concepts of Lines and Angles (Ramdhani et al., 2017). In traditional classrooms, a teacher draws an angle on the whiteboard, mentions its measure, and verbally explains the definition and associated features to the students, who listen, take notes, and complete some practice activities (Özerem, 2012). Students describe learning of such topics as remembering definitions and properties and forgetting them after exams (Biber et al., 2013; Özerem, 2012). We created a *ScholAR* module on Lines and Angles as part of the AR intervention to encourage active engagement from students as they grasp the actual application of the ideas taught. Students may use it to engage with an augmented 3D object and further recall, visualise, recognise, and label the type of angle by drawing on it.

5.3.2. The Design of the Module

The content of the chapter on Lines and Angles in the textbook was analyzed and the types of angles taught on that topic were classified. The questions for the AR activities were then defined based on the type of angle to be determined and distinguished by the students while setting the context of finding the angles in a house. One question from each topic of Lines and Angles was taken. To incorporate the interaction of Draw and Annotate, the AR activities were designed to let the students find an angle and draw that angle by annotating the degrees or any other information. To be able to find all possible types of angles in a single virtual 3D object, we chose a 3D model from the free online sources that contained this possibility.

An android based markerless AR application was built in Unity engine using the ARCore SDK, which makes use of motion tracking, environmental understanding, and light estimation. With the movement of the phone, ARCore is able to track its position and develop an understanding of the surrounding world and estimate the lighting conditions around. On starting the application, a grid appears to indicate the scanning of a textured surface on which a virtual graphic gets augmented. In *ScholAR*, once the grid appears, a 3D house gets augmented by tapping on the screen of the tablet with two fingers. By detecting the height and position of the held tablet, the 3D house gets augmented at the eye level of the user, the calculation of which is enabled by ARCore at the backend. In order to provide an immersive experience, the manual rotation of the 3D house is disabled so that the users can themselves move inside and outside the 3D house to explore it from all sides, the way they would do in reality. The house could be scaled down or up by tapping farther or closer respectively, with two fingers on the detected grid on the horizontal plane. Using the ARCore draw feature, the users can draw anything on the screen using one-finger tap and drag. In order to erase the drawn marks, the users need to tap with three fingers inside the house. The augmented house disappears if the three fingers tap is done outside the detected plane of the house.

The topic selected for the study was Lines and Angles. The activities were further built upon three sub-topics:
(1) *Types of angles:* The learning objective was that at the end of this activity, the students will be able to identify and distinguish between acute, obtuse and right angles in their surrounding objects.
(2) *Pairs of angles:* The learning objective was that at the end of this activity, the students will be able to classify the different pair of angles: complementary, supplementary, adjacent and linear pairs of angles in the examples of real-life objects.
(3) *Interior and exterior angles of a triangle:* The learning objective was that at the end of this activity, the students will be able to locate a polygon in their surroundings and practice calculating its sum of interior angles.

The module consisted of three different AR learning activities with multiple problems (Fig. 5.2.) targeted towards recalling, Visualising, identifying the example of a type of angle and marking it on an augmented 3D object (3D house in our study) by the draw-enabled feature of AR. Fig. 5.3. shows the framework of the module.

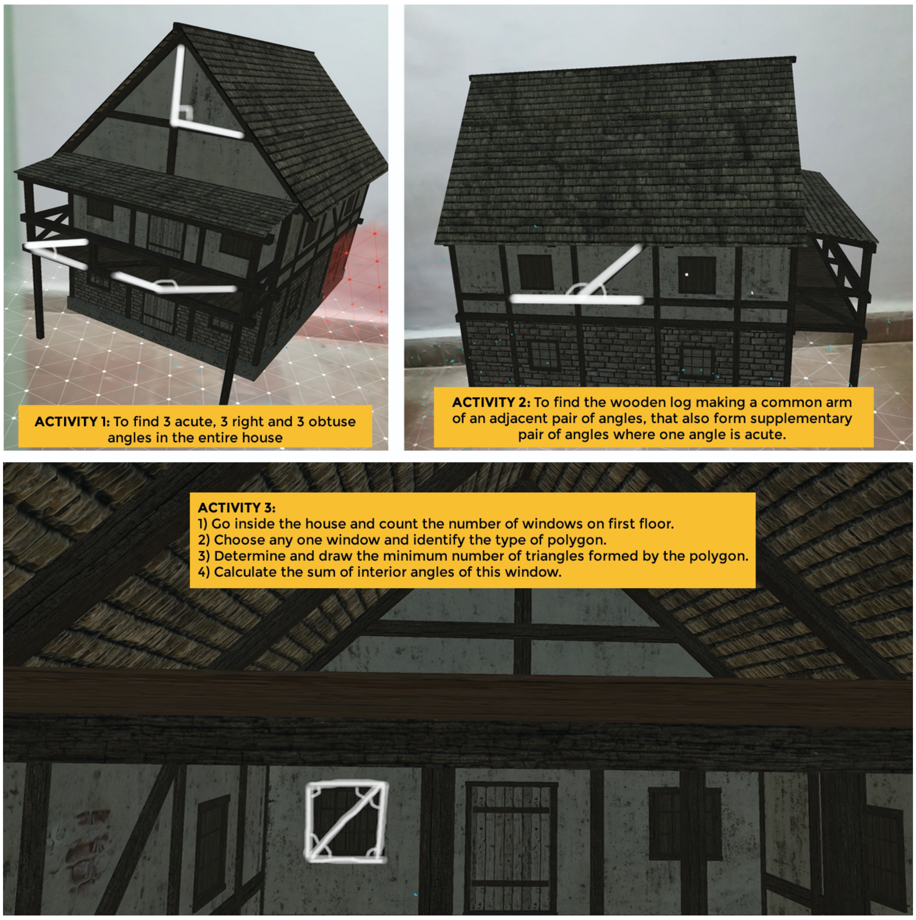


Fig. 5.2. Types of questions for the AR learning activities designed

Activity	Activity 1: Types of Angle	Activity 2: Pairs of Angles	Activity 3: Interior and Exterior Angles of a triangle
Learning Objective	To be able to identify and distinguish between acute, obtuse and right angles in their surrounding objects.	To be able to classify the different pair of angles: complementary, supplementary, adjacent and linear pairs of angles in the examples of real-life objects.	To be able to locate a polygon in their surroundings and practice calculating its sum of interior angles
Learning Theory	Experiential Learning, Embodied learning		
Van Hiele Level	Level 0: Visualization	Level 1: Analysis	Level 2: Informal Deduction/ Abstraction
Problem Solving Method	Repetition: Multiple Possible Solutions	Contextual Problem	Breaking into smaller problems
Target Actions	Recall → Visualize → Identify → Mark		
Technology Support	AR on tablets using ARCore		
Interactions Defined	One Finger Tap – Draw on the screen like a pencil Two Fingers Tap – Get the House on the detected plane, zoom in and out Three Fingers Tap – Erase the content drawn on the screen		

Fig. 5.3. The Framework of Lines and Angles module of *ScholAR*

5.4. STUDY 4 - Evaluation of Lines and Angles Module

In our further study, we were keen to see the participation level when the AR activities were performed in dyads and/or individually. This study was done to address:

1. the difficulties that the students faced with the geometric concepts,
2. interaction features and the Draw and Annotate interaction medium in the ARLE.

The research question addressed in the study was:

RQ 2a: What is the effect of the designed module on 'Lines and Angles' of ScholAR on the students' cognitive, affective, and social learning?

5.4.1. Study Design

We conducted a pilot test with 6 participants. This was done to check and refine the instruction delivery, time, and execution of the designed activities. We were thus able to verify the estimated time of the study and the use of the data collection instruments. The study was then conducted in the lab setting with 21 participants of 8th grade who had studied the topic of Lines and Angles in 7th grade. The students belonged to the age range of 11-13 years (M=12.14, SD=0.57). The participants were randomly distributed into 6 dyads and 9 individuals and a comparative study was done between the two groups. Three researchers acted as facilitators, who helped the participants revise the concepts, gave a demo of this module of the *ScholAR* app, observed the actions of the participants during their participation in performing the activities, and conducted interviews with them.

5.4.2. Data Sources and Analysis

Learning was evaluated through pre and posttest, along with the evaluation of usability and motivation to use the intervention. Pre and posttests were conducted to evaluate the cognitive learning outcome of the participants. These assessment instruments were designed to address the requirements of 7th grade Mathematics curriculum and focused on 'understand' and 'apply' cognitive levels and 'conceptual' and 'procedural' types of knowledge within the chosen topic. Also, a motivation questionnaire developed from the Instructional Materials Motivation Survey (IMMS) (Song and Keller, 2001) was provided to understand the motivation of the two groups, in order to study the affective learning in the students. The usability of the application was further evaluated using the System Usability Scale (SUS) questionnaire (Brooke, 1996), shown in Appendix E.2. The broad goal of the study was to observe and identify the ways that motivated the dyads and individuals to approach solving the AR-based problems. Analysis of data from transcribed interviews, videos, test results, and survey questionnaire responses investigated if the collaborative use of the Lines and Angles module of *ScholAR* along with the teacher acting as the facilitator can act as a supplement in the classroom.

5.4.3. Results

1) Students' perspectives on the use of AR individually and in dyads

We focused on understanding the students' perspectives on the use of AR individually and in dyads. Through Thematic Analysis of the user statements during the interviews, it was noted that the participants preferred to perform the AR learning activities in collaboration than alone (Table 5.1). This was primarily for three reasons:

1. Holding the tablet and marking the angles simultaneously can be eased out.
2. Partners can help in recalling the definitions and understanding the related concepts through discussion and applying the same with minimal prompts from the facilitator.
3. They gain confidence with the assurance of the partner's help.

However, as opposed to the results in a former comparative study of dyads and individuals (Chen, 2008), the learnings from the AR learning activities got reflected in the performance of dyads in the posttest. A significant difference at $\alpha=0.05$ ($t=2.21$, $p=0.048$) in the performance of the dyads was observed as compared to individuals with a positive gain between the pre and posttest. The participants stated that the AR learning activities helped them in understanding the posttest questions better and could relate the test problems with the activities.

Earlier studies have revealed that the use of AR lessons can help students in learning and investigating progress (Chen, 2008). With the multiple designed activities, the participants were able to realise the relevance of AR. The majority stated that the immersive experience of interacting with the 3D house shown in real-time was a fun and engaging experience, which cannot be obtained while sitting in the classroom and jotting down the taught concepts in the notebooks from the blackboard. They felt that because of their ability to watch and perform the AR learning activities themselves, they were able to concentrate more and understand the concepts better. However, it was observed that a number of participants had difficulty recalling the definitions of the taught concepts. As a result, the researchers had to prompt to repeat the definitions to help them recall and identify the required angles. It has been reported that with AR content, students are able to retain the content more as compared to non-AR mediums (Cai et al., 2019). Many of our participants stated that the repetition along with the practical application through AR learning activities indeed helped them in understanding the concept of Lines and Angles better which they lacked while learning in the classroom.

Table 5.1: Thematic analysis to identify the role of collaboration as perceived by the participants

Themes	*User Instances*
Explanation of learned concepts to partners	"We explained each other and then marked the answer", "I showed him the answer and explained why that answer has been marked", "one who remembers a concept would explain to the partner"
Encourages discussion	"Before marking the angles, we would discuss with each other", "Discussion helped us to understand a few things on our own", "in case one of us would not remember the definition, we would ask and then discuss with each other"
Correcting mistakes	"If one marked the wrong answer, other erased it and marked the correct one", "we would correct each other's doubts", "we would correct each other's answers"
Guidance of each other for quick actions	"In a group we can solve quickly using both minds", "we can help each other quickly if get stuck", "by helping each other, the activities can be finished quickly"
Alternate turns to solve the AR learning activities using one tablet	"We took alternate turns to mark the answers for equal participation", "In the first activity, we had to mark multiple angles of a type. We took turns to do that.", "We took alternate turns to hold the tab"
Better understanding	"In group we can coordinate and understand with each other's help", "asking partner before the facilitator to understand the problem"

2) Approaches taken by students in solving the AR learning activities

We then focused on the approaches taken in solving the AR learning activities. We provided an immersive experience, by asking the participants to move around and explore the 3D house. For this purpose, we disabled the feature of rotation of the house. Activity 1 helped them in getting familiarised with the AR interactions. It was observed that one-third of the students had difficulty in recalling the definition of obtuse angle, taking a lot of time to find one. Also, they had difficulty in visualising and marking the angles in the mirrored reference (i.e. 0° to 360° in the clockwise direction). All the participants took maximum time in solving Activity 2. It was realised that this activity had to be broken into smaller problems by the facilitators to help the participants recall, visualise, identify, and mark the answers. The excitement in the 3rd activity was observed to be the highest among all. This is because the participants were unaware that they could go inside the 3D house and explore the multiple floors and roof from within, enhancing their immersive experience. They took the least time in solving this problem as it was already broken into six smaller problems, making this activity the most liked one. The usability of the *ScholAR*'s module on Lines and Angles was calculated using SUS Usability Questionnaire (Brooke, 1996). The overall usability was slightly less than the average score of 68. Moreover, the average usability score of the individuals (70.28) was higher than the dyads (65.23). The possible implication is that with more time in solving the AR learning activities as compared to the dyads, the individuals might have become more satisfied in using *ScholAR*. Thus, to increase the usability score for the dyads, the AR learning activities need to be redesigned for providing a better user experience to the dyads.

3) The motivation of using *ScholAR*

The motivation for using *ScholAR* was evaluated and reported as it is suggested that interactivity may result in increased motivation in addition to other learning outcomes (Kennedy, 2004). The motivation was evaluated using the questionnaire developed from the Instructional Materials Motivation Survey (IMMS) (Song & Keller, 2011) that evaluates the motivation level of the learners in the four dimensions of the ARCS (Attention, Relevance, Confidence, Satisfaction) model (Keller, 2010). The reliability of motivation questionnaire data was obtained using Cronbach alpha value (Wessa (n.d.)) and was found to be 0.91 indicating good reliability (Namdeo & Rout, 2017). The Cronbach value for the items of the scale of Attention (0.71), Relevance (0.75), Confidence (0.70), and Satisfaction (0.88) all indicated to be reliable.

The overall motivation level of all 21 participants was positive with a mean score of 3.99. The minimum overall motivation level score was 2.58 of a participant who performed the AR learning activities in the dyad. The maximum overall motivation level score was 4.64 of a student who solved the AR learning activities individually. Based on the score range, the motivation levels are divided into low (<3.00), medium (3.00-3.49), upper-medium (3.50-3.99), and high (4.00-5.00) (Namdeo & Rout, 2017). Ten participants (47.62%) had high motivation levels, another set of 10 participants (47.62%) had upper-medium motivation levels and only one participant (4.76%) had low motivation levels. As can be seen in Fig. 4.8, Item 3 of the Relevance scale i.e. “completing this study successfully was important to me” scored to be of the highest motivation level (M=4.62), indicating they believed that the completion of the AR learning activities was of a lot of importance to them. Whereas, Item 3 of the Confidence scale i.e. “After the revision at the beginning of the study, I felt confident that I knew what I was supposed to learn from this study” scored the least (M=2.71). This may be because the activities required recalling some of the definitions of the types of angles at multiple steps. It was difficult for the participant to recall at one go and required the assistance of their partners or the facilitators.

To compare the motivation levels of the dyads (N=12) and the individuals (N=9), unpaired t-test was conducted. From the analysis, it was indicated that at α=0.05 (t=0.69, p=0.49), there was no significant difference in the motivation levels of the dyads and individuals. However, the average motivation level of the individuals (M=4.07) was 0.13 scores more than the dyads (M=3.94). This means that the individuals were comparatively more motivated in using the *ScholAR* than the dyads.

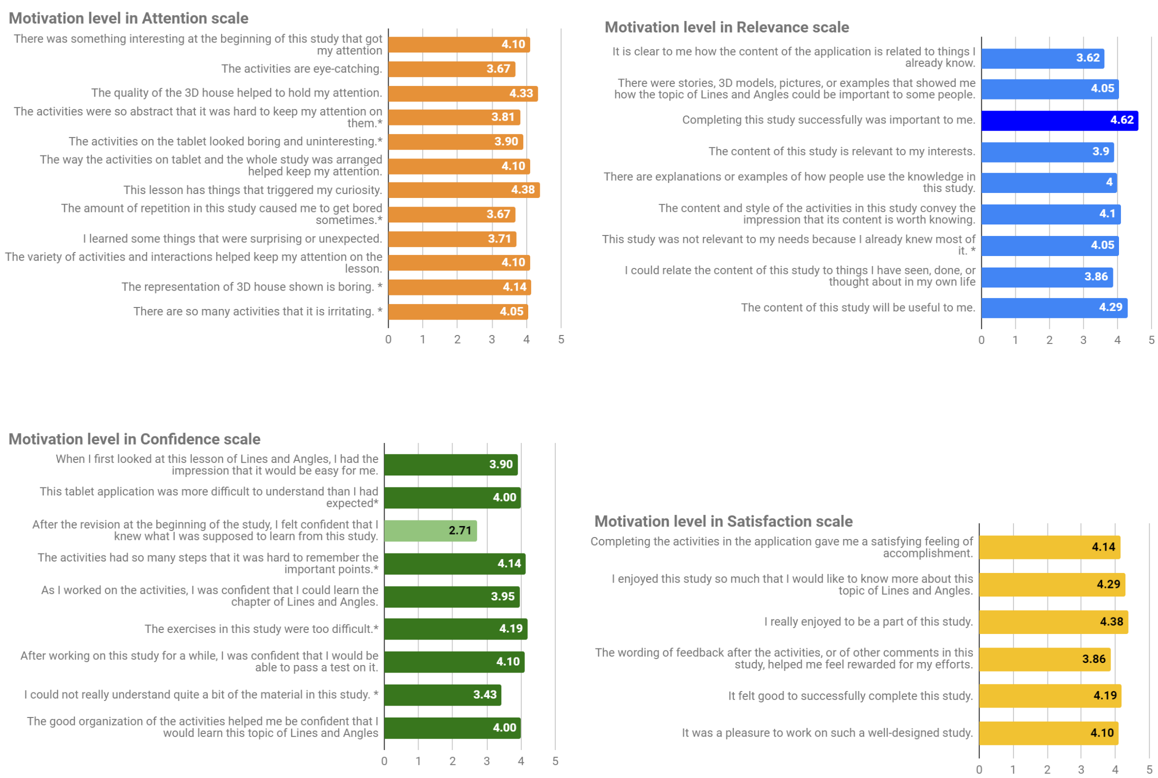


Fig. 5.4: Mean Motivation levels of items from the four scales of the ARCS Model

Thus, it implies that the collaborative use of *ScholAR*'s Lines and Angles module along with the recalling prompts can be a worthy supplement for the teachers to bring in active participation through practical exploration. However, there is a minor requirement for redesigning the AR learning activities in order to make it more satisfactory to use and motivating for the participants. Moreover, the redesign must be done in order to facilitate the collaboration of the participating students for collaboration being the preferred mode rather than the individual.

4) Learning Impact

In terms of learning impact, the results from the pre and posttests were evaluated to analyze the effect of *ScholAR*'s module on Lines and Angles, on the participants' learning. Table 5.2. gives the descriptive statistics derived from the normalised results of the pretest and posttest scores of those who participated in the study either by performing the AR learning activities individually or in dyads. It shows the mean scores and standard deviation in the pre and posttest results for both the groups. The standard error obtained from the mean scores has been reflected on the bar chart as error bars in Fig. 5.5. The error bars represent the variability in the groups and test scores, giving a sense of whether or not a difference is significant.

Table 5.2. Descriptive statistics on the pretest and posttest scores of dyads and individuals.

	Dyads (N=12)		**Individuals (N=9)**	
	Pretest	Posttest	Pretest	Posttest
Mean (M)	4.00	5.17	4.31	4.75
Standard Deviation (SD)	1.85	2.91	2.38	2.45
Standard Error ($SE = SD/\sqrt{N}$)	0.53	0.84	0.79	0.82

Fig. 5.5. represents the mean pretest and posttest scores of the participants who performed the AR learning activities either in dyads or individually along with the error bars. By looking at Fig. 5.5, it seemed that on comparing the overall performance of the dyads and those performing individually, there may be a significant difference between their performance. On observing the plotted pretest scores and the posttest scores, it seemed like the posttest scores may be significantly higher than the pretest scores. Also, it was interesting to investigate if there is a significant difference in the pretest and posttest scores of the dyads as there was a slight overlap in the error bars. Similarly, as the overlap is quite a bit in the

error bars, indicating that there is no significant difference in the pretest and posttest scores of those who performed the AR learning activities individually, it was required to statistically investigate the same.

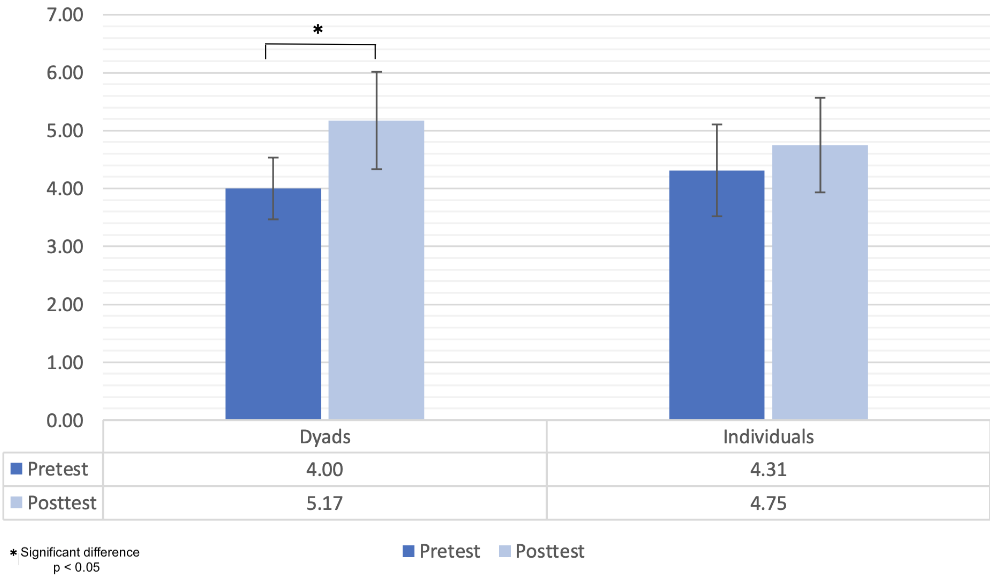


Fig. 5.5. Bar chart representing the mean pretest and posttest scores of participants who performed the AR learning activities in dyads and individually

To test the normality of the data, Shapiro-Wilk Test was done. At α=0.05, the statistical test on the scores of pretest (p=0.832) and posttest (p=0.912) for those who performed the AR learning activities individually indicated that the data was normally distributed. Similarly, at α=0.05, the statistical test on the scores of pretest (p=0.661) and posttest (p=0.085) for those who performed the AR learning activities in dyads indicated that the data was normally distributed. On attaining the normality, a paired sample t-test was done on the scores obtained from the pre and posttest results. At α=0.05 (t=-0.34, p=0.37), there was no significant difference in the pretest scores of the participants before performing the AR learning activities individually and in dyads. However, at α=0.05 (t=2.21, p=0.048), the dyads performed significantly higher after interacting with the AR-based module, which is indicated in Fig. 5.5. Moreover, at α=0.05 (t=0.86, p=0.41), there was no significant difference in the performance of the participants who solved the AR learning activities individually. This indicated that the peer discussion and correction of mistakes, as stated by the participants during the interview, might have led to the dyads understanding and performing better after performing the AR learning activities. Since the test scores have been evaluated for the pre and posttest results of the same participants belonging to either of the two groups (individuals and dyads), one-way ANOVA with repeated measures was calculated. This statistical test is used for the analysis of variance between two or more groups. The between-group ANOVA indicated no statistical difference ($F(2,21)=0.003$, $p=0.956$, $\alpha=0.05$). As there was no significant difference between groups, ANOVA could not be followed by a post-hoc test to tell which means differ.

5.4.4. Discussion

In terms of AR interactions, the feature of manually rotating the house was disabled in our application in order to provide the students with an immersive experience of moving around the augmented 3D house. This was done as the learning experience tends to enhance through physical movement (Wilson, 2002). One-third of participants had difficulty recalling the definition of an obtuse angle which took them time to identify and mark one. Also, they had difficulty Visualising and marking the angles in the mirrored reference i.e. 0° to 360° in the clockwise direction. Thus, prompts from the facilitators were required at times when the participants faced difficulty in recalling the definition or properties of a certain type of angle. The facilitator had to break down the contextual problem in Activity 2 into smaller questions for the participants to easily visualise the required angles. The participants were most excited to solve Activity 3 as they could go inside the 3D house and explore the multiple floors in a way they would actually explore a real house. This activity took them the least time to solve as the problem was already broken into six smaller problems. Hence, this became the most liked activity. The overall average usability score was slightly less than the standard score of 68 for a system to be considered to have a good design. This implies that the system needs to be re-designed to tackle the conceptual and interaction difficulties that the students faced while using the current system.

5.4.5. Implications

The students were given active control of the AR app, while the teachers verbally put forth the questions to find the ability of the students in identifying a type of angle in the augmented 3D object. The two-way communication happened between student-student, student-teacher, and student-system. The interactions of drawing, annotating, and erasing were instant but lacked synchronicity in terms of system feedback which impacted the ways the students responded and the amount of teacher prompts required. Though there was active participation among the students while they explored the practical applications of the learned concepts in real-time, there is a requirement to make changes in the design of the application for satisfactory use by the dyads, with a balance of teacher prompts and system feedback. In the next section, the design and evaluation of another module of *ScholAR* on Visualising Solid Shapes have been described.

5.5. Design of Visualising Solid Shapes Module

5.5.1. Theoretical Foundations of the Intervention

One of the integral parts of Mathematics is Geometry, which further consists of 2D and 3D geometry. As students begin to develop the ability to logically think and grasp abstract concepts at around 11-15 years of age, this course is introduced and implemented at the middle school (6th to 8th grade) level (Ojose, 2008). Geometry may be used in numerous other fields of mathematics and helps in the study and interpretation of examples from the real world (Özerem, 2012). Learning Geometry is not confined to only learning the definitions. The properties and theorems of 2D and 3D geometry should also be studied with a view to forming geometric relationships while solving related problems (Narayana et al., 2016).

As AR technology is booming, it has given us aid in the provision of visual presentations. To increase students' attention to mathematical concepts and techniques, diverse modes of interactive geometry have been developed (Zbiek, 2007). The interactive geometry program aims to help students learn and explore geometric concepts by manipulating geometric objects such as dots, lines, circles, etc. (Koyuncu et al., 2015). One such software is GeoGebra which helps in exploring and learning the various mathematical representations of an object (Edwards & Jones, 2006). There is more software that falls under the category of Dynamic Geometry Software (DGS) such as Cabri-Geometre (Straesser, 2002) and SketchPad (McClintock et al., 2002), which facilitate deeper exploration and analysis of geometric forms by means of dynamic manipulation (Jones, 1998). A comparative study conducted earlier with GeoGebra software (Banu, 2012) showed that it is difficult to do this kind of exploration for pen and pencil-based learning. These interactions, however, are often limited to using a laptop with a keyboard and the mouse used as deceptive tools. Thus, the need is to explore other manipulatives that can be used to dynamically explore the 3D object properties.

Augmented Reality (AR) technology tends to work as a manipulative in the education sector among various emerging technologies. Moreover, with the ubiquitous use of mobile phones and tablets, the research has been expanded to developing mobile AR platforms (Papagiannakis et al., 2008) as it can provide the opportunities for "ubiquitous knowledge construction" (Peng et al., 2009). Such affordances of AR have been explored in Geometry learning by manipulating 3D objects in AR (Kaufmann & Schmalstieg, 2003), to enhance 3D thinking skills (İbili et al., 2019), spatial ability (Liao, Yu, & Wu, 2015), mental rotation skills (Kaur et al., 2018), etc. All such explorations have been primarily done in 3D Geometry. There are very few studies on exploring the application of 2D Geometry using the AR platform, wherein one study, the 3D objects are developed from the drawn 2D shapes in AR (Banu, 2012). There also exist studies that suggest the collaborative use of AR can help in improving visualisation skills, critical thinking skills, problem-solving skills, and communication of the participating students (Kaufmann & Schmalstieg, 2002; Chen, 2008; Dunleavy et al., 2009; Cai et al., 2019). While using the AR platform, collaboration is more effective with the learners when they get individual controls and personalised views for all the individuals working collaboratively in a group (Radu, 2012; Cai et al., 2019). Considering the varied design explorations for AR designs, the effective design of interactive ARLE for classrooms is being explored in our research.

5.5.2. The Design of the Module

Based on the expectations of the users from an ARLE in classrooms (as discussed in Chapter 4), and the literature on existing design principles for ARLEs, we initiated the design process of the module by defining the affordances of AR that can be explored to attain some of the user expectations. The affordance of a perspective view, contextual content, and embodied interactions were decided upon.

As the topic of Visualising Solid Shapes was chosen, the spatial thinking skill was targeted, though not evaluated. The interactions were that of tap, move, and view, which was incorporated in the design while keeping some time-based activities, creating a diluted version of a gamified experience. This was done to incorporate the design principles of enabling and challenging, driven by gamification, causing curiosity as suggested by Dunleavy (2014). In this, the role of the teacher was expected to be minimal and the students would explore and solve the problems themselves by interacting with each other. The system feedback was provided for all the responses that were provided by the students.

An android based markerless AR application was built in Unity software using the ARCore software development kit (SDK) which makes use of motion tracking, environmental understanding, and light estimation. With the movement of the phone, ARCore is able to track its position and develops an understanding of the surrounding world, and estimates the lighting conditions around (ARCore (n.d.)). The topic selected for the study was Visualising Solid Shapes. The activities were further built upon two sub-topics - (1) types of 3D shapes, and (2) vertices, edges, and faces of 3D solids. Each of the subtopics had 3 activities (Fig. 5.1.) where the first activity was an exploratory activity, the second activity was based on applying the understanding of the explored content, and the third activity was testing the applied skills learned. Following are the details of the activities of the sub-topics:

1) *Types of 3D Shapes:* The motive of this section of activities was to make the students understand the different 3D shapes and their existence in the real world.

- Activity 1: In this activity, the learners are shown five different types of 3D shapes: cube, cuboid, sphere, pyramid, and cylinder. On tapping any of these shapes, a menu appears with three options to choose from one basic form and two real-life examples of that shape. The students can choose to see the objects either on the ground or at eye level. This activity was designed to help the learners explore the features of AR, learn about the different types of 3D shapes and their examples, and creatively develop forms by Visualising and combining different shapes.

- Activity 2: In this activity, the learners are supposed to choose the shapes matching a given silhouette from a cluster of 3D shapes placed in the surrounding area. The button for 'Drop' was given in case they had the realization of picking the wrong shape.

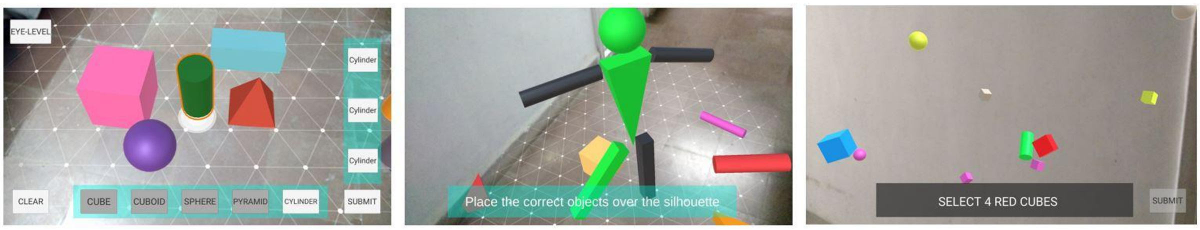
- Activity 3: In this activity, the learners are asked to find 4 shapes of a particular type and color among the other scattered objects in the space around them. Each of the four objects was placed in four different directions. The students are indicated if they submit the wrong answers and can correct their answers.

2) Vertices, Edges, and Faces: The motivation of this section of activities was to make the students understand the difference between vertices, edges, and faces, and be able to count those for a given 3D geometric shape.

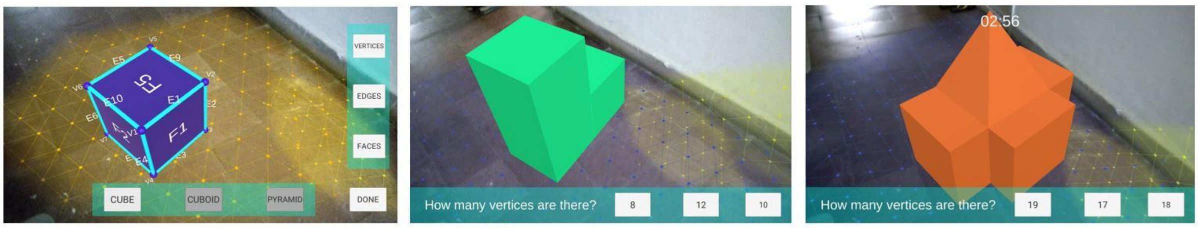
- Activity 1: In this activity, the students are guided to count the number of vertices, edges, and/or faces from the given options of 3D shapes.

- Activity 2: In this activity, the learners are given a combination of two geometric 3D shapes and are asked to count the number of vertices, edges, and faces separately in three questions. The right answer gets highlighted in green along with musical feedback. The wrong answer gets highlighted in red. The next question appears only after marking all three right answers.

- Activity 3: In this activity, a slightly complex 3D shape is given for which the students have to correctly count the vertices, faces and edges asked separately as three questions. This was a timed activity, to be done in 3 minutes. A score out of 3 is given in the end for the correct answers.



(a) Sub-topic: Types of 3D Shapes – Activity 1, 2 and 3



(b) Sub-topic: Vertices, Edges and Faces - Activity 1, 2 and 3

Fig 5.6. Activities designed using ARCore

5.6. STUDY 5: Evaluation of Visualising Solid Shapes Module

The research question addressed in the study was:

RQ 2b: What is the effect of the designed module on 'Visualising Solid Shapes' of ScholAR on the students' cognitive, affective, and social learning?

5.6.1. Study Design

Participants

We conducted the study in a school which followed the blackboard method of teaching. They had one projector screen in a classroom to be used by all the grades and a few classrooms available to be used as subject labs. However, the students in this school used benches to sit and faced the blackboard while the teacher taught. Through convenience sampling, the study was conducted with 32 students in 7th grade belonging to the age group of 12-14 years (M=12.53, SD=0.67). These 32 students were randomly divided into two groups of 16 each (by picking chits) where one group was the experiment group, the other was the control group.

Procedure

The quasi-experiment was conducted on a single day in a classroom of 32 students in 7th grade. This grade was chosen as the topic used for testing was never introduced to the students before. The two groups of students – experiment and control groups with 16 students in each - were made to sit in two different classrooms. The learning objectives included giving an introduction to 3D solids, the difference between 2D and 3D, the types of 3D solids, and the terms Vertices, Edges, and Faces. The same teacher was asked to teach in both the classrooms as all these 32 students were taught Mathematics subject by this teacher. The change in teaching style could have been a confounding variable for our study.

5.6.2. Data Sources and Analysis

After the use of the intervention, students were asked questions on their experience of using the application, their learnings from the activities, and suggestions if any, on the improvement in the application. They were then given the posttest papers to answer a few questions related to the topic covered. The question paper was validated by the teacher before the experiment was conducted. The posttest comprised six questions with subparts in a few questions. The questions tested the first three stages of Bloom's taxonomy (Anderson & Krathwohl, 2001). The first question was designed to test the first stage i.e. remembering the facts and concepts, and the second and third question was designed to comprehend them. The rest four questions were testing their ability to visualise and apply the learned concepts.

5.6.3. Results

The goal of RQ 3a was to observe and report the interactions of the school students collaboratively using the *ScholAR* application and its effect on their performance. In different phases of the experiment, three different ways of handling the phones among the group members of the four groups were thus observed:

1. One participant in the group held and moved the phone while others pressed the buttons on the AR application.
2. One participant in the group held the phone while others held that person's hands to move the phone accordingly to observe the objects.
3. One participant tried exploring the application's features while the others watched and then passed on the phone to the next team member.

The results indicated that *ScholAR*'s module on Visualising Solid Shapes aided in developing the visualisation skills of the students and realizing the existence of 3D shapes in the surroundings. This was observed when each of the four groups tried to recreate different scenarios or objects using the basic 3D shapes given in one of the activities such as "Mountain on top of Sun", "Making a palace", "Toy train crossing a forest", "Making a hut".

Perception of Learning: The following were some of the responses when asked about the learnings obtained by using the application: "Learned about 3D shapes", "We can make any object with shapes", "Many things around us are made of these shapes".

Usefulness of Application: One participant tried exploring the application's features while the others watched and then passed on the phone to the next team member. "The application is very helpful for the beginners", "Fun element added with the man activity", "It made Mathematics interesting for me", "It was easy to learn about shapes using this application because of the examples shown. Teacher would sometimes bring the objects to show in class, sometimes not.", "The different types of activities make the application interesting"

Challenges in using the Application: Some of the concerns raised by the students when they were asked about the challenges they faced while doing the activities included: "Unable to rotate the objects while trying to get a particular orientation", "A setting should be there to place one object on top of other", "The time away went too soon in the last activity"

Their perception of learning, the usefulness of the application, and the limitations of the application helped in defining the design considerations for the redesign of the application.

The results of RQ 3b implied that the collaborative exploration of the interactive application enhanced the performance of these students as compared to those learning by the traditional blackboard and textbook teaching method. The learnings from the application got reflected in their performance in the posttest conducted. A significant difference at $\alpha=0.05$ ($t=2.18$, $p=0.018$) was observed in the performance of the experimental group as compared to that of the control group.

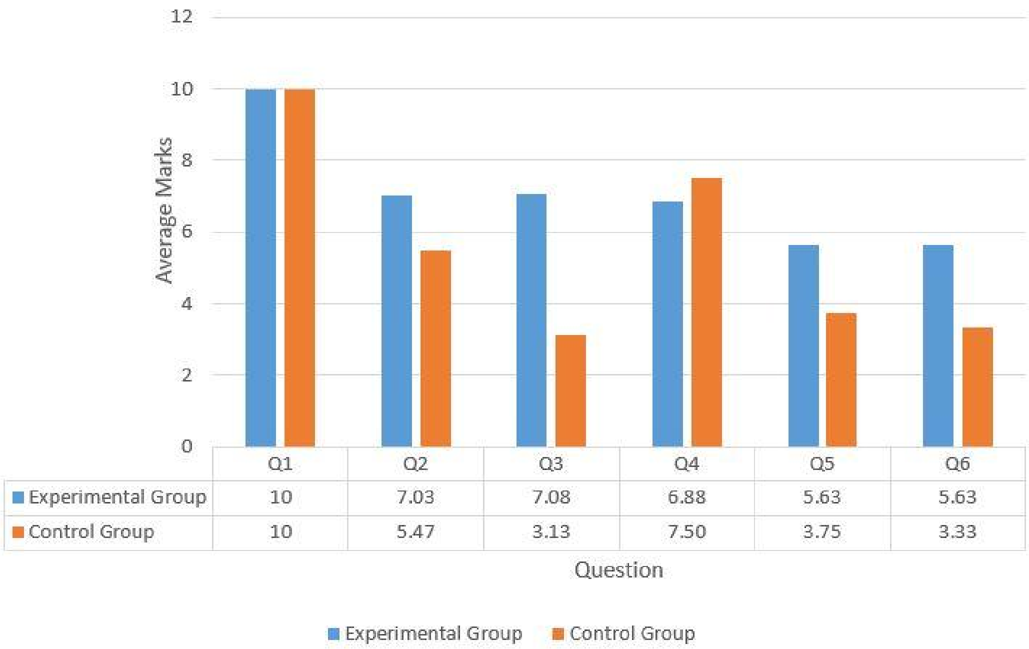


Fig. 5.7. Results of the posttest questions.

The posttest results indicated that the first three stages of Bloom's taxonomy i.e. remember, understand, and apply were successfully attained by the students using the application. From the results obtained for each type of question (Fig. 5.7.), we could claim that overall the collaborative use of the *ScholAR* application was able to enhance their understanding and cognition, which helped them apply the concepts that were briefly introduced by the teacher.

5.6.4. Discussion

The students took on an average of 10 minutes in activity 1 as they were exploring the application. When prompted by the researcher to try making some forms out of the shapes, they came up with interesting ideas to design in a short time. They could visualise the object or scenario in its basic form that can be made with the shapes. Thus, we can claim that the *ScholAR* application can help the students in developing their visualisation skills. However, while developing the forms, they faced problems in placing one object on top of another as the feature of rotation of a 3D shape to a particular orientation was not added as we wanted the students to move around the objects and see it from all sides in the real environment. The rotation feature can thus be added in the redesign of the application.

From the posttest results and the responses to the questions asked in the post test, it is evident that the experimental group performed better as compared to the control group. All the students of both groups remembered the names of the 3D shapes that were shown to them in class or in the application. However, the understanding of the taught concepts was better in the case of the experimental group as seen from the answers and scores of question 2 and 3. A probable reason for such a result could be that the students of the experimental group were able to discuss their doubts and learned concepts with each other using the AR application in collaboration, which the other group could not do. This might have given the experimental group more clarity about the learned concepts. Question 4 was only one question in which the control group outperformed. In their classroom, the teacher had repeated multiple times the number of vertices, faces, and edges of the basic shapes which the students had repeated aloud after her. There is a possibility that the students might have memorised the number of faces, vertices, and edges of each of the basic 3D shapes and answered the question on the basis of rote learning. Whereas, the experimental group was made to themselves count the vertices, edges, and faces of different 3D structures. So the experimental group performed better in questions 5 and 6 when slightly complex 3D shapes were presented and they had to count the number of vertices, faces, and/or edges. Overall there was a consistency in the performance of the experimental group which the control group lacked. From the results obtained for each type of question, we can claim that the collaborative use of *ScholAR* application was able to enhance their understanding and help them apply the concepts that were briefly introduced by the teacher.

5.6.5. Implications

In study 4, we tested six tasks on the topic of Visualising Solid Shapes with an experimental group of 16 students of 7th grade as that is when they begin to develop the ability to reason logically and expand conceptualizing skills. We did a comparative study with the control group of 16 students who were taught the same topic using the usual teaching method followed in their school. The results of the study, observations and analysis of the use of this AR application in a collaborative environment and the effect of collaboratively using the AR application on the students' performance were reported.

5.7. Summary

The chapter described the design and development phase along with the evaluation and reflection phase of the first cycle of DBR. Based on the inferences from the problem analysis and exploration phase of DBR, certain design decisions, strategies and methods were adopted from the literature to design the interactive ARLE. The two different embodied AR interaction mediums - (1) Tap and View and (2) Draw and Annotate were incorporated separately into two modules of our AR application, named *'ScholAR'*. These two modules were based on the topics of Visualising Solid Shapes, and Lines and Angles from 7th grade NCERT syllabus of Mathematics subject. Thus, two different studies have been conducted for the two different interaction mediums.

Study 4 was conducted in the classroom setting, where the students interacted with the *ScholAR*'s module on Visualising Solid Shapes. The teacher's involvement was there in the first activity, and then was kept minimal till the end. As some of the activities were timed ones, the students randomly chose the answers while performing the AR learning activities. Along the three dimensions of learning i.e. cognition, affective and social (Illeris, 2003), the first and third dimensions were qualitatively addressed from the data sources and analysis.

Study 5 was conducted in two different settings - lab and classroom. For the lab setting (study 5a), a comparative study on the module of Lines and Angles was conducted between the dyads and individual participants. This setting involved the researchers acting as the facilitators. For the classroom setting (study 5b), the teacher participated along with the students who performed the AR learning activities in dyads. The data sources were similar for both studies. Along the three dimensions of learning i.e. cognition, affective and social (Illeris, 2003), results were obtained for the learning impact, motivation and interaction patterns with the system, peers, and the teacher.

The inferences from study 4 and study 5 indicated the requirement of refining the *ScholAR*'s design which will be discussed in the design and development phase (Chapter 7). It was clear that in instances where the activity was planned and considered, students used higher levels of cognitive activity and achieved greater learning outcomes when compared to students who sought information through unstructured answering strategies (Oliver, 1996). Thus, it was felt that the improved design of the *ScholAR*'s module in the second cycle of DBR needed the involvement of the design decisions, strategies, and methods as perceived and conceived by the potential designers of ARLEs (education researchers, interaction designers, and/or AR developers), which has been described in the next chapter (Chapter 6).

Chapter 6

DBR 2 Redesign and Evaluation of ScholAR (Lines and Angles)

This chapter describes the second cycle of the Design and Development phase and the Evaluation and Reflection phase of DBR. Inferences from the first cycle of DBR (as described in Chapter 5), directed us towards refining and redesigning the *ScholAR 2.0*'s module on 'Lines and Angles'. As is the norm in DBR, our goal for the evaluation was two-fold. In the previous study, we were able to highlight how the design features of the *ScholAR*'s module on 'Lines and Angles' helped the learners in gaining cognitive, affective, and social learning. This chapter reflects the redesign of this module based on the reflections from the first cycle of DBR. We will then evaluate the impact of the same on students' social learning.

The broad research question in this phase and cycle of DBR involves:

Broad RQ 3: *What are the effective design strategies for the designed modules of ScholAR 2.0, leading to cognitive, affective, and social learning?*

6.1. STUDY 6 - Evaluation of Lines and Angles Module

In the previous study, it was realised that performing the AR activities was preferred in dyads Hence, this study involved the same activities where changes were done to the ways of interaction with the *ScholAR* application. The objective of this study was to find the sequential behavior patterns of the dyads while performing the AR learning activities. This study focused on the following research question:

RQ 3a: What is the effect of the designed module on 'Lines and Angles' of ScholAR 2.0 on the students' social learning?

6.1.1. Redesign of *ScholAR*'s module on Lines and Angles

In the first study it was observed that beyond the cognitive difficulties, the participants faced certain issues with the AR interface and interactions. While drawing on the virtual 3D house, the marked lines were floating when the participants moved to the other side of the house. This made it difficult for them to show the facilitator(s) their final answers by overlaying the lines back on to the identified angles on the house. Moreover, the house would disappear on tapping with three fingers outside the house. Thus, certain amendments were done in the interactions for the next round of study. The lines drawn by the participants would snap on to the house to prevent the marked lines from floating on changing the perspective of the house while moving around. They could scale the 3D house the general way, i.e. by sliding two fingers closer and farther. Also, changes were done to prevent the augmented house from disappearing if the three fingers tap was done outside the detected plane of the house.

6.1.2. Study Design

This one-group pretest-posttest study was conducted in a rural school. The procedure of the entire study was the same as the earlier one. However, this study was conducted only with 14 dyads (N = 28) of 7th grade with the age range of 11-13 years (M=12.53, SD=0.67). Moreover, the students had recently covered the topic of *Lines and Angles* in their class, hence a quick revision of only 10 minutes was done by the teacher for these participants. The data sources and instruments in this study were also the same as the earlier study. However, the language of instruction and data instruments was as per the local language of the participants i.e. Marathi. To answer RQ3a, the audio recordings from the tablet screen recordings were transcribed and translated to English. Based on the earlier study, we were able to generate certain codes that focused on the behaviours of the students while performing the AR learning activities. For all the three activities, Protocol Analysis (Ericsson and Simon, 1984) of the tablet screen and video recordings of the participating groups were done. The codes, refined after the second study, have been classified into three categories: Peer Involvement, AR Interactions, and Teacher Prompts also shown in Table 6.1.

6.1.3. Data Sources and Analysis

To visualise the appearances of the behavioral sequences lag sequential analysis (Bakeman and Gottman 1997) was performed. Two researchers coded the sequences of appearances of each dyad's behaviors for every activity. The three activities generated 14 code strings in total, consisting of 2193 behavioral codes. The reliability coefficient came out to be 0.91% (Cohen's kappa) between the two researchers generating the codes. The Z-scores of the sequences obtained were then calculated. The Z-scores of 1.96 or greater has been considered as it indicates a significant sequence ($p < 0.05$).

6.1.4. Findings

In the follow-up study, the participants were made to perform the activities in dyads. This was done by identifying the patterns using lag sequential analysis (Bakeman & Gottman, 1997) based on the defined categories and related behavior of Peer Involvement, Teacher Prompts and AR Interactions (Table 6.1.).

The significant sequences are shown in Fig. 6.1. In the shown diagram, the arrow indicates the direction of transfer for each sequence and the thickness represents the level of significance. These sequences can be read from anywhere as there is no starting point. The numerical value on each arrow represents the Z-score of the significant sequence. In total, 32 sequences with significant z-scores have been depicted in the diagram.

Table 6.1. Coding scheme of collaborative learning behavior while performing the AR learning activities.

Code	Meaning
Peer Involvement	
P1	Task Coordination: Discussing what to do in the task
P2	Explanation of concept to the partner
P3	Discussing where to mark
P4	Discussing how to mark
P5	Correcting each other
P6	Physically moving each other
P7	Discussing to mark accurately
P8	Marking without discussion
P9	Discussion irrelevant to the activity
P10	Physically following other
P11	Discussing to hold the tab
Teacher Prompts	
TP1	To scale the house
TP2	To mark and/or erase
TP3	To explain the concept
TP4	To move to the other side of the house
AR Interactions	
D1	Draw curvy incomplete lines and erase
D2	Draw wrong lines/answers and erase
D3	Draw right answer/complete lines and erase
D4	Draw correct answer and retain for at least 10 seconds
S1	Scaling of the house by moving forward/backward
S2	Scaling of the house using fingers on the screen
M1	Moving to change the side of the house
M2	Came out of the house

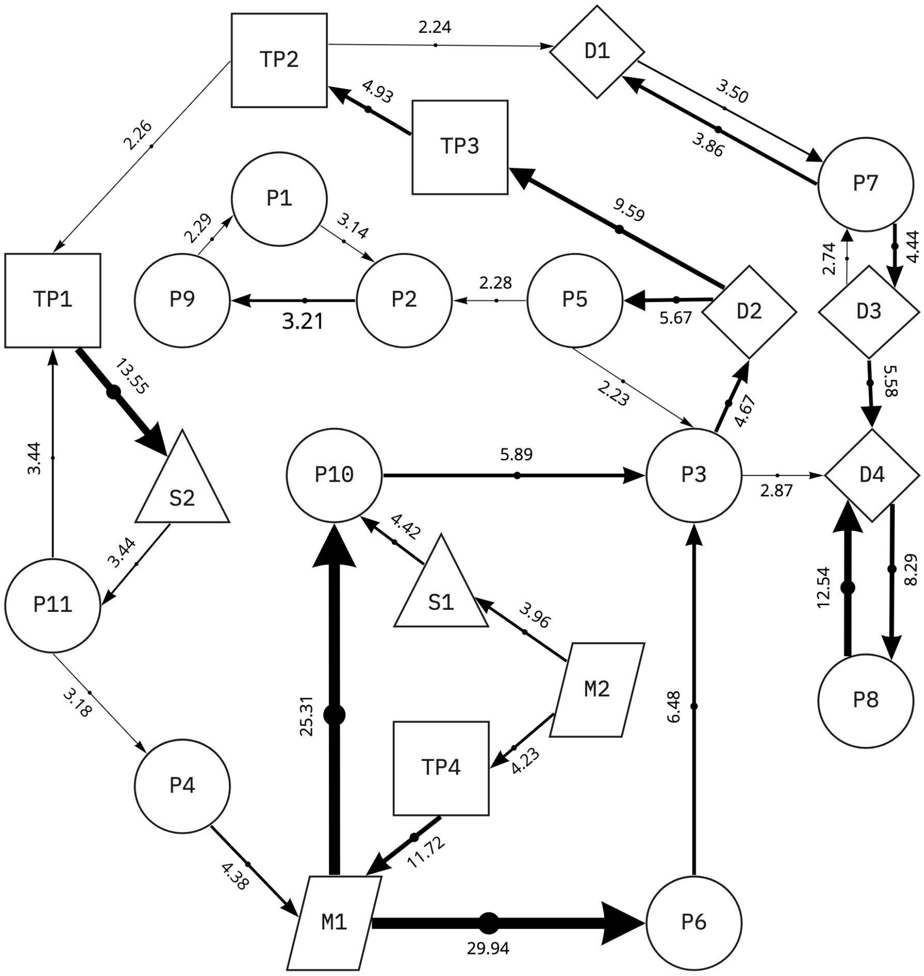


Fig. 6.1. Sequential patterns of learners' behaviors while performing the AR learning activities on Lines and Angles.

A bi-directional sequence between P7 ⇄ D1 and P7 ⇄ D3 indicates that the dyads discussed and tried to help each other to correctly draw the identified angles. However, on identifying the angles on the 3D house, one of the participants in the dyad would keep drawing until neat lines and angles for the final answers have been obtained, indicated by the bi-directional sequence between P8 ⇄ D4.

The two most significant sequences were M1→P6 and M1→P10 indicating that the participants were immersed in the AR experience of viewing the 3D house from all sides to find the answers. In doing so, the dominant behavior was both the participants moved together around the 3D house while holding the tablet.

The cyclic sequence of TP1→S2→P11 indicated that the participants required prompts from the teacher to scale the house using the feature of two-finger sliding on the screen, which was followed by one of the participants in the dyads asking the partner to hold the tablet while trying to scale the 3D house. Another cyclic sequence D2→P5→P3 was observed showing that if one of the participants in a dyad drew the wrong angle as the answer, the other partner would correct it and both would discuss where to mark the answer correctly. The third cyclic sequence of P9→P1→P2 indicated that in case of any discussion that was irrelevant to the study, the dyads would get back to understanding the problem and explain to each other the related concept.

P3 had the highest frequency of significant sequential relationships among the behaviors of peer involvement, including P10→P3, P6→P3, P5→P3, P3→D2, and P3→D4. This described that the answers by a dyad were marked predominantly after peer discussion.

6.1.5. Discussion

It was evident from the results that the participants discussed most on where to mark the angle on the 3D house. Thus P3 was the most predominant behavior among the peer involvement behaviors as it was involved in five significant sequences. In terms of the AR interactions, the participants in a dyad significantly moved together to change the side of the house (indicated by the significant sequence of M1→P6) and moved forward or backward to scale the house. The other scaling feature by sliding the two fingers on the screen was not quite intuitive for the participants. Hence, they had to be often prompted by the teacher to scale the house by sliding the two fingers. This resulted in a significant cyclic sequence of TP1→S2→P11. The participants in a dyad also helped each other to mark the angles by correcting each other wherever needed. This was validated by three significant sequences of P7 ⇄ D1, P7 ⇄ D3 and the cyclic sequence of D2→P5→P3. Moreover, the participants explored the feature of AR by the ability to move around the house from all sides, which was indicated by the most significant sequence of M1→P6 and M1→P10. The significant sequences thus mentioned, were relatable to the perceived notions of the participants in the first study.

6.1.6. Implications

The inferences from studies 4, 5, and 6 indicated the requirement of refining the *ScholAR*'s design. Our theoretical conjectures were not supported; i.e. students were unable to gain cognitive learning with only the contextualised questions. This was because the design conjectures were not supported and students were unable to instantly recall the new concepts, leading to excessive teacher prompts to use the features of *ScholAR* for problem-solving. It needed appropriate instructional scaffolding at system and instructor level. Moreover, appropriate demonstration of the concepts in AR was required to be explored by the students, where they take time to explore the content followed by performing a related AR learning activity. It was clear that in instances where the activity was planned and considered, students used higher levels of cognitive activity and achieved greater learning outcomes when compared to students who sought information through unstructured answering strategies (Oliver, 1996). Thus, it was realised that the improved design of the *ScholAR*'s module in the second cycle of DBR needed the involvement of the design strategies pertaining to appropriate exploration and instructional scaffolding in the system, for the students to overcome the challenges while performing the AR learning activities.

6.2. Summary

This chapter describes the second phase of DBR, i.e. problem analysis and exploration, and design and evaluation. The inferences from study 4 and study 5 indicated the requirement of refining the *ScholAR*'s design. In this chapter, the changes made to the design of *ScholAR*'s module on Lines and Angles have been discussed. As the changes in the design were done to the interactions involved, keeping the contextualised questions same, the evaluation of the impact of the design was done only for the social learning concerned with interactivity. Thus, the peer participation and immersive experience of AR as perceived by the participants in study 4 was validated through the significant sequences in study 6. In the process, it was realised that further improvements are required in the design of *ScholAR*'s module with a defined framework for its pedagogy. Hence, next chapter highlights the redesign requirements of *ScholAR 2.0* and its holistic evaluation on cognitive, affective, and social learning.

Chapter 7

DBR 2 Redesign and Evaluation of *ScholAR* (Visualising Solid Shapes)

This chapter describes the second cycle of the Design and Development phase and the Evaluation and Reflection phase of DBR. In Chapters 5 and 6, inferences from the first cycle of DBR (as described in Chapter 5) and the Problem and Analysis phase of the second cycle of DBR (as described in Chapter 6), directed us towards refining and redesigning the *ScholAR*'s module on Visualising Solid Shapes. As is the norm in DBR, our goal for the evaluation was two-fold. First, to understand how the design features of *ScholAR* are helpful to solve the visualising problems, which will contribute to design guidelines. Secondly, to understand how the learners interact with *ScholAR*'s module on Visualising Solid Shapes to attain cognitive learning abilities.

7.1. Redesign Requirements

From the evaluation and reflection phase of the first cycle of DBR, we realised that certain major changes were required in the redesign. The first module of *ScholAR* on Lines and Angles involved the teacher's role as a facilitator who checked students' responses with no system feedback. On the other hand, the second module of *ScholAR* on Visualising Solid Shapes consisted of system feedback but had minimal teacher input. In both cases, it was realised that in the classroom scenario, both the teacher intervention and the system feedback held importance while the students collaboratively performed the AR learning activities (Liu et al., 2012). Thus, even when the teacher is there as a facilitator, the system feedback is an essential component to be incorporated in the AR simulation.

The two modules of *ScholAR* were separately tested with two different interactions and styles of teaching-learning using the applications. Hence, it was required to have a common framework that could be followed across different modules.

Thus, at the micro-level of the design, it was required to incorporate the appropriate AR interactions along with the system feedback. At the macro-level of the design, it was required to integrate the appropriate roles of the teacher and the students while the ARLE was used in the classroom.

The second iteration of the module on Visualising Solid Shapes incorporated the interactions and design approaches that were reflected upon in the previous studies. We began the redesign process by adopting design strategies that were reflected in studies 4 to 6, to create this interactive module of *ScholAR*.

7.2. Design Strategies for *ScholAR 2.0*

Following the proposed design strategies and the results obtained from study 3 to 6, the design of the topic of Visualising Solid Shapes was redefined. It was then required to define the design strategies at micro-level (AR application) and macro-level (Classroom pedagogy). The following were the key design strategies adopted by us at the different stages of the design strategies for the design of *ScholAR*'s module on Visualising Solid Shapes:

1. Design Strategy for Content and Need Analysis

As the topic of *Visualising Solid Shapes* from the grade 7th syllabus was taken, it was required to understand the topics of this chapter that can be converted to AR. In the earlier version described in chapter 5, the two topics considered were: (1) the introduction of solid shapes and (2) vertices, edges, and faces.

To select the topics in the redesign version, the contents of the chapter were first listed based on the different topics. The examples related to each topic provided in the chapter and the expected learning outcome were then listed down. These helped in reflecting upon the ones that can be recreated in the AR environment. It was decided that the different types of solids can be introduced together with the concept of *Vertices, edges, and faces* as the variation in the values have to be observed across the different types of solid shapes. In addition to that, the *Nets of Solids* was another topic that the teachers suggested was difficult for the students to visualise otherwise and mostly required to be explained using origami activity. The expected learning outcome for both the topics include:

- *Vertices, edges, and faces* - students should be able to predict the applicability of Euler's formula for a given 3D solid shape by counting the number of vertices, edges, and faces.
- *Nets of Solids* - students should be able to visualise and create the net for a given 3D solid shape.

For both the topics, the examples given in the textbook were taken and developed digitally in the 3D form to be represented in the AR environment.

2. Design Strategy for Appropriation for AR

It was then required to outline the translation of the textbook content for the appropriation for AR. The textbook examples and the ways by which the different affordances can be utilised to create interesting AR simulations to explain the concepts were considered. This was followed by defining the possible AR interactions based on our previously conducted studies. Among the different affordances of AR, the ones that could be executed to achieve the expected learning outcomes were decided. Thus, we decided to incorporate the affordances of real-world annotation, perspective exploration and embodied interactions. Based on our previous studies, the Tap and View, and Draw and Annotate interactions were embedded. While deciding upon the appropriation for AR, the textbook examples seemed to be suitable to create an AR simulation, where the values and interactions can be manipulated by the users. Moreover, while defining the way to use AR in the classroom, it was assumed that the design of ARLE will be suitable when used as a teaching aid in the classroom to explain the examples by letting the students explore the virtual objects in the AR world along with practice questions.

3. Design Strategy for Group Dynamics

As we are considering the classroom setting where the handheld AR application will be used by the students in collaboration, we had to design keeping in mind the group dynamics. The potential group formation was argued to work efficiently in the classroom scenario. This decision influenced the type of AR tracking that would be applicable in the context and the levels of complexity and interactions to be incorporated. To make it a student-centered experience (Normand et al., 2012), from the literature it was prominent that the collaboration of students plays an important role while performing the AR learning activities (Santos et al., 2013). In study 3, the students interacted with the AR application in groups of three. In study 4, students performed the AR learning activities individually and in dyads. In study 5, the students collaborated in groups of four to perform the AR learning activities. In study 6, the students formed dyads to perform the AR learning activities. Based on our observations from studies 3 to 6, it was realised that the efficient group formation was that of dyads. Hence, it was decided that in this version, the AR learning activities will be performed in dyads.

To incorporate the group dynamics, the potential group formation was argued that will work efficiently in the classroom scenario. This decision influenced the type of AR tracking that would be applicable in the context and the levels of complexity and interactions to be incorporated. As the group formation was decided, it was interesting to determine the AR tracking mechanism while performing the AR learning activities. With the marker-based tracking, the view and the movement of the students will get restricted around the placement of the marker. In the case of markerless tracking, the wider scanning of the surface will help in a wider tracking zone. Thus, markerless AR tracking was considered, to also remove the hassle of creating and handling multiple AR markers. Also, the tasks were directed towards incorporating collaborative interactions.

4. Design Strategy for Integrating Learning

On elucidating the possible content, considerable affordances of AR, and the feasible group dynamics, the integration of learning in the process was the next targeted step. To translate the textbook content to AR and integrate learning, design decisions and strategies were adopted around the type of learning methods, active learning strategies, the complexity of the problems, and the ways to bring in curiosity while enhancing the skill of spatial thinking ability.

To bring in the curiosity while performing the AR learning activities, a problem-based approach was taken, where through multiple and varied levels of problems, the learning can be attained. Thus, the activities were decided to be designed for multiple levels of complexity with the need for the students to reflect on what they have learned, dividing them into three phases: Exploratory, Activity, and Reflective Questions while getting feedback from the system. Drill and Practice method along with active learning strategies were proposed to ensure active participation of the students in all the phases. The skill acquisition of spatial thinking was proposed, though this won't really be tested.

It was decided that the AR application will be used as a teaching aid to explore the taught concepts while practicing a few problems, to bring in curiosity among the students (Miller & Dousay, 2015). Moreover, among the various active learning strategies, TAPP, POE, TPS, and PI were considered to be some of the potential active learning strategies that can be kept optional to be utilized while the students performed the AR learning activities.

5. Design Strategy for Instructional Scaffolding

Even though the design proposed is for student-centered learning, from our previous studies it was realised that the teacher as a facilitator would be required in different ways and stages while the students perform the AR learning activities. Implementing the AR application in a holistic approach, it was required to define the role of the teacher while still keeping dialogic interactivity and a student-centered approach. Thus, within the design of the AR application, the role and control of the teacher at various stages of the AR application were defined. While abiding by the reduction of orchestration load for teachers, Cuendet et al. (2013), certain roles were decided and defined to be incorporated at the different stages of the application. The teachers are expected to be the facilitator in the process by guiding the students wherever they get stuck or have doubts. It was decided that to provide authority to the teachers while still keeping a student-centric experience, the teachers can (1) assign the AR tasks, (2) monitor the students' action live, (3) unlock the levels, and/or (4) assess the performance of the students.

6. Design Approach to Design Prototypes

On conceptualizing the design of the ARLE, along with all the assumptions, the low fidelity, followed by high-fidelity prototypes of the design were created to be tested with the users. The information architecture provided a holistic view of the techno-pedagogical design to be implemented in the classroom. Several paper prototypes and low-fidelity prototypes of the UI were created before developing the application on Unity using ARCore SDK. The final designed prototype will then be tested with the users for its usability testing. While referring to the heuristics for evaluating the usability of the AR application (Endsley et al., 2017; de Paiva Guimarães & Martins, 2014), multiple iterations of the UI design were created for both the teacher side dashboard and the students' side interface. As the design solution involved the role of the teacher as well as the students, where the students had an active role to play, the information architecture was designed to define the flow and execution plan of the AR application. On determining the steps of execution, paper prototypes with multiple possibilities were designed. The final iteration leads to high-fidelity prototypes.

7.3 The Framework of *ScholAR*

The general framework of *ScholAR* comprises three stages, as shown in Fig. 7.1. This framework has been proposed for the different topics of a chapter that are covered over multiple days in a week or two in the classroom.

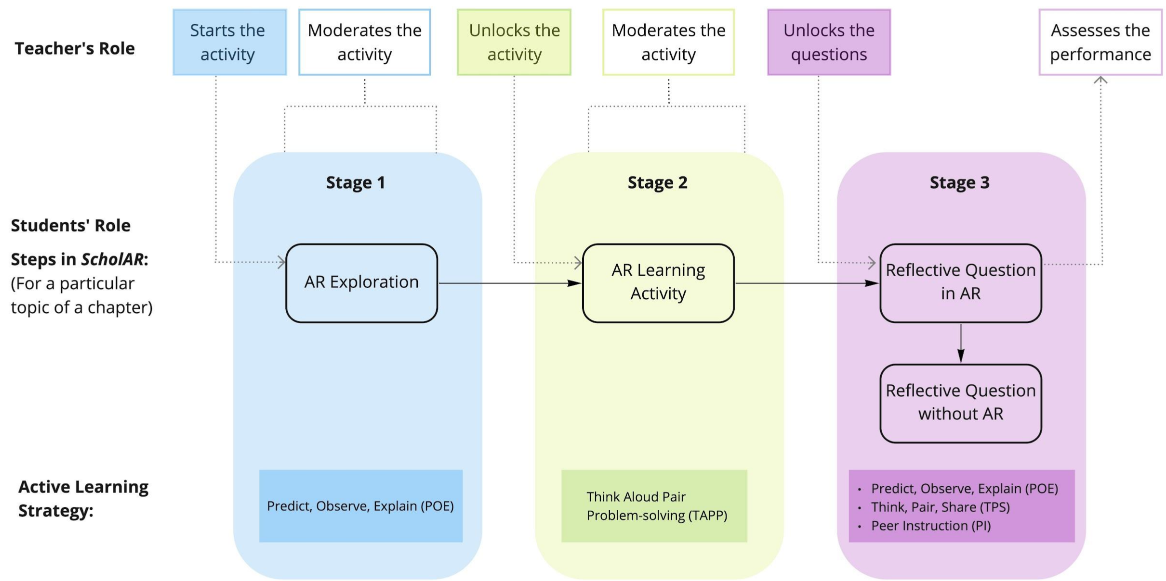


Fig. 7.1. The framework of *ScholAR* application

This AR application is assumed to be used in the classroom while teaching the basics of a topic in the chosen chapter. To begin the *ScholAR* application, the teacher selects from the three stages to be attained in that day's class. The students enter their roll numbers on their respective tablets or mobile phones. On the teacher's side of the screen, the number of students joining the connection is visible. The teacher then broadcasts the exploratory activity. There are three stages and for a particular day, the teacher can select which stages are to be completed. Each of these stages incorporates an active learning strategy when the students perform the activities in the AR space. In the process, the influence of the teacher keeps fading.

The three stages are as follows:

1. **Exploration:** In this stage, the teacher has the authority to start the activity. On broadcasting the activity, the students get to see a 3D virtual object as an example to explain the concept behind the topic. The students explore the object and the related concepts by moving around it and manipulating the concerning values or parameters. In the process, the active learning strategy of *Predict, Observe, Explain (POE)* is followed where the teachers can verbally pose a question for the students to predict its answer. The students can observe the answer by manipulating the content using the applicable interaction, viewing, or moving around the 3D object. This is followed by the explanation provided by the students for the choice of their answer. During the entire process, while the students explore themselves, the teacher moderates it to clear any doubts or confusion arising.

2. **Learning Activity:** This stage involves performing the AR learning activity. This learning activity is a non-evaluative one that the students perform when the teacher unlocks it for everyone in the class. Through the active learning strategy of *Drill and Practice* or *Think Aloud Pair Problem-solving (TAPP)*, the students in dyads play and keep switching the roles of problem-solver and listener while solving the AR learning activity. In the process, they discuss the probable solutions. For a topic, this stage can have closed or open-ended questions. For closed questions, the system instantly provides feedback on the correct or wrong answer(s). On the other hand, the answers to the open-ended problems are submitted to the teacher, who evaluates them later. During the process, the teacher acts as a facilitator to help students when they are stuck.

3. **Reflective Questions:** The final stage involves two forms of reflective questions:

    a. **Reflective Question in AR:** This includes a reflective question that is shown in the AR environment. The 3D object is supposed to be observed while answering the question. Before the students submit their answers, either of the three active learning strategies can be followed: *Predict, Observe, Explain (POE), Think, Pair, Share (TPS),* or *Peer Instruction* (PI). In POE as explained earlier, the students predict an answer, then observe it in the AR space and explain the reason for choosing the answer. In TPS, the students first think of the possible answer individually, then discuss it in pairs to arrive at a consensus, and share the answer with the entire class. In PI, the students answer individually using clickers or raising hands while showing the option number. They then convince their neighbour or peer about the chosen answer and tell the revised answer. The teacher then tells and describes the correct answer. On submitting the answer, the system also gives feedback about the correct and wrong answers.

b. **Reflective Question without AR:** In this question, the students answer the question as shown on the screen, having multiple options to choose from. It is devoid of the AR space and the 2D representation of the 3D object is shown. There is no facilitation of the teacher involved in this stage. The students take a call on the answer by discussing together. On submitting the answer by clicking on the probable answer, the system shows the correct answer to that question. In the end, the combined score of both reflective activities is shown.

7.4. Conjecture Map of *ScholAR 2.0*

Based on the identified design features, the conjecture map was revised as shown in Fig. 7.2. The rectangles in grey indicate features that were revised in the second version of *ScholAR,* leading to an addition in the mediating process.

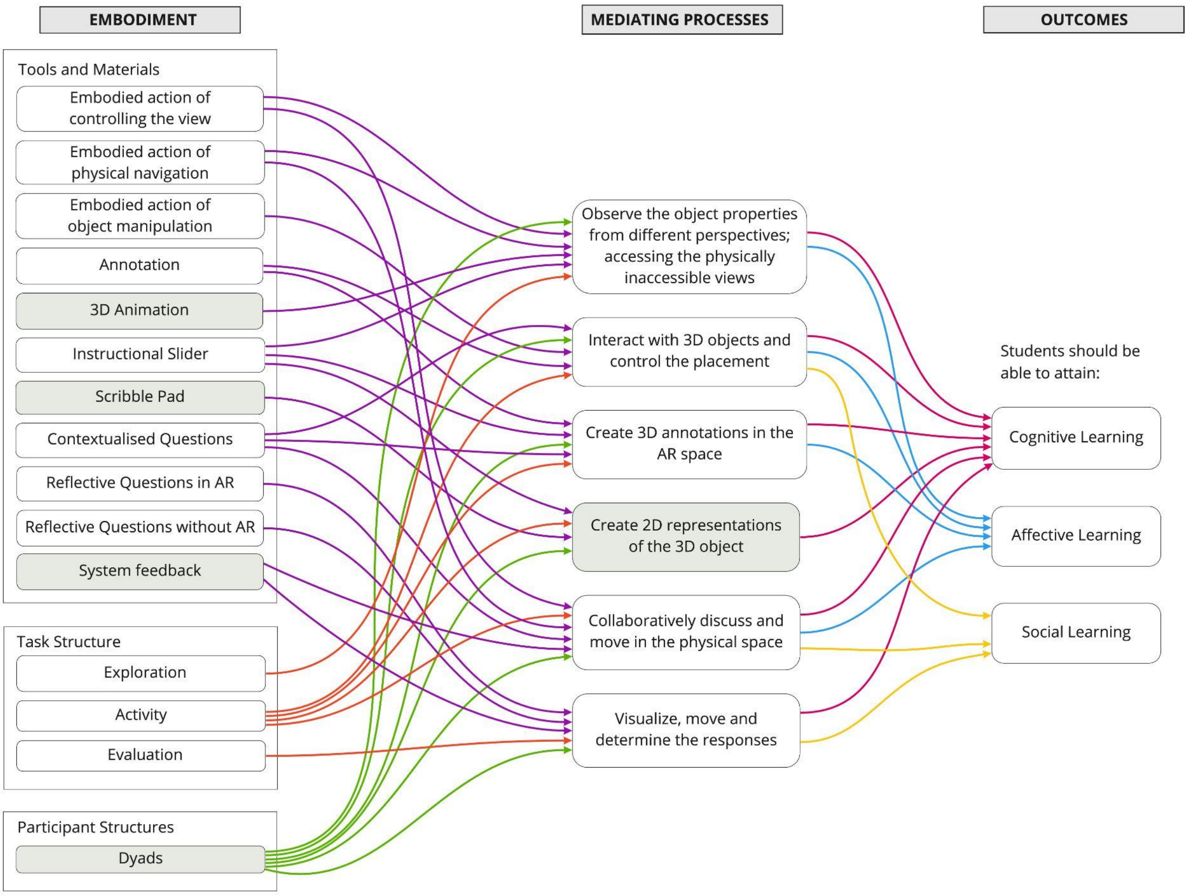


Fig 7.2. Conjecture map of *ScholAR 2.0*

The design conjectures for *ScholAR 2.0* are as follows:

1. If the students in dyads use the embodied actions of controlling the view, physical navigation, 3D animation, and the instruction slider to explore the content, they will be able to observe the object properties from different perspectives which will enable accessing the physically inaccessible views.

2. If the students in dyads use the embodied actions of object manipulation, annotation on the augmented object, and contextualised questions to perform the activity, they will be able to interact with 3D objects and control their placement.

3. If the students in dyads use the annotation, the instruction slider, and contextualised questions to perform the activity, they will be able to create 3D annotations in the AR space.

4. If the students in dyads use the instruction slider and the scribble pad to perform the activity, they will be able to create 2D representations of the 3D object.

5. If the students in dyads use the embodied actions of controlling the view, physical navigation, contextualised questions, and system feedback to perform the activity, they will be able to collaboratively discuss and move in the physical space.

6. If the students in dyads use the reflective questions in AR and without AR, along with the system feedback to do the evaluation, they will be able to visualise, move and determine the responses.

Our theoretical conjectures, which we tested in studies 4, 5, and 6 now become:

Conjecture 1:
If the students are able to observe the object properties from different perspectives, interact with 3D objects and control their placement, create 3D annotations in the AR space, create 2D representations of the 3D object, collaboratively discuss and move in the physical space, visualise and determine the responses, then the students will be able to attain cognitive learning.

Conjecture 2:
If the students are able to observe the object properties from different perspectives, interact with 3D objects through active control, create 3D annotations in the AR space, collaboratively discuss and move in the physical space, then the students will be able to attain affective learning.

Conjecture 3:
If the students are able to interact with 3D objects through active control, collaboratively discuss and move in the physical space, and visualise and determine the responses, then the students will be able to attain social learning.

7.5. The Design of ScholAR

The entire system for the study comprised the experimenter's, the teacher's, and the student's sides. The experimenter's and the teacher's sides looked alike. The session would begin with the experimenter generating and providing a unique session ID and giving it to the teacher. The teacher used that session ID and name to begin the session. The START button activates only when the correct session ID is provided. The teacher then selects the topic to be covered that day i.e. Vertices, Edges, and Faces or Nets of Solids. The teachers tell the students to type their names and the same session ID to login. As soon as a student logs in, the teacher can see the names of the students who joined. Once the students join, the teacher can select from the three stages - DEMO, ACTIVITY, QUESTIONS to be covered in that day's class. For the study purpose, all three were selected in a day's session. The teacher then taps on START SESSION to begin. Once the students join, the teacher can see their screens together, their individual progress through individual progress bars, their combined progress bar, and the log of the actions that they are doing throughout. We have provided a markerless AR platform that uses ARCore. Hence, the students begin the AR tasks by first moving their phones to scan the space shown by a grid. On identifying the scanned space, the virtual 3D object appears to superimpose on the real environment in real-time.

Key Global Features

1. **Info Slider:** The students need to follow the instructions that will be displayed on the slider at the bottom left of the screen. After a few seconds, the slider slides back. It can be brought back by tapping the **i** icon.
2. **Screen Share:** A student can seek help from the counterpart and see his/her screen to observe their actions using the screen share. A **blue pointer** appears to help the student share the screen indicate the place where the counterpart must pay attention.
3. **Audio:** By default, the audio is on mute. The students and the teacher can unmute to speak with each other.

7.5.1. The Design of Tasks on Vertices, Edges, and Faces

Stage 1: DEMO

In the Demo stage, the students learn about the formation of a 2D shape i.e. square by joining the vertices, edges, and faces. This is followed by the 3D animation of the formation of a cube from a square. The students can select to see the number of all the vertices, edges, and faces separately or together by checking the needful checkboxes. Below the checkboxes, the derivation of **Euler's formula** (V+F-E=2) applicable for platonic solids can be observed which the teacher explains simultaneously. Similarly, the annotated details of the number of vertices, edges, and faces can be observed for other 3D solid shapes like cuboids, cones, prisms, pyramids, cylinders, and tetrahedrons. In the process, the teachers can follow the *POE* learning strategy by asking the students to predict and tell the vertices, edges, or faces of any given 3D shape, then select that shape and observe its properties, and the students explain the difference in their choice of answer. The derivation and application of Euler's formula can be observed simultaneously. The key interactions involved are tapping and viewing the 3D object by moving around it.

Fig. 7.3. Snippets of the Exploratory phase for the topic of Vertices, Edges and Faces

Stage 2: ACTIVITY

In this phase different 3D solid shapes are scattered in the space around the students. They are asked to choose one of the objects from the scattered ones having a defined number of vertices, edges, or faces. Through repeated practice of counting the asked parameters, the students select the different 3D solid shapes and keep placing them as indicated on the screen. For example, the question slider poses the question, "place the object with 2 edges and 3 faces at the marker", where the students find a cylinder from the scattered objects as its response. The system provides instant feedback on placing the correct or incorrect object by highlighting the placed 3D object in green or red colour respectively. In case of placing a wrong selected 3D object, the students can keep attempting to select and place the right one. When all the intended questions have been answered by the students, they can see the formation of a rocket, which in turn adapts the dynamic properties and motion to launch.

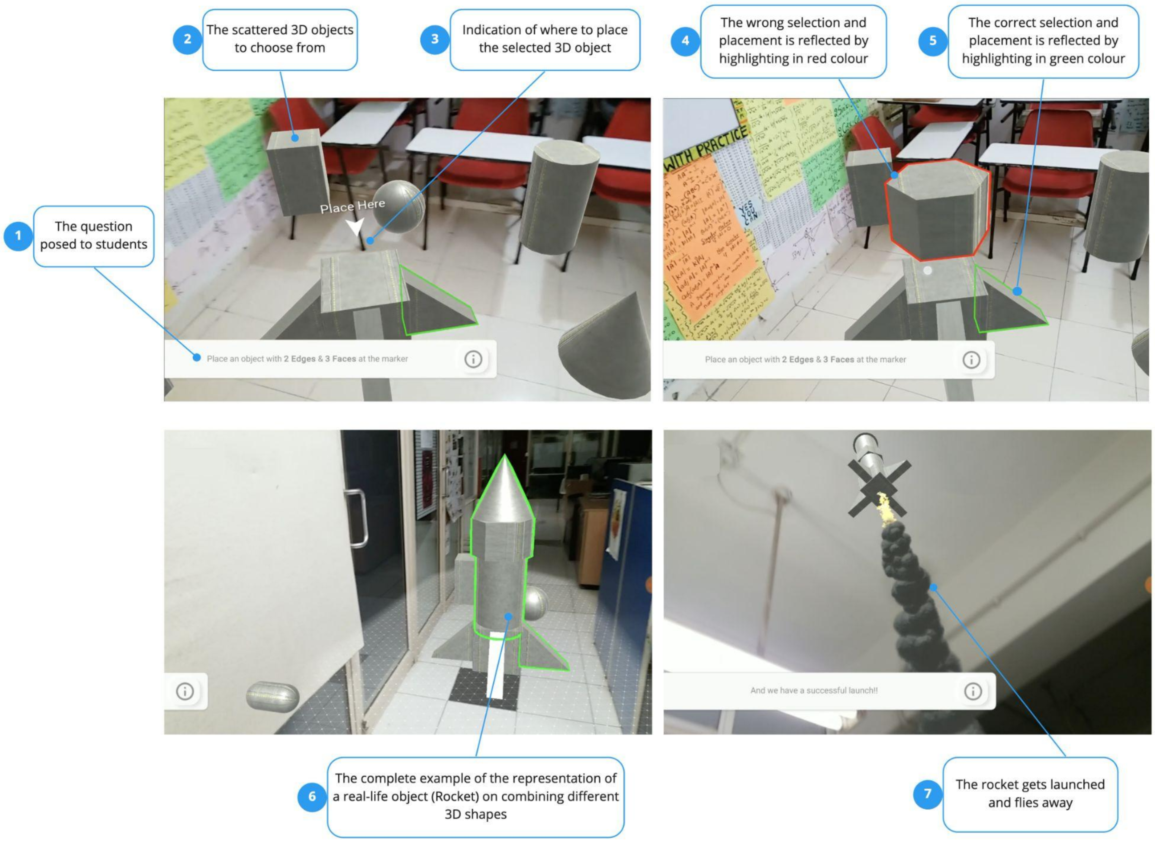


Fig. 7.4. Snippets of the Activity phase for the topic of Vertices, Edges and Faces

Stage 3: REFLECTIVE QUESTIONS

For reflective questions in AR, a slightly complex 3D shape is shown in the virtual space for which the students need to input the number of vertices, edges, and faces. In the process, they view the object from different sides to determine the count. For the final answer that is submitted, the correct answer is indicated in green, and the incorrect answer is indicated in red along with the correct answer.

In the end, another reflective question is provided as a 2D picture like the way the students would generally otherwise answer. An image of the 3D object is shown and the students need to input the answer for the number of vertices, edges, and faces. The AR interaction and teacher's participation are completely withdrawn in this stage. On submitting the answer for every value, the correct and incorrect answers are shown. The activity concludes by displaying the review of the responses.

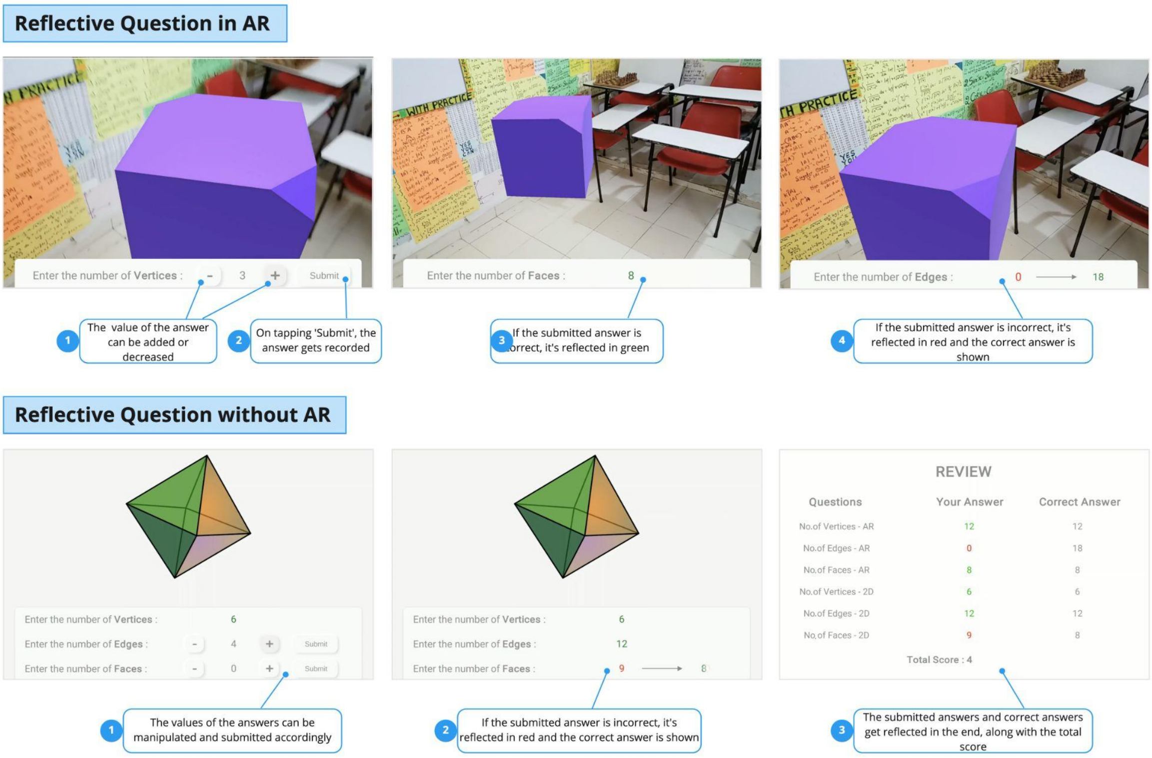


Fig. 7.5. Snippets of the Reflective Question phase for the topic of Vertices, Edges and Faces

7.5.2. The Design of Tasks on Nets of Solids

Stage 1: DEMO

In this stage, a cubical gift box is shown in the AR space and the system indicates to tap on specific faces of the box. With each tap, the box unfolds and the final net of the box is obtained. The students can then move the slider and see the formation of the net from the cube or vice-e-versa. This step is followed by observing the net formation for other 3D shapes. In the process, before seeing the net for a shape, through *Predict, Observe, Explain* learning strategy, the students were asked to predict the net of the shape by drawing in the notebook, then observe the formation of the net in the AR space by moving the slider and then explain the drawn and refined answer.

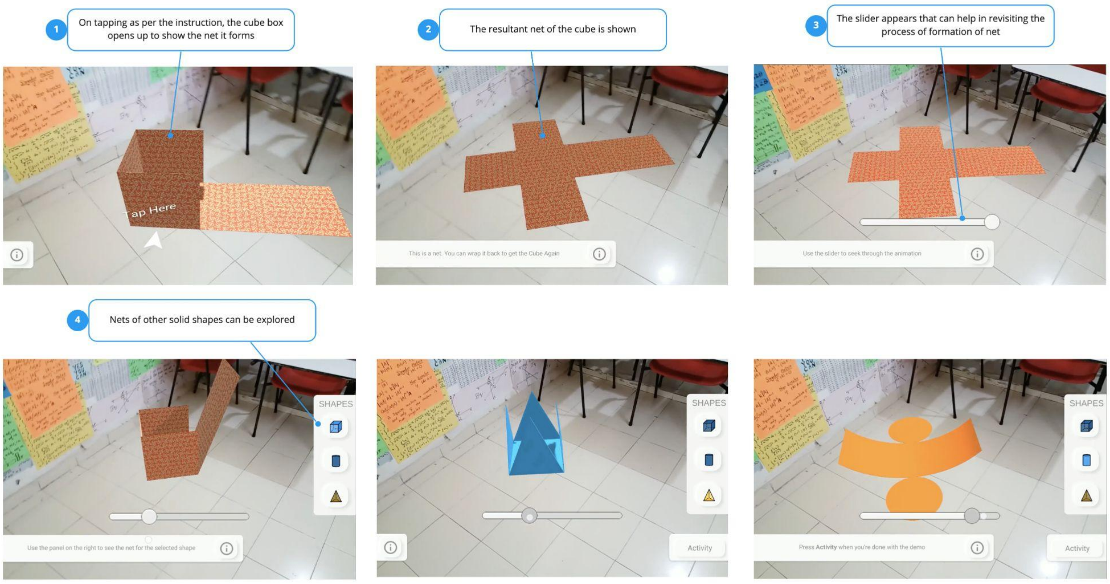


Fig. 7.6. Snippets of the Exploratory phase for the topic of Nets of Solids

Stage 2: ACTIVITY 1

A simple object in the 3D space is shown to the students. The students can discuss, move around the 3D object and draw the net of that object in the drawing space provided on the screen. The students can draw free-hand or use 2D shapes to draw the net. The students can also undo the last action or drawn line, and/or erase the entire drawing to redraw the net. On submitting the answer, the teacher receives the screenshot and can later evaluate the work accordingly. A more complex shape is provided in the next step which follows the same procedure.

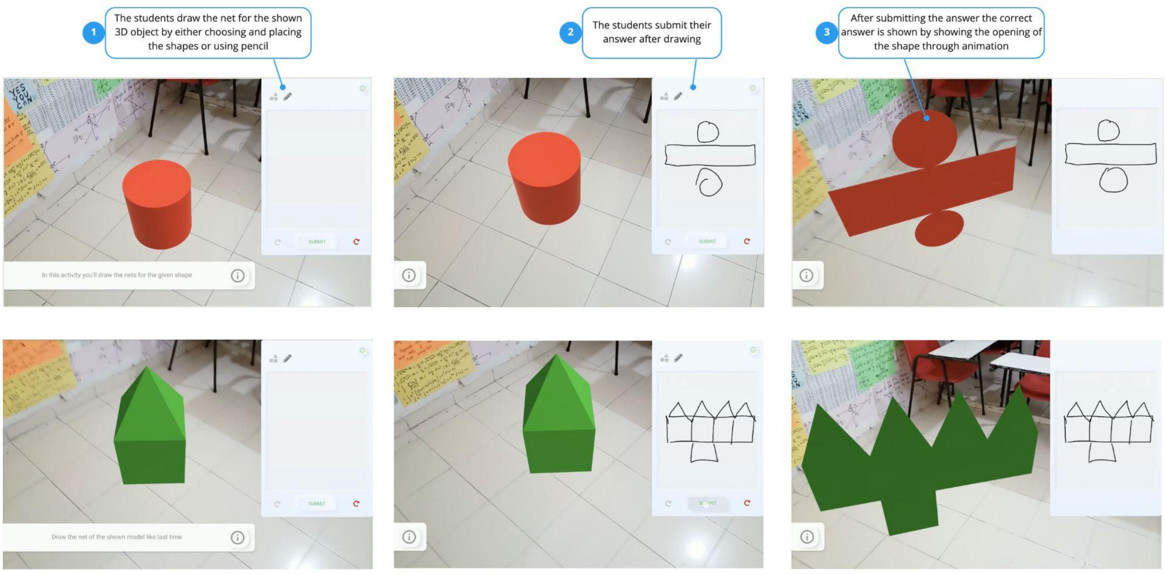


Fig. 7.7. Snippets of the Activity 1 phase for the topic of Nets of Solids

Stage 2: ACTIVITY 2

On the right side of the screen, a cube with various symbols seen from three different sides is shown. The students need to draw the symbols on the given net to obtain this cube. They can use the slider to fold back and open the net and move around to draw on the net. The students can also undo the last action or drawn line, and/or erase the entire drawing to redraw the symbols. On submitting the answer, the teacher receives the screenshot and can later evaluate the work accordingly. The students also get to see the correct answer and can compare their answers. Here the teachers discuss with the students to reflect on their answers.

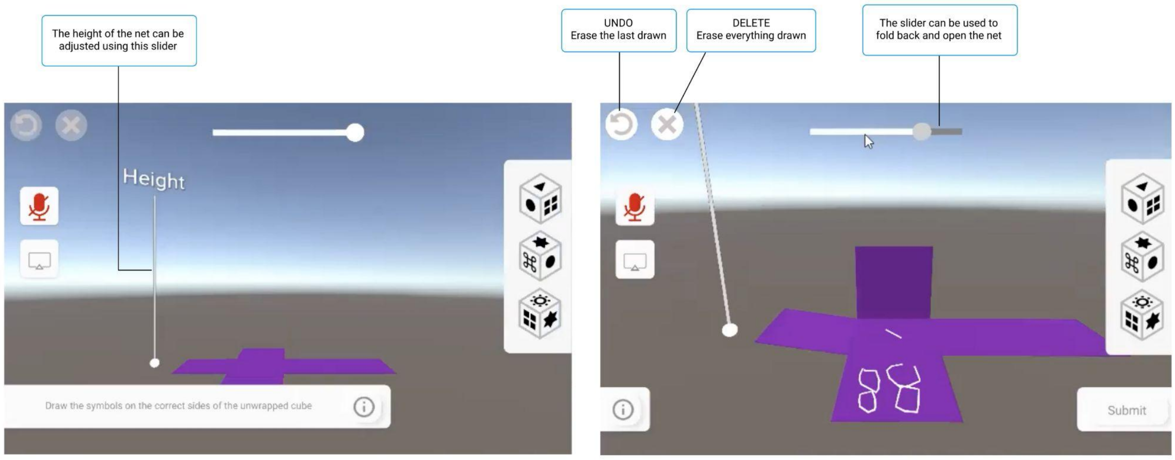


Fig. 7.8. Snippets of the Activity 2 phase for the topic of Nets of Solids

Stage 3: REFLECTIVE QUESTIONS

For the reflective question in AR, a net is shown to the students for which they need to choose from the different options available in the 3D space. To answer this question, the students need to move around the 3D objects to observe them from all sides and answer accordingly. For the final answer that is submitted, the correct answer is indicated in green, and the incorrect answer is indicated in red.

In the end, an image of the cube is shown and the students need to choose the correct net. As the cube has 11 possibilities for forming a net, for this question the visualising ability will be tested at this stage. The AR interaction and teacher's participation are completely withdrawn in this stage. On submitting the answer for every value, the correct and incorrect answers are shown.

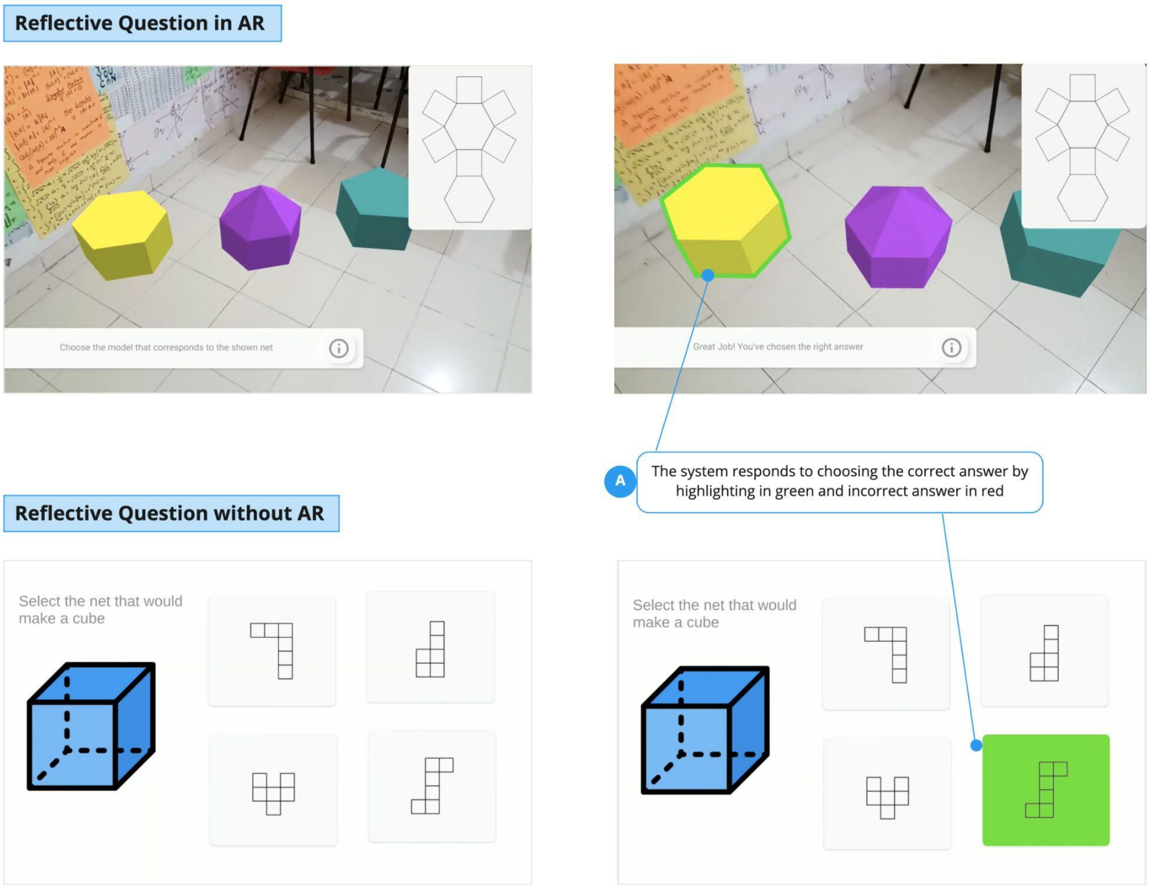


Fig. 7.9. Snippets of the Reflective Question phase for the topic of Nets of Solids

7.5.3. Teacher's mode

The teacher-side application is supported on Windows laptops or PCs. Once the students join, the teacher can see their screens at the same time, their progress through individual and overall progress bars, and the log of the actions that they are doing throughout. The first log indicates the directory in which the log files and the screenshots are saved. If a teacher/experimenter wants to communicate with a student, they can tap on the student's screen. A **blue pointer** appears to help the teacher point at a student's screen and explain to that student as shown in Fig. 7.9.

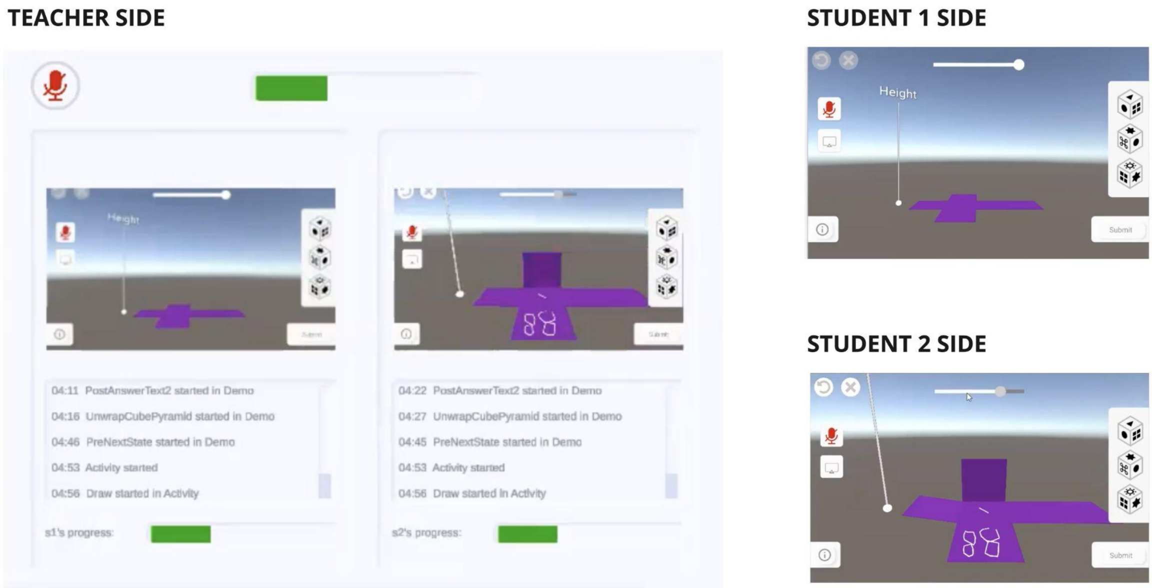


Fig. 7.10. The teacher side of the application

7.5.4. The Desktop Version

Considering the current classroom scenario during the pandemic, the teachers have been sharing their screens while explaining the concepts on a digital whiteboard, by showing videos, and/or using online mathematics tools. All these ways have been explored using the mediums that run on desktops. Hence, considering this current mode of teaching, we designed similar tasks for the desktop version to analyze the difference in the interaction and learning using the mobile AR version. While the desktop version required the students to use keyboard and mouse controls for manipulations, the AR version involved interactions like physical movement around the virtual object and moving a finger on the screen to draw on the virtual object. The keyboard controls involved WASD/Arrow keys for movement, Q and E or 8 and 2 on Numpad to increase and decrease the height respectively. With the mouse, the controls involved holding the right mouse button to look around and scrolling to change the height. With the mousepad of the laptop, the controls involved holding the right mouse button to look around.

7.5.5. Implementation

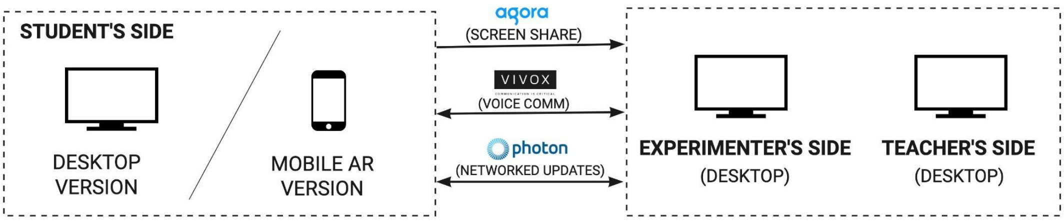


Fig. 7.11. Implementation scheme of *ScholAR*

A session in our experiment involved three different applications, the experimenter's application to initiate and oversee the session, the teacher's side which is identical but without the option of initiating the experiment, and the student side which had the interactive spatial content. All of them were built in Unity 2018.4.23f1.

The experimenter's and teacher's sides were deployed for windows, while the student's application had both windows (desktop version) and android (AR app version) variants. The applications were networked using Photon Bolt, which allowed the teacher and the experimenter to control the student side remotely, mainly to let them progress to the next level and to reset their level in case of errors. Students' interactions and progress in the app were also sent as logs to the experimenter and teacher. Additionally, their screen was broadcasted using Agora SDK and voice chat was supported through Vivox SDK. In order to further improve communication, interacting with another device's screen share through touch/mouse spawned a blue marker at the corresponding screen position in the other device.

For the student-side application, ARcore is used in the android version for 6 DOF tracking, so the spatial movement in the scene corresponds with the student's physical movements. In the desktop version, the movement is mapped to keyboard keys and is similar to first-person games.

7.6. STUDY 7: Evaluation of Lines and Angles Module

This study focused on the following research question:

RQ 3b: What is the effect of the designed module on 'Visualising Solid Shapes' of ScholAR 2.0 on the students' cognitive, affective, and social learning?

7.6.1 Participants and Recruitment

To answer the RQ, a two-group pretest-posttest study was conducted. With the approval from Institute Ethics Committee (IEC), an online study was conducted with 70 students (27 females, 43 males) of 7th grade and 10 Math teachers (1 male, 9 females) from two Indian schools. Due to internet connectivity issues, 5 students dropped in between. Thus, the analysis of the final 65 students (26 females, 39 males) participating in the entire study has been presented. The students belonged to the age range of 12-13 years (M=12.25, SD=0.43). The average age of the teachers was 40 years, with an average of 17 years of teaching experience. All the participating teachers and only 24.61% of the participating students were familiar with AR. The 65 students were randomly divided into two groups, where one was the experimental group, and the other was the control group. The experimental group comprised 33 students (15 females, 18 males) who performed the AR tasks on mobile phones collaboratively in dyads. One male student had to continue individually due to the dropout of the partner in between. Thus, the data of this student has not been considered in further analysis of this work, resulting in the consideration of the remaining 32 students in the experimental group. The control group comprised 32 students (11 females, 21 males) who performed similar designed tasks in the current classroom teaching method at the time of the pandemic, i.e. the Desktop version.

7.6.2 Procedure

Before the study, informed consent was taken from the teachers, students, and their parents. They were also informed that all the sessions will be recorded. A questionnaire was given to the students to collect the details of age, gender, familiarity with AR, and previous mathematics marks. For the teachers, the details of age, gender, familiarity with AR, present technology types used in online and offline teaching, and years of teaching experience were collected. Additionally, a 1.5 hours session was conducted with the teachers on *Zoom* to give the demonstration of the *ScholAR* application.

As the study was conducted online due to the pandemic, the sessions expanded for 5 days a week for a student to reduce internet fatigue. The entire study lasted for three weeks. For a week, at least 4 teachers participated, where two teachers were randomly assigned to be in charge of the experimental group, and the other two were assigned the control group. At least 4 students participated in each group in a week who were taught by the same teacher for being used to the teaching style. Thus, at least four parallel sessions were run at the same time which was observed by one volunteer in each group. On the first day, the session lasted for one and a half hours. It began with an ice-breaker session where the students, teachers, and volunteers briefly introduced themselves and mentioned their favorite city, food item, and an experience related to it. For the next 30 minutes, the students were given an introduction to AR and its use in education. This was followed by a 30 minutes demo session of a few existing AR applications and the features incorporated in the *ScholAR* application. On the second day, the students were divided into the experimental (AR app) and control (desktop app) groups. The teacher in charge of each group taught the topics of Vertices, Edges and Faces, and Nets of Solids in a regular manner. On the third day, the students answered the pre-test questionnaire for around 30 minutes. They then performed the tasks of the *ScholAR* app on Vertices, Edges, and Faces along with the teacher in charge, which lasted for around an hour. On the fourth day, the students performed the tasks on Nets of Solids for around an hour. On the fifth day, the students answered the posttest and the immersion questionnaire. This was followed by rating their experiences and focus-group interviews.

7.6.3 Data Collection and Analysis

The aim was to study the way the design strategies of this module led to cognitive, affective and social learning. In order to answer the research question, certain instruments were used to collect the data.

1. The online study was recorded to capture the interactions and actions of the participants while they solved the designed tasks.
2. The experimenters also noted their observations which included the immediate observable behaviours, doubts raised, controlling actions and discussion triggers with peers and teachers.
3. While the students performed the tasks, the log of their actions, progress, and submitted answers were saved in a directory file.
4. The students were given the pre-test and posttest papers as Google Forms to evaluate their learning performance. Both the questionnaires comprised equivalent questions which were designed to test the students' learning in terms of 'understand' and 'apply' cognitive levels, and 'conceptual' and 'procedural' types of knowledge as per the two-dimensional taxonomy framework as proposed by Anderson & Krathwohl (2001). Thus, two questions from each of the four categories - Understand Conceptual, Apply Conceptual, Understand Procedural, and Apply Procedural were made. Before the

study, the questionnaires were validated by two Math teachers for comprehension and clarity of the questions.

5. Moreover, we wanted to measure the perceived immersion of the students while performing the tasks. Thus, an immersion questionnaire inspired by the Augmented Reality Immersion (ARI) questionnaire (Appendix E.3) was created which comprised 21 questions on three scales - engagement, engrossment, and total immersion. It needed to be answered in the 7-point Likert scale of Agreement. Though the questions were originally designed for location-based AR, we found them to be appropriate in our context of the study, with slight modifications. Engagement (interest and usability), engrossment (emotional investment and focus of attention), and total immersion (presence and flow) are the three constructs of the ARI questionnaire. These variables assess how immersed the users are while using an AR application.
6. To measure the perceived usability of *ScholAR*, both groups were provided with a System Usability Scale (SUS) questionnaire (Appendix E.2). It consisted of 10 questions, to be answered on the 5-point Likert scale of Agreement. In the end, focus group interviews were conducted to gather the perceived usefulness of the application.

In order to answer about the impact of using *ScholAR 2.0* on cognitive learning, the pretest and posttest results were calculated. Incentivizing learning using *ScholAR 2.0* leading to affective learning was answered using the immersion and SUS questionnaire, and interview responses on perceived usefulness. The social learning gained from *ScholAR 2.0* has been evaluated through interaction analysis with the lens of learner-learner, learner-content, and learner-instructor interaction.

7.6.4. Results

1) Students' Learning Performance

The pre-test and posttest results were evaluated to analyze the effect on students' learning performance using *ScholAR 2.0*'s module on Visualising Solid Shapes. The descriptive statistics for the normalised results have been shown in Table 7.1. It shows the mean score, standard deviation, paired t-test result of the pre and posttest scores of the control and experimental groups, and independent t-test result of the posttest scores of control and experimental groups. The normality of the data was tested using the Shapiro-Wilk Test.

The group equivalence was done based on the pretest scores, where there was no significant difference between the control and experimental group at $\alpha = 0.05$ ($t = -0.32$, $p = 0.74$).

Table 7.1: Pre and posttest Scores for Control and Experimental Groups

Group	Pretest Mean (SD)	Posttest Mean (SD)	Paired t-test: Sig. p-value	Independent t-test: Sig. p-value
Control	3.88 (1.19)	4.54 (1.35)	0.04	0.04
Experimental	3.98 (1.01)	5.16 (1.10)	0.00	

There was a significant difference at $\alpha = 0.05$ ($t = -2.0$, $p = 0.04$) in the posttest scores of both the groups. For the control group, the difference between the means is statistically significant at $\alpha = 0.05$ ($t = -2.0$, $p = 0.04$). Moreover, at $\alpha = 0.05$ ($t = 3.99$, $p < 0.0004$), the experimental group performed significantly higher after interacting with *ScholAR 2.0*.

2) The perceived usability and usefulness of *ScholAR 2.0*

To measure the usability of the AR and desktop applications provided to the students, the SUS score was calculated. The standard average SUS score is considered to be 68, below which requires improvement in the design and usability of the intervention. The SUS score for *ScholAR 2.0* was 70.11. The SUS score for the desktop version was 68.23. Thus, the SUS score was higher for the experimental group as compared to the control group, indicating the need for amendments in the desktop version. The reasons for the same were mapped with the interview responses.

In terms of likeability, the participants had varied reasons for liking a particular AR learning activity. For both groups, the activity that involved the formation of the rocket was the most liked one as it gave a fun learning experience while going through the drill and practice method to answer the questions and simultaneously constructing the rocket. Activity 2 of Nets of Solids was a challenging task for most students as it needed the time to visualise and draw the required symbols accurately. Moreover, the students were highly satisfied with the feature to share screens with their peers to solve a question on getting stuck. The teachers provided positive feedback on being able to communicate remotely with students and helping them to perform the hands-on tasks. One of the teachers mentioned:

"It was good to see how students were comprehending the information correctly which was coming on info slider and creating the rocket on their own. Students were curious at first when they were selecting different solid shapes then towards the half they had some idea and when they were able to make the complete rocket and launched it inside their room... it was an amazing sight and experience for them."

In terms of the experience of using the AR technology on the tablets, the participants perceived to have been able to focus and concentrate better while performing the AR activities that were based on the syllabus. They realised the affordances of AR by stating that moving around the virtual 3D objects as well as being able to draw on them gave an immersive and engaging experience which is otherwise not possible while seeing a 2D image of a 3D example in the textbooks. Moreover, they perceived that the ability to draw on the virtual 3D objects gave them an experience similar to drawing on a sheet, with a lesser effort to erase a mistake. Thus, the majority of participants preferred learning using AR activities in place of their usual classroom teaching method, which made them copy the taught concepts in their notebooks. They stated that the fun, interesting and active way of learning using the AR activities helped them to "watch, do and learn the concepts" themselves. For the desktop group, though the students enjoyed the activities, they felt a high dependency on the keyboard and mouse controls for manipulation.

3) The level of immersion with *ScholAR 2.0*

The overall Cronbach alpha for the ARI scale was 0.79, with subscales ranging from 0.72 to 0.84, showing acceptable reliability. With the subdimensions of interest, usability, emotional investment, the focus of attention, presence, and flow, the mean values for engagement, engrossment, and total immersion have been shown in Table 7.2. Each of these values seems to be higher than the average of 3.50 for the 7-point Likert scale indicating a good level of immersion.

Table 7.2: Mean value of the subdimensions

Engagement	Mean (SD)	Engrossment	Mean (SD)	Total Immersion	Mean (SD)
Interest	6.25 (0.82)	Emotional Investment	5.59 (1.12)	Presence	5.10 (1.41)
Usability	5.91 (1.13)	Focus of Attention	5.51 (1.27)	Flow	5.18 (1.46)

4) The interactions and interactivity with *ScholAR 2.0*

The interaction analysis has been done for the group which performed all the activities of *ScholAR 2.0* correctly and scored the highest in the posttest to witness the influence of the interactions while performing the AR activities on social learning. These students have been tagged as G1P5S11 and G1P5S12. The analysis of performing the AR Activity stage (Stage 2) using *ScholAR 2.0* has been closely observed through the lens of learner-learner, learner-content, and learner-instructor interactions and has been reported as actions that were generic` across the majority of students or specifically observed in G1P5S11 and G1P5S12.

Learner-learner interaction

While solving the task of the Activity stage on Vertices, Edges, and Faces, the two learners moved around the objects with their respective devices while verbally guiding each other using the audio feature of the app. For example, G1P5S11 was informing the partner about where to look and move for the answer of one of the shapes among the scattered ones.

> *"This shape is kept towards your right. Look to your right, turn to your right!... Yes, the first one, cylinder! Yes, that's the one having 2 edges and 3 curved faces, right?"*

In the Activity stage on Nets of Solids, the first activity involved drawing the nets of the shown 3D object. The screen sharing option was seen to be explored by the students for this activity where G1P5S12 was able to draw the net first and asked G1P5S11 to observe the answer using screen share. Once the screen share was enabled, the G1P5S12 was seen explaining to the partner how the answer was derived.

> *"If we open the cube from this face, we will be obtaining this net. Do you see how it happens? You can draw the same and submit."*

In the Activity stage on Nets of Solids, the second activity involved drawing the shown symbols on each face of the net to obtain the cube shown in the reference. Due to the complexity of the problem, the two were seen to take confirmation from each other while drawing a symbol on any face.

G1P5S11: *"I think the star must come to the left of the circle symbol. We can draw it here (while the screen share is on). What do you say?"*

G1P5S12: *"Let's draw it as of now. We can see if this works"*

The students were also observed taking confirmation while submitting the answers to the reflective questions.

Learner-content interaction

The learners were accessing the screen sharing and the pointer to help the peer reach the same steps in the process being followed. With the slider, the students were observed to open and close the net multiple times. This functionality was especially useful when the symbols needed to be drawn in the second activity of the Activity stage of Nets of Solids. Additionally, they were observed moving around and bending to see the bottom of the 3D objects as the rotation function was disabled. Hence, they interacted with the 3D object in a way they would interact with any object in their physical environment.

Learner-instructor interaction

For the Activity stage of Vertices, Edges, and Faces, the teacher was often seen to be pointing using the pointer and the audio button if a student was finding difficulty in identifying the last object to attach and form the rocket for its launch due to the complexity of the object.

For the Activity stage of Nets of Solids, the teacher prompted the students using the Audio button to explore the drawing board features to be able to draw the answer. Due to the limited drawing space, the teacher was often seen prompting the students to begin from the extreme left of the drawing board and draw the net of the shown 3D solid shape. As the teacher could monitor the entire performance of a student, the teacher prompts were mostly providing directions to the students if they got stuck at any point.

For G1P5S11 and G1P5S12, the majority of prompts were provided in directing them to draw smaller shapes and from the extreme left to bring out the drawn net.

7.6.5. Discussion

This study focused on the design, implementation, and evaluation of a remote AR application for the students to learn the topic of *Visualising Solid Shapes*. Answering RQ3b, it could be seen that the students from the experimental group performed significantly higher after using

ScholAR 2.0. The students using the desktop application stated to feel restricted with the manipulation controls of the keyboard and mouse. Though there were interactions with the 3D object(s), they did not feel much immersed in the process and would often get distracted while using the controls. On the other hand, the experimental group of students felt immersed in the learning process as they felt they were interacting with an actual object. However, at times while listening to the teacher through the audio of the app, the students got distracted and lost the tracking. Thus, the technical aspect of the app can be improved in further versions to take care of the tracking issues.

The Activity stage for both the sub-topics went for a longer duration as compared to other stages. However, the students claimed to have enjoyed the experience and did not feel fatigued in this process. According to them, as they were curious to see the final outcome, they were more engaged in completing the activity without considering the time. This indicated that the AR learning activities need to be designed to bring in curiosity, as was also pointed out by Santos et al. (2013). This would ultimately create an engaging and enjoyable experience for the students.

Based on the results, we could posit, similar to an existing study (Eldokhny, 2021), that our mobile *ScholAR 2.0* app is more effective in supporting learning performance in virtual classrooms as compared to using the existing medium of desktop-based learning method. One of the existing studies implemented POE strategy with AR (Kaur et al., 2018). They claimed that the students ignored the explanation part as the interface required them to write the answer. However, with the pedagogy framework of our application, such a scenario could not occur as the students verbally gave the explanation to the teachers. Moreover, the framework of *ScholAR 2.0* involved the integration of various other learning strategies, making it unique in terms of other applications.

7.7. Summary

In this chapter, with the design of the module on *Visualising Solid Shapes* in *ScholAR 2.0*, we discussed the effect of the adopted design strategies on the cognitive, affective, and social learning of the learners. The effect of the design strategies for the content dimension has been evaluated by the pre-posttest learning gain which was higher for those who performed the AR learning activities. For the incentive dimension, the interest through user perceptions and immersion score were calculated where both the groups showed keen interest and felt immersed in the learning environment. For the interaction dimension, interaction analysis was conducted through the lens of learner-learner, learner-content, and learner-learner instructor. The results indicated the fulfilment of our theoretical and design conjectures. The next chapter discusses the summary of the research work in this thesis, the proposed framework for designing an ARLE, the claims, generalizability, limitations, and recommendations of this thesis.

Chapter 8

Discussion

8.1. Overview of the Research

In this thesis, two iterations of design-based research (DBR) have been reported to characterise the design strategies and create an ARLE (*ScholAR*) for cognitive, affective, and social learning of 7th grade learners. In the analysis and exploration phase of the first cycle of DBR, the key objective was to understand the required design strategies for a classroom-based ARLE. For this, three studies were conducted to iteratively identify the design strategies. To begin with, the expectations of students, teachers, and parents from having an ARLE in the classroom were outlined. Further, the suitable AR interaction mediums that can be used for collaborative AR problem-solving in the classrooms were identified. This was followed by conducting a workshop with the designers of an ARLE, i.e. in groups consisting of an interaction designer, an education researcher, an AR developer, and a middle-grade Math teacher. These design strategies identified from the literature and the workshop conducted with the designers guided us in designing an ARLE (*ScholAR*) in two iterations.

With the help of *ScholAR*, the 7th grade learners could explore the AR content, perform the AR learning activities and answer the reflective questions with and without AR for the topics of *'Lines and Angles'* and *'Visualising Solid Shapes'*. The primary objective of these AR learning experiences was to provide the learners with an authentic context and involve embodiment while performing the AR learning activities. Besides this, the learners could gain (a) cognitive learning while exploring the concepts and solving the problems in AR, (b) affective learning while getting immersed in the process through embodiment, and (c) social learning while collaborating with peers and teachers to solve the problems in AR. Such learning experiences are critical for embedding concepts and practices into pedagogy and aiding learners' key learning processes while performing the AR learning activities. Further, the DBR approach helped in identifying the features of the AR learning activities like embodied controls such as physical navigation, 3D object manipulation and annotation in the augmented space, instructional slider and prompts, etc. In total, two iterations of the two modules of *ScholAR* were developed and evaluated through four research studies as part of the two DBR cycles.

The first version of *ScholAR*'s modules on *Lines and Angles* was evaluated with 21 students in the lab environment, where students either performed the AR learning activities in dyads or individually. The *Visualising Solid Shapes* module was evaluated with 32 students who belonged to either the group performing the AR learning activities or the group learning the same topic using the available physical objects. In the second DBR cycle, refinement of pedagogy, evaluation of the revised version of *ScholAR*'s modules, and development of the final version of the learning environment were done. We reflected upon the effective design strategies, and the corresponding changes required in the design were done. Additionally, the evaluation of the revised design was done with dyads. The revised version of *Lines and Angles* was evaluated with 28 students and *Visualising Solid Shapes* was evaluated with 65 students where the students either performed the AR learning activities or performed similar activities on the desktop version.

8.2. Answering the Research Questions

This section highlights the answers to the research questions addressed in this thesis:

What are the potential design strategies required to create classroom-based ARLEs?

In this research question, we wanted to understand the design strategies that can be possibly adopted to create ARLEs for classrooms leading to cognitive, affective, and social learning.

This research question was investigated through exploratory studies and literature review. The first part of the exploratory study included interviewing the key stakeholders of the education system i.e. students, teachers, and parents about their expectations from a classroom-based ARLE (Study 1). The thematic analysis provided 12 key characteristics of the user expectations falling under the three dimensions of learning:

1. *Visual cues*: Enabling indication of AR elements in the mediums
2. *Familiarity:* Relating with prior knowledge of the associated content
3. *Situational re-generation*: Explaining the working of past events and situations
4. *Exploratory:* Sense of experimenting with the AR components
5. *Immersive:* Feeling of being engrossed in the interaction of elements and learning
6. *Developing interest:* Finding it engaging while the content is explained
7. *Intuitive engagement:* Sense of efficiently understanding in one go
8. *Motivational instances:* Feeling of excitement while experimenting with the mediums
9. *Controlling the dynamism*: Controlling the interactive motion of contents
10. *Interactive content*: Sense of interactivity with the elements of AR
11. *Information delivery*: Instructor and/or system prompting related details and information with the 3D graphics
12. *Responsive:* paying attention to the AR interactions and reacting in a suitable way

Additionally, on the technology front, a few interactions were identified from the literature, implemented, and tested to determine the satisfactory means of use by the learners. *Tap and View*, and *Draw and Annotate* were found to be the suitable interactions (Study 2).

The analyzed results from these two studies became the indicative basis of the workshop activity conducted in groups comprising a teacher, an interaction designer, an AR developer, and an education researcher (Study 3). The analysis of the discussions further provided the potential design strategies for creating an ARLE. Enabling exploration, ensuring immersion, and promoting collaboration were the three key design strategies suggested previously in the literature (Santos et al., 2013). The other design principles suggested in the literature (Dunleavy, 2014; Miller & Dousay, 2015; Santos et al., 2015) broadly fitted into these three design strategies. We were able to classify these three design strategies into the three dimensions of learning leading to cognitive, affective, and social learning respectively, and add more design strategies to these categories through the literature review and the design workshop. Thus, the following potential design strategies were identified for each category, as shown in Table 8.1.

Table 8.1. Classification of the potential design strategies based on the three dimensions of learning

Design Strategies		
Augmented Content for Cognitive Learning	Incentivizing AR Learning Activities for Affective Learning	Interactions and Interactivity in AR for Social Learning
Contextual Content Representation	Ensuring Immersion	Promoting collaboration
Enabling Exploration	Motivating through real-time feedback	Embodied interactions
Content Manipulation	Multi-level challenging problems	Instructional scaffolding

How do the potential design strategies of creating an ARLE incorporate the dimensions of learning?

In *ScholAR*, the design strategies considered for the module of *Lines and Angles* involved contextual content representation by placing the 3D house in the real environment, with the embodied interaction of annotating the lines and angles on the 3D object while physically moving to get the immersive experience of moving inside and outside the house. Three-level questions were given where the students had to identify the angles accordingly. In the process, it was realised that the students had to be provided with instructional scaffolds to guide them in recalling the properties of the different types of angles, which has been emphasised in the literature previously (Fan et al., 2020). The prompts were provided by the teacher wherever required. In this iteration, cognitive learning through pre-posttest and affective learning in terms of motivation score, usability score, and responses on interest in the AR learning tasks were evaluated. The social learning was reflected in the interview responses received where performing the activities in dyads was preferred for being able to confidently answer by discussing with the peer. The analysis of interactions in dyads needed further investigation. With the results of Study 4 where positive scores were obtained for both and the feedback of the teachers received, we could posit that the design of the *ScholAR*'s module on Lines and Angles was leading to cognitive, affective, and social learning with a few amendments required in its design for further ease of use by the students.

The *Visualising Solid Shapes* module of *ScholAR* involved design strategies such as contextual content representation by placing the different shaped 3D objects in the real environment, with the embodied interaction of tapping and snapping the 3D objects one on top of the other while physically moving to get the immersive experience of interacting with the 3D objects like the way one would do with real-life objects. Three-level activities were given where the complexity of the activities increased with each level, and the final level involved time-based questions. However, in Study 5 we found that the time-based activity seemed to have been casually handled by the students as they were selecting the answers randomly to submit them within the stipulated time. A similar observation has been reported in the literature, suggesting that timer at times tends to negatively affect learning (Thamrongrat & Lai-Chong Law, 2020). Hence, amendments were required in the design of the module to further encourage the students to sincerely approach the problem-solving of the AR learning activities.

What are the effective design strategies for the designed modules of *ScholAR 2.0*, leading to cognitive, affective, and social learning?

In *ScholAR 2.0*, the design strategies considered for the module of *Lines and Angles* were similar to the ones in *ScholAR* with a major change in the design implementation where earlier the drawn annotated line would float while changing the perspective. Hence, in the revised version, the annotated lines and angles were made to snap on the 3D house that continues to stay at the same spot while changing the perspective to mark other angles. To study the dimension of interaction, Lag Sequential Analysis was performed in Study 6. In terms of interaction, the learner-learner interaction was found to be the most significant one regarding where to mark the angle on the 3D house. The participants in a dyad helped each other to mark the angles by correcting each other wherever needed. Similar behaviour has been previously reported where dyads have been observed to run into roadblocks and required assistance from group members while constructing relationships between theoretical notions or distinguishing concepts from one another (Lin et al., 2012). Moreover, the participants explored the feature of AR with the ability to move around the house from all sides. In terms of learner-content interaction, the participants in a dyad significantly moved together to change the side of the house and moved forward or backward to scale the house. The other scaling feature of sliding two fingers on the screen was not quite intuitive for the participants. Hence, they had to be often prompted by the teacher to scale the house by sliding two fingers, leading to significant learner-instructor interaction. The significant sequences thus mentioned were relatable to the perceived notions of the participants in the first study. Hence, the peer participation and immersive experience of AR as perceived by the participants in Study 4 could be validated through the significant sequences in Study 6.

In *ScholAR 2.0*, for the module *Visualising Solid Shapes*, the key design strategies involved tap and snap interaction, 3D annotations, animation slider, full-body embodiment, and collaborative actions of students and teachers through audio and screen sharing. In Study 7, to observe the dimension of content and its impact on cognitive learning, the pre-posttest learning gains were obtained for both the groups, i.e. those using *ScholAR 2.0* and those using the similar activities designed for the desktop. The learning gain was higher for the former group. The key reason for the same has been reported previously in the literature that with AR, the flexibility of virtual manipulatives can be combined with the concreteness of physical manipulatives, which is not possible otherwise (Bujak, et al, 2013). The level of immersion, interest, and user perceptions of usability and usefulness were positively reported, indicating its impact on affective learning. Moreover, the intrigued interaction at the learner-learner, learner-content, and learner-instructor levels obtained through interaction analysis indicated the impact of *ScholAR 2.0* on social learning.

Hence, from the results obtained in studies 4 to 7, we are able to posit that the design strategies of *ScholAR 2.0* along the lines of the three dimensions of learning, i.e. content, incentive, and interaction, are leading to cognitive, affective, and social learning.

8.3. CoASAR: A framework of design strategies to create ARLE

The results of the studies conducted in this thesis can be summarised in the generalised CoASAR framework (Fig. 8.1). The framework guides towards the requirements for designing a mobile-based ARLE for the classrooms while considering the three dimensions of learning - content, incentive, and interaction leading to cognitive, affective, and social learning respectively. CoASAR stands for "**Co**gnitive, **A**ffective, and **S**ocial learning using **A**ugmented **R**eality". The framework is spread across three layers from inside to outside, guiding in determining the plausible design strategies in each layer. Considering the analysis of the content required for a chosen topic to be translated to AR is identified, the design of the ARLE module can be defined using the layers of the framework.

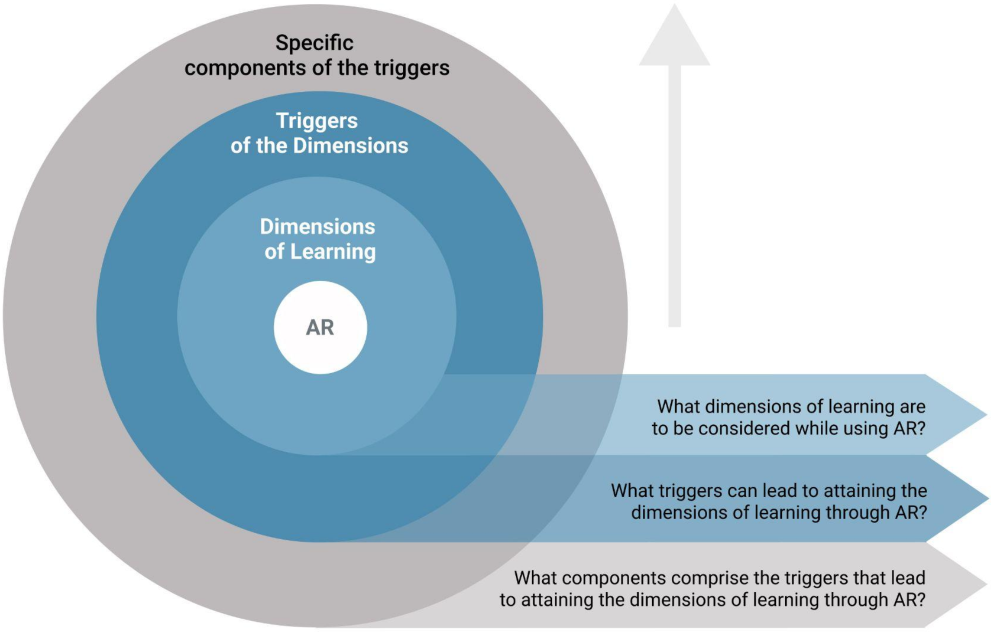


Fig. 8.1. The generalised CoASAR framework of design strategies to create an ARLE

Layer 1, which is the inside most layer, specifies the dimensions of learning to be considered for evaluating the effectiveness of the ARLE to be designed. These dimensions of learning will cater to the learning processes under consideration. The broad RQ for this layer includes:

RQ1: What dimensions of learning are to be considered while using AR?

Moving outwards, layer 2 specifies the triggers needed to be decided to attain the identified dimensions of learning while aligning with the problem context and requirement. For each dimension, there needs to be at least one affordance of AR as the trigger. The number of triggers for each dimension may vary based on the characteristics of a particular dimension suitable in the AR environment. The triggers for a particular dimension may have a dependency on each other. The broad RQ for this layer includes:

RQ2: What triggers can lead to attaining the dimensions of learning through AR?

Layer 3 specifies the specific components of the triggers that will lead to attaining the identified dimensions of learning. Again, the number of components for each trigger may vary based on the characteristics of a particular trigger in the AR environment. The specific components of a trigger are independent based on its individual characteristic and role in the trigger. The broad RQ for this layer includes:

RQ3: What components comprise the triggers that lead to attaining the dimensions of learning through AR?

In this thesis, the results obtained from studies 1-7 helped us in identifying the constituents in each layer of the framework in Fig. 8.1. This resulted in the detailed framework of design strategies considered in this thesis, as shown in Fig. 8.2.

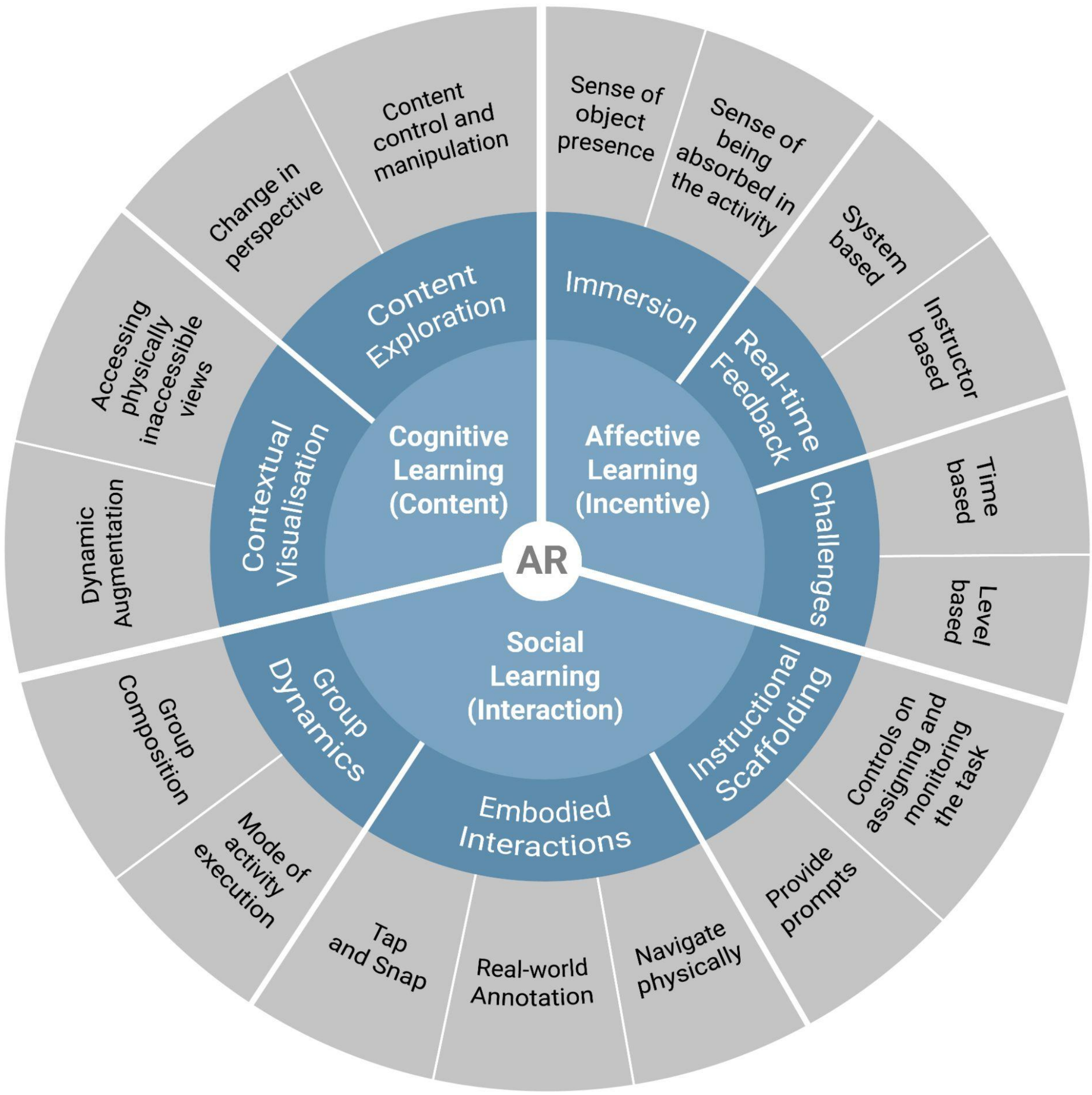


Fig. 8.2. The CoASAR framework of design strategies to create an ARLE

Layer 1 of the framework includes the dimensions of learning that need to be incorporated in the design of an ARLE. Based on the theoretical underpinnings from the literature (Section 2.2.2), we were able to gather the three dimensions of learning proposed by Illeris (2003), namely content, incentive, and interactions that lead to attaining cognitive, affective, and social learning respectively. For each of these dimensions, recommendations on how to design or implement a module in the subsequent layers have been provided. In layer 2, the triggers for each of the mentioned dimensions have been provided. The constituents of this layer were defined based on the co-creation activity with the designers of ARLEs described in Chapter 4 (Section 4.3). Layer 3 highlights the specific components of each trigger, many of which have been considered in the design of *ScholAR* (Chapter 5-7). The recommendations on how to define the triggers of a dimension have been described below:

The 'Content' dimension leading to Cognitive Learning

To bring in this dimension of learning while learning the abstract concepts in AR, two triggers have been identified:

- **Contextual visualisation:** This trigger involves the creation of virtual content (3D graphics, animation, etc.) in a specific context. In the design of *ScholAR*'s module on *Lines and Angles*, the context set was that of a house where the angles were supposed to be identified. In the module on *Visualising Solid Shapes*, the context was that of the classroom where the virtual 3D objects can be placed, and their properties are studied. In order to do so, the following components were considered:
    - **Dynamic augmentation:** It involves meaningful and interactive augmentation of the virtual objects and annotations (Saadon et al., 2020). In *ScholAR*'s design, the dynamic real-time augmentation of the 3D house and the 3D-shaped objects were involved.
    - **Accessing physically inaccessible views:** With the 2D and 3D virtually created content, AR facilitates seeing the unseen (Wu et al., 2013) in the set context. In *ScholAR*, the students were able to explore the properties of all the angles in the virtually created house. Similarly, the learners could explore simple and complex 3D shapes from all angles, some of which may not be available in the real life to observe.

- **Content Exploration:** This trigger involves the modification and examination of the superimposed content for the purpose of conceptual understanding (Yuen, Yaoyuneyong & Johnson, 2011). To attain the same, the following components can be considered:

- **Change in perspective:** The learners could move around the object or themselves to observe the superimposed object and the related properties from different perspectives. For example, the property of the right angle identified on the roof of the house was explained by the instructor with a changing perspective. For the 3D shapes, the change in perspective guided in viewing them from all sides.
- **Content control and manipulation:** While viewing the virtual objects from different perspectives, the learners can be provided with the ability to access and manipulate the virtual content (Bujak et al., 2013). The house in the *ScholAR*'s module could be resized with two fingers. The annotation on the same was possible using an index finger. The 3D objects on the other hand could be opened and closed to see the net by controlling the animation slider. These abilities gave the students the authority and the confidence to control the content and learn at their pace.

<u>The 'Incentive' dimension leading to Affective Learning</u>

To bring in this dimension of learning, three triggers have been identified:

- **Immersion:** One of the key affordances of AR involves immersion where the engrossment in the content enhances concentration and leads to constant engagement (Georgiou & Kyza, 2017; Santos et al., 2013):
  - **Sense of object presence:** The 3D objects in display in the real world aligning with the textbook content must be designed in a way to give the illusion of accessing them in reality. In the Lines and Angles module, the 3D house is present in the real world, and in Visualising Solid Shapes, the 3D objects in the multi-level tasks were created to give a similar experience.
  - **Sense of being absorbed in the activity:** The 3D objects present and the interactions involved, such as moving inside or outside the enlarged object, or dragging and dropping the object, involve the learner in being absorbed in the activity. In *ScholAR*'s module on Lines and Angles, the movement inside and outside the house created the illusion of moving inside an actual house. Similarly, while moving the objects scattered around to form the rocket in the

activity on Visualising Solid Shapes, the learners lifted and placed the objects replicating a real-life instance.

- **Real-time Feedback:** The degree of success while performing an AR learning activity is said to be supported by real-time feedback and scaffolding (Bacca et al., 2018). Thus, the two can be attained in the following two ways:
  - **System-based:** The feedback of the actions is provided by the system dynamically in real-time. This tends to provide the learners with the support of agreement for every action that is performed and gives the scope of understanding and improving any mistake. In the AR learning activities and reflective question stages of *ScholAR* where the learners need to answer certain questions based on their actions, the system provides feedback with the green or red highlights of the correct or incorrect responses respectively.
  - **Instructor-based:** The system tends to provide feedback after an action has been performed. However, before or while an action is being performed by the learners, the validation of the same with appropriate scaffolds and reasoning can be provided by instant feedback from the instructor monitoring the activity.

- **Challenges:** It's vital to employ the AR learning activities in a way that allows learners to access and understand the knowledge and activities contained inside the AR experience and then challenge them with higher-level difficulties (Dunleavy, 2014). Two ways have been identified for the same:
  - **Time based:** The first iteration of *Visualising Solid Shapes* involved time-based activities where the students had to respond to the reflective questions within a stipulated time. In this case, the attentiveness and interaction of the learners seemed to increase in order to provide correct answers within the defined time.
  - **Level based:** The practicing and engaged behaviour of the learners may be created by putting up several connected smaller challenges while demonstrating the associated ideas with the use of overlaid virtual content. In both the modules of *ScholAR*, three levels of the problems were defined, the complexity of which raised with the increasing level. The complexity of the problem can be defined based on the levels of Bloom's taxonomy (Anderson & Krathwohl, 2001)

The ‘Interaction’ dimension leading to Social Learning

To bring in this dimension of learning, three triggers have been identified. These triggers are based on learner-learner interaction, learner-content interaction, and learner-instructor interaction (Moore, 1989).

- **Group Dynamics:** In a classroom-based environment and encouraging collaborative learning using AR, determining the appropriate group dynamics becomes essential. Here, group dynamics has been defined by deciding the appropriate group composition and the mode of executing the activity in collaboration. These two components have been described further:
  - **Group composition:** While the literature suggests the formation of groups to collaborate and perform the AR learning activities (Santos et al., 2013; Bujak et al., 2013), deciding the number of learners in a group becomes crucial. The behaviour of the group seems to differ accordingly. The *ScholAR*’s effectiveness in collaborative learning was explored in dyads (study 4, 6, 7), triads (study 2), and groups of four (study 5).
  - **Mode of activity execution:** As derived from study 3, different modes of execution in terms of using the mobile device and the type of dependency on the content for a group become a deciding factor. The activity content may have similar or different activities for all the groups. In *ScholAR*, the same AR learning activities were performed by all the groups on the tablets. The approaches to solving the problems differed on the basis of the interactions involved. The instructor also had a tablet to monitor the groups’ shared screens and used a pointer on a group’s screen to guide them further.

- **Embodied Interactions:** The sense of sight and the sense of touch supports the elaboration of knowledge where the learners learn by creating associations to make sense of and remember information (Santos et al., 2013). Thus, to bring in the sense of sight and touch, embodied interactions with the AR environment can be introduced, but not limited to, in the following ways:
  - **Tap and Snap:** Multiple objects can be placed by tapping on the object and placing it at the designated spot. This interaction helps in understanding the

spatial presence of virtual 3D objects. The learners were able to place the parts of the rocket (Section 7.4.1) in the *ScholAR*'s module on *Visualising Solid Shapes* with the tap and snap interaction while observing the shapes from different perspectives.

- **Real-world annotation:** The annotation can take place in two ways. The first method involves system-generated information related to the virtual object in the display is superimposed on the real world, which is observed through a mobile screen. In the exploratory activities of *ScholAR*'s module on *Visualising Solid Shapes*, such annotations guided the students to understand the properties of the 3D shapes. The second method involves the ability to annotate on the virtual object. In the *Lines and Angles* module, the student could annotate on the virtual object by dragging a finger onto the screen.
- **Navigate physically:** The full body embodiment is another driving force in the learning process, which involves physically moving around in the learning environment (classroom in our context). The objects and controls in all the activities of *ScholAR* involved the physical movement of the learners to be able to see the properties of the 3D objects from all sides.

- **Instructional Scaffolding:** While the student-centered approach of learning is followed in designing the ARLEs, in a classroom setup, the involvement of the instructors also plays a crucial role (Cuendet et al., 2013). Thus, the instructional scaffolding becomes an essential part of the ARLE design which has been proposed to be carried out in the following, but not limited to, two ways:
    - **Provide prompts:** While performing an AR learning activity, the learners may at times get stuck due to a lack of conceptual understanding, inappropriate interpretation of the problem, or issues in handling the AR technology. In the case of *ScholAR*'s design, the shared screens helped the instructors to provide the prompts in the form of cues using the pointers to help the learners perform the task or use a strategy.
    - **Controls on assigning and monitoring the task:** Due to the different learning styles and pace, the empowerment of access to the content cannot be given entirely to the learners. The instructors must be provided with the control of initiating a task once the previous task has been completed by everyone in the class. Also, the instructor's device showing the live status of the groups'

performance helps them to dynamically monitor the progress of each group. The learners' challenges are then monitored and supported with prompts and scaffolds wherever needed.

8.4. Claims

8.4.1. Towards ARLE Design Strategies

The content of the AR learning activities incorporating contextual visualisation and exploration leads to attaining cognitive learning among the learners. Immersion, real-time feedback, and challenges while performing the AR learning activities lead to attaining affective learning among the learners. Social learning is attained among the learners through learner-learner interaction, learner-content interaction, and learner-instructor interaction by determining the group dynamics, embodied interactions, and instructional scaffolding, respectively, in the AR learning activities.

The design of *ScholAR* involved dynamic real-time augmentation, accessing the physically inaccessible views, change in perspective, and content control and manipulation as the functionalities that help the students attain cognitive learning. In Study 4, 5, and 7, the same was measured using pre-posttests wherever applicable. A statistical difference in the learning gain in all three studies indicated the effect on cognitive learning for the students using *ScholAR*. Further, the designed activities involved multi-level problems involving immersion with the set interactions, and system-generated and instructor-based feedback that led to affective learning. Study 4 obtained the same for the module on Lines and Angles by measuring the motivation and understanding the engagement through interest and usability. The positive motivation score, usability score, and responses for interest in the AR learning activities around the involved design strategies indicated the attainment of affective learning. Similarly, Study 7 indicated the attainment of affective learning for the module on Visualising Solid Shapes. Additionally, the collaborative interactions of a learner with a peer learner, content, and the instructor, were studied in Study 6 for Lines and Angles through Sequential Lag Analysis and in Study 7 for Visualising Solid Shapes through Interaction Analysis. Both the studies indicated effective social learning due to the defined design strategies.

8.4.2. Towards Learning Design

The learners should collaborate in dyads when performing the AR learning activities.

In Study 2, the students performed the AR learning activities in triads. Though, they collaborated enthusiastically in solving the questions and exploring the mediums, the dominance of two students in a team of three was commonly observed. In Study 4, the students performed the AR learning activities individually and in dyads. Of those who performed individually, the majority stated that they could have performed better and confidently by collaborating with another peer. In Study 5, the students performed the AR learning activities in groups of 4 students. The dominance in leading the physical movement and control of the manipulations in the AR environment could be seen in dyads, where the remaining two followed them. Hence, it was commonly observed that in the case of more than two students, only two engage fully while using the AR application. Others remain distracted or underpowered. Thus, the student's behavior in all these scenarios directed us towards creating the AR learning activities that can be performed in dyads.

8.4.3. Towards *SchollAR*

***SchollAR* pedagogy promotes learners to simultaneously engage with situated concepts, embodiment, and problem-solving. With practice, the learners are able to attain cognitive, affective, and social learning using *SchollAR*.**

SchollAR and *SchollAR 2.0* were designed as instantiations of the design strategies to support learning via authentic context and embodiment. We provided affordances such as physical navigation, annotation, object manipulation, animation controls, and multi-level contextualised questions. This was targeted to trigger cognitive, affective, and social learning in the learners. Studies 4 to 7 indicated that with the help of the designed modules of *SchollAR*, the students were able to use the AR affordances and gain cognitive, affective, and social learning. Further, the learners reported that practicing on such a medium would help them in visualising the concepts for real-life scenarios and solving the related problems.

8.5. Generalizability

The thesis work was set to determine the design strategies for an ARLE, to design one, and test its effectiveness on the three dimensions of learning. Thus, the central idea of the thesis has been the design strategies identified and the claims based on the results of the experiments that tested the effectiveness of *ScholAR*. Hence, the generalizability of the thesis is being discussed at two levels around the aspects of design strategies and the design of *ScholAR*.

8.5.1. Generalizability of the design strategies

Establishing generalizability of claims about testing effectiveness of design strategies

The generalizability of claims about testing effectiveness of the design strategies is mainly governed by the learners and the instrument. The instrument was very specifically designed to cater to the requirement of assessing conceptual and procedural knowledge in 7th grade curriculum. Thus, the claims can be generalised for specific types of knowledge from courses with a similar pedagogical requirement for 7th grade population.

Moreover, the generalizability of the design strategies for factors such as learner age and learner characteristics would need further investigation and may form as future directions of the thesis research work.

8.5.2. Generalizability of *ScholAR* Design

The design of *ScholAR* for problem-solving is based on supporting the three dimensions of learning which include content, incentive, and interaction. The triggers for these dimensions have been identified based on the inputs from literature, key stakeholders' recommendations (teachers and students), and designers' process of creating an ARLE. *ScholAR* has currently been instantiated and evaluated for two Geometry topics of 7th grade that require visualisation of the concepts. These two topics include *Lines and Angles* and *Visualising Solid Shapes*. Here we examine whether the design is generalizable for other learners, topics, and contexts.

Generalizability Related to Learners

The quantitative and qualitative analysis of data gathered regarding the learners' experiences with the pedagogy and the learning environment guided the design decisions of *ScholAR*. The learners in the study were 7th grade students who had prior exposure to technology mediums being used in the classrooms. Considering such classrooms, the studies to evaluate the effectiveness of *ScholAR*'s modules on students' learning were done in rural (study 6), peri-urban (study 4 and 5), and urban settings (study 7). Though the pace of interacting with *ScholAR* varied with the demographic setting, the ease and challenges in performing the AR learning activities were similar. Additionally, the instructional scaffolding in the regional or preferred language further guided the execution. Thus, the design of *ScholAR* and the required scaffolds are generalizable for learners across different demographics.

Generalizability to Other Topics and Domains

The design and scaffolds in *ScholAR* depend on the underlying design strategies to guide problem-solving that requires visualisation of abstract concepts. The problems chosen in *ScholAR* derive their context from the domain of Geometry, which is heavily based on the visualisation of the taught concepts. In the existing modules of *ScholAR*, the complexity of the problems has been increased subsequently within three stages i.e. AR exploration, AR learning activity, and reflective questions (with and without AR). Additionally, Study 2 and Study 3 observed the influence of the interaction mediums and design strategies respectively for other topics in the Math curriculum of 7th grade. These topics included Symmetry and Congruence, Probability, Fractions, and Mensuration (Area and Volume) which require visualisation of the concepts at various stages. Thus in these topics, the pedagogical requirements such as translating the visualising concepts to AR activities, mastering multi-level procedural tasks, applying the interaction mediums, defining the group dynamics and the instructional scaffolding were applicable. This may be expanded to more challenging topics in Mathematics such as Trigonometry. Additionally, there are topics from different domains in the literature in which similar defined pedagogical requirements may be applicable such as the ones listed below:

- Chemistry: Atoms and molecules, lab experiments
- Biology: Human anatomy, DNA, botany
- Physics: Electromagnetism, elastic collision
- Language: Words and meanings, prepositions, action-verbs
- Geography: Solar-system, plantation
- History: Historical incidences

However, the applicability of the ScholAR pedagogy in the above domains and topics remain to be examined and may be taken up in the future directions.

Generalizability to other contexts

We instantiated our design and scaffolds into ScholAR where the students could use the scaffolds and interact with the content, peers, and instructor to solve problems. The iterations of the designed modules were tested in the lab and classroom settings where the students collaboratively explored the AR learning activities with the limited number of tablets available. In the near future, on acquaintance with AR, the activities may be designed for self-learning purposes, where the students can begin to explore the content all by themselves beyond the classrooms. Once the activities are learned in the classroom along with the peers and instructors, more practice AR learning activities may be designed to be explored individually at home. This would further entail learning via practice.

8.6. Limitations

This section highlights the limitations of the research conducted in this thesis:

8.6.1. Limitations related to learner characteristics

This research work is scoped to 7th and 8th-grade students from Indian urban and peri-urban schools. The work lacks exploring if the same *ScholAR* pedagogy would be effective for the learners at other school levels or college levels. The medium of instructions in the AR application is English, though the instructors and students could use the language they were comfortable in, while communicating with each other. The implementation of the AR application in any regional language was beyond the scope of this research.

Learners at different levels will have varied attributes connected to problem-solving and even the comfort of working in an AR environment, such as motivation, curiosity, self-efficacy, and so on. This thesis does not go into detail on how these learner attributes affect students' success while participating in AR activities. Additionally, the thesis does not cover the cognitive processes involved in learning using *ScholAR*. While we tried to ensure a mixed spread of gender in every study of this thesis, the influence of the use of AR technology on gender has not been considered in this work.

8.6.2. Limitations related to the context

The research work has been done in the context of Indian school education. *ScholAR*'s modules have been designed to be used by the students in classrooms, while the teacher acts as a facilitator. It is intended to be used as a supplementary learning material in the classroom, designed as per the academic curriculum. In the research, it was considered that AR technology is explored by the students while working collaboratively. Thus, the context can be elaborated in terms of making it a part of the academic curriculum and can be spread across different academic levels.

8.6.3. Limitations related to topics and domain

The topic chosen is critical in developing and exhibiting problem-solving skills using AR. *ScholAR* covered two topics in its design, i.e. *Lines and Angles* and *Visualising Solid Shapes* as they are more inclined towards involving the visualisation of the concepts. It is conjectured that the findings of this work may be applied to advanced topics involving the requirement to visualise the concepts. Because the interaction of complex ideas in advanced topics and grades may alter learning in AR through problem-solving, more studies are needed to support this conjecture. Thus, even within the school curriculum, one must critically assess the peculiarities of the topics and domain in order to remark on the generalizability of the findings. Any school curriculum will include a number of courses, each of which will address a different set of skills and abilities. Hence, to build more such modules of *ScholAR*, understanding the depth of the concepts and their execution will be required.

8.6.4. Limitations related to research method

The research questions answered in this thesis helped us in deciding the effectiveness of the design strategies identified for creating *ScholAR*'s modules. In this thesis, for analysis of the results, several methods have been used to appropriately answer the research questions. Broadly, mixed approaches were used that included short-term studies and their qualitative and quantitative analysis. However, another researcher may adopt the approach of conducting longitudinal studies to observe the long-term impact of the modules of *ScholAR* on the learners' cognitive, affective and social learning skills.

In order to build the modules of *ScholAR* supporting cognitive, affective, and social learning we used DBR, a pragmatic research approach that examines the impact of *ScholAR*'s design on problem-solving in AR and aims to iteratively alter the supports in order to enhance the learners' performance. As a result, evaluating the impact of each element on learner's performance is outside the scope of this work; our objective was to optimise the architecture as a whole. However, now that the design has been modified and validated, it is worthwhile to investigate the various components of *ScholAR* to discover which have significant and minor effects on learning performance.

The objective of the thesis was to come up with the design of an AR intervention and a useful theory, for which DBR was found to be an appropriate research method involving both qualitative and quantitative studies. Though DBR involves certain limitations such as deciding when to discontinue the iterative process, the influence of Hawthorne effect while designing and executing the intervention, and discarding certain data due to limited time and resources (Wang & Hannafin, 2005). Moreover, due to a few external constraints such as introducing a new topic, limited number of tablets, limited access to AR supported devices (Study 7) led to conducting quasi-experiments instead of taking the classic experimental approach.

The emphasis of our investigation is on how learners engage with *ScholAR* for topic-specific problem-solving. The cognitive, affective, and social processes that developed from learners' interactions with *ScholAR*, as well as how they led to the solution of the problem, have been studied. However, how interaction with *ScholAR* aids learners in learning how to tackle such new problems would need many encounters with *ScholAR*. The frequency and nature of such interactions can be investigated more in the future.

8.6.5. Limitations related to collaborative activity design

The learners were encouraged to perform AR learning activities in collaboration. As the studies tested the students' interactions for different group compositions and individually, the AR learning activities were designed independently of the actions of the group members. The role of the students within the groups was not defined while they explored the activities during the learning process using *ScholAR*.

8.6.6. Limitations related to the tools and technology

In this research work, the development of the technology-enhanced learning environment has been created with the support of the Unity engine and Google ARCore SDK. The AR implementation is *markerless*, which gets triggered by scanning the surrounding environment, without using any fiducial marker (Brito & Stoyanova, 2018), designed for Android-based tablets and mobile phones that support Google ARCore. Thus, having ARCore supported devices stood out to be the utmost requirement of the implementation of the *ScholAR* application in the studies conducted in this thesis. There are other different mediums of using AR on mobile devices, such as marker-based and location-based AR, which have not been explored in this thesis. With the limitations of the technology itself, the properties of the designed AR learning activities may differ based on the medium of execution which can be further examined.

8.7. Recommendations for Stakeholders

The findings and contributions of this thesis may be of particular relevance to a variety of stakeholders concerned with the domain of education. In this section, suggestions are being provided on the ways in which the contributions and findings of this thesis might assist these stakeholders in the education domain.

8.7.1. Recommendation for teachers

The teachers can use the designed *ScholAR* application in this thesis to teach the concepts of *Lines and Angles*, and *Visualising Solid Shapes* for 7th grade students and describe their experiences of using the application. They can further think of the ways and propose ideas to create more such ARLEs for different subjects, topics, and grades. The teachers can conduct workshops in the educational institutions on co-creation to design ARLEs and collaborate with other key stakeholders for designing them. Their contextualised inputs regarding the concepts and converting the challenging tasks in the curriculum to AR medium activities can lead to the design of an ARLE targeted at attaining cognitive, affective, and social learning. This can further guide in enhancing the proposed framework of the design strategies that can be validated by conducting longitudinal studies.

8.7.2. Recommendation for interaction designers

The interaction designers may use the characteristic user expectations and the proposed framework in this thesis to design classroom-based ARLEs. The modules of *ScholAR* designed in this thesis can be considered as the initiation examples, and the source of ideas that can be built upon or new such concepts can be designed for other educational subjects, topics, and grades. Additionally, the design strategies, concepts, and the user experience can be defined with the co-creation method explained in Chapter 4, i.e. brainstorming with teachers, AR developers, and education researchers. Further, they can collaborate with the AR developers for the implementation of the defined user experiences.

8.7.3. Recommendation for education researchers

The open gaps identified in the literature review may be taken up by the researchers and experts of educational technology to investigate further and conduct more studies. With gradual upgradation in the use and acceptance of the technology in the classrooms, the user expectations can be evaluated in the evolving times. This may add more to the knowledge body of the required components for designing the AR learning activities while targeting the dimensions of learning. The co-creation method may be explored to define the design strategies. Additionally, the framework may be explored to design AR-based educational interventions that support cognitive, affective, and social learning. The framework may be validated by creating the applications as per the guidelines for different topics, subjects, and grades. Further, the effectiveness of the designed AR intervention on the dimensions of learning can be evaluated. The researchers may conduct longitudinal studies to evaluate the effectiveness of AR on the dimensions of learning with the fading away of the novelty factor.

8.7.4. Recommendation for AR developers

The AR developers may use the characteristic user expectations and the proposed framework in this thesis to follow the design strategies for designing and developing a classroom-based ARLE. The framework defines the components and requirements to successfully support the three dimensions of learning, i.e. content, incentive, and interaction leading to cognitive, affective, and social learning respectively. The AR developers may follow the example of the designed *ScholAR* modules and the recommendations of the framework to design and implement small modules of a classroom-based ARLE. They may follow the co-creation method and the framework to come up with ideas for designing more AR modules in different topics and domains. Further, the types of interactions are not limited to the framework. They can explore and implement more forms of embodied interactions and test them in the classroom environment that can be integrated into the framework to improvise it.

8.7.5. Recommendation for students

The modules of the *ScholAR* application that have been designed in this thesis may be used by the students of 7th grade to explore the specific topics of *Lines and Angles*, and *Visualising Solid Shapes*. In the process, the students must go through the three stages of AR exploration, AR learning activity, and reflective questions. Additionally, students from different grades or educational grades can use this application as an example and/or the framework to further design new applications on other topics and domains. The exploration of the AR technology with its design and development can further encourage the students to create their own ARLEs.

8.7.6. Recommendation for educational institutions

If an educational institute intends to use integrate the use of AR technology in the curriculum, the results of this thesis may be considered for decision-making. In this thesis, two modules using AR have been developed to learn and apply the concepts of *Lines and Angles* and *Visualising Solid Shapes*. Thus, the two modules may be presented as examples to suggest the use of more such ARLEs in the classrooms for other learning domains and educational levels. Moreover, while considering the inclusion of this technology in the curriculum, the educational institutions may consider the results from this thesis regarding the impact of the use of AR application on the learners' cognitive, affective, and social learning.

8.8. Summary

In this chapter, the outcomes of the research questions were highlighted, which were targeted at the beginning of the thesis. The qualitative and quantitative analysis of the obtained results led to the triangulation of the derived conclusions. In the process, the design strategies adopted and the relevance of *ScholAR* in attaining the dimensions of learning were highlighted, which gave rise to the CoASAR framework described in Section 8.3. This framework provides the guidelines for designing a classroom-based ARLE. There are certain limitations to the generalizability of the findings of this study. Both the generalizability and limitations have been discussed in this chapter. This is followed by the recommendations for the key stakeholders of the education domain. The contributions of this thesis and the future work will be described in the next chapter.

Chapter 9

Conclusion

9.1. Contributions

This research work contributes to the existing knowledge of the design and development of Technology Enhanced Learning Environments (TELE), more specifically involving the integration of design strategies to create an Augmented Reality Learning Experience (ARLE) to help the learners in contextually solving problems. The contributions are based on an analysis of the results of studies conducted as part of this research work.

9.1.1. Theoretical Understanding of Design Strategies

In this section, the key contributions of the thesis to theory have been highlighted.

1. This thesis is the first to provide a list of the characteristics of the user expectations from a classroom-based ARLE. These characteristics have implications for researchers in educational technology, designers, and developers who wish to understand the expected AR features and affordances across different subjects and topics while creating a classroom-based ARLE.

2. This thesis provides a detailed characterization of the design process and the set of design strategies for creating an ARLE for classrooms. These characteristics have implications for researchers in educational technology, designers, and developers who wish to understand the design process and decisions involved in creating a classroom-based ARLE.

3. Based on the design strategies adopted by the designers and validated by the researchers, the CoASAR framework for designing an ARLE has been proposed that leads to cognitive, affective, and social learning. We posit that this can help the education researchers, designers, and developers in the design space while conceptualizing and designing an ARLE for classrooms.

9.1.2. *ScholAR* Pedagogy and Learning Environment

In this section, the key contributions of the thesis to pedagogy and learning design have been highlighted.

1. This thesis provides a pedagogical design framework for the AR learning environment that indicates the phases of applying the design strategies. This design can be directly adopted by instructional designers, interaction designers, and developers to design and develop ARLEs and school instructors to teach using the designed ARLE.

2. This thesis proposed several AR learning activities in *ScholAR* that help the learners to solve contextual problems while attaining cognitive, affective, and social learning. This has direct implications for students who can use *ScholAR* independently for self-learning of the geometry concepts outside school and for the instructors who can deploy *ScholAR* in their classrooms or labs.

3. *ScholAR* is an instantiation of an AR learning environment with the pedagogical framework that enables the learners to solve multi-level problems and attain cognitive, affective, and social learning. It can be easily designed for multiple problems in different contexts that involve 3D visualisation of a concept across topics and subjects. This can be adapted by educators and researchers in problem-solving to design ARLEs for their specific type of problem-solving in AR.

9.2. Future Work

In this section, a few aspects of future work have been presented that emerge as a solution to the limitations of this thesis, as mentioned in the previous chapter. While others emerge with the intention of pushing the research agenda of the thesis forward.

9.2.1 Extended Application of Design Strategies

In this thesis, a set of design strategies have been identified for the three dimensions of learning - content, incentive, and interaction that lead to cognitive, affective, and social learning. Along similar lines, design strategies may be identified for any other dimensions of learning that may be leading to attaining any other learning skills such as spatial visualisation, spatial orientation, mental rotation, etc. Additional research can lead to the discovery of design strategies for specific types of content involving 3D visualisation and in specific domains such as mathematics, science, geography, etc. Further, the design strategies may be extended from the context of school education to higher education levels.

9.2.2 Validation of the CoASAR Framework

The CoASAR framework proposed in the previous chapter (Section 8.3) is based on the studies conducted in this thesis. We posit that this framework can be used by the designers of a classroom-based ARLE. Here designer is referred to anyone who is creating an ARLE and may include interaction designers, AR developers, learning sciences experts, education researchers, etc. As part of the future work, the validation of this proposed framework using a multi-method approach is required. The probable research questions for this can be:

RQ: How do designers of a classroom-based ARLE use the CoASAR framework?
RQ: What is the usability and usefulness of the CoASAR framework?

To answer the research questions, triangulation by conducting comparative studies, focus group studies, and longitudinal studies can be done with the designers of ARLEs where they create an ARLE using the framework for varied topics. Further, the potential adoption of the framework in other topics or domains can be evaluated. The framework can be further enhanced to accommodate users with various demands, such as a simplified-layered version for users with little design experience.

9.2.3 Use Learning Analytics to Analyze the Learning Behaviours

Incorporating learning analytics approaches is another viable route for future development. More extensive investigations through repeated measures research can be used to obtain further analyses and behavioural patterns. Understanding learner behaviour and developing their degree of skill in problem-solving will be aided by a combination of exposure to topic complexity and time. A probable research question for this can be:

RQ: How do time-based and level-based problems in AR influence learning behaviour?

It is possible to accomplish it by coding the learner's behaviours using screen-recording data and analyzing it using various learning analytics models. The next step might be to create a prediction model that can guide learners at various degrees of learning accomplishments.

9.2.4 Use of Eye Tracking to Analyze the Cognitive Processes

Another interesting approach for future research is to use eye-tracking to confirm the learners' supposition of cognitive processes when interacting with *ScholAR*, applicable for mobile-based interactions. We can hope to learn more about how and why learners' interaction behaviour influences their learning performance as a result of this research. The probable research questions in this piece of research can be:

RQ: How do different learners behave as they interact with the various features of the ARLE?
RQ: What factors influence the varying learning behaviour of the learners interacting with the designed ARLE?

We will be able to discover the characteristics of high scorers in comparison to low scorers as a result of this comparison. Knowledge of the differences in behaviour of learners with varying degrees of performance may also aid in the refinement of the design and the recommendation of certain learning routes. This research will aid in identifying student characteristics, fine-tuning the system, and providing recommendations for future eye-tracking-based ARLE assessments.

9.2.5 Further Development of *ScholAR*

The impact of *ScholAR* on cognitive, affective, and social learning was investigated in this research in the domain of Geometry and for the topics of *Visualising Solid Shapes* and *Lines and Angles*. The significance of this research's findings is determined by the context of the domain. It is especially critical in the development and demonstration of problem-solving. Thus, one of the future research aspects can involve validating the conjectures of generalizability to different topics and domains. The first step towards achieving this aim will be to select a different topic or different domain for which *ScholAR* modules will be designed.

9.3. Final Reflection

The instantiation of the thesis involved the motivation of bringing together design and learning through AR technology. The literature and a few exploratory studies guided us with the possible design strategies in designing a classroom-based and mobile-based ARLE to attain the three dimensions of learning - content, incentive, and interaction leading to cognitive, affective, and social learning, respectively. These identified design strategies were further used by us to design two modules of our ARLE named *ScholAR*. The two modules were based on the topics of *Lines and Angles* and *Visualising Solid Shapes* in Geometry. The assessment of *ScholAR* pedagogy has been done qualitatively and quantitatively in this thesis. Thus, broadly the effort of the thesis was situated towards identifying the design strategies and using those to design a classroom-based ARLE that can guide the students in learning abstract concepts. To get the intended benefits, we propose that a learner must interact with the modules of *ScholAR* multiple times.

Reflecting on the research processes, the thesis started with two broad goals. With the Design Based Research methodology, the RQs, sub-RQs, literature questions, and design questions kept evolving in each phase and iteration of the DBR cycle. Thus, the journey involves initiating with a broad goal and converging with exploratory investigations, design, and reflection to arrive at the proposed framework. This journey has been evolving with time and experience and has helped me in raising my curiosity for knowledge and growing as a researcher. The process has many learnings involving patience, sensitivity, having a critical perspective and realization of the facts of the situation, and closely observing the unexpected to be able to add to the pool of knowledge.

Appendix A

Consent Forms

Appendix A.1

Consent Form (Parents)

	Informed Parental Consent Template for Research Involving Children (Qualitative Studies)	Document No	IITB-IEC/2019/019
		Revision No	0
		Page No	Page 1 of 5

Informed Consent Form for parents of middle school students (grades 6-8) participating in the study.

Study Title: Investigating students' spatial thinking and creativity through collaborative problem solving using Augmented Reality.

The research study involves investigating spatial thinking and creativity of middle school students while they are engaged in collaboratively solving problems using Augmented Reality.

This research is being conducted by Jayesh S. Pillai (PI), Assistant Professor at IDC School of Design, IIT Bombay.

This Informed Consent Form has two parts:

- **Information Sheet (to share information about the study with you)**
- **Certificate of Consent (for signatures if you agree that your child may participate)**

You will be given a copy of the full Informed Consent Form

Part I: Information Sheet
Introduction
I am Jayesh S. Pillai, Assistant Professor at IDC School of Design, IIT Bombay. I am here to invite your child to participate in a research study which will give your child a chance to solve simple mathematics problems in collaboration using Augmented Reality.

Purpose
Students are introduced to a lot of new concepts which are difficult to visualize. This is particularly true if they have to imagine some day to day scenario to solve course curriculum problems. Thus, this study aims at understanding the challenges that middle school students face while imagining to understand new concepts and solve problems. The study further focuses on how an immersive experience using Augmented Reality technology can help them in doing that. Participation in this research will help them in enhancing the spatial thinking and creativity while solving real-life problems using Augmented Reality.

Type of Research Intervention
The intervention involves the design of a digital and tangible AR application (to be used on tablets/phablets/mobile phones) in Mathematics as per the syllabus of CBSE board with small activities to test the learning abilities using Augmented Reality for the students of class 6 to 8.

This may be later generalized across subjects and classes. Hence, AR can be helpful for students in having shared learning experience through spatial visualization and interactive collaboration.

Selection of Participants
All students are welcome to participate in this research study. No prior knowledge is needed.

Voluntary Participation
The participation of your child in this study is completely voluntary and you are free to choose if your child should participate in the study or not. We hereby reassure that your child will receive all the services they usually do, even if they do not participate in the study. It would be helpful to include your child for their input into the decision. Participation in this research will **not** have any direct effect on your child's grade in the school. Voluntary participation of your child in this research will greatly help us advance our understanding of how middle school students think and enable us to create resources for helping them improve their spatial thinking and creativity using Augmented Reality.

Procedure
On giving the consent for conducting the study, questions related to their knowledge about existing technologies will be asked. They will then be made to sit in groups and given a tablet/mobile phone with the Augmented Reality application. They will need to solve few problems shown in the application. These questions will be based on the topics of their curriculum. The learning experience of students using the AR technology will be recorded using pre and post-tests of the topics that will be covered while testing the use of the application. Observations and questions based on the usability of the intervention will be made. Questions based on the perception of the users in using the intervention will be asked. Audio/Video recordings of the interactions with the digital intervention will be taken. Students may be asked to maintain a reflective journal to pen down any new solution they may think of at any time other than the time of the experiment. Pilot study will be conducted at a lab in IDC and field study will be conducted in the school's classroom.

Duration
The duration of the study may vary from 1 day (max.1 hour session) to 1 week (1-2 hour sessions per day) depending on the total time available for student work. It will be ensured that it does not hinder other academic or non-academic endeavours of the child.

Risks and Discomforts
The risks involved in this study are minimal and are the same as one would face in their daily life.

Benefits
Participation in the research study will give your child a chance to solve simple mathematics problems in collaboration using Augmented Reality technology. Your child may learn about this technology while solving real-life problems, that may further help in enhancing the spatial thinking and creativity. There will be no monetary benefit for the students by participating in this research.

Reimbursements
Students are not expected to incur any expenses by participating in this research.

Confidentiality:
The audio/video recordings of the sessions will be used for the purpose of data analysis, by logging the data anonymously. The raw data i.e. the recordings are not published anywhere. All identifying information collected accidentally during the data collection process will be removed immediately and only the de-identified data will be saved on secured department storage clouds or devices in the IDC School of Design department at IIT Bombay. This data will be accessible only to the research team conducting this study. Any clippings or images of the study, if used for publishing to explain the interactions of the users with the application, will involve the blurring of the faces of the participants to not reveal their identity. The researchers have no role to play in the academic assessment of the child. Before the analysis of data, all data will be anonymous.

Sharing of Research Findings
The results and insights from the data collected and analysed will be published in journal papers and conference publications. The confidentiality of the participants will be maintained by anonymous data collection. The images or video clippings, if used to explain the interactions of the user with the application, will involve blurring of faces and/or any form of identity revelation.

Right to refuse or withdraw
The participation in the study is completely voluntary. Along with your consent, the child will also be asked to agree or assent. The child's concerns and wishes will be taken very seriously.

Who to Contact
For any questions or concerns prior to or after the completion of your child’s participation please contact Prof. Jayesh S. Pillai by email- jay@iitb.ac.in

This proposal has been reviewed and approved by the Institute Ethics Committee of IIT Bombay, which is a committee whose task it is to make sure that research participants are protected from harm. If you wish to find about more about the IRB, contact Ms. Joyita Roy Sarkar, Technical Officer, IRCC (4039)

PART II: Certificate of Consent

Certificate of Consent
This research requires my ward to participate in a research study conducted by Prof. Jayesh S. Pillai and his team at IIT Bombay.
I have read the foregoing information, or it has been read to me. I have had the opportunity to ask questions about it and any questions that I have asked have been answered to my satisfaction. I consent voluntarily for my child to participate as a participant in this study.

Print Name of Parent or Guardian __________________

Signature of Parent of Guardian___________________

Date ___________________________
Day/month/year

If illiterate
A literate witness must sign (if possible, this person should be selected by the participant and should have no connection to the research team). Participants who are illiterate should include their thumb print as well.

I have witnessed the accurate reading of the consent form to the parent of the potential participant, and the individual has had the opportunity to ask questions. I confirm that the individual has given consent freely.

Print name of witness_____________________ AND Thumb print of participant

Signature of witness ______________________

Date ________________________
Day/month/year

Statement by the researcher/person taking consent
I have accurately read out the information sheet to the potential participant, and to the best of my ability made sure that the participant understands the requirements of the study as outlined in the Information Sheet.
I confirm that the participant was given an opportunity to ask questions about the study, and all the questions asked by the participant have been answered correctly and to the best of my ability. I confirm that the individual has not been coerced into giving consent, and the consent has been given freely and voluntarily.

A copy of this Informed Consent Form has been provided to the parent or guardian of the participant

Print Name of Researcher/person taking the consent: Pratiti Sarkar

Signature of Researcher /person taking the consent

Date ______________________________________
Day/month/year

Print Name of Principal Investigator: Prof. Jayesh S. Pillai

Signature of Principal Investigator__________________________

Date ______________________________________
Day/month/year

Appendix A.2

Assent Form (Students)

	Informed Assent Form Template for Children/Minors	Document No	IITB-IEC/2019/019
		Revision No	0
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An Informed Assent Form does <u>not</u> replace a consent form signed by parents or guardians. The assent is in addition to the consent and signals the child's willing cooperation in the study.

Informed Assent Form for middle school students (grades 6-8) participating in the study.

Study Title:
Investigating students' spatial thinking and creativity through collaborative problem solving using Augmented Reality on Mobile Phones and/or Tablets.

This informed assent form is for children studying in grades 6-8 and who we are inviting to participate in our research study investigating spatial thinking and creativity while they are engaged in collaboratively solving problems using Augmented Reality.

This research is being conducted by Jayesh S. Pillai (PI), Assistant Professor at IDC School of Design, IIT Bombay.

This Informed Assent Form has two parts:

- **Information Sheet (gives you information about the study)**
- **Certificate of Assent (this is where you sign if you agree to participate)**

You will be given a copy of the full Informed Assent Form

Part I: Information Sheet

Introduction
Hello. My name is Jayesh S. Pillai and I am an Assistant Professor at IDC School of Design, IIT Bombay. I am here to invite you to participate in a research study which will give you a chance to solve simple mathematics problems in collaboration using Augmented Reality.

Purpose: Why are you doing this research?
Students like you are introduced to a lot of new concepts which are difficult to visualize. This is particularly true if you have to imagine some day to day scenario to solve course curriculum problems. Thus, this study aims at understanding the challenges that middle school students like you face while imagining to understand new concepts and solve problems. The study further focuses on how an immersive experience using Augmented Reality technology can help you in

doing that. Participation in this research will help in enhancing the spatial thinking and creativity while solving real-life problems using Augmented Reality.

Choice of participants: Why are you asking me?
You are being invited to participate in this research study because you are studying in grade 6^{th}, 7^{th}, or 8^{th}. We are trying to understand what challenges middle school students like you face while imagining to understand new concepts and solve problems and how you might attempt to overcome these challenges using our intervention. You do not need to know anything related to the Augmented Reality technology beforehand for participating in this research.

Participation is voluntary: Do I have to do this?
The participation in the study is completely voluntary. If you decide not to participate then your decision will be respected and no data will be collected from you. Your grades will not be affected if you do not wish to participate. Your concerns and wishes will be taken very seriously. However, we hope that you will decide to participate and help us understand how students like you think and how can Augmented Reality technology be used to help in the process.

I have checked with the child and they understand that participation is voluntary __(initial)

Risks: Is this bad or dangerous for me?
The risks involved in this study are minimal and are the same as you would face in your daily life.

Discomforts: Will it hurt?
The activities in this study will be similar to your day-to-day activities and will not hurt or provide discomfort.

I have checked with the child and they understand the risks and discomforts ____(initial)

Benefits: Is there anything good that happens to me?
Participation in the research study will give you a chance to solve simple mathematics problems in collaboration using Augmented Reality technology. You may learn about this technology while solving real-life problems, that may further help you in enhancing your spatial thinking and creativity.

I have checked with the child and they understand the benefits_____ (initial)

Reimbursements: Do I get anything for being in the research?
You are not expected to incur any expenses by participating in this research.

Confidentiality: Is everybody going to know about this?

Your identity will be kept confidential. Confidential means, the data that we collect from the study, which is your audio/video recordings, reflection journal, and your interview responses, will not be shared with anyone other than the researchers involved in the study. Your parents will also be aware that you are participating in the study.

Compensation: What happens if I get hurt?
We do not expect anyone to get hurt by participating in this study. However, in the unlikely event of you getting hurt, please inform Prof. Jayesh S. Pillai as well as the IIT Bombay Ethics Board and due diligence will be followed.

Sharing the Findings: Will you tell me the results?
Findings from this research will be shared via journal papers and conference publications. Your identity will be kept confidential so no one can trace the information back to you. If you wish to access the findings, then you can contact Prof. Jayesh S. Pillai for a copy of the published papers.

Right to Refuse or Withdraw: Can I choose not to be in the research? Can I change my mind?
The participation is voluntary and you can withdraw and refuse to participate at any point of time.

Who to Contact: Who can I talk to or ask questions to?
The proposal has been approved by your school authority. You can also talk to your teacher, parents or anyone, about your participation in the study.
For any questions or concerns prior to or after the completion of your participation please contact Prof. Jayesh S. Pillai by email- jay@iitb.ac.in

PART 2: Certificate of Assent

I have read this information (or had the information read to me)
I have had my questions answered and know that I can ask questions later if I have them.
I agree to take part in the research.

OR

I do not wish to take part in the research and I have not signed the assent below.___________(initialled by child/minor)

Only if child assents:

Print name of child ___________________

Signature of child: ____________________

Date:________________
day/month/year

If illiterate:

[A literate witness must sign (if possible, this person should be selected by the participant, not be a parent, and should have no connection to the research team). Participants who are illiterate should include their thumb print as well.]

I have witnessed the accurate reading of the assent form to the child, and the individual has had the opportunity to ask questions. I confirm that the individual has given consent freely.

Print name of witness (not a parent)_________________ AND Thumb print of participant

Signature of witness ______________________

Date ________________________
Day/month/year

I have accurately read or witnessed the accurate reading of the assent form to the potential participant, and the individual has had the opportunity to ask questions. I confirm that the individual has given assent freely.

Print name of researcher_________________

Signature of researcher___________________

Date_________________
Day/month/year

Statement by the researcher/person taking consent

I have accurately read out the information sheet to the potential participant, and to the best of my ability made sure that the participant understands the requirements of the study as outlined in the Information Sheet.
I confirm that the participant was given an opportunity to ask questions about the study, and all the questions asked by the participant have been answered correctly and to the best of my ability. I confirm that the individual has not been coerced into giving consent, and the consent has been given freely and voluntarily.

A copy of this Informed Consent Form has been provided to the parent or guardian of the participant ____

Print Name of Researcher/person taking the consent: Pratiti Sarkar

Signature of Researcher /person taking the consent:

Date ____
Day/month/year

Print Name of Principal Investigator: Prof. Jayesh S. Pillai

Signature of Principal Investigator:

Date ________________________________
Day/month/year

Appendix A.3

Consent Form (Teachers)

	Informed Consent Form Template for Qualitative Studies	Document No	IITB-IEC/2019/019
		Revision No	0
		Page No	Page 1 of 5

Informed Consent Form for School Teacher/ Design Researcher/ Education Researcher/ Curriculum Developer

Study Title: Investigating students' spatial thinking and creativity through collaborative problem solving using Augmented Reality on Mobile Phones and/or Tablets.

The research study involves investigating spatial thinking and creativity of middle school students while they are engaged in collaboratively solving problems using Augmented Reality.

This research is being conducted by Jayesh S. Pillai (PI), Assistant Professor at IDC School of Design, IIT Bombay.

This Informed Consent Form has two parts:

- **Information Sheet (to share information about the study with you)**
- **Certificate of Consent (for signatures if you choose to participate)**

You will be given a copy of the full Informed Consent Form

Part I: Information Sheet

Introduction
I am Jayesh S. Pillai, Assistant Professor at IDC School of Design, IIT Bombay. I am here to invite you to participate in a research study which will help us investigating students' spatial thinking and creativity while they solve simple mathematics problems in collaboration using Augmented Reality.

Purpose of the research
Students are introduced to a lot of new concepts which are difficult to visualize. This is particularly true if they have to imagine some day to day scenario to solve course curriculum problems. Thus, this study aims at understanding the challenges that middle school students face while imagining to understand new concepts and solve problems. The study further focuses on how an immersive experience using Augmented Reality technology can help them in doing that. Participation in this research will help them in enhancing the spatial thinking and creativity while they solve real-life problems using Augmented Reality.

Type of Research Intervention
The intervention involves the design of a digital and tangible AR application (to be used on tablets/phablets/mobile phones) in Mathematics as per the syllabus of CBSE board with small

activities to test the learning abilities using Augmented Reality for the students of class 6 to 8. This may be later generalized across subjects and classes. Hence, AR can be helpful for students in having shared learning experience through spatial visualization and interactive collaboration.

Participant Selection
You are welcome to participate in this research study as you have a key role in imparting the textbook knowledge to the students. Moreover, no prior knowledge is needed for this study.

Voluntary Participation
Your participation in this study is completely voluntary and you are free to choose if you should participate in the study or not. We hereby reassure that you will receive all the services you usually do, even if you do not participate in the study. Your voluntary participation in this research will greatly help us advance our understanding of how middle school students think and enable us to create resources for helping them improve their spatial thinking and creativity using Augmented Reality.

Procedures
On giving the consent for conducting the study, questions related to their knowledge about existing technologies in the field of education will be asked. You will then be made to use the Augmented Reality application on the tablet/mobile phone. You will need to solve a few problems shown in the application or assist the students in solving. These questions will be based on the topics from the curriculum. Your interactions and perceptions on the design and use of the application will be audio/video recorded. Further questions for the feedback and suggestion will be asked to enhance the design of the intervention. You may be asked to maintain a reflective journal to pen down any new solution you may think of at any time other than the time of the experiment..

Duration
The duration of the study may vary from 1 day (max. 1 hour session) to 1 week (max. 1-3 hour sessions per day) depending on your total time available. It will be ensured that it does not hinder your other endeavors.

Risks
The risks involved in this study are minimal and are the same as one would face in their daily life.

Benefits
Participation in the research study will give students a chance to solve simple mathematics problems in collaboration using Augmented Reality technology. They may learn about this technology while solving real-life problems, that may further help in enhancing the spatial thinking and creativity. For other participants, they get to observe the nature of the application and its impact on the learning outcome of the students while giving the required inputs in the

system's operation and design.

Reimbursements
You are not expected to incur any expenses by participating in this research.

Confidentiality
All identifying information collected accidentally during the data collection process will be removed immediately and only the de-identified data will be saved on secured department storage devices in the IDC School of Design department at IIT Bombay. This data will be accessible only to the research team conducting this study. Before the analysis of data, all data will be anonymous.

Sharing the Results
The results from the data collected will be published in journal papers and conference publications. The confidentiality of the participants will be maintained by anonymous data collection.

Right to Refuse or Withdraw
The participation in the study is completely voluntary. Your concerns and wishes will be taken very seriously.

Who to Contact
For any questions or concerns prior to or after the completion of your participation please contact Prof. Jayesh S. Pillai by email- jay@iitb.ac.in

This proposal has been reviewed and approved by [name of the local IRB], which is a committee whose task it is to make sure that research participants are protected from harm. If you wish to find about more about the IRB, contact Ms. Joyita Roy Sarkar, Technical Officer, IRCC (4039)

Part II: Certificate of Consent

This research requires me to participate in a research study conducted by Prof. Jayesh S. Pillai and his team at IIT Bombay.
I have read the foregoing information, or it has been read to me. I have had the opportunity to ask questions about it and any questions I have been asked have been answered to my satisfaction. I consent voluntarily to be a participant in this study

Print Name of Participant__________________
Signature of Participant ___________________
Date ___________________________
Day/month/year

If illiterate
I have witnessed the accurate reading of the consent form to the potential participant, and the individual has had the opportunity to ask questions. I confirm that the individual has given consent freely.

Print name of witness____________ **Thumb print of participant** | |

Signature of witness _____________

Date ________________________
Day/month/year

Statement by the researcher/person taking consent

I have accurately read out the information sheet to the potential participant, and to the best of my ability made sure that the participant understands the requirements of the study as outlined in the Information Sheet.
I confirm that the participant was given an opportunity to ask questions about the study, and all the questions asked by the participant have been answered correctly and to the best of my ability. I confirm that the individual has not been coerced into giving consent, and the consent has been given freely and voluntarily.

A copy of this Informed Consent Form has been provided to the participant.

Print Name of Researcher/person taking the consent: Pratiti Sarkar

Signature of Researcher /person taking the consent:

Date ___________________________________
Day/month/year

Print Name of Principal Investigator: Prof. Jayesh S. Pillai

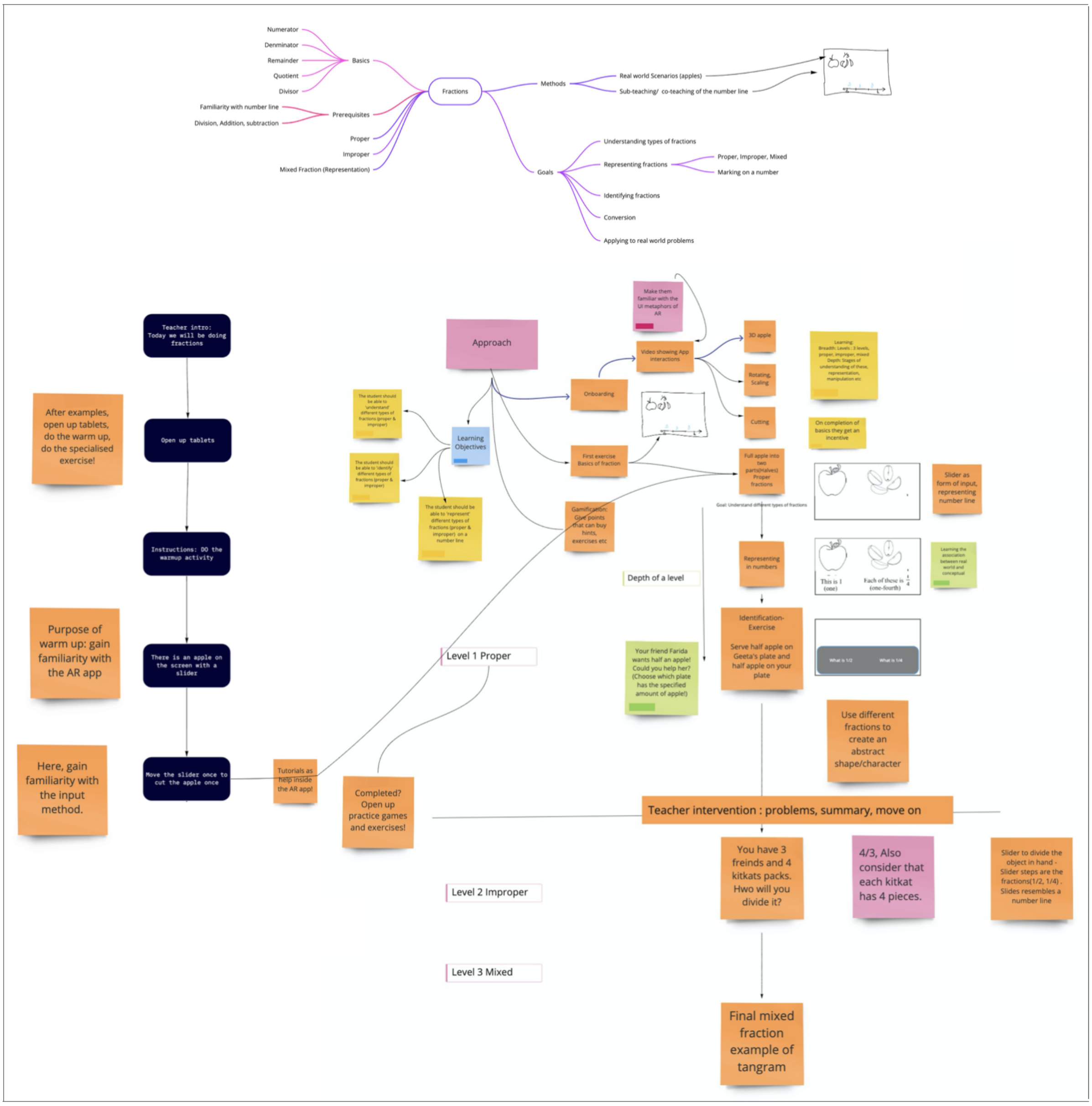
Signature of Principal Investigator:

Date ___________________________________
Day/month/year

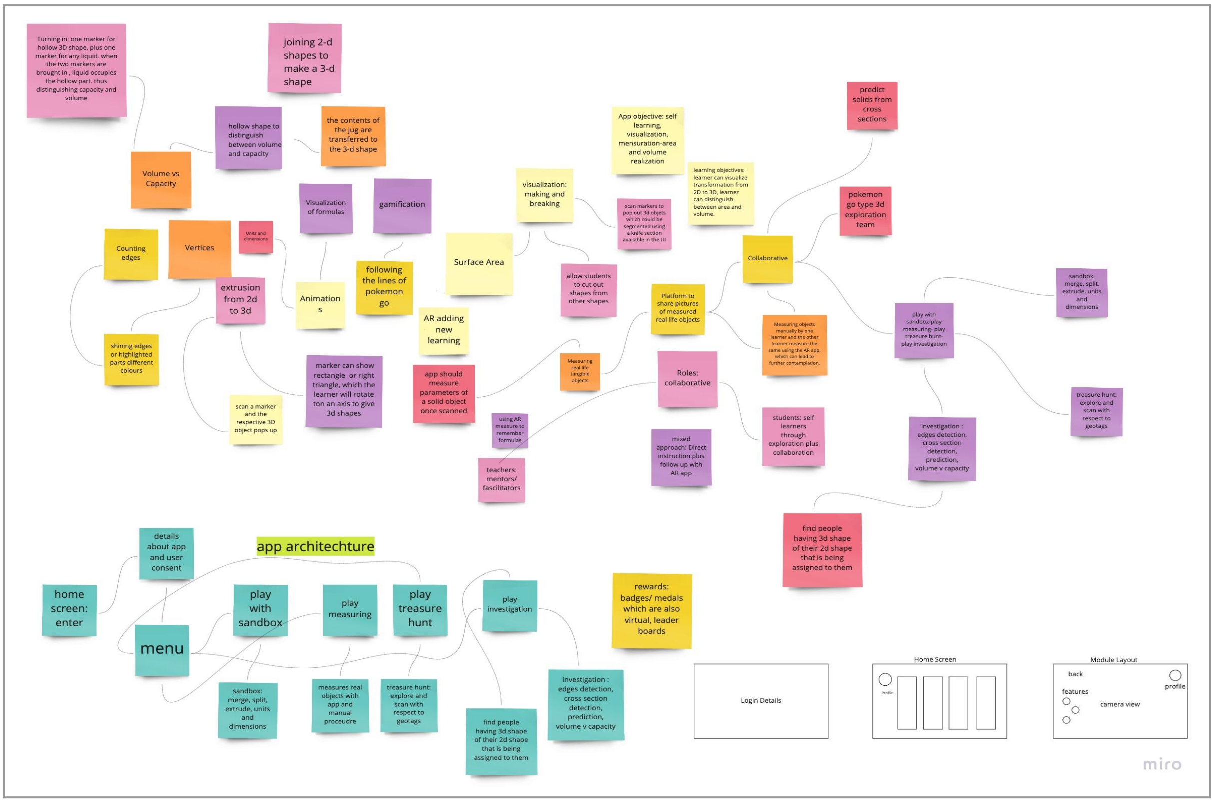
Appendix B

Study 2 - Boards of the Participating Groups

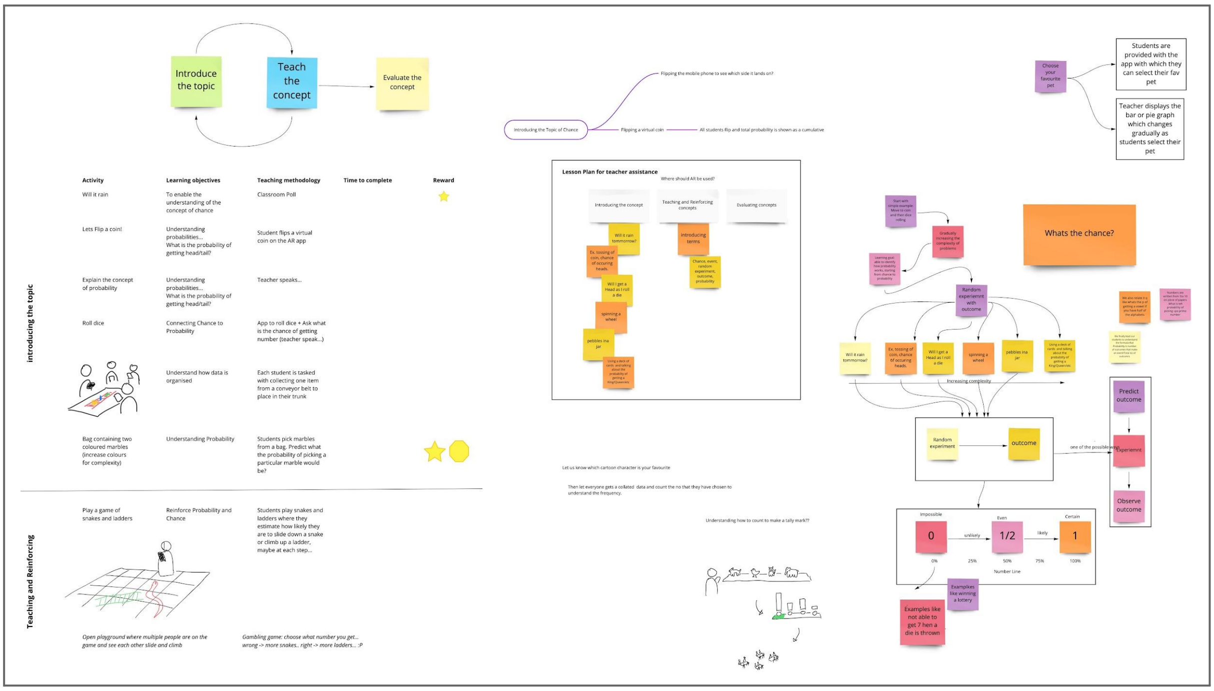
Group 1: Fractions



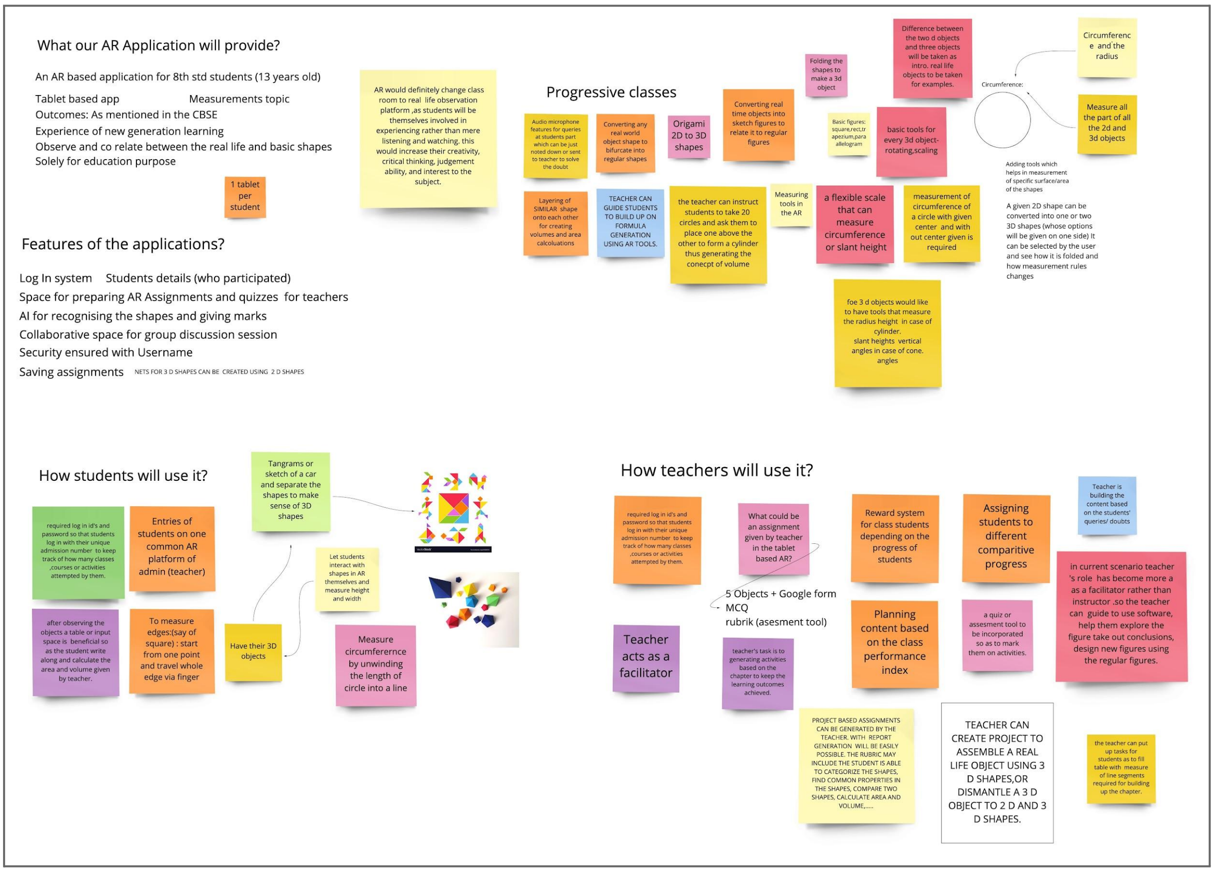
Group 2: Mensuration



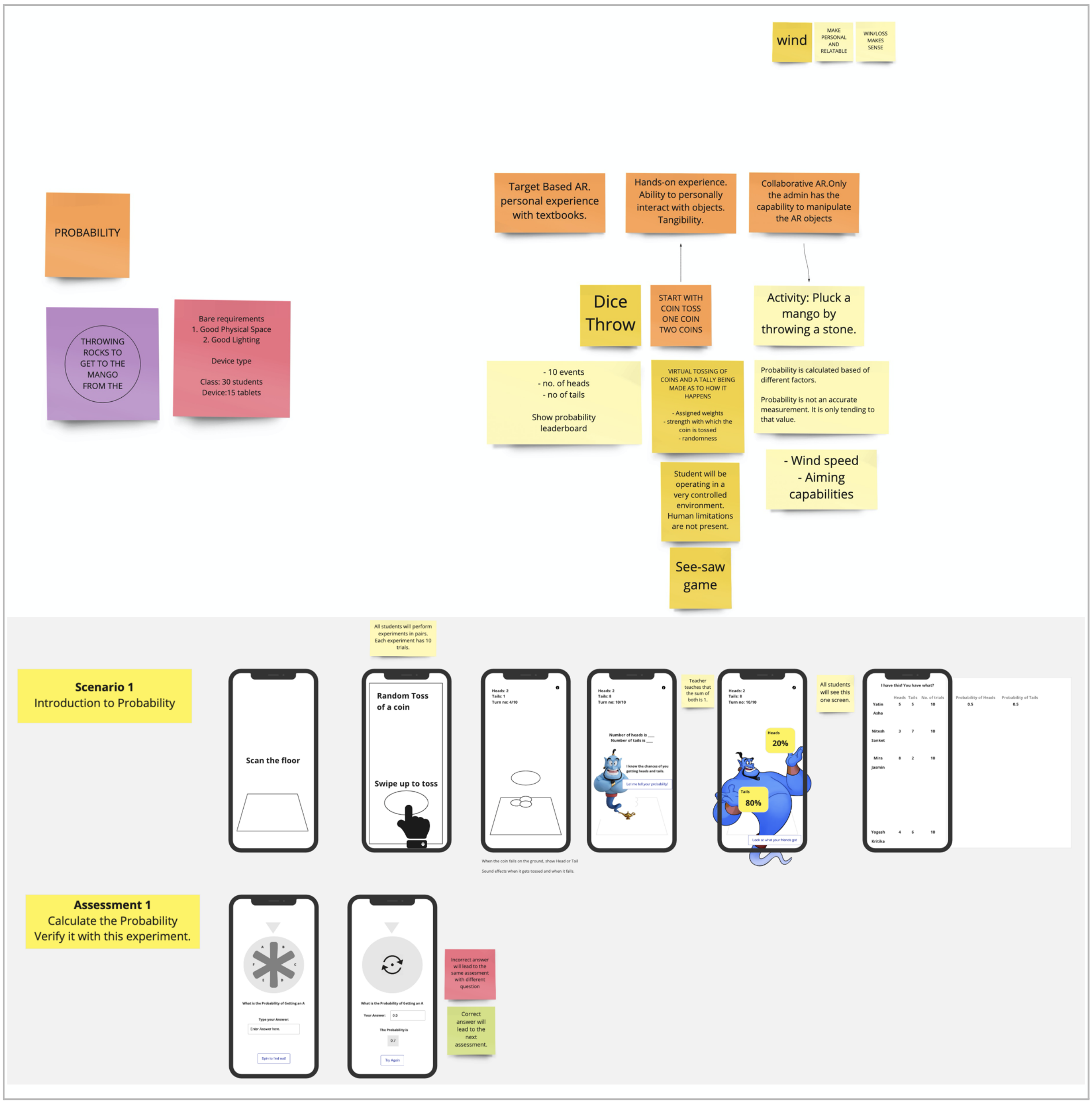
Group 3: Probability



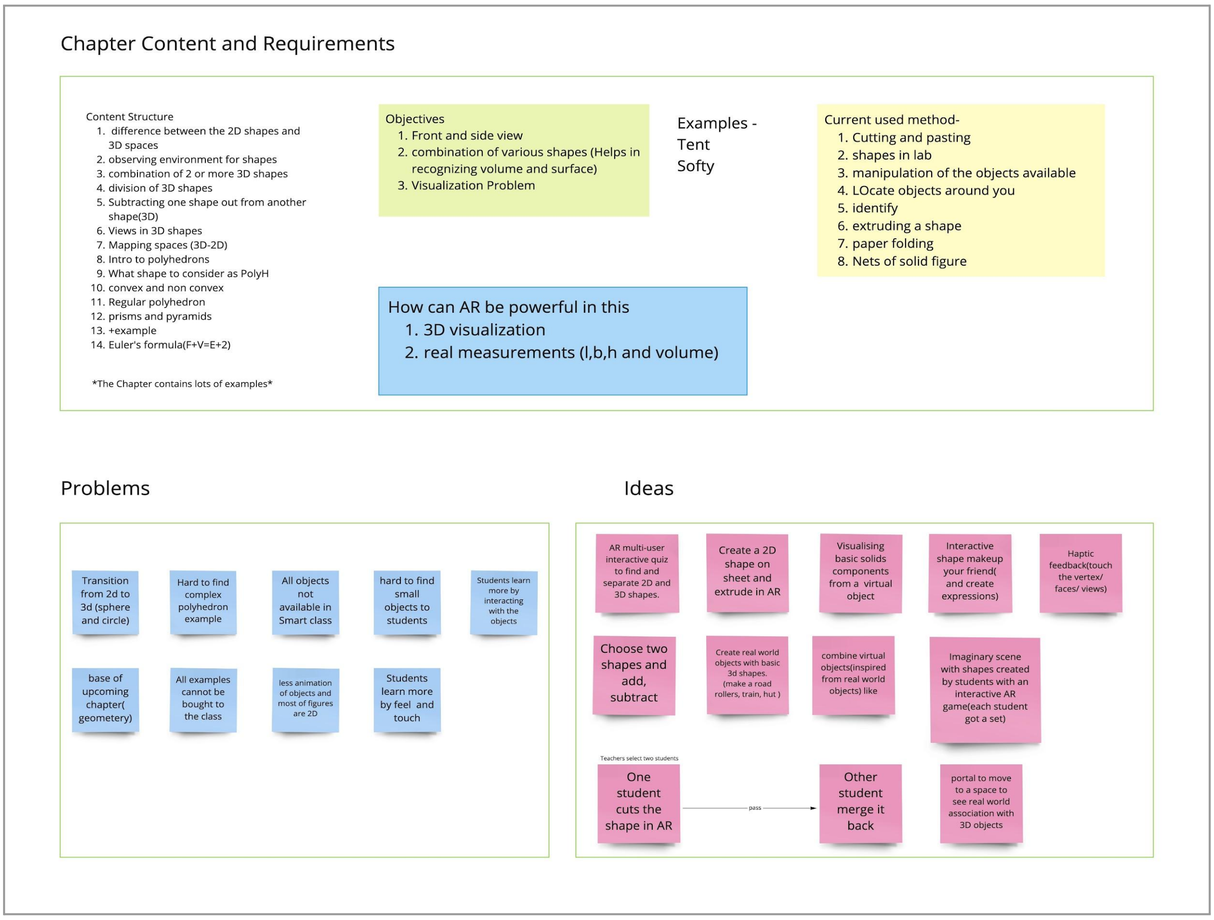
Group 4: Mensuration



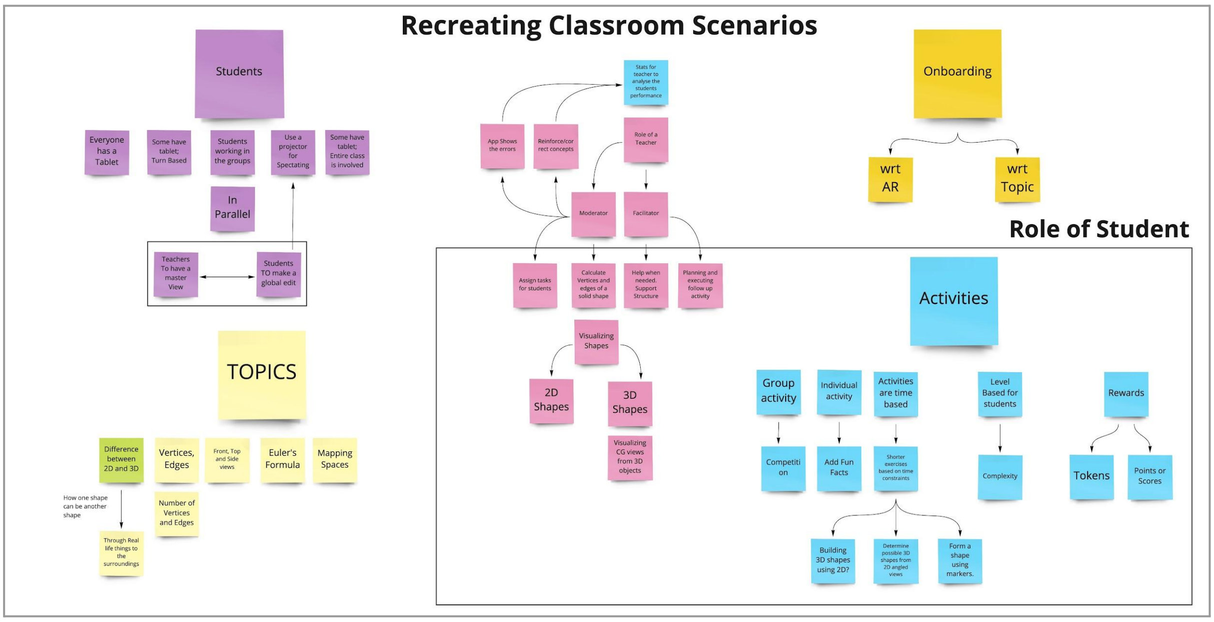
Group 5: Probability



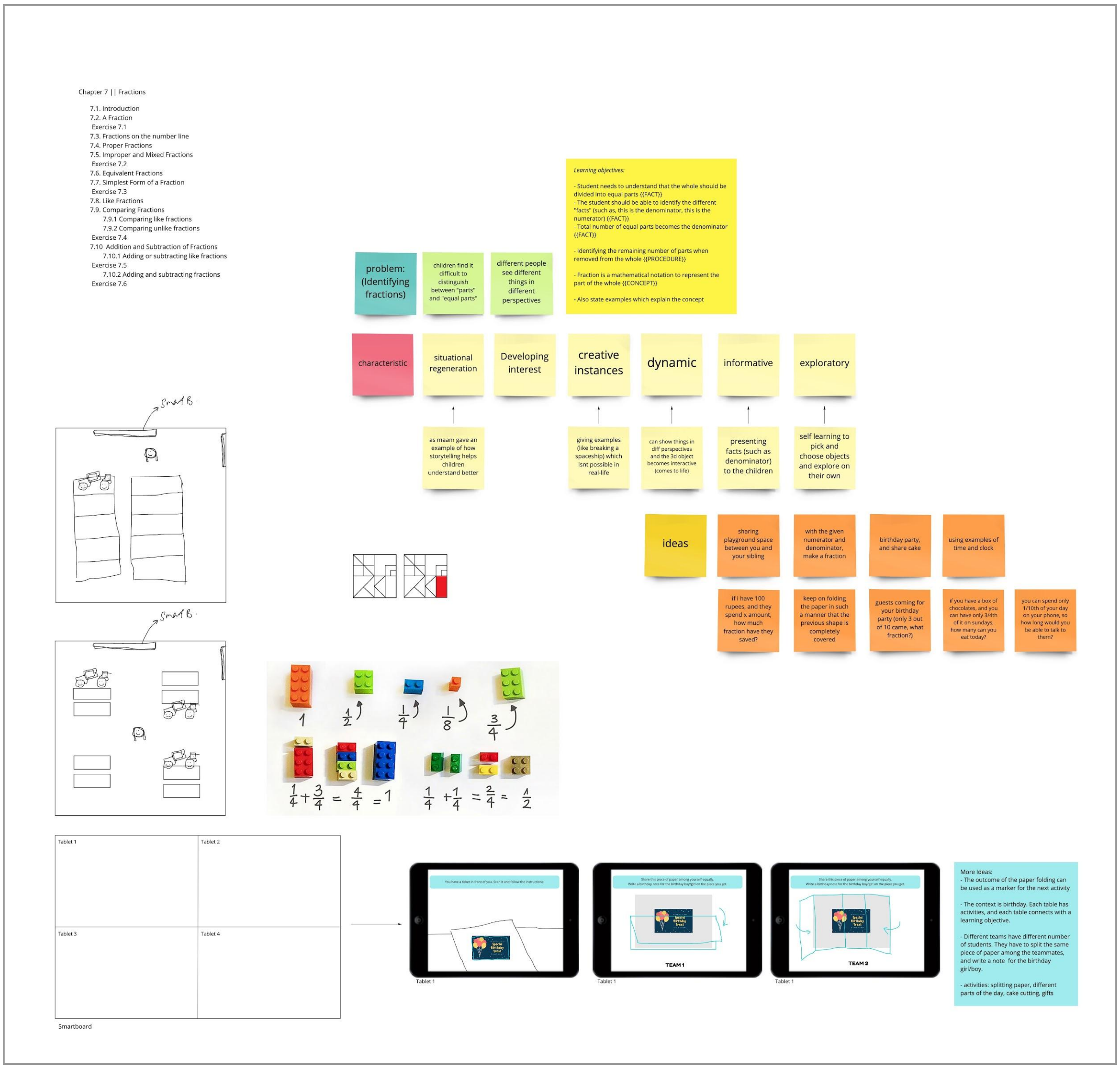
Group 6: Visualising Solid Shapes



Group 7: Visualising Solid Shapes



Group 8: Fractions



Appendix C

Pretest and Posttest Papers on Lines and Angles (Study 4 and 6)

Appendix C.1

Pretest Paper on Lines and Angles
(Study 4 and 6)

Name: ____ Roll No. ___________________

Class: __________________________ Section: _________________ Age: ______________

Q1:

(a) If the sum of the measures of two angles is 180° they are known as ___________________ angles**.**

(b) If the sum of the measures of two angles is 90° they are known as ____________________ angles.

(c) The sum of the measures of the angles in a linear pair is ______ degrees.

Q2: Classify each angle as right, acute, obtuse or straight.

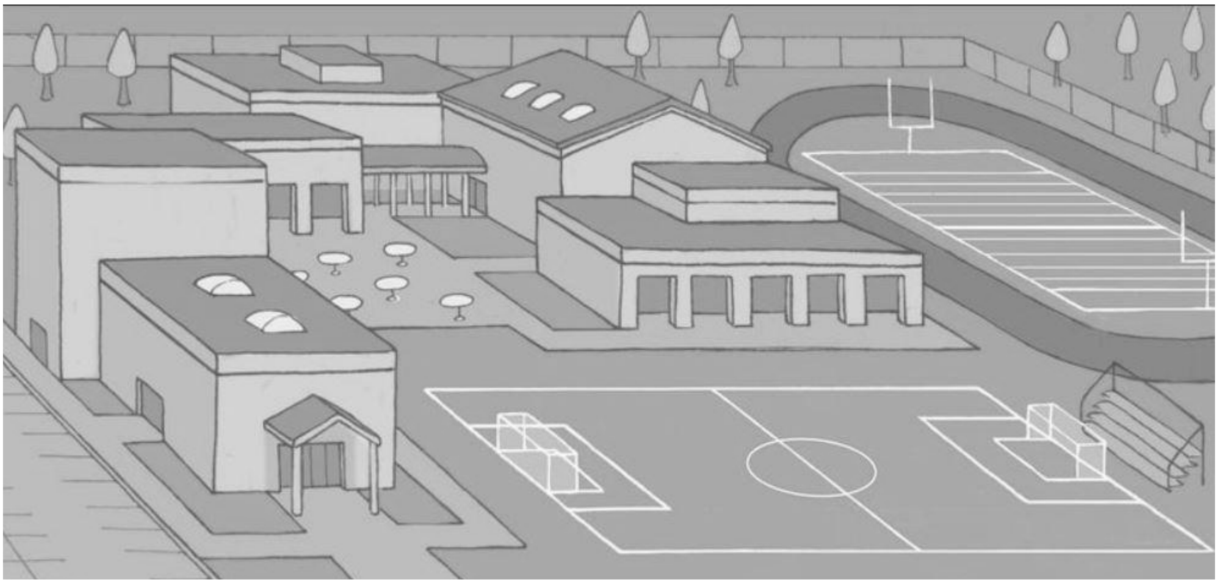
1) 2) 3)

________________________ ____________________ _____________________

Q3: The sum of interior angles of a quadrilateral (with 4 sides) is ____________.

Q4: Draw the pairs of angles which are both **supplementary and adjacent.**

Q5: A picture of a school ground is given below. From the given five types of angles
(1) adjacent pair of angles
(2) linear pair of angles
(3) supplementary pair of angles
(4) complementary pair of angles or
(5) vertically opposite angles
identify any <u>three</u> pairs of angles in this picture. Mark and label the three identified pairs of angles on this picture.



Q6: Draw an object from your surroundings which has 1 pair of vertically opposite angles.

Appendix C.2

Posttest Paper on Lines and Angles
(Study 4 and 6)

Name: ______________________________ Roll No. ______________

Class: ____________________ Section: ____________ Age: __________

Q1:

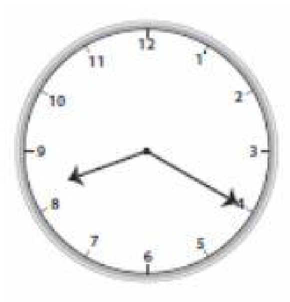
(a) If the sum of the measures of two angles is 90° they are known as ________________ angles.

(b) If the sum of the measures of two angles is 180° they are known as ________________ angles**.**

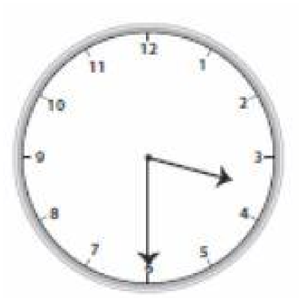
(c) Two acute angles can form a pair of supplementary angles. (True/False)

Q2: Classify each angle as acute, obtuse, right or straight formed by the hands of the clock.

1)



2)



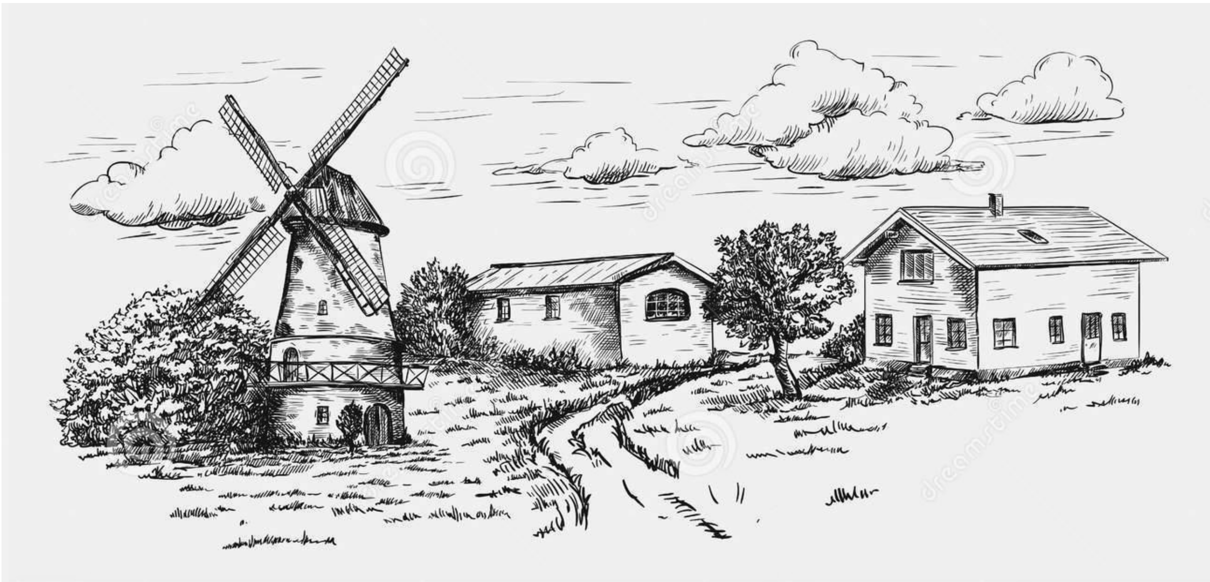
3)

__________________ __________________ __________________

Q3: The sum of interior angles of a pentagon (with 5 sides) is __________.

Q4: Draw the pairs of angles which are both **complementary and adjacent.**

Q5: A picture of a farm field is given below. From the given five types of angles
(1) adjacent pair of angles
(2) linear pair of angles
(3) supplementary pair of angles
(4) complementary pair of angles or
(5) vertically opposite angles
identify any <u>three</u> pairs of angles in this picture. Mark and label the three identified pairs of angles on this picture.



Q6: Draw an object from your home which has 1 pair of complementary angles or 1 pair of vertically opposite angles.

Appendix D

Pretest and Posttest Papers on Visualising Solid Shapes (Study 7)

Appendix D.1

Pretest Paper on Visualising Solid Shapes (Study 7)

Name: ______________________________ Roll No. ______________

Class: ____________________ Section: _____________ Age: ___________

Q1: Choose the shape/shapes that have 8 vertices?

◯ Square Pyramid ◯ Cone ◯ Triangular Pyramid ◯ Cylinder ◯ Cuboid

Q2: An icosahedron has 30 edges and 12 vertices. How many faces does it have? Explain.

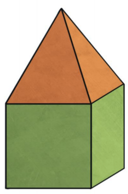
____

____

____

Q3:

a) How many edges, faces, and vertices does this object have?



Edges (E): _____________________

Faces (F): _____________________

Vertices (V): ___________________

b) If we separate the two coloured shapes, what are the orange and the green shape called?

Orange shape: ____________________________

Green shape: _____________________________

c) Draw the orange and green shapes obtained on separating the two.

d) How many edges, faces, and vertices are there for these two shapes?

Shape colour	Number of Faces F	Number of Edges E	Number of Vertices V
Orange			
Green			

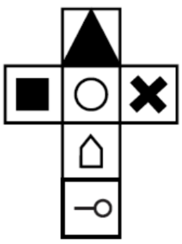
e) Find and explain the relationship between V, F and E for the cases in Q3.d.

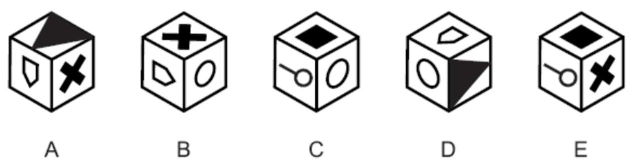
Q4: Draw the net of the shape that has 5 faces, 8 edges, and 5 vertices.

Q5:
(a) Draw the shape formed by attaching a triangular pyramid on top of the triangular face of the triangular prism.

(b) Draw the net of this object.

Q6: Which cube can be made from the given net? Explain how you obtained this answer.





Appendix D.2

Posttest Paper on Visualising Solid Shapes (Study 7)

Name: ____ Roll No. ___________________

Class: __________________________ Section: _________________ Age: ______________

Q1: Choose the shape/shapes that have 6 faces?

◯ Square Pyramid ◯ Cube ◯ Triangular Pyramid ◯ Cylinder ◯ Cuboid

Q2: Can a polyhedron have 19 faces, 34 edges, and 18 vertices? Explain.

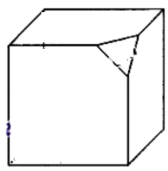
____

____

____

Q3:

a) How many faces, vertices, and edges of the cube are there when one vertex of the cube is cut, as shown in the figure?



b) Draw the solid shape that is obtained on removing it from the above cube.

c) What is this new shape called? (choose from the given options)

◯ Square Pyramid ◯ Triangular Prism ◯ Triangular Pyramid ◯ Triangle

d) Draw the net of this new shape.

e) Now fill the following table, when similarly more vertices are cut from the original cube:

Number of vertices cut and removed	Number of Faces F	Number of Edges E	Number of Vertices V
2			
3			

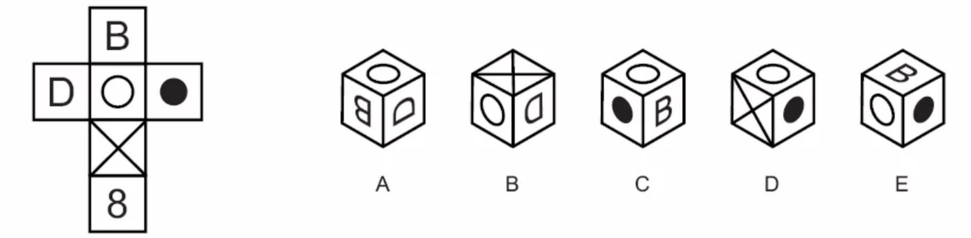
f) Find and explain the relationship between V, F and E for the cases in Q3.e

Q5:

(a) Draw the shape formed by attaching a square pyramid on top of a cube.

(b) Draw the net of this object.

Q6: Which cube can be made from the given net? Explain how you obtained this answer.



Appendix E

Interview Questions and Usability & Experience Questionnaires

Appendix E.1

Interview Questions

Study 1

Questions for Students

The following questions were asked to every participating student to obtain their understanding, perception, and expectations regarding the use of AR in classrooms:

1. Do you use any smartphones? Whose smartphone are you using?
2. Do you use any other gadgets at home? If yes, please mention it.
3. For what purposes do you use the smartphone?
4. If you use the smartphone for games, which all games do you play on it?
5. Roughly how much time do you spend daily playing games on the smartphone?
6. Do you use any educational applications on the phone? If yes, please mention it.
7. Have you heard about *Pokémon GO* game? Have you ever played it?
8. Do you know what type of technology was used to design the game?
9. Have you heard about Augmented Reality (AR)? If yes, can you describe what happens using this technology?
10. Which is your favorite subject and why?
11. Which is a difficult subject for you and why?
12. Which topics do you think can be shown in the AR environment?
13. Would you like to visualize the difficult topics using AR technology
14. Would you like to use such an application in the classroom or at home?
15. How do you think AR can be used in the classroom to learn?

Questions for Teachers

The following questions were asked to every participating teacher to obtain their understanding, perception, and expectations regarding the use of AR in classrooms:

1. Do you use a smartphone?
2. Do you use any other gadgets at home? If yes, please mention it.
3. For what purposes do you use the smartphone?
4. Roughly how much time do you spend daily on the smartphone?

5. Do you use any educational applications on the phone? If yes, please mention it.
6. What (a) methods, (b) tools, and (c) examples do you use to teach your subject in class?
7. In which topics of your subject do students face difficulty in learning?
8. What difficulties do students face in the following topics?
9. Why do you think students face such difficulties?
10. How do you address these difficulties?
11. How do you think such difficulties can be handled with/without technology?
12. Have you heard about *Pokémon GO* game? Have you ever played it?
13. Do you know what type of technology was used to design the game?
14. Have you heard about Augmented Reality? If yes, can you describe what happens using this technology?
15. Which topics of your subject do you think can be shown in the AR environment?
16. How do you think AR can be used in the classroom to learn?

Questions for Parents

The following questions were asked to the parents who were observing the AR display experience at RCity Mall with their children. The objective was to obtain their understanding, perception, and expectations regarding the use of AR in classrooms:

1. How has your experience been in witnessing the display?
2. Have you heard about *Pokémon GO* game? Have you ever played it?
3. Do you know what type of technology is used behind this display and the game?
4. Have you heard about Augmented Reality? If yes, can you describe what happens using this technology?
5. Does your child use a smartphone?
6. Does your child use any other gadgets at home? If yes, please mention it.
7. For what purposes does your child use the smartphone?
8. Roughly how much time does your child spend daily on the smartphone?
9. Does your child use any educational application on the phone? If yes, please mention.
10. In which topics of your subject does your child students face difficulty in learning?
11. Why do you think your child faces such difficulties?
12. How do think such difficulties can be handled with/without technology?
13. Which topics do you think can be shown in the AR environment?
14. How do you think AR can be used in the classroom to learn?

Study 3

The following questions were asked to every participant at the end of the study to obtain their feedback regarding the workshop:

1. What motivated you to participate in this workshop?
2. Are there any things that you particularly liked in the workshop?
3. Are there things you particularly disliked in the workshop?
4. Did you get what you expected out of the workshop?
5. Did the workshop inspire you on a personal level?
6. Did the workshop inspire you at a professional level?
7. What we could have done better?
8. Is there something else you would like to mention to us?

Study 4 - 7

The following questions were asked to every student at the end of the study to understand the perceived usefulness of the AR intervention introduced to them:

1. How was your overall experience of this workshop? Please elaborate.
2. What did you learn today?
   (a) Did you find the activities easy or difficult?
   (b) Is there any specific activity that you found to be difficult?
3. How was it different from solving the problems on paper?
4. What was the most difficult thing for you in the activities?
5. Which activity in the *ScholAR* application did you like the most?
6. Why did you like the above chosen activity the most?
7. Which activity in the *ScholAR* application did you dislike the most?
8. Why did you dislike the above chosen activity the most?
9. What would you like to change in the activities?
10. Will you be interested to participate in similar workshops in the future?

Appendix E.2

System Usability Score (SUS) Questionnaire

Q: Mark any one circle per row:

	Strongly Agree	**Agree**	**Neither Agree nor Disagree**	**Disagree**	**Strongly Disagree**
I think that I would like to use this system frequently	○	○	○	○	○
I found the system unnecessarily complex	○	○	○	○	○
I thought the system was easy to use	○	○	○	○	○
I think that I would need the support of a technical person to be able to use this system	○	○	○	○	○
I found the various functions in this system were well integrated	○	○	○	○	○
I thought there was too much inconsistency in this system	○	○	○	○	○
I would imagine that most people would learn to use this system very quickly	○	○	○	○	○
I found the system very cumbersome to use	○	○	○	○	○
I felt very confident using the system	○	○	○	○	○
I needed to learn a lot of things before I could get going with this system	○	○	○	○	○

Appendix E.3

Augmented Reality Immersion (ARI) Questionnaire

Q: Mark any one circle per row:

	Strongly Agree	Agree	Neither Agree nor Disagree	Disagree	Strongly Disagree
I liked the activity because it was new and different	○	○	○	○	○
I liked the types of the activities	○	○	○	○	○
I wanted to spend the time to complete the activities successfully	○	○	○	○	○
I wanted to spend time to participate in the activities	○	○	○	○	○
It was easy for me to use the AR application	○	○	○	○	○
I found the AR application confusing	○	○	○	○	○
The AR application was unnecessarily complex	○	○	○	○	○
I did not have difficulties in controlling the AR application	○	○	○	○	○
I was curious about how the activity would progress	○	○	○	○	○
I was often excited since I felt as being part of the activities	○	○	○	○	○
I often felt suspense by the activities	○	○	○	○	○
If interrupted, I looked forward to returning to the activities	○	○	○	○	○
Everyday thoughts and concerns faded out during the activity	○	○	○	○	○

I was more focused on the activity rather on any external distraction	○	○	○	○	○
The activity felt so real that it made me think that the virtual objects existed for real	○	○	○	○	○
I felt that what I was experiencing was something real, instead of a fictional activity	○	○	○	○	○
I was so involved in the activity, that in some cases I wanted to interact with the virtual objects directly	○	○	○	○	○
I was so involved, that I felt that my actions could affect the activity	○	○	○	○	○
I didn't have any irrelevant thoughts or external distractions during the activity	○	○	○	○	○
The activity became the unique and only thought occupying my mind	○	○	○	○	○
I lost track of time as if everything just stopped, and the only thing that I could think about was the activities	○	○	○	○	○

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List of Publications

In Journals:

1. Sarkar, P., & Pillai, J. S. (2021). *Approaches for Designing Handheld Augmented Reality Learning Experiences for Mathematics Classrooms.* Proc. ACM Hum.-Comput. Interact. 5, CSCW2, Article 461 (October 2021), 25 pages.

2. Sarkar, P., Kadam, K., & Pillai, J. S. (2020). *Learners' approaches, motivation and patterns of problem-solving on lines and angles in geometry using augmented reality.* Smart Learning Environments, 7(1), 1-23.

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3. Sarkar, P., Kadam, K., & Pillai, J. S. (2019, December). *Collaborative approaches to problem-solving on lines and angles using augmented reality.* In 2019 IEEE Tenth International Conference on Technology for Education (T4E) (pp. 193-200). IEEE.

4. Sarkar, P., Sakhardande, P., Oza, U., & Pillai, J. (2019). *Study of Augmented Reality Interaction Mediums (AIMs) towards Collaboratively Solving Open-Ended Problems.* In 27th International Conference on Computers in Education (ICCE 2019), Dec 2019, Kenting, Taiwan.

5. Sarkar, P., & Pillai, J. S. (2019). *User Expectations of augmented reality experience in indian school education.* In Research into Design for a Connected World (pp. 745-755). Springer, Singapore.

6. Sarkar, P., Pillai, J. S., & Gupta, A. (2018, December). *ScholAR: a collaborative learning experience for rural schools using Augmented Reality application*. In 2018 IEEE Tenth International Conference on Technology for Education (T4E) (pp. 8-15). IEEE.

7. Kaur, N., Pathan, R., Khwaja, U., Sarkar, P., Rathod, B., & Murthy, S. (2018, December). *GeoSolvAR: Augmented reality based application for mental rotation.* In 2018 IEEE Tenth International Conference on Technology for Education (T4E) (pp. 45-52). IEEE.

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