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Co-designing augmented reality books:

Connections between student distributed cognition and technology design

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Abstract

This study focuses on the relationship between community-based knowledge construction and participatory technology design. Contextualized against digital divide research, the goals of this study are twofold: understand how students from a low socioeconomic background perceive an emerging technology as a tool to learn with and understand how the iterative and inherently reflective process of technology design may influence student knowledge construction. Grounded in distributed cognition theory, this study examines this relationship by co-designing an augmented reality book with an eighth-grade class in New England, USA. Augmented reality (AR) is an emerging technology that allows users to place virtual models into the physical world using a mobile device or headset. The students created a book about COVID-19 and worked with the researcher to build an iOS app that projected virtual models atop the book. The analysis answers questions about how students perceive and use AR as a tool to learn with, demonstrating that students use AR as an exploratory tool, first broadly across a diverse set of topics, and then deeper into specific details. The study also examines the influence of iteration, observing how students switched between roles of producer and consumer as they sought to improve the app, thereby encouraging critical reflection on the material. Ultimately, this study shows the ways in which individual students used the unique affordances of AR to contribute and modify information for the advancement of the community's knowledge.

1.0.0. Introduction

"Educational technology must be of secondary concern to the people and relationships within classrooms." (Garcia & Lee, 2020)

In the era of the COVID-19 pandemic, educational technology has experienced a surge of global investment and interest (Teräs et al., 2020; Williamson et al., 2020). Schools in many countries were forced to rapidly move online, and undoubtedly, technology played a crucial role in preserving education while quarantines and lockdowns remained prevalent (Starkey et al., 2021). Just as the pandemic threw health inequities into sharp contrast, so too did inequities within education technology become overtly apparent. Students of colour, forced to use online proctoring software during their exams, struggled as the facial recognition software failed to recognize dark-skinned students or differentiate between Chinese students (Swauger, 2020). Students of varying socioeconomic backgrounds experienced distance learning in widely different manners: students from higher socioeconomic backgrounds were more likely to have their own device, stable Internet connections, and support from family members at home while students from lower socioeconomic backgrounds were more likely to experience the opposite (Hargreaves, 2021).

And yet, the criticisms of education technology are nothing new, nor are they necessarily specific to the intersection of education and technology. Technical interventions in education have been proven to have little to no positive effect on students, despite the constant hype of innovation, disruption, and 'fixing' education (Reich, 2020). Similar promises of technology for development and empowerment of historically marginalized populations have similar results, often carrying with them neo-colonial narratives and reinforcing existing power imbalances (Harrington et al., 2019; Zheng, 2009). Embedded within this is an acknowledgement that technology is not neutral; it has been built by humans and thus carries their beliefs and their biases, their assumptions and their values (Noble, 2018). If technology is viewed as a social construct, then the design of technology is a space of power. Who designs, who decides, and who builds matters.

This has led to two commonly proposed solutions: participatory approaches in technology development and local solutions for local communities (Dearden & Rizvi, 2008; Spinuzzi, 2005; Walsh et al., 2013). To include more people in the design of technology, focus less on scale, and address specific solutions for concrete, community-identified problems is to begin to solve some issues present in technology today. What might seem simple is complicated by the intricacies of social contexts. What skills are required to design a technology? Who identifies participants? How does one prevent embedding power dynamics *within* communities into the design and the design process? Perhaps more insidiously, as Harrington et al. (2019) suggests, does the participatory design process promote a narrative of technosolutionism and fail to address larger structural issues?

It is with these questions in mind that this study focuses on the relationship between participatory technology design and community knowledge construction. In doing so, this study hopes to further explore the suggestion made by Garcia and Lee (2020) at the beginning of this chapter: place students and their relationships above the use of education technology. Rather than focusing on recommendations for the design of education technology, this study examines how the technology design process influences the knowledge construction of the individual and the community and thus seeks to avoid the trap of technosolutionism. This research is largely grounded in Pea's (1993) description of the theory of distributed cognition, which treats technology as a reification of patterns of reasoning and technology design as an exchange between individual and community desires. Furthermore, distributed cognition identifies the iterative process of technology design as a natural way to promote reflection and criticality (Cash, 2013), two concepts also identified as crucial to promoting equity within education and technology (Garcia & Lee, 2020; Zheng, 2009). By leveraging the co-design process, a branch of participatory design methodology, and contextualizing results using distributed cognition and digital divide research, this study seeks to understand the relationship between technology design and knowledge construction, particularly for students from a low socioeconomic background.

To study these relationships, this study worked with an eighth-grade science class at an all-girls school in New England, USA, and co-designed an augmented reality book. Augmented reality allows a user to project virtual 3D objects into the world around them, using a device such as a mobile phone, tablet, or headset (Azuma, 1997). An augmented reality book allows the user to hold their device to a physical book and virtual objects will appear above the pages of the book (Hornecker & Dünser, 2007). Given augmented reality's perception as an emerging technology (Dunleavy, 2014), it is a useful technology to focus on as students have more freedom to design without the influence of preconceived notions as to how it is supposed to work. Where designing a website might be strongly influenced by students' previous experiences with websites, augmented reality is a relatively new technology and not yet commonly integrated into the classroom. It is also an opportunity for students historically excluded from technology design processes to adapt the technology to their desires, rather than adapting themselves to the technology (Garcia & Lee, 2020). Over the course of four sessions, these students built an augmented reality book about COVID-19 and its effect at the cellular level. This study will show that these students used augmented reality's unique affordances as a tool for exploration, finding new perspectives on the material by connecting existing, seemingly disparate knowledge areas together and by looking for absences in community knowledge. Moreover, the iterative process served as a structured way to move from broad questions to specific details and allowed students to find these new perspectives by placing them in different roles, from technology designer to user. Students also used these roles and various avenues of engagement to place themselves alongside the community knowledge or against it, ultimately leading to a diverse knowledge base.

This study is organized into five chapters, beginning with this introduction. The remaining four chapters are organized as follows: (2) a literature review that encompasses an overview of distributed cognition, the digital divide and the exacerbated inequities it causes, and a brief summary of educational technology and the use of augmented reality in the classroom, before posing the research questions; (3) methodological approaches and motivations, including a discussion of ethics and limitations, a summary of the procedures, and a brief description of the analytical framework chosen; (4) findings and discussion, in which the findings are presented as themes and implications are discussed in the context of existing literature; and, (5) conclusion, which summarizes the work done before moving on to suggest further research in this area.

2.0.0. Literature Review

2.1.0. Distributed Cognition

2.1.1. Overview of Distributed Cognition

The theory of distributed cognition starts with desire. An individual's desire shapes what activities they perform, which in turn, shapes what tools are built to accomplish those activities. Distributed cognition recognizes that this desire (and subsequent activities and tools) can all be influenced by social and environmental factors. Pea (1993) states:

> Persons are situated in the physical, artifactual, and social worlds and continually use and redesign them to achieve the activities they desire. The distributions they so chose to design or participate in may change over time, cultural as well as ontogenetic. How social models and social pressures, and individual desires and aesthetics, come to shape these changing patterns of distribution over time is a reformulation of the basic question of developmental psychology. (p. 80)

The tension between individual and community impacts a person's actions as they attempt to redesign their environment in order to pursue the activities they desire. As this tension changes over time, so do a person's goals and thus, their efforts to reshape their environment. Taken on the community level, these individual efforts coalesce into social institutions which fundamentally change individuals' ways of thinking: "we are individually products, and collectively are producers, of these cognitive institutions, tools, and practices" (Cash, 2013, p. 63-64). Individuals are influenced by the social institutions, practices, and tools around them, but also contain the capacity to influence these social institutions, practices, and tools. Thus, distributed cognition suggests that simply studying the individual is insufficient; one must consider the individual and the society together.

Given this, learning and knowledge construction processes are not considered individualistic. Although there is variety in the definition of distributed cognition, most believe modelling cognition as a distributed system is more accurate and can shed light on hinderances to learning processes (Moore & Rocklin, 1998). The design of the environment, the tools one uses, cultural norms, and interactions with others all influence how an individual "distribute[s] their cognition in the process of learning" (Doroudi, 2021, p. 16). Social psychology research seems to corroborate that thinking patterns are heavily influenced by an individual's experiences and culture (Nisbett, Peng, Choi, & Norenzayan, 2001 as cited in Ertmer & Newby, 2013).

Conversely, how an individual distributes their cognition also influences the knowledge of the community (Pea, 1993; Scardamalia & Bereiter, 1994). Scardamalia and Bereiter (1994) identify free access to information, diversity of knowledge, and collaboration as key to productive knowledge construction amongst students. Instead of forcing students to learn the same material, Scardamalia and Bereiter (1994) found that distributing knowledge across students allowed for deeper understanding by the individual and novel connections to be made between knowledge bases when students collaborated. Collaboration, in particular, also builds community knowledge by mediating differences in individuals' perspectives (Pea, 1993; Wenger, 1998). As shown by Scardamalia and Bereiter (1994), by treating knowledge construction as a reciprocal relationship between an individual and their social environment, one can study the effects on both the individual and the community.

2.1.2. The Role of Technology in Distributed Cognition

This reciprocal relationship also exists within the tools created and used. The tools and artefacts an individual uses are shaped by cultural, social, and individual desires, and these desires, in turn, are shaped by the tools (Salomon et al., 1991). By analysing the design and usage of tools, one can gain insight on the desires of the individual and community. Pea (1993) writes:

> These tools literally carry intelligence in them, in that they represent some individual's or some community's decision that the means thus offered should be reified, made stable, as a quasi-permanent form, for use by others. In terms of cultural history, these tools and the practices of the user community that accompany them are major carriers of patterns of previous reasoning. (p. 53)

The design of a tool carries certain affordances, or indications of how it must be used in order to complete a certain task (Oliver, 2016). What affordances are made and how they are designed is a social process: some logic was agreed upon and made permanent by building it into the tool. The history of a technology is made up of countless decisions and iterations, each of which can lend insight as to how people think about the activities they want to complete. As such, the tool becomes an artifact of the community, an object within which the community's ways of thinking can be observed.

It is important to note that how the tool is designed and how it is used are two separate phenomena. Scardamalia and Bereiter (2020) found when students were given an artificial intelligence technology (ECHO), they started trying to trick it into blatantly false conclusions, such as dinosaurs never went extinct. Similar exploitations have been seen with Microsoft's Tay chat bot, which attempted to learn from Twitter users and was quickly shut down for offensive and explicit tweets. While tools can be designed to promote certain behaviours and encode certain logics, individuals exert their agency by choosing how to use these tools (Neff & Nagy, 2016). This can have positive results, as play and dissatisfaction encourages individuals to act and develop deeper understandings of the tools at hand, or to build entirely new tools altogether (Scardamalia & Bereiter, 1994). Critical engagement with tools on an individual level forces reflective learning (Scardamalia & Bereiter, 1994) and ultimately enhances capacities for individual cognition as well as the community's cognitive institutions and practices (Cash, 2013). This critical engagement can be studied from three perspectives: behaviourally, or how students participate in class activities; emotionally, or how students feel about the activities; and cognitively, or how student work matches up with the set standards (Fredricks et al., 2004; Trowler, 2010). The amount of engagement and participation will influence knowledge construction on both the individual and community level (Pea, 1993; Wenger, 1998). Thus, distributed cognition maintains that tools, learning, communities, and individuals are all interrelated; changing one will inevitably impact them all.

2.1.3. Advantages and Disadvantages of Technology in Learning

When thoughtfully designed technology is deployed, users experience several benefits. In the traditional learning process, as students learn more about a concept, they move from learning basic facts and procedures to thinking critically (Ertmer & Newby, 2013). This linear process assumes that if a student does not master the basic skills, then they cannot progress to more abstract thinking about this new concept. Pea (1993) posits, "What opportunities are lost for learner participation in higher-level activities, and meaningful contributions rather than basic skills practice, if one does not allow for distributed-intelligence support for those activities involving artefacts and other persons?" (p. 74). Technology empowers students to engage in more complex thinking by "off-loading" basic skills. Calculators, knowledge databases, and other technologies can act as scaffolding to enable critical thinking in parallel with basic skills practice and allow for deeper engagement with the material from the beginning. Furthermore, engaging novices in the discourse allows them to "[point] out what is difficult to understand and, in turn, inadequacies in explanations" which can improve the teaching of the material (Scardamalia & Bereiter, 1994, p. 275). This process of self-reflection and identifying what is hindering the learning process is uniquely supported by technology. Pea (1993) writes, "Students would be empowered both through the reflective use of new tools and through the invention of new tools and social distributions of activities" (p. 82). Through using the tools and designing and building new ones, students can learn more about themselves, "their sense of who they are, what they know, what they want, and what they can do" (Cash, 2013, p. 67). More engagement by more students theoretically benefits the entire community, as it allows for better promotion of "more effective tools, practices, and institutions" for all (Cash, 2013, p. 67).

However, in practice, integrating technology into the classroom has had varying effects. Basic skill practice is often easier to design tools for, as the skills themselves often do not change over time and technology can remain unchanged. Indeed, most education technologies today often fall under behaviourist traditions, using shallow implementations of gamification to reward and penalize students into desired behaviours (Manolev et al., 2019). It is also argued that technology deskills students and teachers alike, placing more power into the hands of companies as they build technology that mediates the interactions between teachers and students (Perrotta et al., 2021). Personalized learning systems that rely strongly on data may increase extractive practices and surveillance within the classroom (Komljenovic, 2021). Moreover, when it comes to studying the effects of these technologies, companies often claim that the technology alone has created some effect, when in fact, research shows that technology may not have as strong of an effect as the larger context and increased resources to incorporate the technology (Salomon et al., 1991). Technology alone is not a solution, and must be developed alongside cultural practices in order to truly receive the benefits distributed cognition claims will occur.

There are clear suggestions and design guidelines to be followed to fully realize these benefits. Embracing true distributed cognition implies that the practice and skills evolve in parallel with students using and re-designing technology (Pea, 1993). Ultimately, learning with technology becomes less about delivery of material and more about supporting students in their learning processes. Scardamalia and Bereiter (2020) argue technology can act as a "computational black box" and to combat potential negative effects, technology must be designed to "maintain student epistemic agency" (p. 22). Thus, technology must be designed carefully to adapt to students' changing needs as they learn. Technology cannot remain static, nor can it dictate how a student learns; it must grow with the student and "preserve a central role for the students themselves, lest they be reduced to passivity" (Scardamalia & Bereiter, 1994, p. 276). Distributed cognition stresses the importance of the individual's engagement with their environment as a way to bring about change in the community's knowledge, tools, and practices. It so follows that technology should not impede upon individual agency, as it will result in less individual participation and engagement.

2.1.4. Distributed Cognition and Social Inequity

Although distributed cognition stresses the importance of individual participation within their community, it has not yet fully addressed the larger power dynamics and social inequities within a community that may prevent individuals from participating. If cognitive processing is not individualistic, then it necessarily "[takes] place in a context of a broader political arena, as well as an arena of personal status differentials" (Moore & Rocklin, 1998, p. 110-111). Communities are not inherently neutral; therefore, the context within which we are raised "instills in us our community's collective intelligence and wisdom, its practices and techniques, its norms and role models, its judgements and attitudes (but also its stereotypes, prejudices, and oppressive practices)" (Cash, 2013, p. 66). While distributed cognition acknowledges we are products of our social environments, it has not acknowledged how the power dynamics within a community may shape the individual and the community's knowledge, tools, and practices. For example, the resources and training available are typically unequally distributed along political categories like race, gender, age, or socioeconomic status (Protevi, 2009). Distributed cognition maintains that the tools an individual interacts with will influence how an individual learns and how the tools are re-designed to fit their desires (Moore & Rocklin, 1998; Pea, 1993). Thus, it can be argued that the unequal distribution of training and resources will result in different learning processes and unequal participation in technology design. Garcia and Lee (2020) write,

> By ignoring these institutional constraints and structured forms of marginalization, young learners are again forced to adapt to the tools, rather than the tools adapting to their needs. In this way, educational technology simply perpetuated and reifies the same inequitable conditions found in dominant schooling practices that ignore, invisibilize, and discount the experiences/backgrounds and epistemological traditions of marginalized communities. Rather than see value in who they are and the communities they are from, they are forced to erase their identities to acquiescence to the dominant culture and its practices. (p. 248)

Incorporating power dynamics into distributed cognition theories can help us understand the "important political and ethical dimensions of human cognition and the resources on which it depends, and to use this understanding to better improve these resources and their distribution" (Cash, 2013, p. 69-70). In order to holistically analyse an individual's cognitive processes, we must first deeply understand the larger political and social forces that shape the individual and the resources they have access to. This understanding also enables us to study the reciprocal: how individuals uniquely participate in the shaping of their community and how to promote a more equitable distribution of resources and training. In summary, distributed cognition presents a social model of cognitive processing but does not fully account for the nuances in power dynamics that shape individual identities. More careful study into how these dynamics influence an individual's desires, subsequent tool usage, and engagement with society is required.

2.2.0. The Digital Divide

2.2.1. Overview of the Digital Divide

What distributed cognition lacks in addressing power dynamics, digital divide research addresses directly. Digital divide research focuses on the interplay between information and computer technology (ICT), participation, and political categories (age, gender, and socioeconomic status, etc.). More specifically, this research studies how the adoption and diffusion of technology might be used to reinforce power dynamics within communities (Hargittai, 2003; Selwyn, 2004; van Dijk, 2012). There are several levels to the digital divide, ranging from physical access to skill. While initial digital divide research concentrated mainly on access to computers and the Internet, later research has focused on digital literacy, skills, and usage. When new technology is introduced into a society, access is the initial barrier: "The dominant category is the first to adopt the new technology" and as a result "uses this advantage to increase its power in its relationship with the subordinate category", where the category might be age, gender, race, or other political categories (van Dijk, 2012, p. 58). However, most technologies tend to diffuse throughout a population over time, reducing problems of access and introducing problems of skill. Better access does not necessarily imply equal usage, nor does it imply improvements in the social inequities that caused this imbalance in the first place. Jung et al. (2001) write, “if a technology is marketed to particular racial, gender, or age groups as a toy rather than a tool, the technology, although being successfully employed for entertainment purposes, may not necessarily contribute to career enhancement of these groups” (p. 508). ICT usage and skill are driven by a variety of factors – social capital and support, technical training, psychological attitude – which may or may not positively influence individuals’ capital and resources (i.e., the difference between using the Internet to apply for jobs and using it to stream videos) (Jung et al., 2001; Selwyn, 2004; van Dijk, 2012). Furthermore, digital illiteracy can prove dangerous when attempting to identify and share trustworthy sources of information and can result in the proliferation of “fake news” (Mutsvairo & Ragnedda, 2019; Selwyn, 2004). Digital literacy, skills, and usage give way to a new potential third level of the digital divide, algorithmic awareness. Information on the Internet is filtered through algorithms, which prioritize, organize, and display information to users. Some individuals have developed a new skill to “trick” the algorithm into making their content more visible than others. This involves using unrelated trending hashtags on social media posts or adding keywords to resumes so job applications pass through a company’s filtering algorithm or using search engine optimization (SEO) techniques to make content appear in the top results in Internet searches. This has several repercussions as those who lack this skill will be less likely to have their content shown (Gran et al., 2021). As ICTs have grown and propagated throughout society, so too has the digital divide evolved from access to skill to critical awareness.

Moreover, these levels have implications in societal participation. For example, although the Internet is largely accessible today, *how* the Internet is accessed still proves to be an issue that can impact an individual’s ability to participate in society. Individuals of a lower socioeconomic status tend to be more likely to depend on smartphones for Internet access but face a disadvantage because most websites are built for laptop or desktop usage. Smartphones have less memory, less processing power, and less screen real estate than laptops or desktops. As such, many websites are either not available or have reduced functionality on smartphones. Any “capital available through Internet access including social, economic, and political resources” are made less accessible to those who cannot afford a laptop (Tsetsi & Rains, 2017, p. 242). Thus, socioeconomic status influences an individual’s access to ICTs, which, in turn, presents additional barriers to the individual’s accumulation of social capital. Unequal access results in unequal participation in several aspects of society, including “economic (such as jobs), social (e.g. social contracts), political (voting and other kids of political participation), cultural (participating in cyber-culture), spatial (being able to lead a mobile life) and institutions (realizing citizenship rights)" (van Dijk, 2012, p. 62). Beyond access, those with more skill and experience with technology benefit even further because they are able to use ICTs in a variety of complex ways (Hargittai, 2003). This divide covers not only the consumption of content, but also the production of content. Those with more consistent access and skill are able to produce and share content online, including "creative expressions like fan fiction and digital mash-ups as well as collaborative problem-solving, group affiliation and media circulation", which further improves their skills as well as expands the content available to others online (Hargittai & Walejko, 2008, p. 241). The levels of the digital divide serve to reinforce various power dynamics, allowing some to participate in various spheres of society while preventing others from doing the same.

2.2.2. Implications of the Participation Divide

Following the theory of distributed cognition, participation in society influences both community knowledge as well as community tool design. The digital divide, and subsequent participation divide, substantiates this claim. Unequal participation has been shown to influence knowledge production and dissemination, as well as technology design. Those who have ICT access and skill are easily able to share their content and garner more views (Hargittai & Walejko, 2008). Similar to the power of newscasters and reporters, these individuals have the power to set the tone and viewpoint of public discourse, due to the size of their audiences (Hargittai & Walejko, 2008; Mccombs & Shaw, 1972). Those who understand the nuances of newsfeeds and search algorithms can make their content visible to an even larger audience, thus increasing their influence on the public (Gran et al., 2021). The introduction of machine-learning recommendation algorithms can also create echo chambers, which only show users information that they are likely to agree with, running the risk of "reinforcing whatever democratic deficit existed in the first place, weakening the condition for an informed public and democratic participation" (Gran et al., 2021, p. 1792). These critiques are not necessarily new: mass-media researchers often stress the importance of diverse, local perspectives in accurately portraying the issues marginalized communities face (Artz & Murphy, 2000; Kendall, 2011; Mccombs & Shaw, 1972). Emphasizing diverse perspectives allows for a better-informed public as well as more holistic view of community issues. However, the current digital divide has created an underrepresentation of some and overrepresentation of others, skewing the community's perception of social issues and leading to biased and incomplete knowledge bases (Schradie, 2011).

Unequal participation also influences the design of technology, as suggested by distributed cognition and digital divide research. Software companies design and iterate on their products based off user data (Cagan, 2017). However, due to barriers of access or skill, the user base of a certain product may not accurately reflect the potential total number of users. This creates a feedback loop of exclusion: companies use the data from their existing users to improve upon the product based upon their desires, those who were unable to use the product to begin with are further excluded, as the product fails to match their desires. This trend can be seen in technologies like WhatsApp. WhatsApp was developed in North America but is used globally. While it is extremely popular in Africa, the parent company is not beholden to African governments, thereby allowing Facebook to ignore the demands and problems of African users (Mutsvairo & Ragnedda, 2019). Furthermore, this exclusionary phenomenon has recently been identified within the algorithms themselves. Machine-learning algorithms that depend on aggregated user data often fail to recognize underlying biases within the data. In recent years, there have been countless examples of algorithmic bias originating in data: search engines displaying racist and sexist results for searches about black women (Noble, 2018), facial recognition failing to recognize people of colour (Buolamwini & Gebru, 2018), job application AIs automatically rejecting women (Dastin, 2018), automatic essay graders discriminating against students of colour (Dixon-Román et al., 2020) to name a few. In summary, because some users are excluded from using the technology as intended, they become excluded from the data sets that feed the algorithms. This has the potential to reinforce existing power dynamics and deepen divides within the community (Gran et al., 2021). One proposed solution is to over-emphasize historically marginalized users within the data sets and design choices, thereby reorienting the product towards a more equitable set of communal desires (Baker, 2021). Regardless, these examples demonstrate the importance of equal participation and the dangerous implications of excluding users in technology design.

2.3.0. Education Technology

2.3.1. Education Technology in Classrooms

As computers, tablets, and mobile phones have integrated into the classroom, several different uses of technology within the classroom have emerged. There are broad suites of applications, ranging from mobile learning games (Lynch & Gerber, 2017) to learning management systems (Chen et al., 2020) to behavioural modification systems (Manolev et al., 2019), with varying degrees of success (Delgado et al., 2015). Despite the proliferation of technology and education applications, there are no concrete gains attributed solely to the introduction of technology in the classroom. This is likely because education technology is most effective when it is highly localized, and tailored to the specific learning environment (Chauhan, 2017; Garcia & Lee, 2020). Some technologies like Google Drive and wikis have been used to successfully foster students' writing and collaboration skills, most likely because these tools are generic enough that students can tailor them to their own desires. Rather than dictating usage, they simply provide students a set of tools to accomplish certain tasks with ease (Sadik, 2017; Zhou et al., 2012). Other technologies have been deployed to support collaborative learning, particularly in recent times with the COVID-19 pandemic. Distance learning technologies like Zoom, Google Meet, and Blackboard have been heavily utilized in order to create collaborative learning environments while schools remained shut but come with their own host of issues (Chen et al., 2020; Wen et al., 2021). It is worth noting that the technology alone does not cultivate skills within the student: teachers still play a critical role in guiding and facilitating meaningful student usage of the technology (Alghasab et al., 2019). Both students and teachers must be considered throughout the design process to maximize the benefits of technology.

2.3.2. Education Technology Design and Education Theory

However, much of education technology is not tailored to specific communities or individuals. Rather, it is "designed for a general (e.g., early readers) or highly targeted audience (e.g., students who have failed algebra)" and often fails to take into consideration the diverse environments these learners are situated within (Garcia & Lee, 2020, p. 248). Theories like distributed cognition (Moore & Rocklin, 1998; Pea, 1993) or communities of practice (Scardamalia & Bereiter, 1994; Wenger, 1998) have shown that the unique aspects of community and learning environments strongly influence students' learning experiences. Indeed, many critics of education technology point out that the field tends to ignore theory and does nothing to "help us learn something new that could advance a particular theory" (Hew et al., 2019, p. 968). This can have injurious effects on students, as technologies like ClassDojo or other gamified apps tend to promote cultures of performativity rather than authentic learning (Lynch & Gerber, 2017; Manolev et al., 2019). These apps tend to rely solely on external rewards (i.e., points and badges) which prevents genuine play and learning through experimentation and failure, key elements in gamification theory (Juul, 2013; Lynch & Gerber, 2017; Resnick, 2018; Scardamalia & Bereiter, 2020). Engaging deeply with educational theory is key to designing effective educational technology; otherwise, apps can end up having little to no positive effect on students.

More thoughtful examination of knowledge construction processes is necessary when it comes to designing technology for student collaboration and knowledge sharing. At the very least, theoretical engagement helps us understand how a technological intervention might have brought about certain student outcomes (Hew et al., 2019). Engaging with educational theory can also help us understand how to highlight and include historically marginalized learners in education technology design (Garcia & Lee, 2020). Furthermore, it provides us a framework with how to combine the user-centred focus of technology design with equity- and inclusion-focused education (de Alvarez & Dickson-Deane, 2018). Purposefully centring historically marginalized voices and epistemological perspectives in the design process benefits both the designer and the users: marginalized individuals can participate in community tool design and designers are able to better create tools that benefit more users. This process may even uncover new knowledge construction processes, for the betterment of the entire community (Garcia & Lee, 2020). These ideas are matched with growing calls for design-based research, which "ensure[s] explorations of emerging technologies and affordances… are grounded in appropriate pedagogical strategies and informed by learning theory" (Aguayo et al., 2017, p. 37). Participatory methods, with a focus on marginalized learners, provide an opportunity for equitable, effective education technology development.

2.4.0. Augmented Reality Technology in Classrooms

2.4.1. Augmented Reality Affordances

Augmented reality (AR) is broad in scope, with several definitions. For the purposes of this dissertation, I have chosen to follow Azuma's (1997) definition of augmented reality, as "systems that have the following three characteristics: 1) Combines real and virtual 2) Interactive in real time 3) Registered in 3D" (p. 2). This definition accounts for augmented reality experiences through different devices, including head mounted displays, mobile phones, tablets, and computers, but still limits the scope to exclude computer generated visual effects or other non-interactive visuals. Augmented reality can be further organized into three categories: marker-based, markerless, and location-based (Chen & Tsai, 2012). Marker-based AR relies on image recognition; a camera will scan the area for some visual marker (e.g., a QR code, an image, or a poster), and trigger some event or visual display if the marker is present. Markerless AR is somewhat similar but uses object recognition to identify planes and surfaces in the physical world upon which virtual objects can be placed automatically. Lastly, location-based AR leverages GPS and additional sensors in devices to display information based on a user's physical location (Pellas et al., 2019). In summary, AR technology combines devices, virtual renderings, and the physical world to provide opportunities for unique interactions and experiences.

As such, augmented reality's affordances can be leveraged to teach and learn in new ways. Wu et. al.'s (2013) research suggests five ways augmented reality can be used in learning: content can be 3D instead of limited to 2D representations, content can visualize invisible forces, learner engagement can increase through increased sense of presence and immersion, learning can be collaborative and situated, and augmented reality can be used to bridge informal and formal learning spaces. The interactivity of augmented reality content encourages students to engage with the material, thereby increasing the potential for learning. The ability to portray 3D objects implies AR might be best used to teach subjects that require spatial awareness, such as geometry or physics (Billinghurst & Duenser, 2012; Pellas et al., 2019; Sahin & Yilmaz, 2020). Location-based AR allows for situated learning, as contextual information changes based on the physical location of the user. This has been used in museums and historical sites and shows how augmented reality can be used to increase learner immersion as well as how to bridge the gap between formal and informal learning (Petrucco & Agostini, 2015). These affordances allow augmented reality to potentially improve learning experiences, but the technology is not yet mainstream, and neither larger, generalizable studies nor many longitudinal studies have been performed yet to fully prove the benefits of augmented reality in the classroom.

2.4.2. Examples of AR in the Classroom

There are few examples of augmented reality used in classrooms, usually due to specific studies introducing them into the classroom. Overwhelmingly, augmented reality technology has been applied to science, technology, engineering, and mathematics (STEM) fields (Pellas et al., 2019), but there are some examples of augmented reality being used for art and history, with varying degrees of success (Di Serio et al., 2013; Petrucco & Agostini, 2015). A popular form of augmented reality technology in classrooms is AR books and flashcards, because it combines traditional print media with extra visualizations (Hornecker & Dünser, 2007; Plunkett, 2019). Furthermore, AR books link text with 2D and 3D visualizations, videos, and sound, providing a multisensory experience that can allow students to learn how they wish to learn (Billinghurst & Duenser, 2012). Alhumaidan et al. (2018) point out that the "bring-your-own-device model" AR books suggest might further "a status gap between students" as well as promote "a lack of social communication between groups/individuals" (p. 35). To combat this, they suggest treating AR books as a collaborative experience: an activity that encourages interacting with other students by joining their textbooks together or sharing tablets in class (Alhumaidan et al., 2018). Other research has focused on building AR authoring tools so that students and teachers might build AR content on their own. The process of creating interactive AR content (including AR books and flashcards) is posited to create a learning experience in and of itself, allowing students to reflect on how they learned the material in order to create the content (Billinghurst & Duenser, 2012; Hsu et al., 2019). Currently, there is a high barrier to entry for creating augmented reality content; creators must know how to code as well as use computer graphics software such as Unity or Unreal Engine. Simplifying authoring tools lowers this barrier and allows more students and teachers to create the content they want to see (Villanueva et al., 2020).

2.4.3. AR Educational Design Considerations

While AR apps are becoming more widespread, many studies stress the importance of good design; without it the learning benefits tend to be lost (Billinghurst & Duenser, 2012; Dunleavy, 2014; Petrucco & Agostini, 2015). Properly designed interfaces guide students through tasks, help them map the virtual environment with the physical environment, and recognize how they interact together; poorly designed interfaces tend to do the exact opposite, confusing students and increasing frustration (Squire & Jan, 2007). Good AR design should also include interaction design and a careful consideration of the audience. Creating AR content for children might improve their motivation but can "[raise] too high expectations about which physical actions have meaningful effects" and ultimately negatively influence their learning experiences (Hornecker & Dünser, 2007, p. 5). Dunleavy (2014) argues for three simple principles for positive AR experiences: "(1) Enable and then challenge (challenge); (2) Drive by gamified story (fantasy); and (3) See the unseen (curiosity)" (p. 29). Thus, AR technology must provide a clear set of protocols and expectations, such that students know what is and is not possible to accomplish within the experience. Once the constraints are established, the app must support students through their own inquiries and explorations.

Aside from usability concerns, using AR for education requires careful integration of education theories. Billinghurt and Duesner (2012) write:

> Current AR educational experiences are largely the ad hoc creation of either educators with little understanding of the technology or developers with little understanding of the education. The design of next-generation AR experiences will be purposeful. Education and sound learning theory will be at the forefront of design decisions from the bottom up. Such thoughtful design will aid in maximizing learning outcomes and ensure that educators apply AR technology where it is likely to have the most benefit. (p. 62)

Education theory will help AR designers determine the best way to deliver content. For example, it can help answer questions around how "information [should] be distributed and flowed between two realities and among different devices" (Wu et al., 2013, p. 47). Given that AR can support situated and collaborative learning, distributed cognition and constructivism have been put forth as potential suitable theories for the design of effective augmented reality (Dunleavy, 2014; Wu et al., 2013). Thus, combining educational theory with user design principles and a participatory approach to augmented reality design can help create beneficial, educational AR experiences for students.

2.5.0. Research Questions

This context identifies three important actors: the individual, the community, and technology. Tensions between individual and community desires can be seen in technology design and usage (Pea, 1993). The affordances developed within technology are social processes and therefore influenced by the biases present in communities. Phenomena like the digital divide suggest that biases encoded within technologies further cement social inequities and prevent equal participation (van Dijk, 2012). However, individuals can exert agency over how they use the technology. Individual critical engagement with tools can help expose biases and offer new empowering ways to use technology (Cash, 2013; Scardamalia & Bereiter, 2020). Theoretically, actively encouraging equal participation in the technology design process improves the technology as the features developed will better represent the needs and desires of the whole community. Technologies can then be used to prevent (instead of enforce) further marginalization of individuals. Given that technology design requires reflection and iteration, Pea (1993) theorizes that this process can also empower students to learn more about themselves and how they learn. Centring marginalized learners in the design of new technologies like augmented reality provides the opportunity to shape the technology in an equitable manner while celebrating and highlighting marginalized communities' knowledge bases. It is against this backdrop that I ask the following questions:

1. How do middle school students distribute information across different people and mediums (paper vs. augmented reality) during their knowledge construction processes?
2. How do low socioeconomic status (SES) middle school students perceive using augmented reality as a tool to learn with? What affordances do they identify as useful in the context of learning?
3. How do the answers to the previous questions change throughout the iterative technology design process?

3.0.0. Methodology

This study focuses on the relationships between technology design, marginalization, and learning processes to understand how critical engagement can make more inclusive technology while also influencing community knowledge construction. There is a specific focus on augmented reality as it has not yet become mainstream for educational use. As a result, there is an opportunity for students to engage with an unfamiliar technology and simultaneously design and integrate it into their learning processes. Throughout the iterative design process, I will also be able to study how new technology influences student learning processes as students continue to integrate their new versions of the technology into their workflows. This study focuses on students from low socioeconomic backgrounds due to the historical exclusion of these demographics in technology design. Taken altogether, these aims align with participatory action research (PAR) as both stress the importance of participation as a democratizing force and reflexivity as an avenue to critical engagement. This section will go over the principles of participatory design, participatory ethics, and the research design, including sampling strategies and data analysis.

3.1.0. Principles and Aims of Participatory Design

Participatory design, a branch of PAR, is founded on constructivist principles, resulting in an emphasis on power-sharing amongst researchers and participants. Participatory design mainly focuses on participatory approaches to technology design, where users are encouraged to provide input into technology design (Walsh et al., 2013). The underlying assumption is that contributing diverse perspectives both helps design better technology and aides in empowerment for those participating (Read et al., 2014). Participatory design (and PAR more generally) is rooted in constructivism, which embraces a contextualized and interpretive view of knowledge, thus inherently suggesting no two perspectives are alike (Papert & Harel, 1991). As such, "participants' knowledge is valorized rather than deprecated, and their perspectives therefore become invaluable when researching their activity and designing new ways to enact that activity" (Spinuzzi, 2005, p. 165). This is true regardless of the background of the participant; Druin (1999) stresses the importance of treating children as experts in their own right, particularly when it comes to articulating their own needs. Participatory design values the generative dialogue that occurs between diverse perspectives throughout the process of tool design, as this results in "construction and transformation of meaning" for everyone involved (Sanders & Stappers, 2014, p. 6). By valuing every perspective and supporting transformative knowledge, participatory design "[encourages] the researchers to step down and share control and the consumers to step up and take more control" (White et al., 2004, p. 8). While historically researchers have dictated all stages of the research, true PAR research encourages power-shifting in all respects, including within the research process itself (Harrington et al., 2019). Thus, there are no strict rules in participatory design methodology; rather, researchers are encouraged to remain flexible and fit their research process and goals into the participants' epistemology and ontology, as opposed to the other way around (Spinuzzi, 2005; White et al., 2004). At the centre of participatory design is an emphasis on valuing diverse perspectives equally.

Participatory design also stresses the learning gained throughout the research process. When every perspective is seen as valuable and unique, then everyone who participates can learn something from everyone else. As Druin (1999) acknowledges, "the technology that is discussed…is not the only result of my work. I find what the team members can learn as a result of the research and development experience to be critical" (p. 597). Thus, the technology designed is not the sole focus of the participatory design; the learning caused by dialogue between participants and researchers is equally, if not more, important. The iterative nature of technology design is seen as a mechanism to centre conversations and prompt reflection (Spinuzzi, 2005). Implicitly, this suggests that *how* these participatory design sessions are organized can influence the quality of learning that takes place, thereby reiterating the importance of power-sharing between researchers and participants as a way to value all perspectives and information (Walsh et al., 2013). Druin (1999) dubbed this outcome "design-centred learning" and notes that this learning can occur for all participants, regardless of whether it is an adult learning from a child, or a technical professional from a technology novice (p. 598). Design-centred learning aligns closely with Pea's (1993) argument of distributed cognition, which suggests that students will learn more by building the tool than using the tool. Indeed, through debate and collaboration, student understanding may shift and change while building the tool.

3.2.0. Participation Ethics

3.2.1. Common Critiques of Participatory Approaches

It is important to note that participatory design is not inherently democratic. Depending on who is included and how participation is facilitated, participatory design may end up exacerbating existing power dynamics and further marginalizing some participants (Harrington et al., 2019). Thus, researchers must carefully consider how they structure the participatory design process to ensure equitable and fair participation for all participants. Part of doing so necessarily requires acknowledging what skills participants will need in order to contribute (Dearden & Rizvi, 2008). This is particularly true with designing technology, as phenomena like the digital divide (van Dijk, 2012) demonstrate that technical knowledge and skills are unequally distributed across political categories. Any participatory effort then, must also focus on what skills are required for individuals to participate *and* building these skills for all participants such that everyone can contribute equally (Harrington et al., 2019). Read et al. (2014) argue for a "a fair and equitable process that is describable and defensible" such that every participant knows how their "contribution is collected, valued, and used" (p. 105). By providing students with many opportunities to interact with augmented reality throughout the process and including student feedback in the planning of the study, I aimed to build their capabilities of reflection and technical skill, both necessary to contribute to this study. Furthermore, the use of the TRAck (tracking, representing, acknowledging) Method for equitable participation (see Read et al., 2014) provides a clear system for students to trace how their specific contributions were added to the final product.

The complexities of democratic participatory design extend into all facets of the process, including informed consent. Informed consent is crucially important to the power-sharing aims of participatory design, as informed consent empowers participants to understand what values exist within the study and more practically, how the data collected might be used in the future (Read et al., 2014). Given historical colonial practices of extraction in research, where data was often used to further marginalize a community, informed consent (and similarly, informed refusal) redistributes the researcher's power to the participants (Harrington et al., 2019). However, informed consent is somewhat problematic in the context of participatory design, particularly when the participants are children. Fully informed consent is infeasible because of the flexible and community-led aims of participatory research; individuals cannot be fully informed at the beginning of the project because not even the researcher knows where the research will lead (Lofman et al., 2004). This concern is compounded when working with children, as it can be unclear how much the child understands what the research aims are. As such, it was important to remind participants of their rights to withdraw from the study at regular intervals (Read et al., 2014). Regardless, no student refused to participate.

Lastly, participatory design in this study, due to its reliance on technology design, can fall prey to technosolutionism. Prototyping tends to shift participant attention to minor details of how the technology works, rather than examining the larger context and motivations behind the design decisions (Spinuzzi, 2005). Furthermore, the focus on technology may implicitly advocate for technological solutions, at the risk of ignoring more sustainable solutions built out of existing resources in the community (Harrington et al., 2019). Simply focusing on representation and inclusion within the participant group is not enough; researcher efforts must also focus on encouraging wider critiques about the larger socio-technical system (Dearden & Rizvi, 2008; Donia & Shaw, 2021). Using evaluation frameworks like Collaborative Analysis of Requirements and Design (CARD) (Muller, 2001) and building in ample time and opportunity for reflection can help mitigate the tendency towards technosolutionism (Björgvinsson et al., 2012; Nazneen & Sultan, 2014). Above all else, it is important to stress to participants that the technological artefact is not the goal of the research, but rather a way to focus observations, perspectives, and discussion on the problem identified (Sanders & Stappers, 2014).

This study also underwent the Central University Research Ethics Committee (CUREC) ethics review process, which required detailed information on topics such as informed consent (for both parents and children), secure data collection and storage, and a copy of all student-facing materials (see Appendix A). This study aimed to address the critiques listed above through regular feedback, informed consent through building capabilities, and the usage of frameworks like the TRAck method. These approaches were carefully outlined and vetted during the CUREC ethics approval process and was approved under the code CIA-22HT-004 (see Appendix A).

3.2.2. Positionality

It is important for me to address my own positionality and how it influences the research done, particularly when this research focuses on marginalized communities (Harrington et al., 2019; Nazneen & Sultan, 2014). I majored in computer science as an undergraduate, with a focus on computer graphics, which naturally influenced my decision to study augmented reality and its educational potential. Computer science education has also influenced my theoretical choices, which foreground constructionism and distributed cognition, incorporating technology and building artefacts into the study of learning effects. Given the different aspects of my identity, I was simultaneously an insider and outsider to the class of students I worked with (Bilgen et al., 2021). The study took place in an all-girls middle school in New England, USA. While I identify as female and grew up in the region, I lived in a more affluent area, which likely influenced the power dynamics between me and the students. Similarly, I am a person of colour from a predominantly white state (US Census Bureau, 2021), and I share some cultural similarities with the students (i.e., living in a joint family, multilingual home) which helped me better relate to students. However, I come from an Indian background and no student in the study identified as Indian. Thus, I have a different set of experiences which sets me apart from the students studied. These nuances all influenced how students perceived me as the researcher, which in turn, influenced the relationship between me and the students and the research produced.

3.3.0. Data Collection and Analysis

3.3.1. Sampling Strategy

Given the research's focus on students from low socioeconomic backgrounds, schools that mostly serve students from low socioeconomic areas were predominantly contacted. This led the discovery of Ada School, an all-girls tuition-free private middle school (fifth to eighth grade) in New England, USA. For the sake of anonymity, the school and all participants have been placed under pseudonym. Although the school is a private school, the tuition is largely paid for by donors, with families contributing an average of $50 per month (this varies based on household income) *(Ada School*, n.d.*).* 82% of the student body qualifies for free or reduced-price meals (*Ada School*, n.d.). 95% of the student body identifies as one or more minority (*Ada School – U.S. News Education*, n.d.). After discussing with school faculty, I was allowed to work with the eighth-grade class, specifically during science class period and break time (90 minutes total) once a week, for 4 weeks. The entire eighth-grade class consists of 12 female-identifying students and no students were excluded in participating in the study. Not all students were able to attend every session due to the COVID-19 pandemic, with some students ill or quarantined for 1 to 2 sessions. All students already owned iPhones, as well as a Chromebook, a science textbook, and class notes, all of which were used during the research process.

3.3.2. Procedures

3.3.2.1. Recruiting Participants. This research followed the stages of design as outlined by Spinuzzi (2005) and White et al. (2004), the first stage of which is recruitment. Ada School was uniquely suited for this research, as its private school basis allowed for more flexibility and disruptions in the standard curriculum. Furthermore, the school is driven by a culture of social justice and women's empowerment, placing value on the critical engagement, participation, and perspectives of women such that they are empowered to accomplish their dreams (*Ada School,* n.d.), which aligns well with the goals of participatory research. Per White et al.'s (2004) recommendation, I started all communication with school administration and students with a description of the project, benefits of involvement, and reasons for choosing Ada School. I also stressed the fluidity of this research and a desire to integrate this as much as possible with existing school workflows and curriculum. I worked closely with the eighth-grade science teacher to do so.

3.3.2.2. Session 0: Informed Consent. Informed consent is identified as crucially important to level the power dynamics between researcher and participant. As such, I held an in-person information session with AR demonstrations, so students were able to familiarise themselves with the technology and make an informed decision. Students were split into groups that rotated through stations with different versions of AR, including an AR colouring book, an AR face filter app, and an AR basketball app. Devices were available at each station for students to use.

I also ensured that the information sheets, consent forms, and presentation all used non-technical language by asking family members and friends (of varying ages and technical backgrounds) to review the content to make sure it was easily understandable by eighth grade students and their parents. White et al. (2004) argue that "content that is presented in easy-to-understand fashion facilitates participation by stimulating ideas, discussions, and overall responsiveness of consumers to researchers" (p. 8). The in-person information session also allowed students to discuss the research with me and ask questions before signing consent forms. Furthermore, the "opt-in" nature of the research was stressed and every student was aware of their right to refuse to participate, something particularly important when working with marginalized communities (Albornoz et al., 2019). I also continually asked for verbal consent throughout the process and informed them of their right to withdraw their data for the research.

3.3.2.3. Session 1: Discovery Processes. As Spinuzzi (2005) outlines, the discovery process allows researchers and participants to identify participant goals and understand existing student workflows. To ensure democratic collaboration, I used the TRAck Method, as outlined by Read et al. (2014). The TRAck Method provides a framework for ensuring all individuals can provide input and no single idea dominates the group process. This is done through cycles of individual input, small group collaboration, and lastly, whole group discussion.

The beginning of the session summarized points from the information session and asked students to recall the unique features of augmented reality. This group discussion resulted in a list of features compiled on the white board. Students were then asked to go through their notes, Google Classroom, textbooks, and previous assignments, and on index cards, anonymously write down concepts they found confusing. These index cards were then collected and aggregated into another list, also displayed on the whiteboard. Students were then led through a discussion of these concepts and asked to choose one item from the AR feature list and one item from the concept list and envision how AR could help explain the concept. Once again, they were asked to anonymously write down their ideas on index cards, which were then collected and presented to the class. Lastly, the ideas were put to a vote to decide what the content of the AR book should be. The topic decided upon was how COVID-19 affects the cell, and the teacher helped students prepare for the next session by assigning some reading (this was done of the teacher's own volition, without my encouragement).

3.3.2.4. Session 2: Prototyping. The prototyping phase moves towards a technical solution for the problem identified in the discovery phase. Prototyping is an iterative process, where the researcher and participants will continually shape the technology until it fits into the participant workflows (Spinuzzi, 2005). While prototypes can be digital, there are benefits to creating simple paper prototypes. As Druin (1999) highlights, "since children may have a difficult time communicating to adults exactly what they are imagining, prototyping offers a concrete way to discuss ideas" (p. 593). Paper prototypes do not require any specific technical skill; thus, children can focus on their ideas, rather than learning how to use a digital prototyping tool.

The beginning of this session summarized the previous sessions and then started with a discussion about what students had learned through their readings of how COVID-19 affects the cell. I asked if the participants had any further questions, and students posed several questions. These questions became the foundation for further research, and eventually the focus for the student prototypes. Students were given 20 minutes to research their questions using the Internet and write down notes, and then were asked to build a prototype model that helped visualize the answer to the question. Using the "bags of stuff" prototyping technique (Walsh et al., 2013, p. 2895), I carefully deliberated on a standard set of materials given to all participants, ensuring that the materials reflect the research area (Druin, 1999). See Figure 1 for a complete list of all materials students were given. Students were given a choice to work together or work separately, with most students choosing to build individual models. By the end of the session, students were asked to present their prototypes and describe their ideas (Walsh et al., 2013). I then took this information, the models, and their research questions and compiled them into a 4-page handout with an accompanying AR app, to be used by students in the following session.

This iOS app was built using Maya, Unity, and XCode. Given the similarity of 2 of the physical models, I combined them together to form one virtual model. Some of the models were taken from open-source websites (see Appendix C). Maya was used to edit, build, and combine virtual models, Unity was used to create an AR app, and XCode was used to compile and launch the iOS app on iPhones. The Unity project can easily be exported for Android phones, but since all students had iPhones, there was no need to build an Android app. The app was also loaded onto additional iPad tablets, in case students were not able to access the app on their phone. Two students did end up using iPads over their own devices, due to storage limitations and out-of-date operating systems.

3.3.2.5. Session 3: Iteration and Evaluation. Iteration is an important part of participatory design; as such, the final session required students to reflect on the process so far, then revisit their designs and the app prototype to make improvements. The avenue of reflection, both for the prototypes and the research process, centred around a modified CARD technique (Muller, 2001) that divides types of feedback into discrete components. Different coloured Post-It Notes represent different types of feedback, including likes, dislikes, and suggestions (Alhumaidan et al., 2018; Druin, 1999). For the prototype evaluation, writing down this feedback provided concrete points for discussion and focus for the next iteration of the prototype (Walsh et al., 2013). Students were placed into groups based on the similarity of their research questions (i.e., everyone who studied the loss of taste and smell were placed together) and then asked to collaboratively review the app and write down feedback. This feedback was anonymously collected, as students were discussing each other's models and felt more comfortable providing feedback without their name attached to it. Following a group discussion, students were then asked to return to their groups, revisit their own paper prototypes, adjust their models based on the feedback given, and present their changes to the class. At the end of the final session, students were asked to reflect on the entire process and write down what they might have learned, thus encouraging them to reflect on "the implication of the research results for their own work" (Spinuzzi, 2005, p. 171). Through the Post-It Notes technique, participants were able to organize their feedback into standard components, thereby focusing discussions to improve the prototypes.

3.3.3. Materials

Following the "bags of stuff" prototyping technique (Walsh et al., 2013), students were given a collection of arts and crafts materials from which they were asked to build their paper prototypes. Given the 3D nature of augmented reality, special care was taken to include 3D Styrofoam objects and clay so students could create 3D models. Students were also given a "viewport", or a frame that matched the size of a smartphone, so they could determine what would be seen as users moved their phones.

Figure 1: Materials for physical prototypes. (from left to right) plain paper, Post-It Notes, pipe cleaners, wooden sticks, pom-poms, Styrofoam blocks, phone-frame "viewports", markers, foam sheets, Styrofoam spheres, and clay. Not pictured: glue and scissors, provided by the school.

3.3.4. Data Collection

Several forms of data were collected throughout these sessions. The paper prototypes (from the individuals and small groups) were photographed at the end of each session and the presentations were recorded and transcribed (audio-only). These two sources, along with the Post-It Note reflections, were used for thematic analysis to find patterns in student sentiment about the technology as well as to observe how students integrate the technology into their learning.

3.3.5. Analysis

Thematic analysis is uniquely suited for the data analysis in this study. Clarke and Braun (2017) suggest that it can be used to "identify patterns within and across data in relation to participants' lived experience, views, and perspectives" and so, particularly suited to "understand what participants' think, feel, and do" (p. 297). Given that the aims of this study are to examine the perceptions of augmented reality and students' critical engagement with technology, thematic analysis can help systematically explore student practices and discussions as it relates to the construction of their augmented reality book. Pea's (1993) distributed cognition theory argues that technology has values embedded within it; thus, the thematic analysis must include analysing both visual and textual elements. Systematic Visuo-Textual Analysis is a framework that acknowledges artefacts as an additional form of communication, rather than a way to simply start a conversation (Brown & Collins, 2021)**.** This framework involves 3 elements (visual only, textual only, visuo-textual combined) and 2 levels (noticing/describing, conceptualization), with frequent movement between the two. The first level encourages the researcher build the initial set of codes by observing the use of colour, perspective, etc. in the visual work and the use of language, phrases, etc. in the textual work. For the visuo-textual combined, the research must connect the observations of both the visual and textual (Brown & Collins, 2021). This level generates the initial set of codes, upon which the next levels begin to collate the codes into coherent themes.

The figure originally presented here cannot be made freely available via ORA because of copyright. The figure was sourced at Brown, N., & Collins, J. (2021). Systematic Visuo-Textual Analysis: A Framework for Analysing Visual and Textual Data. *The Qualitative Report*. https://doi.org/10.46743/2160-3715/2021.4838

Figure 2: "Tabular Introduction to Levels and Elements of Interpretation Within the Systematic Visuo-Textual Analysis" (Brown & Collins, 2021, pg. 1281).

Figure 2, taken from Brown and Collin's (2021) paper, depicts the matrix of levels and elements; where the first level is done per participant, the second level aggregates all observations together. For this study, this first level is done for each model and transcript. Only one student spoke about the model during the student presentations, but some models were built in groups. Therefore, the written process feedback acted as the textual element for students who contributed to the models but did not speak, and the app feedback was used as a textual element to support general comments about the technology specifically (see Table B1). Per Brown & Collins's (2021) framework, the second level then looks for commonalities across all visual observations (visual elements that unite artefacts), all textual observations (themes), and all visuo-textual observations (see Table B2).

While this format combines both visual and textual forms of data, it does not immediately account for the iterative process of co-design. Where the original framework assumes one model and one transcript per participant, this study extended the framework to account for 2 models and transcripts for each participant. By adjusting the framework in this way, the Systematic Visuo-Textual Analysis is also extended to include a 3rd level: change across time (see Table B3 and B4). Thus, the first level can be analysed in two ways: "vertically" investigating the change in each element (visual, textual, visuo-textual) across all participants (i.e., the second level) and "horizontally" investigating the change in models per participant and across all iterations (i.e., the third level). Following the columns and rows of this grid naturally invokes iteration during the coding process as researchers weave between the levels (Brown & Collins, 2021; Clarke & Braun, 2017). This "grid" format (see Table B1) is also useful because it can account for student absences between sessions while still including their input when present, thus allowing for analysis of discrete events and longitudinal data. More importantly, this systematic analysis across the rows and columns allows the researcher to learn more about the individual and the community: analysing across the iterations (the row) suggests changes and similarities for the individual and analysing down each element (the column) suggests changes and similarities in model creation, transcript description, and visuo-textual elements for the entire community (see Figure 3). The systematic analysis of both the individual and the community aligns well with the intentions of this study, which aims to examine the relationships between the two. Where the first level helped generate the initial list of codes, the second and third levels helped aggregate these codes into themes related to the individual and the community.

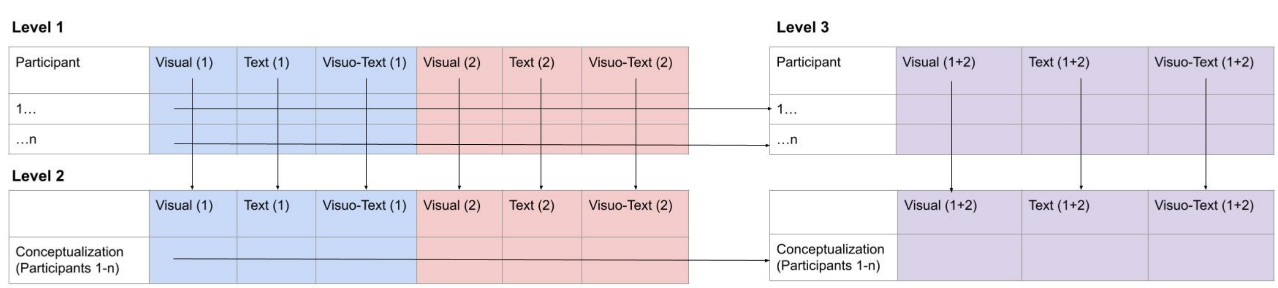

Figure 3: Analysis directions in the extended model of Systematic Visuo-Textual Analysis.

3.4.0. Limitations

This study has several limitations. Perhaps most obviously, this study only contains one iteration of development, whereas a more expansive version of this study with multiple iterations and opportunities for reflection would likely result in more nuanced data and deeper engagement with the material. This study was also designed with a small sample size in mind, and it would require significant resources to scale up, a challenge Wu et al. (2013) identifies as prevalent in many AR studies. This study also requires skilled knowledge in both app development and animation software, and thus may require an interdisciplinary team of researchers in the future, or researchers with technical backgrounds. As the study occurred during the school day, it was thus limited by the subject and length of the class period. Students were required to focus on a science-related AR book and only had 90 minutes each session to do their work. The prototyping and iterative phases might have benefited from longer sessions, where students could better flesh out their ideas without feeling rushed. Furthermore, given this study took place in a school setting, children may not have felt capable of refusing to participate, because the larger institution had already allowed the study to take place (Lofman et al., 2004). The school is also an all-girls school, and results may vary if the population studied is highly diverse across political categories such as gender (Moore & Rocklin, 1998). At the same time, the flexibility of the school and its participatory culture were critical components of the research, something that may be difficult to find in other schools, public or private. As such, this study may be difficult to replicate in other school settings and may be better suited to after-school sessions. Lastly, this study is dependent on mobile devices. Students who do not own smartphones, students who are unfamiliar with smartphones, or researchers who do not address these nuances will face greater challenges with participating in the design and development of an augmented reality book.

4.0.0. Findings and Discussion

By the end of the four sessions, the students had designed a 4-page handout and accompanying AR app about COVID-19. The handout poses and answers several questions that the students themselves generated, such as "Why does COVID-19 result in a loss of taste and smell?" and "Why is COVID-19 so contagious?" The handout followed the marker-based AR pattern (Chen & Tsai, 2012) and contained "key" images that the app identified and used to display and position specific models (see Figure 4).

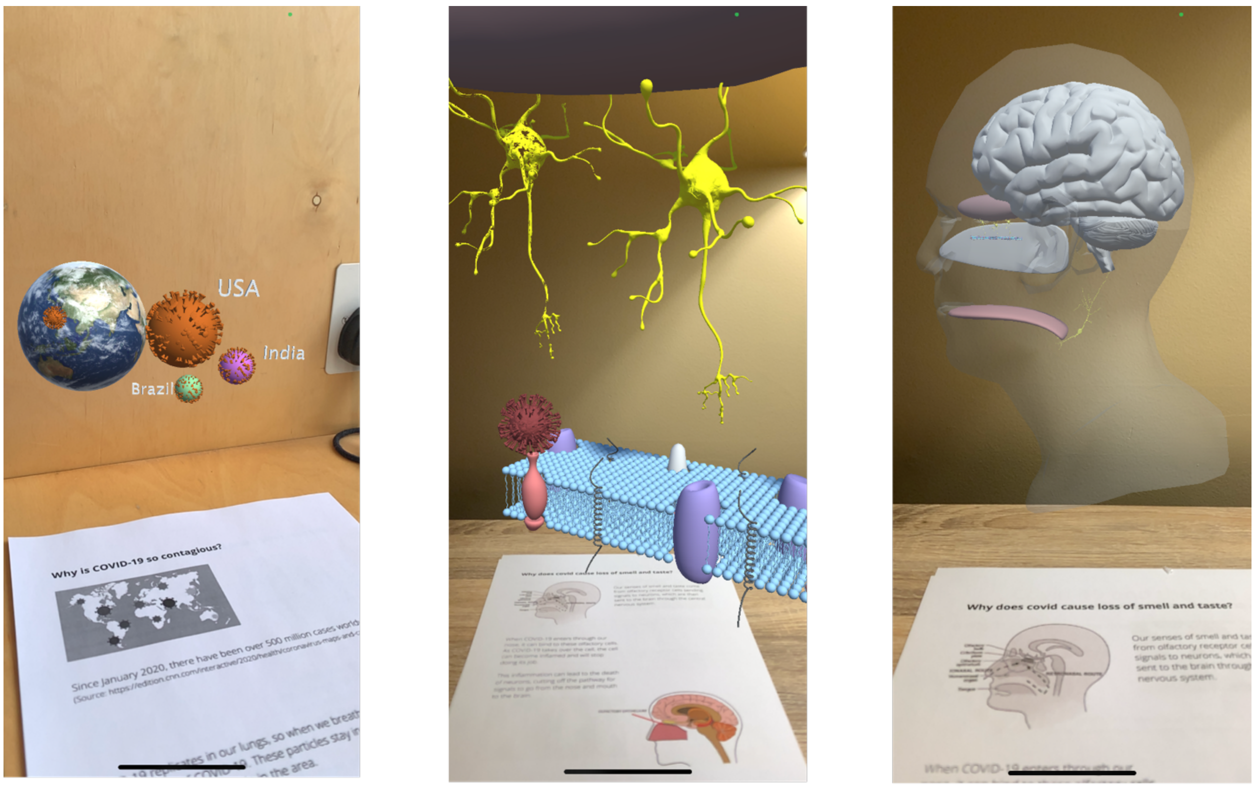

Figure 4: Examples of handout and student models shown via app.

It is with the data collected from the development process, alongside student reflections and discussions, that I return to the previously stated research questions:

(1) How do middle school students distribute information across different people and mediums (paper vs. augmented reality) during their knowledge construction processes?

(2) How do low SES middle school students perceive augmented reality as a tool to learn with? What affordances do they identify as useful in the context of learning?

(3) How do the answers to the previous questions change throughout the iterative technology design process?

By the end of the analysis process, the data was aggregated into three themes, centred around new perspectives, student engagement, and iteration. These themes delve into how students posed themselves with or against the community knowledge and how the technology was integrated into their workflows as a tool to learn with. Ultimately, the technology and the iterative co-design process was used as an opportunity to explore, first across a wide range of questions and then more deeply on specific details.

4.1.0. Examining new visual perspectives using AR

After experimenting with AR technology, students almost immediately identified the ability to see new visual perspectives as an affordance of the technology. During the brainstorming session, students were asked to experiment with various augmented reality apps and list out the unique features of the technology. One of the first affordances listed was the ability to move the device around and gain new perspectives on virtual models. Indeed, other augmented reality research has identified this as a potential feature useful for learning, arguing that the freedom to view from any angle can help in knowledge construction (Kang et al., 2011), particularly as it relates to abstract or invisible phenomena (Dunleavy, 2014; Wu et al., 2013). Other researchers (see Billinghurst & Duenser, 2012; Hsu et al., 2019; Pea, 1993) focus more broadly on the content creation and technology design process, arguing that it helps students engage with the content while simultaneously helping students learn how to better use the technology to accomplish the desired task. In this vein, students used the opportunity to create an AR book as an *exploratory* tool to learn with, a tool to find new perspectives. Throughout the entire process, it became apparent that they built these new perspectives through two means: connection and absence.

4.1.1. Sub-theme: New perspectives can be found by connecting existing resources together

In the brainstorming and initial model creation sessions, students were more interested in using the technology to connect their own understandings of discrete topics together (i.e., cell biology and COVID-19) as compared to drilling deeper into distinct topics. In the brainstorming session, students were asked to make two lists: unique features of AR and concepts they had learned in the past year. They were then asked to choose one from each list and envision how AR might help explain that concept. While I originally suggested focusing on concepts that the students felt were confusing, most students responded that none of the concepts were confusing on their own. As such, some students decided to combine two concepts they had learned (cell biology and COVID-19) by creating visualizations of how COVID-19 interacts with the cell. When deciding on the final topic by popular vote, 5 out of the 6 students present voted for this concept (the other student wanted to focus solely on cell organelles). In developing this idea, students were connecting their existing knowledge about cell biology with their first-hand experience and general knowledge of the COVID-19 pandemic, thus resulting in a new perspective on COVID-19's effect on the body. This idea also indicates a nascent understanding of AR as a tool to "make visible the otherwise invisible" (Dunleavy, 2014, p. 32), something further emphasized as students later began to build their own models and visualize phenomena not visible to the naked eye. While creating AR content that connected their existing knowledge of COVID-19 and cell biology together, students began to enrich their knowledge of both subjects and increase their understanding of the technology itself.

This theme of using AR to connect information together was later reaffirmed during the final session, when students were asked to list what they had learned throughout the entire process. Student answers were overwhelmingly interdisciplinary: there were six references to learning about augmented reality as a technology, six references to learning more about computer programming (despite never working with code), five references to learning about COVID-19, and three references to learning about human biology or cell biology (see Table B5). This implies that students were aware of the connections between not just the content of the AR book but also how it related to the technical details of AR. One student, Ramona, even stated, "*I learned that there is… more to code than just numbers and boring stuff*", suggesting a new perspective and increased awareness about the complexities and interdisciplinary potential of computer programming. Such comments echo claims from Billinghurst & Duenser (2012), who suggest that AR content creation activities in the classroom will result in interdisciplinary, contextualized learning.

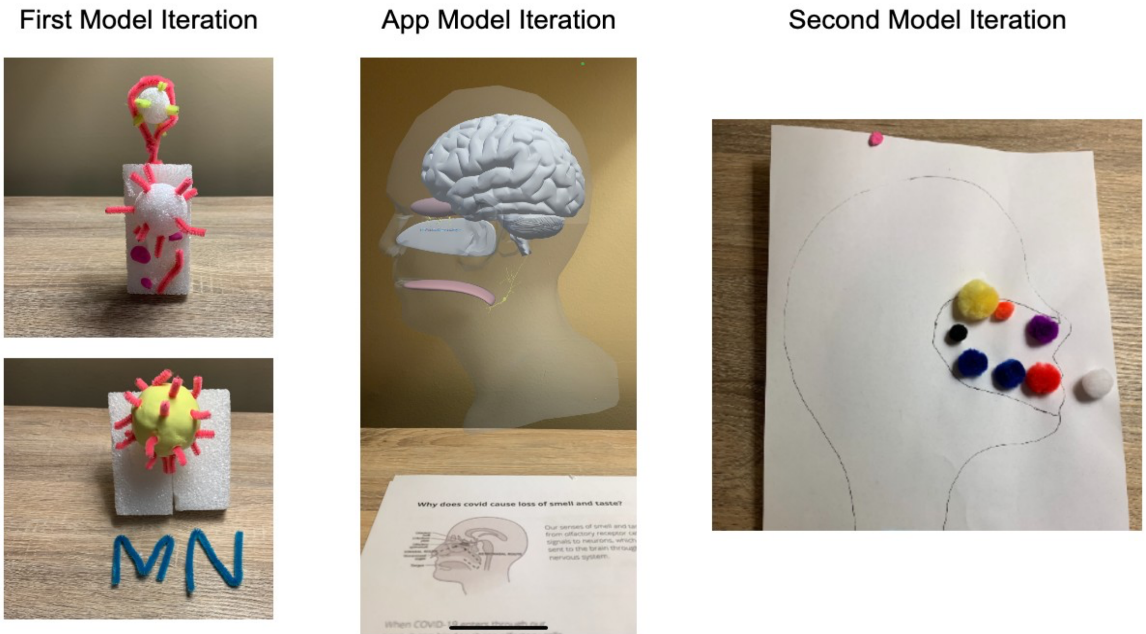

Figure 5: Catherine and Maribel's model iterations. (top left) Catherine's first model, (bottom left) Maribel's first model, (middle) combined virtual model, (right) Catherine, Maribel, and Ramona's final model

4.1.2. Sub-theme: New perspectives can be found by looking for "what's missing"

As students began work on their models, focus shifted towards looking for what was lacking in the technology and in the presentation of material. For example, when asked about their motivations behind their models, five students mentioned that something was missing: either the text was missing visualizations for better clarity, the model was missing detail, or the content was missing altogether (see Table B5). The latter case was particularly clear with Catherine's model iterations. Catherine was originally confused about how to start with her model, and ultimately decided to follow her friends and focus on why COVID-19 causes a loss of taste and smell. Her initial model was quite symbolic, depicting COVID-19 interrupting the path between the brain and the body (see Figure 5). Her model also contains some misleading representations, as it depicts COVID-19 particles in the brain, despite the lack of evidence for COVID-19 directly affecting the brain. In her second iteration, she worked with two other students, Maribel (who worked on a similarly abstract model that focused on COVID-19 blocking the mouth and nose), and Ramona (who had missed the previous two sessions). The three together compared their models with what was presented in the app and decided that what was missing was an accurate visualization of how COVID-19 enters the body. As such, their improved model focused solely on explaining how COVID-19 enters the mouth and nose and then begins to "[block] it to stop people from smelling". For Catherine, her motivation was ultimately defined in contrast to the larger community knowledge as the desire to produce new information that the community had not yet considered. The benefits of Catherine's shift in motivation were two-fold: the community gained a piece of missing information and she gained a better perspective of COVID-19's effect on the body (as evidenced by the more accurate depiction of COVID-19 remaining in the nasal cavity).

In some cases, students focused on what was "missing" from the models but included in the handout, arguing that both mediums should contain all information. One participant, Amber, originally focused on how COVID-19 spreads but later decided to focus specifically on the details of the COVID-19 particle. When presenting her new model, she said:

> *I redid this thing but the process to redo it was to show this squiggly part inside it because of the fact that we didn't talk about it much so I redid it and actually made it like the sheet and probably just the squiggly stuff in the middle. I don't even know what it is myself.*

Amber is referring to the initial discussion of COVID-19, where students and I covered the physical components of the coronavirus, but no student decided to focus on this during the first model building session. For the purposes of providing background information in the handout, I decided to include a virtual model of the outside of coronavirus particle alongside a 2D image of the inside of the particle (see Figure 6), showing its RNA ("the squiggly part").

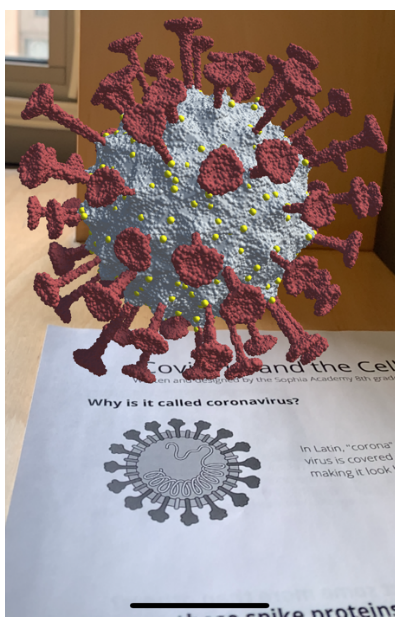

Figure 6: 2D image of the inside of the coronavirus particle versus 3D coronavirus particle.

In another instance, one virtual model showed a "zoomed out" view of the olfactory epithelium while the student text described each component and its relationship to the brain (see Figure 5). The anonymous app feedback suggested students responded negatively to this pattern, where the image and text showed different information compared to the model, with some regarding the split as confusing. This echoes this study's first research question surrounding the distribution of information, as well as a similar question Wu et al. (2013) posed: "How should the information be distributed and flowed between two realities and among different devices?" (p. 47). Within this study, it became clear that information was distributed differently when students were creators of their own models versus when students were consuming or reviewing other models. While students originally divided information between their physical model and the text, when working with the app, students were much more prone to point out that the model and the text did not perfectly match. Although one motivation of an AR book is to augment the information provided (Billinghurst & Duenser, 2012), Amber argued that the prototype was too confusing because it required the handout in order to decipher it. This suggests that she still views the app as distinct from the handout, rather than two items that work together, and as such, both should be able to stand alone. This raises questions of how students like Amber would permanently integrate the technology into their studies, potentially using it as an "either-or" situation, rather than in conjunction with the paper component. More generally, the initial models created and the subsequent feedback generated suggests that researchers cannot automatically assume students can create educational content for others when designing with emerging technology. The student review and feedback process was valuable in that it forced students into the role of reviewer and consumer, allowing them to better understand what "users" might expect or want.

4.2.0. Engagement is hands-on, user-directed, and collaborative

Student engagement can be broken into three facets: behavioural engagement, which addresses student participation in class discussions and assignments; emotional engagement, which addresses positive or negative student emotions tied to the tasks at hand; and cognitive engagement, which addresses if students exceed expectations with the work produced (Fredricks et al., 2004; Trowler, 2010). Student engagement in this study was examined in three different contexts: engagement with the material, the technology, and the co-design process. The data shows that student engagement varied slightly for each context. Students enjoyed building the models and explored the material with greater interest when given the opportunity to do so. This desire for "hands-on" opportunities extended to the technology as well, albeit through increased opportunities for user interaction. In the context of the entire co-design process, students indicated a desire for further collaboration to offset boredom with some of the required tasks.

4.2.1. Sub-theme: Engagement with the material is hands-on

While most students enjoyed the collaborative aspects of this project, some called for even further engagement through a variety of means. Students largely acknowledged the ability to work with their hands as positive and helpful to their learning. Anecdotally, students almost unanimously disliked the length of the class: but, when building the models, students indicated they were willing to work even longer to further improve their models. It is important to note that the "hands on" activities the students are mostly referring to are building their own physical 3D models, and not necessarily experimenting with the AR app. While there were some references to enjoying working with the devices, four students specifically called out using the materials to build the model as a positive aspect of the entire study (see Table B5). Wu et al. (2013) call for further research into whether AR models are more effective than building physical 3D models, and these findings echo these calls. Given the small sample size and lack of assessment on educational gains, it is difficult to provide evidence one way or the other, but this study seems to suggest students feel more behaviourally, emotionally, and cognitively engaged while working with physical models than interacting with and designing AR models, which may affect learning gains.

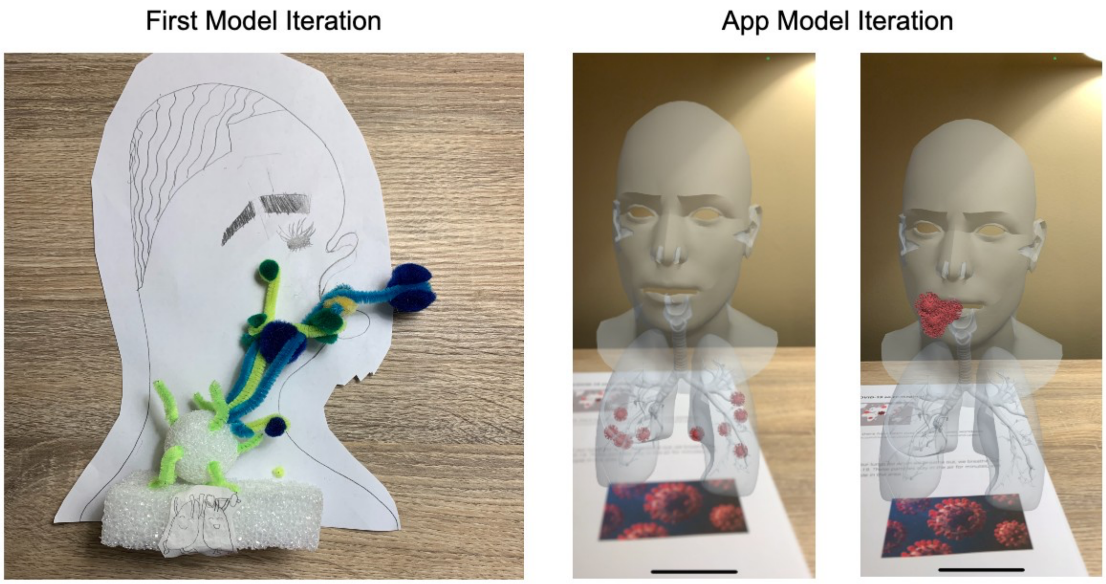

Figure 7: Amber's model iterations. (left) Amber's first model showing a figure exhaling COVID-19 particles, (right) the app model animating a person exhaling COVID-19 particles

4.2.2. Sub-theme: Engagement with the technology is user-directed

This "hands-on" mentality is echoed in some of the feedback for the AR app, as students called for increased user interaction in a variety of ways. One of the unique features of AR is facial recognition, which can then be used to place different filters on the face. This was made popular by social media apps such as Instagram, Snapchat, and TikTok, which all students indicated familiarity with during the information session. For the virtual version of Amber's model (see Figure 7), anonymous feedback suggested the experience would be better if "it was on humans" implying the student wanted to see a virtual projection of COVID-19 particles moving from their lungs and out of their mouths. Doing so would leverage one of the most popular features of AR while better engaging the user with the technology by making the explanation of the spread of COVID-19 more relevant to the user.

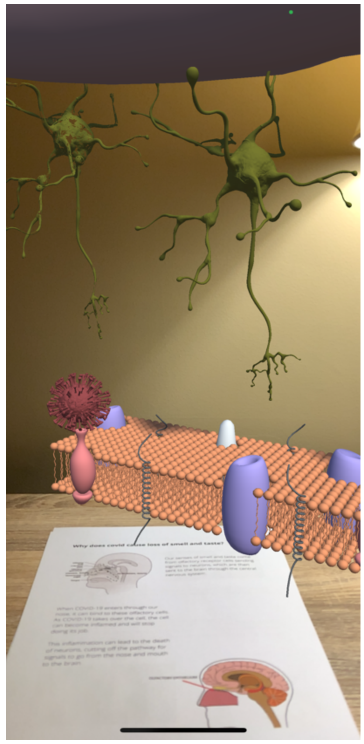

Figure 8: Virtual olfactory epithelium. COVID-19 inflames cells and neurons die, resulting in a loss of taste and smell.

Other students identified mobile-specific user interactions they felt would improve the engagement in the app. Many students complained about the size of the final olfactory epithelium model (see Figure 8), with the creator of the model, Danielle, stating "*this should be smaller because you have to back up when you're looking at it so you can see the whole thing*" and another participant, Monique, stating "*Yeah… I couldn't see the other side of it*". Both comments suggest a desire to have a global perspective of the entire model. Some students suggested common mobile user interaction techniques to solve this, such as pinch-to-zoom or scroll-to-rotate. One student, Ramona, suggested that users should be able to physically move their phones "through" the models to see "inside" as well. Thus, it can be inferred that students did not simply want these new perspectives presented to them, but rather wanted the ability to explore these perspectives on their own. Increased user interaction, whether it leverages specific AR affordances or standard practice smartphone gestures, was a commonly suggested solution by students to help engage further with the technology.

These suggestions are caveated with the ability to provide a smooth user experience. Students made eleven references to disliking the app because of technical issues. While this is part and parcel of the prototyping experience, students argued that solving the current bugs (e.g., the models didn't always show up) would make the experience more engaging as compared to introducing new features. It also became harder for students to critically engage with the technology when the technology was not working smoothly. Dunleavy (2014) reaffirms this conclusion, writing, "it is critical that designers do not create experiences where the technology becomes a barrier to the environment. Rather the technology needs to drive the students deeper into…interaction with the environment and with each other" (p. 32). Naturally, technical bugs at best may draw students out of the experience and at worst may evoke negative feelings of frustration or boredom, as it did for some Ada School students. It is possible that students may have been more forgiving of bugs if they were responsible for the coding elements of this project, but it also might have led to restricting their focus to solely fixing these bugs rather than focusing on the material at hand (Sanders & Stappers, 2014). Regardless, when examining student engagement with technology, it is important to ensure a smooth user experience in order to prevent negative feelings which could lead to reduced emotional engagement.

4.2.3. Sub-theme: Engagement with the co-design process is highly collaborative

While students requested more freedom to direct in the app and generally enjoyed the independence of designing and building the app, some requested more collaboration to make the process more engaging. In the student reflections, there were four references to the process getting boring at times, with two references to increased collaboration as a way to make it less boring. Catherine suggested "*make the class more interactive between classmates*", while Ramona stated that it would be better if "*it was more active and people were all on the same page*". Given the short time frame, how the study built on past work with each session, and that Ramona had missed the second and third session, it is natural to assume she felt a bit lost. While the diversification of knowledge was generally useful as a way to promote collaboration and knowledge sharing between students, Ramona's case indicates that individual contributions can be hard to make without some level of background knowledge. Although it was consistently stated that there were no "right" suggestions, some students might have felt unable to collaborate due to their absences and thus lack of similar experiences to draw from. Thus, while students generally enjoyed the process, more effort is required in focusing on building capabilities for each individual and establishing an engaging and collaborative knowledge building community so students like Ramona can see the value in their contributions, whether they see themselves as novices or experts.

4.3.0. Prototype iteration as a process of shifting from abstract to detail

The final session was perhaps the richest session, as students reflected on the app and revisited their initial models, thus reflecting on their own knowledge construction and that of their peers. Reflection is intrinsic to the iterative technology design process as reviewers must reconcile their own assumptions of how the app should work with how the app actually works. Given the app in this case is largely based in knowledge construction and presentation, students were required to compare their understanding of the phenomena they were studying with how the information was presented in the app. A clear example of this is Skye and Monique's model iterations (see Figure 9). While Skye was present for both iteration sessions, Monique was only present for the final session. Skye's initial model made some use of colour and caricature to compare lung health in adults and children. After using the app, Skye reflected, "*Looking at the ones you made gave me more [inspiration] for mine*". Her model became more detailed and elaborate, using more colour symbolism and animation. Monique specifically added more context surrounding other inhaled particles, extending Skye's colour pattern. Given other student and virtual models that depict COVID-19 particles in the lungs, it is possible Skye and Monique saw this and were inspired to add this information to their own physical model. The end result is a move from an abstract comparison in the first iteration to a more detailed depiction of child and adult lungs in the next iteration, largely credited to their experiences with the app.

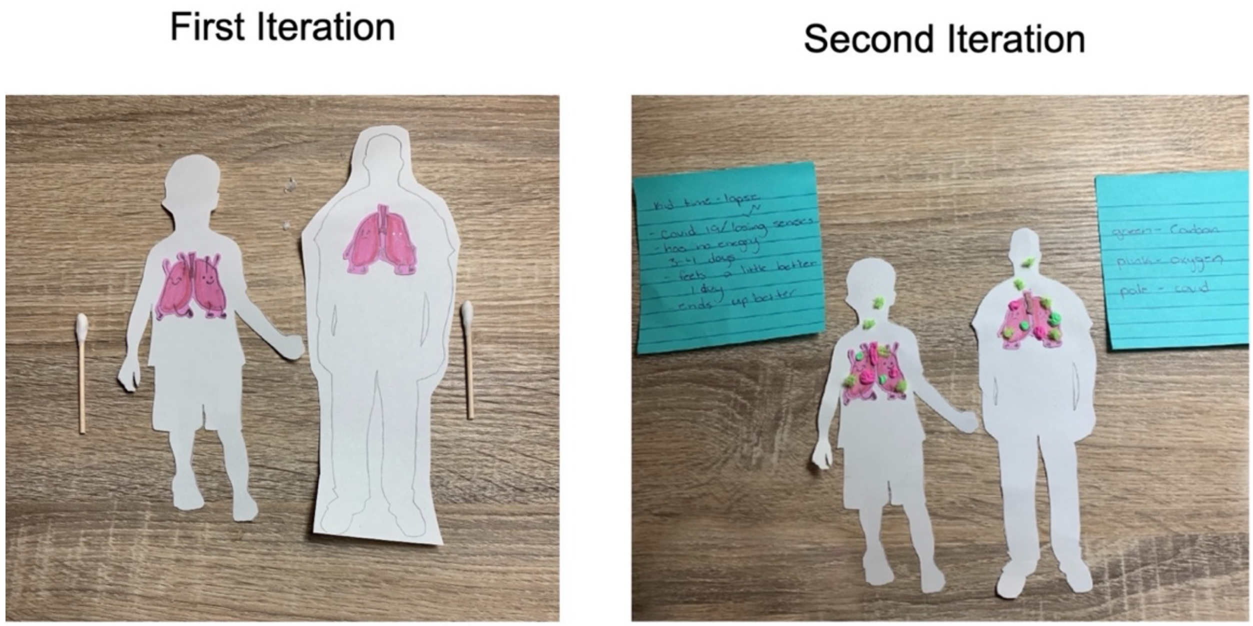

Figure 9: Skye and Monique's model iterations. (left) Skye's original model, (right) Skye and Monique's improvements to the model

This process of interacting with the app and reassessing their models led students to narrow their focus to specific details embedded within the research questions they were asking. While 3 initial models were classified as abstract representations and 1 classified as using a combination of both, all 3 final models were classified as predominantly realistic representations. This "realism" criterion was based on if human body parts were largely recognizable or if the student described their model as attempting to realistically represent some phenomena. In their models, Catherine, Ramona, and Maribel narrowed their focus from "how does covid affect smell and taste" to "how does covid enter the mouth and nose" (see Figure 5); their models became slightly more realistic. It is possible that the virtual models biased students to shift to more detailed, realistic models, as the virtual models were largely lifelike and photorealistic. However, this attention to detail and realism was seen as a positive, as apparent in the anonymous app feedback which contained 6 references to positive feelings for realism and detail. While testing the app, some students commented on the texture of the models, suggesting the bumpy surface of the COVID-19 particle (see Figure 6) made it "gross" but the realistic model was important because COVID-19 should make people feel that way. However, no students attempted to incorporate texture into their physical models, preferring to use colour or caricature to indicate negative feelings.

4.4.0. Implications

As Hew et al. (2019) argue, explicit engagement with educational theory can help contextualize and explain the results of a technological intervention. This study heavily relies on the theory of distributed cognition, as it has been identified as a potentially useful theory for AR development (Dunleavy, 2014) and specifically examines the individual and the technology in the context of the community (Salomon et al., 1991), something that aligns with co-design methodologies. The themes listed above can be further contextualized using the three main actors defined in distributed cognition: the individual, the community, and the technology (Cash, 2013; Moore & Rocklin, 1998; Pea, 1993). For the purposes of this study, the community is recognized as the class of students, and ignores other groups in the larger school community (family, faculty, etc.). These actors do not necessarily exert equal influence upon each other, but it is still worthwhile to examine the impact one has upon the others.

4.4.1. Situational influences on the student

4.4.1.1. Student motivations and the community. Students' shifting motivations can be analysed in relation to the larger class community. Perhaps most interesting is the influence of the *lack* of community presence on the individual. Although students were given a task to create a science-related, augmented reality book, how they created it and what content it would cover was entirely their choice. Given Pea's (1993) argument that individuals would pull from "the properties of the situation" (p. 56), it is particularly interesting that the students chose to research further into COVID-19. On the day of the brainstorming session, 6 out of 12 students were absent for COVID-19 related reasons. The noticeable lack of half the class community as well as the required KN-95 masks for students in the class (both physical signs of the COVID-19 pandemic in the classroom) might have influenced individual student decisions to research it further. Indeed, students such as Catherine, originally unsure of what topic to research, largely followed the direction of others in the community. When it came to model building, Catherine's friends were studying the loss of taste and smell, and as such, she followed suit. Pea (1993) would argue this is a situation where community desires were stronger than individual motivations, and thus the student adapted. However, when tasked broadly with improving the app, students tended to position themselves against the growing community knowledge base in order to find "what's missing". To improve community knowledge is to find new information, which requires positioning oneself apart from the community. This suggests that students felt improvement was necessarily generative, rather than reductive. Furthermore, it demonstrates that students like Catherine valued their *individual* contributions to the larger community when asked to improve the knowledge as compared to the initial, more free-form sessions. Where the first modelling session saw some students conforming to their friends' topics, the second session saw more students branching out into narrower, undiscussed topics. This critical engagement with the material, tools, and community allowed more students to exert their autonomy within the community as they chose what to preserve and what to modify in the existing knowledge base (Cash, 2013). Throughout the entire co-design process, the priority of individual and community shifted as students were tasked with new goals.

4.4.1.2. Student engagement and technology. With respect to the technology itself, the nature of student engagement was heavily influenced by previous experiences with other technologies. Suggestions for incorporating facial recognition filters largely stemmed from previous experience with social media apps like Instagram, Snapchat, or TikTok. These apps are also considered content creation apps and carry within them certain workflows to manipulate and adjust elements. Given that students were creating models for this study, it is possible they pulled from these common practices for mobile design (e.g., pinch to zoom) to incorporate new user interactions with the app. This is most evident in student suggestions to manipulate the model via the mobile phone rather than physically moving the device around the model, a possibility unique to AR and not possible with 2D content creation apps. In doing so, these students are choosing to take up existing practices defined by others and incorporate them into a new tool, thus further reifying these practices in more tools.

With respect to student engagement to the material, it is worth returning to Wu et al.'s (2013) discussion of AR models versus physical models, given Skye's direct reference to the app as a source of inspiration. While physical models may or may not provide more learning benefits, it is interesting to consider the effects of the virtual model on the iterative physical model construction. How does switching between the two mediums influence student knowledge construction? How are affordances of AR (such as animation) represented in physical models? Does the artistic approach of the virtual model (e.g., realistic or stylized) influence the approach to the physical models? The answers to these questions may change if students were to build the virtual models (which one student indicated interest in doing), although this would require significant training in using 3D modelling software and may detract focus from learning the material itself. Conversely, developing the virtual models may give students a greater stake and understanding in the AR development and could result in students using AR in creative, unanticipated ways to further engage with the material. Ultimately, further research is required to develop a nuanced understanding of the relationship between virtual and physical models.

4.4.2. The influence of the iterative co-design process

More generally, this study shows that the iterative technology process allowed students to re-evaluate and assess information though exploration of how to make the app better. I introduced the app as a prototype, something in flux and unfinished. Students were not involved in virtual modelling or coding but were broadly aware of the mechanics required to produce an AR app. In doing so, it might have acted as the ideal black box defined by Scardamalia and Bereiter (2020), "treated only as information…that students are encouraged to evaluate critically, take into account with other knowledge, or ignore as appropriate" (p. 23). It is also possible students felt a separation of ownership, which allowed them to more critically evaluate the information presented in the app. In Danielle's reflections, she referred to the virtual representation of her model as "the model", but in the class presentations she used terms like "my model". The anonymous app feedback compared to the transcript also follows this pattern, suggesting that the students felt their work had morphed into something "other" and thus could detach themselves from their models to critically evaluate it. Indeed, students quickly called out information that was confusing to them without fear or frustration and then worked to clarify it. This ultimately benefited the entire class, as the community knowledge became more detailed and diversified. The implications of this suggest that the value of this study has been in encouraging students to assess their own understanding and challenge community knowledge.

The nature of iteration in this study helped encourage a diverse set of student contributions by placing students in different roles, from designer to producer to user. Switching roles clearly influenced the nature of student contributions, as exemplified by students who initially separated knowledge between the model and the text, but later advocated for the same information to be presented in both the app and the handout. Indeed, these roles might have helped students find their "new perspectives" as they were exposed to different responsibilities and powers based on the role they occupied. While technology consumers do exert some level of power on how the technology is used (Neff & Nagy, 2016), students exerted further power by designing and changing the technology. Rather than largely being forced to adapt to the technology (Garcia & Lee, 2020), this group of students actively designed the technology for their own use. Rather than solely being consumers, students also became producers. This power ultimately led to a diversified knowledge base. Perhaps this is the largest difference between the co-design process with augmented reality and other "black box" technologies like learning analytics or machine learning. While learning analytics tends to handle diagnostic functions and suggest specific actions for the student to enact (Scardamalia & Bereiter, 2020), co-designing with AR places diagnostic responsibility on the students. Furthermore, students are clearly aware of how their input will affect the entire system, giving them a stake in the product while still maintaining a critical eye.

4.4.3. The individual's influence

The drive to provide new perspectives and new connections is useful because it simultaneously improves the community knowledge and the technology. In Scardamalia & Bereiter's 1994 study on computer-supported intentional learning environments (CSILE), fifth and sixth grade students connected previous lessons in physics with medieval history. This, they argued, is an example of "increased and diversified responses to ideas" (Scardamalia & Bereiter, 1994, p. 280), a benefit of collaborative knowledge building. Similarly, the students in this study presented a diverse set of responses to the general topic of "COVID-19 and the Cell", as evidenced by the wide range of questions they posed and answered. Their diverse set of questions, coupled with their later critical eye for "what's missing", helped produce a robust understanding of COVID-19 for the entire community. Cash (2013) argues that critical approaches to tools will also encourage "more effective tools, practices, and institutions for others to use" (p. 67). Thus, by improving the technology, students can also help provide better tools and practices for their community. This process of searching for new information and better design ultimately reflects Pea's (1993) arguments for building "empowering education" as this process can encourage "learners' attitudes and talents in designing distributed intelligence for their use and that of others, not only to participate in the designs of distributed intelligence provided by others" (p. 76). Against the larger context of the digital and participatory divide and historically marginalizing forces within technology, these new perspectives are particularly valuable. Furthermore, it is *through* the perceived affordances of AR (i.e., the ability to see new perspectives) that students looked for new contributions to their community knowledge about COVID-19. Amber and Catherine exemplify this behaviour: when they noticed information was missing in the models or the handouts, they set it upon themselves to learn more about COVID-19's RNA structure and about how COVID-19 enters the body. By explaining these changes in our group discussions and adjusting the handout and app, they contributed new information to the class knowledge base, such that all students could better their understanding of COVID-19. Not only were these students individually able to improve the technology for the betterment of the entire class, but also they helped improve the class's communal knowledge.

5.0.0. Conclusion

This study aimed to examine how a participatory technology design process influences the community and individual knowledge construction process. It did so by observing how students integrated an unfamiliar technology into their learning processes. Through the analysis of student designs, discussions, and reflections, the study attempts to uncover how students perceive augmented reality as a tool to learn with and how students distribute information across the technology and each other. Moreover, the study also observed how the iterative nature of the co-design process influenced student technical designs and knowledge construction. The analysis shows that students used AR as a tool to explore with, first across a diverse set of topics related to COVID-19 and the human body, and then deeper into specific details. The study answers the research questions in the following ways:

(1) How do middle school students distribute information across different people and mediums (paper vs. augmented reality) during their knowledge construction processes?

This study shows that the students as a community ultimately built a diverse set of knowledge surrounding COVID-19 and the human body. Some students became specialists on how COVID-19 causes a loss of taste and smell, others focused on how COVID-19 spreads, and so on. No single student carried all the information, and rather relied on other students to learn new information. Individually, students initially seemed to distribute information across the text and the model. While the handout may describe some information, the models augmented the handout with new information.

(2) How do low SES middle school students perceive augmented reality as a tool to learn with? What affordances do they identify as useful in the context of learning?

Overwhelmingly, students identified "seeing new perspectives" as a key affordance of AR technology. This implies that students perceive augmented reality as a tool to explore and discover new perspectives. Initially, students found new perspectives by using AR as a "connective" tool, bridging together previously disparate knowledge bases. This was reaffirmed in the final session, when students reported an interdisciplinary range of topics learned, including COVID-19, cell biology, computer animation, and computer programming. This desire for exploration was also apparent in student recommendations for increased user interaction with the app, particularly as it relates to the ability to explore the model. One student specifically identified facial recognition and virtual face filters as interesting features of AR that could help make users more engaged with the material, implying that augmented reality can make the material relevant by directly connecting to the user and providing a more personal experience. However, given that students were responsible for building the physical models and not the virtual models, more students indicated they found the physical model building more beneficial than the app engagement. While it is interesting to consider students also engaging with the coding and virtual modelling aspects of building the app, it could detract from engaging deeply with the material.

(3) How do the answers to previous questions change throughout the iterative technology design process?

The iterative process saw students switching roles, from producer to consumer, from building information for themselves to improving the larger community-based knowledge. The most apparent change occurred in how students distributed information across different mediums. Where students individually were comfortable with distributing their own knowledge between models and text, when reviewing other students' work, students expected the same information to be present in both mediums. This implies a dissonance between how the individual constructs their own knowledge and how the individual *expects* new information to be presented to them. The individual and community knowledge construction processes carry different distributions of information, as the material moves from purely one student's perception of the material to something shared across the community.

Students also used the iterative process to move from a broad range of topics into smaller niches, with many students deciding to focus on "what's missing" in the final session. Where students first used AR as a tool to connect information together, students later used AR as a tool to find absences. The reflective process of providing feedback and revisiting models encouraged students to find gaps in the community knowledge and address them. Interestingly, students did not seem to perceive the AR book as their own, despite having contributed the models and information for the handout. There were some benefits to this lack of ownership, namely allowing students to critically engage with the material without fear or frustration. In a way, despite all the information presented in the app coming from the students, the AR app became a black box (Scardamalia & Bereiter, 2020), most likely because I was responsible for aggregating and transforming the information into a community resource. While the information started as "theirs", it became "mine", which was then presented back in a new form, for "their" use and feedback. It is interesting to consider what influence interacting with the AR app had on student knowledge construction; for example, students tended to move towards realistic representations of phenomena in the second iteration which might have been caused by the realistic representation of models in the app.

5.1.0. Moving forward

In comparison to the larger body of literature, some may wonder why this study is important. Why focus on low SES students? Why focus on augmented reality? Why focus on technology when there is little proof that education technology has made any positive impact at all (Reich, 2020)? Indeed, against the greater context of structural inequities in education, particularly those exacerbated by technology, this study does little to directly address these issues. Participation will not solve structural inequality, especially not in the form of designing a piece of technology; to suggest otherwise invites the dangers of technosolutionism (Harrington et al., 2019). However, to not participate in the design of technology – technology that students may be forced to use anyway – carries its own risks, including further exclusion and misrepresentation (Hargittai, 2003). A common solution promoted to reduce bias within technology is to begin with local, community-based solutions for community-level problems and desires (Birhane, 2021; Garcia & Lee, 2020; Zheng, 2009). This study attempts to do exactly that, while subverting claims of technosolutionism by placing less emphasis on technical development and more emphasis on student and community knowledge construction. This study's theoretical underpinnings lie within distributed cognition, a theory that encourages analysis of the dynamics between individuals, communities, and technology while perceiving technology as the product of individual and community desires and not as its own entity (Moore & Rocklin, 1998; Pea, 1993; Salomon et al., 1991). This study's findings align nicely with the theory of distributed cognition, and further research explicitly engaged with distributed cognition may offer new insights on both the theory itself and technology usage within the classroom (Hew et al., 2019). By working with low SES students and augmented reality, this study works to offer a space for those historically excluded from technology design to influence how an emerging technology can be used to promote community knowledge construction. Perhaps more importantly, this study generated new knowledge within this community and outlined a process in which students could explore, reflect, and build on what they learned. This study could arguably be done without any technology whatsoever (remaining just a handout with physical models), but augmented reality played an important role as a black box and helped encourage criticality in an engaging manner. To the larger body of education technology research, this study offers a theoretically grounded analysis of the co-design process as a process of community knowledge construction.

Hopefully, this study inspires further research into community-based technology development as an avenue of knowledge construction. Future studies may benefit from mixed-method approaches that seek to quantify learning gains. This area of research might also benefit from studies with a more diverse group of participants or studies that include more members of the larger school community, such as teachers and parents. Teachers play a critical role in influencing how technology is adopted within the classroom (Alghasab et al., 2019), and they should be included in future work. Within this study, the science teacher made a passing remark about how using 3D materials can help students better visualise 3D phenomena when compared to 2D images in textbooks or websites. Comments like this underscore the valuable insight teachers can bring to the student knowledge building process and should be explored further. Lastly, research like Hsu et al.'s (2019) study on AR creation addresses a gap in this study's work: digital literacy and ethics. While students in this study suggested increased usage of unique AR features like virtual facial filters, they did not address the ethical considerations of using such technology. Facial recognition in particular is problematic and has come under fire for failing to recognize people of colour (Buolamwini & Gebru, 2018). Students in this study used the technology to critically engage with the material, but more scaffolding must be done to encourage students to critically assess *how* they use the technology to engage. Garcia and Lee (2020) argue that fostering critical digital literacy skills are important to improving inequities within education technology. Future studies should follow the direction of Hsu et al. (2019) and measure how co-design and content creation might advance critical digital literacy.

This study has been an exercise of community-based technology development in pursuit of collaborative knowledge building. Ultimately, the technology is secondary; the app was likely deleted from the students' phones and the handouts discarded as summer began and school ended. However, the next time students are exposed to augmented reality technology, they may face it with a better understanding of how it works and what it is capable of. Similarly, as COVID-19 cases rise and fall, students may carry with them a better understanding of COVID-19 and its influence on the body at the cellular level. In the spirit of local solutions for local problems, equitable technology design, and collaborative knowledge building, perhaps that is the most valuable outcome this study has to offer.

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Appendices

Appendix A

Dear Divya,

Co-designing augmented reality books: connections between student distributed cognition and technology design [CIA-22HT-004]

The above application has been considered on behalf of the Departmental Research Ethics Committee (DREC) in accordance with the procedures laid down by the University for ethical approval of all research involving human participants.

Our prior discussion on this was very useful – an impressive team as ever, and project, vastly experienced, and a model of genuine care in relation to research ethics.

I am pleased to inform you, then, that, on the basis of the information provided to DREC, the proposed research has been judged as meeting appropriate ethical standards, and accordingly, approval has been granted.

Please continue to follow all current guidance issued by CUREC during the pandemic, notably COVID-19: CUREC guidance on research involving human participants,
https://researchsupport.admin.ox.ac.uk/governance/ethics/coronavirus

If relevant please also check the CUREC website for their best practice research guides, these can be very useful in refining the writing up of ethical considerations in your research – see
https://researchsupport.admin.ox.ac.uk/governance/ethics/resources/bpg

Good luck with your research study, Keep well and safe,
Yours sincerely,
All good wishes,

Liam
Chair, DREC
Liam Francis Gearon, PhD, FHEA, FRSA, Docent

Senior Research Fellow, Harris Manchester College, University of Oxford Associate Professor, Department of Education, University of Oxford Conjoint Full Professor, Newcastle University, Australia
Docent, University of Helsinki, Finland

Extraordinary Professor, North-West University, South Africa
Visiting Professor, Irish Institute for Catholic Studies, MIC, Limerick, Ireland Honorary Senior Research Fellow, School of Education, University of Birmingham

DEPARTMENT OF EDUCATION

UNIVERSITY OF OXFORD

Co-designing augmented reality books: connections between student distributed cognition and technology design

INFORMATION SHEET FOR PARENTS / GUARDIANS

Ethics Approval Reference: [CIA-22HT-004]

In partnership with researchers at the University of Oxford, [redacted] has agreed to take part in a study investigating how student learning can occur through technology design. We would like to invite your child to be part of this study. We very much hope you would like your child to take part, but before you decide, it is important that you understand why the study is being done and what it will involve.

What are we trying to find out?

This project is looking at how students can learn through designing technology. We are especially interested in how students work together to build a design and how that influences their learning of the subject. Technology design involves sketching out ideas, discussing them, reflecting on what works and what doesn't, and then re-sketching the design based on that feedback. The designs that the students make will show their thought process as well as how technology *should* be designed to help students learn. This project can help us understand how students work together to learn and how they feel about the use of technology as an aid to learning material.

More information about the project can be obtained by contacting the research team:

Divya Mahadevan Email: divya.mahadevan@stx.ox.ac.uk Phone: **[redacted]**	Niall Winters Email: niall.winters@education.ox.ac.uk Phone: **[redacted]**

Why has my child been invited to take part?

We are inviting your child to take part because they are a young person, aged between 12 and 14 years, attending [redacted]. We are inviting the entire 8th grade class to take part.

Does my child have to take part?

No. You can ask questions about the study before deciding whether or not to allow your child to participate. If you do agree to participation, you may withdraw your child and their data from the study at any time, without giving a reason and without penalty, by advising the researchers of this decision.

What will happen if my child takes part?

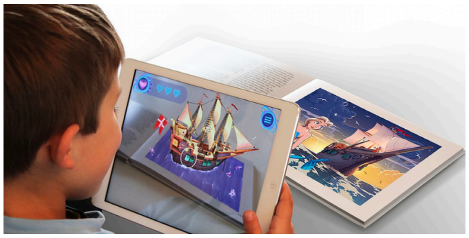

Figure 10: A child using an augmented reality book

We will meet students during their science class period, once a week. We will ask your child to participate in a focus group that will design an augmented reality study guide. Augmented reality (AR) is a new technology, that uses a mobile phone or tablet camera to place "holograms", or virtual objects, into the real world. Students will be designing a study guide for a topic they've learned in the past year, and when a mobile phone or tablet is pointed at the study guide, 3D objects can appear hovering over the page.

We will meet a total of 3 times, once a week, for roughly 1.5 hours each session. This is what we'll do each session:

Session 1: Students identify a challenging concept they've learned in the past year. We will discuss as a group which concept makes the most sense to turn into an AR study guide.

Session 2: Students will work together in small groups to design an AR study guide, and then we'll come together to discuss the various designs. These designs will be done on paper, using various arts and crafts materials (markers, clay, etc.) After the session, the researcher will work on turning the student designs into a simple app. The app will need to use a smartphone back-facing camera (not the front-facing camera), since AR uses the camera to place holograms into the real world. **No** data will be collected by the researcher through the app and the app will **not** be publicly available.

Session 3: Students will be able to experiment with the app that the researcher developed. They will be asked to write down their likes, dislikes, and ideas based on their experience with the app. Once we have discussed these reflections as a group, students will return to their paper designs and make any desired changes in small groups. These small groups will be asked to present their changes and we will discuss further.

During these sessions, the researcher will take notes on the small group discussions and will record the small group presentations (audio only, no video). The researchers will also take pictures of the designs themselves but will **not** take pictures of your child.

Students are not required to do anything outside of these sessions, but their designs and presentations will be saved (with permission) for further analysis.

What are the advantages / disadvantages of taking part?

If your child participates, this study can teach them how the technology design process works, and how their input can influence the design of apps. You child's participation will also contribute to our understanding of inclusive augmented reality technology design. There are no risks to your child, should they participate in this study.

What happens to the data provided? [1]

The information you or your child provide during the study is the **research data**. Any research data from which you or your child can be identified (audio recordings, pictures), is known as **personal data**.

Personal / sensitive data will be stored on University of Oxford's OneDrive for Business, on the cloud. The data will be stored for 3 years, then deleted.

Audio recordings will be immediately turned into text, and then deleted. Pictures of designs and audio transcriptions will use numbered IDs to identify children- their names will not be used anywhere. Within the reports, names will be turned into pseudonyms. No pictures will be taken of your child's face.

Consent forms will be retained by the researchers for 3 years after publication of the work of the research.

Other research data will be stored for 3 years after publication or public release of the work of the research.

The researcher and her supervisor will have access to the research data. Responsible members of the University of Oxford may be given access to data for monitoring and/or audit of the research.

Summaries of our findings will be given to the school and will be available to interested families.

Will the research be published?

The research will be written up as a student's thesis. On successful submission of the thesis, it may be deposited both in print and online in the University archives to facilitate its use in future research. If so, the thesis will be openly accessible.

Who is conducting this research?

The research project is organised by Divya Mahadevan of Oxford University, who is a current master's student. This study has been reviewed by, and received ethics clearance through, the University of Oxford's Central University Research Ethics Committee, reference number: CIA-22HT-004.

Who should I contact if I have any questions?

Parent/Guardian(s) please be aware that under the Protection of Pupil Rights Act. 20 U.S.C. Section 1232(c)(1)(A) you have the right to review a copy of the questions asked, or of materials that will be used with your child(s).

If you have a concern or question about any aspect of this study, please contact Divya or Niall, and we will do our best to answer your query. You can also reach out if you would like to review a copy of the questions or materials. I/we will acknowledge your concern within 10 working days and give you an indication of how it will be dealt with.

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[1] Please refer to CUREC's Best Practice Guidance on Data Collection and Management (BPG 09)

If you remain unhappy or wish to make a formal complaint, please contact the Chair of the Research Ethics Committee at the University of Oxford who will seek to resolve the matter as soon as possible:

Dr. Liam Gearon, **Education Departmental Research Ethics Committee;**
Email: student.curec@education.ox.ac.uk;
Address: Department of Education, University of Oxford, 15 Norham Gardens, Oxford, UK OX2 6PY

Data Protection

The University of Oxford is the data controller with respect to your child's personal data and, as such, will determine how your child's personal data is used in the study.

The University will process your child's personal data for the purpose of the research outlined above. Research is a task that we perform in the public interest.

Further information about your rights with respect to your child's personal data is available from https://compliance.web.ox.ac.uk/individual-rights.

What should I do next?

Please fill in the enclosed form and return it to your child's class teacher if you would like your child to take part in this study. Please remember that you may withdraw your child and their data at any time, without penalty and without giving a reason, by notifying the researcher.

If you would like to discuss the research with someone beforehand (or if you have questions afterwards), please contact:

Divya Mahadevan
Department of Education
15 Norham Gardens, Oxford, UK OX2 6PY
Tel: [redacted]
Email: divya.mahadevan@stx.ox.ac.uk

<u>PARENT/GUARDIAN</u> CONSENT FORM

CUREC Approval Reference: [CIA-22HT-004]

Co-designing augmented reality books: connections between student distributed cognition and technology design

- Your child's school has agreed to take part in a study run by Oxford University looking at how children learn collaboratively while designing an app, specifically an augmented reality book.
- If your child takes part, a researcher would come and visit them at school, and work with them to design versions of an augmented reality book.
- If you are <u>happy</u> for your child to take part, please fill in the form below and return it to your child's class teacher as soon as possible.
- To find out more about the study, please read the attached information sheet. You can also e-mail us at divya.mahadevan@stx.ox.ac.uk, or call Divya Mahadevan on **[redacted]** if you have any questions.

- -

Name of child: ____________________________ ____________________
First name Last name

Name of school: ___________________
I have read and understood the details of the above study, and have had the opportunity to ask questions and discuss the study with others. I have received satisfactory answers to my questions. I understand that the project has received ethics clearance through the University of Oxford's ethical approval process for research involving human participants, and I understand who will have access to the data, how it will be stored and what will happen to the data at the end of the study. I understand that participation is voluntary and that my child and I are free to withdraw at any time, without giving any reason and without my child's education being affected in any way. I understand how to raise a concern or make a complaint.

I understand that my records are protected under the Federal Confidentiality Regulations (42CFR Part 2), Mental Health Law (40.1-2-26) and Health Care Information Act ([redacted] General Laws 5.37.3-4), and cannot be disclosed without my written consent except as otherwise specifically provided by law. Any information released or received as a result of this consent shall not be relayed in any way to another person, organization or entity, without additional written consent from me. I understand that state law mandates reporting of suspected abuse/neglect (to children, elderly and disabled persons) to the appropriate State authorities. I may withdraw this consent by giving written notification to the above party, at any time prior to the disclosure or release of the information.

I agree for my child to be audio recorded	Yes ☐	No ☐
I agree for my child's projects to be photographed	Yes ☐	No ☐
I understand how audio recordings / photos will be used in research outputs	Yes ☐	No ☐

I give permission for my child to take part in the above study.

Name of parent/guardian: ____

Signature: ____________________________ **Date:** _______________

Name of researcher: ____

Signature: ____________________________ **Date:** _______________

If you would like to receive an email summarizing our research, please fill in your email address:

____

RESEARCH STUDY INFORMATION FORM

Co-designing augmented reality books: connections between student distributed cognition and technology design

Ethics Approval Reference: [CIA-22HT-004]

We are inviting you to join in a research study. Our names are Divya Mahadevan and Niall Winters and we work at the University of Oxford in the Department of Education.
Before you decide if you would like to join in, it's important to understand what the study is about, why we're doing it and what it would involve for you. Please read and think about this leaflet carefully. Please feel free to talk to your family, friends, or the researchers about it if you want.
If anything isn't clear or you have more questions you can ask your parent/guardian to give us a call and we can discuss it with you and your parent/guardian.

Important things to know…

- <u>You</u> get to decide if you want to take part
- You can say 'no' or you can say 'yes'
- If you say 'yes' you can always say 'no' later
- You can say 'no' at <u>any</u> time
- We won't be upset at all if you say no

Why are we doing this research?

We want to learn more about how new technology can help you learn. We want to see how young people work together to design a mobile app that would help them learn better. Designing a piece of technology means sketching out ideas, discussing them, figuring out what works and what doesn't, and then re-sketching ideas based on that feedback. The designs you make can show how you think and how technology *should* be designed to help students learn. This project can help us understand how you work together to learn and how you feel about the use of technology as an aid to learning topics.

Who are you?

My name is Divya Mahadevan. I used to a software developer for 4 years, but now I'm a Masters' student at University of Oxford (which is in England), studying education and technology. When I'm not studying, I love cooking, baking, and making 3D animations!

Why have I been invited to take part?

We are inviting you to take part because you are a young person at [redacted], in 8th grade, and know how to use smartphones. We chose [redacted] to participate in this research because of its highly diverse student body. We think technology design hasn't included enough diverse student voices and because of that, we think you and your peers can offer new ideas about how technology should be made to help you learn. We are inviting the entire 8th grade class to take part.

Do I have to take part?

No - It is up to you. We will ask you to sign a form to say that you agree to take part (an assent form). We will give you a copy of this information sheet and your signed form to keep. You are free to stop taking part at any time during the research without giving a reason, by telling the researcher. If you decide to stop, we will not use the information we have already collected from you.

What will happen to me if I take part?

Figure 11: A child using an augmented reality book

Together, we're going to build an augmented reality (AR) study guide. AR is a new technology that uses your smartphone to place "holograms", or virtual objects, into the world. If you've ever played Pokémon Go or used a TikTok face filter, it's similar to that. For this study, you will help design a study guide for some topic you've learned in the past year, and when a cell phone is pointed at the study guide, 3D objects can appear hovering above the page.

If you want to be in this study, this is what will happen:

Session 1: We'll brainstorm some topics you've learned in the past year and discuss as a group which one makes the most sense to turn into an AR study guide.

Session 2: In small groups, you'll design your study guides and then we'll talk about your designs as a big group. These designs will be done on paper using things like markers, clay, etc. After the session, the researchers will turn your designs into an app. The app will **not** be put on any app stores- it's just for you to experiment with.

Session 3: You'll get to use the app the researchers built. You'll be asked to write down your likes, dislikes, and ideas about the app. Then, your small groups will return to your designs to make any changes you want. We'll come back together as a big group to talk about the changes you made.

This research will take 3 weeks. We'll meet 3 times (once per week) for about 1-1.5 hours at a time. We'll meet during your science class period. During these sessions, the researcher will take notes on your small group discussions and will record the whole group discussions (audio only, no video). The researchers may also take photos of the designs you make.

You're not required to do anything outside of these sessions. Your designs and our discussions will be saved (with your permission) for further analysis by the researcher.

What happens to the results of the study?

The information you provide during the study is the **research data**. Any research data from which you can be identified (audio recordings, photographs), is known as **personal data**.

Personal data will be stored on University of Oxford's OneDrive for Business, on the cloud. This will be deleted after 3 years.

The audio recordings will be turned into text and immediately deleted. Pictures of your designs and the text from the audio recordings will not identify you by name- instead we'll use numbered IDs. We will **not** be taking pictures of you. In any reports, we'll use fake names instead of your real ones. If we want to quote you in the final report, we will first ask you to make sure it's ok.

Other research data will be stored for 3 years after publication or public release of the work of the research.

The research will be written up as part of a student's work.

What are the advantages / disadvantages of taking part?

You'll get an idea of what it means to actually design technology- the process we'll go through is really similar to how technology is designed and developed in the real world. That means you'll get to see how your input can change how apps are built. There are no risks to taking part in this study.

Will anyone else know I'm doing this?

We will keep your information private. This means we will only tell those who have a need or right to know, such as the research team and your parent/guardian. We will only share information that has your name and address removed.

What if I don't want to take part in the research anymore?

Just tell your parent/guardian and the people carrying out the research that you don't want to take part. You don't have to give a reason and no one will be annoyed with you. It is YOUR choice.

Who is organising and funding the research?

The research is organised by Divya Mahadevan of Oxford University, who is a current Masters' student.

Who has reviewed the study?

Before any research involving people can start, it has to be checked by a Research Ethics Committee to make sure that it is OK for the research to go ahead. This study has been approved by the University of Oxford Central University Research Ethics Committee.

What if there is a problem or something goes wrong?

Please tell us if you are worried about any part of this study, by contacting the researcher at divya.mahadevan@stx.ox.ac.uk. You may also talk to your teacher/parent/guardian who will let the researcher know. If you are still unhappy or wish to make a complaint, either you or your teacher/parent/guardian can contact the chair of the Research Ethics Committee at the University of Oxford:

Dr. Liam Gearon, **Education Departmental Research Ethics Committee**;
Email: student.curec@education.ox.ac.uk;
Address: Department of Education, University of Oxford, 15 Norham Gardens, Oxford, UK 0X2 6PY

Data Protection

The University of Oxford is the data controller with respect to your personal data and, as such, will determine how your personal data is used in the study.
The University will process your personal data for the purpose of the research outlined above. Research is a task that we perform in the public interest.
Further information about your rights with respect to your personal data is available from https://compliance.web.ox.ac.uk/individual-rights.

Contact details

If you would like to talk about the research with someone before the study starts (or if you have questions afterwards), please contact:

Divya Mahadevan
Department of Education
15 Norham Gardens, Oxford, UK OX2 6PY
Tel: [redacted]
Email: divya.mahadevan@stx.ox.ac.uk

Thank you for reading this – please ask any questions if you need to.

ASSENT FORM FOR CHILDREN UNDER 16

Co-designing augmented reality books: connections between student distributed cognition and technology design

Child/Young Person (or if unable, parent/researcher/teacher on their behalf) to circle all they agree with:

- Has somebody else explained this project to you? Yes/No
- Do you understand what this project is about? Yes/No
- Have you asked all the questions you want? Yes/No
- Have you had your questions answered in a way you understand? Yes/No
- Do you understand it's OK to stop taking part at any time? Yes/No
- Are you happy to take part? Yes/No
- Are you happy for your voice to be recorded? Yes/No
- Are you happy to have photographs of your projects taken? Yes/No

If any answers are "no" or you don't want to take part, that's OK! No one will be mad at you.

If you do want to take part, please write your name below.

Your name ______________________________

Date ______________________________

The researcher who explained this project to you needs to sign too:

Print Name ______________________________

Sign ______________________________

Date ______________________________

Thank you!

Appendix B

Table 1: An abbreviated row from the first level of Visuo-Textual Framework (Brown & Collins, 2021), observing the visual and textual elements of Catherine's models.

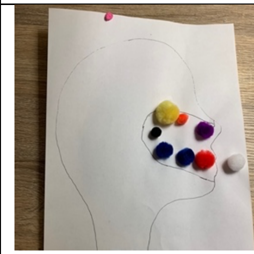
Participant	First Iteration			Second Iteration		
	Model	Transcript Description	Researcher Visual Description	Model	Transcript Description	Researcher Visual Description
Catherine		001: …So this is the body and this is covid going up to the brain to affect the receptors to turn off the sense of smell and taste.	Circular shape at the top, representing the brain, with covid particle nestled inside…		001: Ok so that's covid and it's going up through the nose and like blocking it to stop people from smelling…	The profile of a person is drawn on paper with black ink… Pom-poms of various colors and shapes are glued in to this area.

Table 2: An abbreviated table from the second level of the Visuo-Textual Framework (Brown & Collins, 2021), observing the similarity in all visual codes, all textual codes, etc.

First Iteration			Second Iteration		
All Models	All Transcripts	All Visuo-Text	All Models	All Transcripts	All Visuo-Text
Abstract representations of larger systems	Use of strong action words to describe the motion of covid	Use of abstract representations and spatial relations with broad questions…	More focus on realistic representations	Motivations were more commonly about noticing something was missing…	…This level of focus also lent itself to more drawings… way to include more detail

Table 3: An abbreviated table from the third level of the Visuo-Textual Framework (Brown & Collins, 2021), observing the changes across iterations, per participant.

	Across Iterations		
Participant	Visual	Transcript	Visuo-Text
1	Transition from abstract to realistic…	… narrowed focus on one component based on how the app presented material	Transition from abstract to realistic mirrors narrowing focus and increased accuracy…

Table 4: An abbreviated table from the third level of the Visuo-Textual Framework (Brown & Collins, 2021), observing the changes across all participants and iterations

Across all participants, all iterations		
Visual	Transcript	Visuo-Text
Trend of moving from abstract to realistic	…some students delved deeper into specific parts of the question, others on the UI…	Start broadly, narrow focus on component based on what's missing or individual interest

Table 5: List of all codes, organized by theme/sub-theme

Looking for new perspectives using AR	
New perspectives can be found by connecting existing knowledge	
why loss of taste and smell	5
why is covid so contagious	2
how does the vaccine work	1
why does covid affect some more than others	1
technical learning (programming)	6
technical learning (AR)	6
learning about covid	5
learning about cell biology/human anatomy	3
New perspectives can be found by looking for "what's missing"	
reasoning-something missing	3
reasoning- nobody was doing it	1
reasoning- good to visualize	1
model+paper relationship	7
images on paper	4
labels on paper	2
motion	14
Iteration as a process of moving from abstract to realistic	
realistic representation	7
realistic models (positive)	4
animated models (positive)	2
detailed models (positive)	2
app influencing model	4
abstract representation	4
abstract model (like)	2
abstract model is confusing	3
Engagement is hands-on, collaborative, and user-directed	
working with hands	13
participant choice in process	6
collaboration	2
user interaction	3
model size adjustments	7
working with materials (positive)	5
technical issues	11
Process was boring	4

Appendix C

Open-source models used to create the augmented reality app:

allpolovinkina. (2021). *3D Free Bust Head Base Mesh model*. TurboSquid. https://www.turbosquid.com/3d-models/3d-free-bust-head-base-mesh-model-1832518

bobby95. (2018). *Von Economo Neuron 3D Model*. TurboSquid. https://skfb.ly/6wOEu

Huge_Man. (2021). *Low Poly Base Mesh-530 Tri*. Sketchfab. https://skfb.ly/onsxE

Keller, K. (2018). *Plasma Membrane 3D Model*. Sketchfab. https://skfb.ly/6EqAK

Ringo3D. (2016). *Earth*. TurboSquid. https://www.turbosquid.com/3d-models/earth-max-free/1016431

siddu stone 777. (2022). *Siddartha Human Lungs*. Sketchfab. https://skfb.ly/os8BL

Thomas, T. (2020). *Coronavirus 3D Model*. TurboSquid. https://www.turbosquid.com/3d-models/virus-corona-3d-1548812

Versal. (2014). *Human Brain*. Sketchfab. https://skfb.ly/AE7Y