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Learning from the real and the virtual worlds: Educational use of augmented reality in early childhood

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ABSTRACT

Augmented reality (AR) applications are becoming widely available to support preschoolers' cognitive development and education. AR applications with educational features offer an exciting and unique learning experience by blurring the boundaries between the real world that children are in and the virtual world they see on the screen. Nonetheless, effects of blending these two worlds on children's learning and the cognitive mechanisms underlying their learning with AR have not been discussed. To show why and how AR can have a unique contribution to early education, we review research on the ways that realistic and fantastical themes in narratives, and children's making of connections between the real world and the screen affect their learning. In the light of those findings, we proceed to discuss the affordances of AR and provide a set of recommendations for designers. We argue that a well-designed AR application can support young children's learning by (i) drawing children's attention to the learning material and encourage them to reflect on the content by setting an unconventional scene for learning, and (ii) reducing the representational dissimilarity between the context where children learn new information and the one where they need to apply what they have learned. By providing an overview of developmental research on the effects of themes and screens on children's learning, we aim to provide a psychological basis for the development of educational AR products targeting young children.

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1. Introduction

One of the main motivations of parents for downloading applications for their preschool-age children is to support their learning of new information and skills [1]. Blending physical and virtual worlds, augmented reality (AR) offers a new platform for learning. It is already widely used in educational settings for

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elementary school, high school and university students [2,3], but its implementation is more complicated for preschoolers due to the fast developing cognitive abilities of this age group. AR is a technology which plays with our reality perception; thus, one challenge for designing AR applications aiming at young children concerns their difficulty in learning from non-realistic contexts and screens. Considering that preschool years are critical for the formation of academic skills and intellectual development [4], it is important to explore the educational potential of emerging technologies, such as AR, for young children. In this article, we discuss this potential of AR regarding the relationship between children's reality conception and their learning.

Through a touchscreen device, webcam, or a head-mounted display, AR applications blend physical and virtual worlds [5]. In this article, we focus on non-immersive screen-based AR applications where the system overlays computer-generated information to the physical world around the user, through a screen. Unlike other emerging technologies such as social robots and immersive virtual reality (IVR), AR already met the average consumer because it is relatively cheaper, easier, and safer to implement. Social robots have some hardware issues, such as speech recognition, to be ready for the daily use of children [6], and IVR has some psychological and technical constraints, such as being "too real" for children [7] and motion sickness. They are valuable tools for children's learning, and they may be even better options than AR under certain conditions. Nonetheless, we argue that for the reasons that are expanded in Section 4, AR can be an optimal learning tool specifically for children at the preschool years of age.

With AR, users can simultaneously interact both with the real and the virtual worlds. This turns AR into an exciting entertainment and learning tool for children. Books are a prominent source of knowledge for young children, and children's books with AR elements (e.g., My Very Hungry Caterpillar AR, Ernie's Wish Trail) are becoming popular and accessible. In addition to books, there is an increasing number of mobile applications targeting young children's learning in various domains of knowledge. To illustrate, AR applications aim to teach preschoolers about nature (Disneynature Explore, AR Diorama — Qurious Island), mathematics and geometry (Math Alive, Math Ninja AR, CyberChase Shape Quest), geography and the solar system (SmartGlobe AR), and reading (Letters Alive, Big Bird's Words). In these applications, children can learn new information with the help of the interaction between the touchscreen and a tangible object, such as cards or a globe. While designers rapidly develop and release such applications to the market, cognitive mechanisms that underlie children's learning from them have not received enough attention.

Hirsh-Pasek and colleagues proposed four principles for educational mobile applications based on scientific literature [8]. They argue that in addition to explicitly setting a learning goal, an application can have an educational value only when it enables children to actively participate in the process, includes engaging materials, provides children with meaningful experiences they can relate to, and offers a setting for social interaction all at the same time. A well-designed educational AR application can tick all these boxes. First, AR allows children to actively interact both with tangible and digital tools [1]. Second, children are observed to be engaged and motivated to learn while using AR [9]. Third, as an example of meaningful learning, children can relate the information they see on the screen with the familiar physical environment they are already in and their daily lives [1], instead of being fully immersed to a foreign setting as in IVR. Finally, AR creates an environment for children to discuss and play together with their friends [10]. While these criteria apply to educational AR applications as well, there is a need for a cognitive framework which will inform future AR implications with learning objectives. Children's understanding of mixed realities needs to be placed within the framework, the one which must be built through an information exchange between researchers and designers. To ignite this communication, we hereby offer a psychological ground to the educational use of AR targeting preschoolers.

The aim of this article is to uncover the cognitive mechanisms underlying young children's learning with AR by providing an overview of the empirical research on the role of reality on preschoolers' learning. We believe that understanding these mechanisms will inform designers about the affordances and constraints of AR for the targeted age group. Hence, after providing AR examples targeting early childhood education (Section 2), we address the extent to which the distance between the learning context and reality affects young children's learning (Section 3.1), in addition to children's transfer of learning from screens to the real world (Section 3.2). We then discuss the potential effects of these aspects on preschoolers' learning from AR (Section 4). In the light of research reviewed, we suggest that AR has the potential to contribute to children's learning processes when certain conditions are met (Section 5).

2. AR in early childhood education

In contrast to the rapid commercialization and availability of educational AR products targeting preschoolers [11], research is predominantly conducted for older age groups [2,3]. One review published in 2017 showed that only 1% of the studies targeted preschoolers [2]. Collapsing findings from all age groups, two reviews revealed that AR increases learning performance, motivation, and engagement of students although it may be difficult to use and may create cognitive overload [2,3]. Similarly, one comparative review found that students understood the content better, remembered it more, performed better in physical tasks, collaborated more, and showed more motivation when using AR compared to non-AR traditional or digital media whereas problems with attention, usability, and classroom integration occurred [5]. Thus, despite its shortcomings, AR seems to contribute to the knowledge acquisition of older age groups.

To our knowledge, there are no systematic reviews on preschoolers' learning outcomes with AR. This poses an obstacle for designers who develop evidence-based AR applications targeting this age group. Here, we provide some examples to illustrate young children's learning gains, and the wide range of domains for which AR can serve in early childhood education. We selected the following examples from journal articles and conference proceedings because they (i) had an explicit teaching goal, (ii) targeted children younger than 8 years of age, (iii) exclusively focused on screen-based AR and no other mixed reality tools, and (iv) tested their design with children.

Literacy—including alphabet and word learning, and story comprehension—is a prevalent domain in AR targeting early childhood [12–21]. To begin with alphabet learning, one study used AR to draw 5-year-old children's attention to the learning material when teaching letters. By placing markers on the alphabet book, children were able to see the uppercase and lowercase versions of the letters, corresponding objects (e.g., a banana for the letter B), and the way the letter is drawn, all in 3D images overlaid onto the real world around them on a computer screen. Majority of children correctly recognized the letters and they reported high enjoyment [12]. Another group of researchers developed a picture book with AR to teach preschoolers Chinese patterns. Their descriptive statistics revealed that children who were trained with the AR book were better in writing, reading, and memorizing the patterns than those who were trained with the traditional book [13]. Confirming these findings, another study found that 3- to 5-year-old children improved in Bengali letter recognition following a week-long AR use compared to their peers who learned the letters in the traditional way [21]. To experimentally investigate the effects of AR on alphabet learning, one study used commercially available AR applications to teach the English alphabet in Kuwait. During the 7-week intervention, one group of preschoolers followed the traditional methods while the other group used the AR applications to learn the letters. The AR group performed significantly better on the achievement test compared to the control group. Furthermore, in the AR group, children's level of communicating with their peers and using their senses throughout the intervention were positively correlated with their achievement test scores [14].

In addition to alphabet learning, research has been conducted on preschoolers' learning of new words in first [15] and second languages [16,17,19,20], and story comprehension [18]. In one study, 5- to 6-year-olds were taught words in their native language Turkish with AR-based flashcards, puzzles, and match cards. While children's learning gains were not directly measured, their active interaction with materials (i.e., commenting, questioning) was significantly associated with higher cognitive attainment as indicated by their extensive descriptions of their experience [15]. Studies were more frequently conducted for second language learning. Chinese-reared 3- to 6-year-olds were taught English words either with traditional methods or a mobile AR application with which they could scan cards to see the 3D versions of the words and hear their pronunciations. Children were tested three times with regular intervals. At all age groups and testing points, AR group remembered more words than the non-AR group [19]. Similarly, one study with 5-year-olds raised in Spain found that children's English grades improved following an AR-based curriculum combined with physical activities, videos, and stories [16]. On the other hand, one study conducted with 3- to 6-year-olds in Malaysia did not find a difference between AR and non-AR desktop applications when teaching colors, shapes, and spatial prepositions, although researchers observed a slight increase in the learning gains of children in the AR group [17]. In another study, Taiwanese-reared 4- to 8-year-old children were taught animal, fruit, and vehicle names in English either with an AR game and cards or with traditional cards. The two groups did not differ in their learning gains [20]. Moving to story comprehension, one study used AR to animate the pages of a print picture book. Five to 6-year-olds were mostly able to remember the time, place, and the consequence of the story while they were not as good in remembering its main theme. Their happiness resulting from their interaction with AR positively correlated with their comprehension [18].

Another domain AR is used to teach young children is nature [9,10,22]. For instance, researchers grouped 4-and 5-year-olds into two where both groups had access to the same curriculum on animals but only one group consumed the content with AR. The AR group showed markers to the computer webcam to watch and listen about the coats, corporal temperatures, and reproduction of vertebrates. They also had a marker that served as a magnifying glass; for instance, to look closer at the coats of animals. Teachers then evaluated both groups on their knowledge about animals. Although descriptive statistics reflected slightly better learning for children who were in the AR group, the difference between the two groups was not statistically significant [22]. In another study aiming to teach about animals, preschoolers showed flashcards to the tablet camera to watch the animals in 3D on the screen. Interviews and observations indicated that children paid close attention to the learning material and enjoyed this unusual way of learning [9]. A final example is a study aimed to develop an AR-based system where children created origami animals and let the animals interact with the desktop computer to learn about protecting the nature. Researchers observed that 5- to 6-year-old children played the game in line with the learning objective: they used recycling bins and avoided plastic to help animals to survive [10].

Other domains of AR applications targeting young children include but are not limited to spatial skills [23], numbers [24], handwriting [25], and arts [26]. Except for a few studies on second language learning, studies reported here mostly conclude in AR's favor, indicating its high educational potential. Unfortunately, many of these studies rely on descriptive statistics and observations. They mostly lack strong control conditions or a detailed description of the existing control condition, and robust statistical comparisons across conditions with appropriate sample sizes. Although many studies compare AR applications to traditional methods, they either do not clearly describe the traditional methods they implemented or they make it difficult to filter out the effects of AR by amplifying those methods with extraneous factors such as physical activities. Furthermore, they do not measure or report long-term learning gains. Indeed, systematic reviews point at the lack of explanatory and causal quantitative research that measure short- and long-term effectiveness of AR in educational settings [3]. These shortcomings make it difficult to draw an objective conclusion about the effectiveness of AR in early childhood education.

Nonetheless, covering a wide range of domains, all these studies aim to teach children real information about the real world by enriching it with virtual elements. Importantly, the information to be taught is not immediately accessible to children unless they make the connection between the real world they are in and the virtual world they see on the screen. This raises a question about the role of reality on children's knowledge acquisition: how do children translate knowledge from different contexts to the real world? To address this question, in the following section, we focus on the role of associating new information with reality on children's learning.

3. Reality and children's learning

AR applications offer new information about the real world in a novel context for young children, which is a blended reality with seemingly fantastical elements [11]. Thus, to discuss children's learning from AR, we need to understand if and how they learn from realistic and non-realistic contexts. Furthermore, although many educational AR applications targeting young children are developed for touchscreen devices such as tablets and smartphones, applying new information from screens to the real world is not an easy task for them [27]. Here, we review the ways which the theme of stories, and the connection children build between what they see on the screen and the real world affect preschoolers' learning.

3.1. Learning from realistic and non-realistic contexts

New pieces of knowledge are often presented to young children in fictional contexts, which vastly vary in their resemblance to the real world. The distance between reality and the story in which information is embedded affects children's learning from stories.

There is considerable amount of research showing the facilitating effects of realism in stories on children's learning. To illustrate, preschoolers are more likely to generalize a novel causal relationship to real life when they read it in a realistic picture book than in a book with fantastical events [28]. Similarly, they are more likely to transfer problem solutions to real world when they hear about an analogical solution in a story with a real character compared to a fantasy character [29]. The same pattern appears in anthropomorphic stories where animals unrealistically behave in human-like ways. Children learn more factual information about unfamiliar animals when they hear about those facts in books with factual language and realistic pictures instead of anthropomorphic language and illustrations [30]. Positive effects of realism on learning have not only been shown by comparing realistic and fantastical contents; children's own reality judgments of content also play a role. While children's age affects their comprehension of a foreign word they hear on a television show, this relationship is partially mediated by the extent children judge that language as real or made-up. Hence, children's perception of a language as a real language is partially responsible for their successful learning of new words in that language [31].

Despite these findings in favor of realism, construct of *mise en place* entails that unexpected elements that defy reality call for more attention to and reflection on the content. According to this view, children can learn new information from fantastical stories [32]. Indeed, it was shown that preschoolers learn new words equally well from realistic and fantastical settings, whereas they are better in describing the words when they are exposed to them through fantastical stories and toys [33]. Furthermore, it was argued that violating children's expectations paves the way for learning by improving their memory for the violating information, and prompting children to seek for causal explanations for the violation [34]. For instance, preschoolers learn the names of objects that violate their expectations compared to those that do not, but only when the objects are central to the violation and not when unrelated to it [35]. Thus, in contrast to findings in favor of realism reported earlier, elements of fantasy and surprise can have a positive impact on preschoolers' learning.

It was argued that one reason underlying the discrepancy across these findings may be because different types and amounts of non-realistic elements influence children's learning in different ways [36], and there are studies supporting this argument. For instance, preschoolers were found to remember a problem solution better from a video where fantastical elements were directly related to the solution, compared to videos where such elements were either irrelevant to the solution or videos that did not incorporate much fantastical elements. Furthermore, preschoolers were least likely to apply the solution to real world from a fantasy-irrelevant video, while equally likely from fantasy-relevant and fantasy-low videos [37]. This implies that the relevancy of fantastical elements affects children's learning of new information from a non-realistic context.

In sum, children take the probabilistic structure of a context into consideration when filtering information. Besides judging the context, children face another challenge. As adults, we can go beyond the medium on which new information is presented and directly judge the factuality of content. However, the medium itself influences children's learning. Hence, we next address young children's learning from screen media.

3.2. Transferring from screens to the real world

A substantial amount of educational content today is presented on screens, and this poses a challenge for young children. Screen media (e.g., television, touchscreen devices) is largely based on video (i.e., moving visual images), which is a symbolic form of communication that conveys information through multiple sensory channels such as auditory and visual [38]. Studying young children's learning from video sheds light on their learning from screen media such as electronic books [39] and in our case, screen-based AR applications.

For children to learn from videos, they need to develop an understanding of the representational nature of videos. Thus, they need to comprehend the relation between what is on screen and the real world [38]. Children younger than approximately 2.5 years of age have difficulties in matching the content of videos with real life due to their inability to form and hold dual representations (i.e., to connect the symbolic role of the object to the actual object itself) [40]. In other words, infants and toddlers experience difficulty in understanding what the content of a video (e.g., a giraffe on an animated cartoon) possibly corresponds to in real world (e.g., a giraffe at a zoo) and this results in difficulty in learning from videos, which is termed as *video deficit* [41]. However, as they get older, children accumulate conceptual knowledge both about different representations such as videos, and about the dynamics of the world, which enables them to use videos as a source of information [42].

Applying information to other contexts than video and to the real world is known as *transfer of learning* [43]. Memory plays a key role in this process since transfer of learning requires holding a mental representation in memory to be retrieved later in a different context [44]. As the context to which the information is applied becomes more dissimilar than the context in which the information was acquired, memory demands increase. As a result, children experience more difficulty in transfer of learning [43]. Imitation studies support the presence of this difficulty by showing that for young children, transferring knowledge from a two-dimensional source (e.g., television) to the three-dimensional world is a demanding task and vice versa [45]. For instance, children around 2.5 and 3 years of age struggle transferring what they watch on screens to the real world, and this can be explained by young children's poor memory flexibility, which is the ability of retrieving the encoded mental representation in a novel context [27,44].

In addition to facilitating factors such as repetition of content and appropriate use of formal features (auditory and visual editing methods) [45], children can conquer the difficulty of cross-modal transfer by means of the social nature of learning [38]. Adults help children to understand the association between what is on screen and the world around them. For instance, while toddlers have difficulty in learning the names of novel objects from an adult on video even if they hold the object on the screen in their own hands, they do learn them well when their parents show that the object they hold and the object on the screen are the same [46]. Online video chat technology also assists children in making this connection by offering a contingent social interaction where the on-screen person is able to provide children with immediate, reliable, and correct information [47,48].

Thus, in addition to the probabilistic theme of the narrative, the medium on which that narrative is presented also plays a role in children's learning. Studies on video highlight the importance of the ability to associate the content on the screen with the real world [39]. Children need assistance, mostly from an adult, to make this association and to counteract video deficit. AR provides children the opportunity to physically and mentally play with this relationship by giving them immediate and simultaneous access to both physical and virtual information. We argue that this aspect of AR offers an exciting and potentially effective learning realm for young children. In Section 4, from a psychological perspective, we discuss the affordances of AR in terms of preschoolers' learning, and explain why AR can become a meaningful platform for early childhood education.

4. AR's contribution to young children's learning

As addressed in Section 3, young children evaluate the distance between stories and reality while learning, and they may experience difficulty in applying new information from screens to the real world. Although AR studies we focus in this article also use screens to communicate new information, the unique relationship AR builds between the screen and the physical environment creates the opportunity for an easier form of learning from screens. While it can be argued that mixing realities can impede learning rather than facilitating it [49], we suggest that this ability of AR is its strength. More specifically, we argue that (i) AR can draw children's attention to the learning material and promote reflection on it without fully detaching children from the real world, and (ii) AR can assist transfer of learning by converging real and virtual representations in space and time, and reducing the dissimilarity between learning and transfer contexts.

4.1. Merging realistic and non-realistic elements

Children interpret AR as "magic" and "real" at the same time [15,17,26,50], and some studies using AR aim to exploit that magical feeling to enhance learning gains [18,24]. Although further experimental research is needed, some studies where children judge AR as magical argue that they can learn with it [26]. As discussed in Section 3.1, some research shows that preschoolers are more likely to learn from realistic settings compared to fantastical settings [28]. The *mise en place* construct suggests, however, that fantastical contexts can draw children's attention to the learning material and encourage them to reflect on it, thus entail learning [32]. Such playful environments set a learning occasion where children are motivated to actively seek knowledge by evoking the necessary cognitive tools to do so [51]. A well-designed educational AR application has this potential. This can be accomplished by purposefully and integrally using AR elements towards an educational goal, and by encouraging social interaction during the use.

By superimposing a virtual layer on reality, AR is playful by nature, and playful learning is known to be effective [51]. In one study, 7- to 8-year-olds "learned through play" about marine life with an AR game, and showed a significant improvement in knowledge from pre- to post-test [52]. Nonetheless, AR elements must be relevant and integral to the educational content to not to hinder or disrupt learning by being solely playful. Fisch argues that for children to learn from media, the distance between the narrative that surrounds the educational content and the educational content itself must be as short as possible, to not to overload or divide children's cognitive resources [53]. Similarly, he argues, the educational content must be at the heart of those computer games with a learning objective [54]. Following this approach, we argue that AR elements must be directly relevant and integral to the educational goal and content.

Previous research points at the importance of properly integrating fantastical or surprising elements into the learning material. For instance, one study found that preschoolers remembered and applied a problem solution better when they watched a similar solution in a video where fantastical elements were relevant to the solution (e.g., an anthropomorphized animal performing the solution) compared to a video where fantastical elements were irrelevant to it (e.g., anthropomorphized animals singing) [37]. Another study found that preschoolers learned the names of the objects and actions that violated their expectations and surprised them, compared to objects that behaved expectedly. Importantly, children only successfully learned the words when the object was actively involved in the violation and not when it was a bystander that just happens to be at the scene [35]. These findings indicate that fantastical or surprising elements must be embedded into the targeted piece of knowledge to successfully facilitate learning.

The importance of relevancy and integrality of AR in an application can partially explain why children sometimes show low cognitive attainment while using AR applications. In two studies where AR was used to enrich toys [15] and picture books [55], children predominantly provided plain descriptions of what they saw instead of profound comments on the content, which authors took as an indicator of low cognitive attainment. One reason behind this might be that children were so enthused over AR that they did not have enough cognitive resources left to reflect elaborately on the content. Even though this is a speculation that needs further investigation, when AR elements are used aimlessly or redundantly, children's capability of guiding cognitive effort to the targeted piece of knowledge may diminish. While desultory use of AR may result in low cognitive attainment, it can be better used to direct children's attention to the specific learning-relevant aspects of the application [5]. Therefore, AR must not be the focus of the application but a tool that supports the learning objectives.

Even when AR elements are meticulously used, this may not suffice for preschoolers' learning, unless there is a social component. As in fictional books where parents and teachers may contribute to children's learning by emphasizing the parts to be applied to the real world (i.e., educational content) and parts that are not meant to be transferred (i.e., fictional content) [36], young children need adult guidance to learn that AR provides information about the real world with the aid of seemingly magical features. Humans do not only gather information about the world through their direct interactions with it but also through other people, and this affects their reality judgments. Indeed, children take other people's testimony into account when they judge the existence of the unobservable. For instance, although 4- to 8-year-old children never saw any germs or vitamins before, they judged such scientific entities as real. They also made parallel judgments and explanations for entities that were endorsed by adults such as the Tooth Fairy, although with less confidence. These were in contrast with their judgments regarding equivocal beings such as monsters whose existence they denied [56]. AR applications can exploit the powerful role of testimony in children's learning by incorporating social interaction into their design. Through social scaffolding, children can comprehend that what they see on the screen is an extension of the real world, akin to a microscope, as opposed to pure magic. Thus, to go beyond the embellishments of AR, children must be guided by adults about the experience.

AR has the unique ability to set a playful learning scene without disconnecting children from the real world, thus preserving the advantages of both realistic and non-realistic contexts on learning which are discussed in Section 3.1. This strength can only be actualized by designing applications where AR elements are integral to the learning objectives and by fostering social interaction about the educational content.

4.2. Facilitating transfer of learning

AR provides access to multiple representations (e.g., visual, auditory, tactile) of a piece of information at the same space and time, which potentially reduces cognitive load during learning [5,50]. Furthermore, it can be argued that AR penalizes children less on their dual representation challenges than IVR, in which children are fully immersed into a virtual world [7]. In contrast to IVR, children do not need to constantly hold the representation of the physical world in mind while exploring the virtual world through AR, since they have immediate access to both.

When children learn with AR, their learning and implementation spaces are the same, whether they need to transfer the new information to the real or the virtual world. As addressed in Section 3.2, the discrepancy in the settings of encoding and retrieval of the information impedes young children's transfer of learning [44]. AR, on the other hand, has the potential of reducing the distance between these two settings. It simultaneously provides information on screen and in the physical environment. Complementary relationship between these two sources of information requires constant and iterative monitoring of both, and it gives children a unique opportunity to interact with the real and the virtual worlds at the same time. Thus, similar to online video chat discussed in Section 3.2, AR is also able offer immediate, reliable, and correct information on the screen. This can help children to bypass the difficulty they experience with transfer of learning across mediums. In other words, AR can shorten the distance between the contexts of learning and transfer by blurring the lines between the 3D real world and the 2D digital world. However, this argument is still to be tested.

Even if support is provided by empirical data, this does not imply that AR alone is sufficient to foster children's learning from screens. Children still need social scaffolding to make the most out of this experience. It was found that when reading AR picture books with their children, parents adopt different roles and communication styles. Children could provide extensive descriptions of the book content only when they jointly interacted with their parents while reading the book, instead of the parent or the child dominating the session or the two having low levels of communication. Authors concluded that exchanging ideas on the story and the AR elements with their parents led children to show higher levels of cognitive attainment [55]. Social collaboration around the application is an important aspect of learning not only with adults but also with peers [5]. For instance, 2- to 7-year-olds could not solve a key task in an AR application and needed to observe their older peers to achieve it [10]. Discovering how the AR application works together with friends contributes to children's engagement and learning since it provides them the opportunity to discuss and collaboratively reflect upon the educational content.

5. Future directions and recommendations

By offering a playful interaction between physical and virtual worlds, AR offers an engaging learning platform for preschoolers. Considering that reducing the distance between the context where new information is learned and the context where it has to be transferred assists learning [29], AR has the potential to contribute to young children's learning by merging real and virtual worlds. However, this potential cannot be attained without a mutual flow of information between researchers from different fields and designers.

5.1. Questions for researchers

Rapid commercialization of AR calls for urgent and systematic multidisciplinary research on its academic effects. Psychologists and education researchers need to address theoretical questions which will inform the development of AR applications. How do children conceptualize the intertwinement of real and virtual worlds at different ages? How do individual differences such as children's fantasy orientation affect their understanding and use of mixed realities? How do children perceive this "new" reality? Is it really new, or do they simply judge it as real or fantastical? How does blurring the lines between the real and the virtual affect children's learning? While we have accumulating evidence for children's learning separately in these two modalities as summarized in Section 3.1, we need more information on preschoolers' understanding of mixed realities and its effects on their knowledge acquisition. Furthermore, research is also needed about the domains of knowledge, concepts, and skills that may be more suitable to teach with AR. For instance, it has been argued that books with fantastical themes may be better for teaching children physics than biology and problem solving [57]. Similarly, physical and visual concepts may benefit more from AR compared to abstract concepts.

Meanwhile, design researchers need to carry out controlled experiments to investigate children's learning gains with AR. As mentioned in Section 2, current literature is lacking methodologically strong experiments to study the effectiveness of AR as well as systematic comparisons between AR and other educational mediums targeting preschoolers. It is important to go beyond descriptive statistics and observations, and to conduct empirical quantitative research with AR and other traditional (e.g., picture books) and digital mediums (e.g., electronic picture books) to reveal the unique educational capacity of AR. Furthermore, studies reported in Section 2 were predominantly conducted in classroom settings with teachers. However, children spend a considerable amount of time with their parents during their early years. Studying children's learning outcomes when they use AR with their parents would make a significant contribution to the literature and the market. Research is also needed to disentangle the conditions under which children learn with AR. How should the interaction between adults and children be stimulated while using an AR application? What does AR need to provide for children to help them easily interact with the content? Which features of AR distract children instead of guiding them? In addition to answering such empirical questions, investigation of long-term learning gains of AR systems is also needed. To be able to conclude that AR is an effective teaching medium, we must ensure that knowledge acquired through AR is sustained over time.

5.2. Recommendations for designers

While researchers seek answers to the questions proposed above, designers will continue introducing new educational AR applications targeting young children to the market. To guide them based on the current psychology findings summarized in Section 3, we provide a list of recommendations in Table 1.

Conclusion

AR has the potential of becoming a source of knowledge and development for young children. However, empirical research and multidisciplinary communication are needed to make healthy inferences about the effectiveness of educational AR applications. Answers to the questions we proposed in Section 5.1 will inform designers to develop effective evidence-based AR learning systems for young children, and will inform researchers to have a better understanding of children's conception of reality, virtuality, and mixed reality. With the support of empirical research, screen-based AR applications carry the potential of accommodating the four pillars of educational applications [8], and creating their own additional benchmarks for both educational and entertaining experiences for preschoolers.

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Table 1
Recommendations for designers.

1.	Intertwine the AR elements with the educational goal. One way of doing this is to use AR to give important information that is not otherwise given.
2.	Make sure that AR elements are not disrupting but fostering learning, i.e., AR is not distracting but directing attention to the learning material. One way of doing this is to exclusively use AR at crucial points that are directly relevant to the learning material, and to use it to highlight the target information.
3.	Assist children in relating what they see on the screen with their surroundings and daily life, preferably by fostering social interaction. One way of doing this is to use the affordances of AR to encourage children to explore their physical and social environments.
4.	If it aligns with your goals, design not only for one (a single child) but for two or more (a child and peers or adults), so that it inherently stimulates social interaction. One way of doing this is to position AR as a joint attention element, which requires attention and action from more than one person.
5.	Enable children to easily interact with the application, so that they can focus on the educational content instead of spending too much time and cognitive effort on the technical aspects. One way of doing this is to consider targeted age group's developmental skills (e.g., fine motor development) and technology-related abilities (e.g., pinching, drag-and-dropping).
6.	Guide not only children but also adults about the use and the content of the application, so that it stimulates more content-related talk than technology-related scaffolding. One way of doing this to provide some information about AR, as they may have never used it before, and make it easy to use not only for children but also for adults.
7.	Be aware of novelty effect, so that children's interest in the application does not wear off over time and that learning effects are long-lasting. One way of doing this is to use AR to build characters with which children can build parasocial relationships they want to maintain.

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