Enhancing the vocabulary learning skills of autistic children using augmented reality: a participatory design perspective

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ABSTRACT

Many autistic children[1] face challenges with vocabulary learning. Augmented Reality (AR) has the potential to improve their learning process by leveraging their visuo-perceptual strengths. However, there is a gap in the literature on how AR solutions should be designed, and what guidelines should be considered. Extant solutions supporting autistic children in vocabulary learning using AR have been created without taking into consideration insights from children, their parents, or experts. This paper explores the potential of AR in enhancing vocabulary learning in autistic children through a participatory design approach. Involving experts with a background in psychology, pedagogy, speech therapy, and special education, as well as autistic children and their parents, resulted in a better understanding of the underlying mechanisms used to teach vocabulary and the interaction modalities offered by AR to engage the children. This work will facilitate the design of an AR technology to support vocabulary learning in autistic children.

CCS CONCEPTS

• **Human-Computer Interaction (HCI)**; • **Human-Centered Computing**; • **Empirical Studies in HCI**;

KEYWORDS

Augmented Reality, Language Learning, Autism Spectrum Disorder, Participatory Design, Learning Technology

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[1]We use the term autistic children, following the guidelines from the National Autistic Society: https://www.autism.org.uk/what-we-do/help-and-support/how-to-talk-about-autism

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1 INTRODUCTION

Language learning poses different challenges for some autistic children, possibly due to persistent challenges in communication and social interaction across multiple contexts, together with other needs which are typical of the autism phenotype [4]. These challenges have adverse consequences for the daily functioning of autistic children, their families and caregivers. However, recent developments in learning technologies have created new possibilities for supporting autistic children in language learning, and research suggests a positive attitude of autistic children towards the use of educational technology [3, 23]. Among these technologies augmented reality (AR) offers new approaches to engaging with the real world. Evidence-based research shows that AR can be fairly accessible and affordable and may improve communication abilities in autistic children. Moreover, AR is the preferred technology for contextual learning because it can be used to present context-specific and real-time information interactively [39]. However, language learning is a complex domain that involves various areas, such as phonology, grammar, semantics, and pragmatics. Autistic children display a weakness in acquiring the meaning of words, even when they successfully manage to store their phonology [44]. Specifically, this is more evident in minimally-verbal autistic children, who often appear to learn words by association rather than based on conceptual categories [2, 35], indicating that there may be a problem in symbol formation and symbolic thinking [45]. Studies have demonstrated an agreement among researchers and practitioners on the importance of providing scaffolding support to enhance vocabulary learning in autistic children using AR [37, 41]. AR enables the treatment of autistic children in more ecological and realistic settings that may be modified and tailored according to the different needs and cognitive language profiles of autistic children [14]. Furthermore, AR can improve learning by embedding additional content to promote multimedia learning, which is learning through associations between verbal and imagery information using various sensory and working memory channels [27].

Despite the awareness on the affordances of AR for developing solutions that could support autistic children in vocabulary learning, there seems to be a gap in the existing literature regarding how these solutions have been designed, and what guidelines should be considered when designing them. Specifically, many solutions have been created for children without detailed knowledge of their needs or learning preferences. A Participatory Design (PD) approach that involves the children and their parents, and also domain experts, such as psychologists and speech therapists, who have the expertise necessary to design effective interventions for this population, could help addressing AR solution for vocabulary learning in autistic children. Without the participation of children, their parents and experts in behavioral psychology and speech therapy, these solutions' design may not consider the specific learning needs and cognitive abilities of autistic children. As a result, it is important to involve both children and experienced stakeholders as design partners [8], to provide them with a sense of ownership and empowerment, to create effective solutions that could support vocabulary learning in autistic children. By involving stakeholders and children, a better understanding of how AR can be integrated with current practices used to teach vocabulary learning could be attained, which would facilitate the design of AR technology that is tailored to the needs of autistic children.

Our study poses the following research questions (RQ):

RQ1. What are the learning factors that experts consider most relevant in vocabulary learning among autistic children?

RQ2. What methodologies do domain experts rely on to teach vocabulary to autistic children?

RQ3. What are the design features that a mobile AR application should have to potentially support vocabulary learning in autistic children?

To address those RQs we adopted a PD approach, based on the best practices of Bødker et al. [8]. Through focus groups, workshop and observations we obtained insights from both autistic children, their parents and domain experts (psychologists, speech therapists, pedagogists and school-teachers). We hope that our findings will facilitate the design and implementation of an AR application on mobile devices to support autistic children in vocabulary learning. Finally, our intention is to provide guidelines for researchers and educators in the domain of educational technology, autism and vocabulary learning on how to address the needs and learning abilities of autistic children.

2 RELATED WORK

According to the American Psychiatric Association [4], the autism phenotype is characterized by deficits in communication skills, as well as repetitive behaviors. In addition, autistic children often exhibit difficulties in their ability to learn new words [34]. Studies show that autistic children display problems in categorizing the referents of linguistic labels leading to subsequent problems with using those labels in different contexts [45]. At the same time, findings on children's learning and development indicate that there are several limitations to traditional teaching and learning strategies that rely exclusively on textbooks, images and pictograms, as they may not encourage engagement and motivation. A common approach used by teachers and speech therapists is the use of images and pictograms. Indeed, many autistic children benefit from visual support [31], and alongside language, pictures are a class of symbols that play an extremely important role in children's early language development [1].

Based on these premises and the recent advancements in learning technologies, especially within extended reality (XR) and AR, researchers have investigated the potential of AR to aid vocabulary learning in autistic children. Extant research has documented visual-perceptual strengths in individuals on the autism spectrum [31]. Therefore, we hypothesize that AR can support the process of vocabulary learning and categorization by providing 3D representations of the object words refer to and opportunities to experience and explore them. Furthermore, AR can contribute by providing multiple exemplars of the categories that appear to be necessary for autistic children to consolidate the association between the label and the category. In particular, AR can provide the necessary context in which objects occur in the world and, as such, provide the necessary contextual support needed to acquire the meaning of the related word. As a result, the expectation is that AR can be quite beneficial for vocabulary learning and appropriate for autistic children with different needs and language skills. Several studies documented the use of AR for enhanced vocabulary learning interventions in autistic children. In particular, Mota et al. [30] proposed an AR application using a gamified process to facilitate the association of words and images in autistic children. Their study highlights how AR can be beneficial for learning words associatively. Similarly, Hashim et al. [21] presented 'AReal-Vocab', an AR mobile application to teach English words to children with mild autism. Their solution includes several visual features capitalizing on the observation that autistic children appreciate visual representations. Tang et al. [41] conducted a pilot study with typically developing children using an AR application that leverages deep learning for object recognition to teach new Chinese words to children, but they did not investigate its efficacy in teaching vocabulary to autistic children. However, the reported studies did not involve children and/or experienced stakeholders (design partners) during the design process, and therefore, it is unclear if the proposed solutions can address the users' needs.

2.1 Participatory design in autism

Participatory design (PD), a means of involving users in the design process, is one method that has successfully involved children in the design of educational technology. Involving children as equal stakeholders or "design partners" through PD offers a number of potential benefits [7]. These include giving the children a sense of empowerment and challenge, providing them with an opportunity to develop new skills, and building their confidence both academically and socially [17]. PD is concerned with the needs, wants and desires of users, both as individuals and as a whole. Part of what PD does it helping users understand possibilities and alternatives for building technologies, and what it takes to get there. Bodker et al. [9] emphasized that with PD, participation is when people (design partners) are engaged as representative of their peers, and gives them a sense of ownership of the final outcome.

Research has documented how the practices of PD can be applied and extended involving children with autism. Escobedo et al. [16], for instance, have shown that using PD can contribute to the creation of an AR solution that improves the attention span of autistic children. They used interviews, a workshop, and observations to gather insights on the design features and usability of the AR solution. Their study suggests that a collaborative involvement of both the end-users and experts, as design partners, is beneficial for designing an effective and engaging solution that accommodates children's needs. The use of PD has been demonstrated to be effective to improve numeracy skills in autistic children [33]. The authors argued that employing PD resulted to be more effective in meeting the needs of the primary users, and it allowed to ensure accessibility and inclusion. Research has shown how the use of PD can be effective in the design of digital elements in AR to enhance play experiences in autistic children [11]. The involvement of the children as co-designers influenced the design of the digital elements, based on their preferences, needs and values. Moreover, the use of AR has shown a high degree of engagement and has proven to be a user-friendly technology.

Although the use of PD with autistic children and stakeholders who are involved in their development and learning process seems to be a more established practice in the domain of learning technologies in, for example, robotics [5, 36], virtual reality and mixed reality [42], the use of PD to inform the design of AR-based solutions for vocabulary learning is limited. Moreover, to the best of our knowledge, there are no studies that address vocabulary learning using AR for autistic children through a participatory approach. Therefore, in this paper, we explore the potential of AR in enhancing vocabulary learning for autistic children using PD, to generate insights that will inform the design of a mobile AR solution. In particular, our research proposes guidelines and implications on the design of AR-enhanced vocabulary learning solutions for children (and with children) on the autism spectrum, and our findings can be used to pave the way for future research and practice in AR-enhanced language learning.

3 AUGMENTED REALITY TOOLKIT TO GENERATE VOCABULARY LEARNING EXPERIENCES

Research has shown that the use of cards as a design tool for collaborative design and brainstorming can help speed up the refinement and iteration of ideas [6, 25]. Cards can also help structure design discussion, promoting communication and collaboration among design partners [22]. The use of card-based tools has been demonstrated to be an effective way of supporting idea generation in collaborative design workshops, for example, to generate tangible learning games [12], exertion games [32], or IoT solutions [29].

To enable experts to collaboratively generate ideas and learning content for an AR solution that supports autistic children to master new words, we devised *cARd*, a toolkit that enhances collaboration for generating vocabulary learning experiences using AR. cARd is composed of a physical card deck, a board where cards from the deck can be placed, and an AR prototype for card-scanning. In summary, cARd toolkit (card, board, the application) has been created to empower experts to develop ideas for supporting vocabulary learning with the use of AR by fostering both divergent and convergent thinking. With cARd, we aim to investigate how to design AR technology to support vocabulary learning by engaging end-users and experts in the area of autism, but they are not necessarily familiar with the use of AR technology.

3.1 cARd: physical cards

The toolkit includes 3 different decks of cards, differentiated by 3 different colors, consisting of 18 cards each. The cards have been designed using Figma, and printed out using a cardboard material, with a size of 8x6cm each. The decks represent respectively objects, activities, and locations as indicated on the back side of the cards (Fig. 1). The front side of each card consists of an image representing an element from each of the 3 categories. The categories cover words that can be taught to the children (object), activities or actions that can be performed (*activity*), and a scenario/location where learning could take place (*location*). The rationale behind the choice of these categories is to frame the understanding of a single word into a practical context (e.g., learning that a cup is an object that can be used to drink (action) in the kitchen (location)), and therefore referencing an object card with other cards from the other categories can facilitate a context-based learning experience.

3.2 cARd: board

We designed the board of cARd with the idea to facilitate the generation of a vocabulary learning experience for autistic children that would leverage context-based learning (Fig. 2). Research has shown that autistic children experience several challenges in contextualizing the meaning of words [34, 45]. As a result, the left side of the board presents three distinct rows where the participants can place up to 3 cards per row. To use the board, the stakeholders are required to follow a few steps: (1) place one or more *object* cards in the second row, (2) define one or more possible *activity* cards that the children could perform with the object cards in the first row, and (3) select a *location* where the learning experience could take place in the third row. The intersectionality of cards placed in different rows is expected to foster context-based learning, where the meaning of a word (object) is taught by the symbolic linking with an activity and a location, which represent a context. The physical cards serve as suggestive design tools, but the board also allows the placement of cards drawn and designed by the participants, based on their expertise in terms of what words preschool children on the autism spectrum should learn and how such words can be framed within a real-world context, and based on the interest of the children involved in the study. Each of the placed cards can be scanned using a smartphone or tablet device and their 3D representation appears in AR. Participants can interact with the digital content using touch-screen input, enabling 3D rotation. Moreover, domain experts can use the board to illustrate possible interaction flows that could foster engagement and motivation for the children. The exposure to the different components of cARd (cards, board, and AR prototype) facilitates collaboration and discussion among the stakeholders, to illustrate ideas of learning experiences using AR that could support autistic children in acquiring new words.

3.3 cARd: augmented reality prototype

Our AR prototype was implemented using Unity, where we included a digital representation of the physical cards and the 3D assets to be

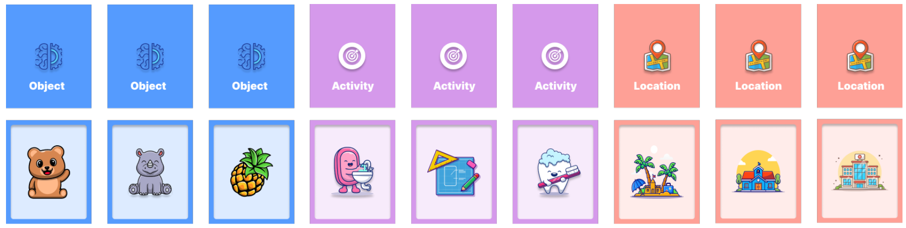

Figure 1: A selection of the cARd physical cards

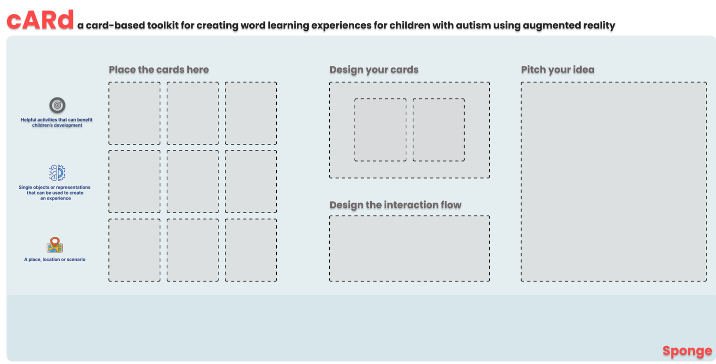

Figure 2: The cARd Board

displayed. To create the AR functionality, we used ARFoundation, a Unity framework that provides tools for markers tracking and allows to have a cross-platform solution supported by both iOS and Android on mobile devices. The prototype consists of a 2D image tracking system, which maps a 3D asset onto each card in the decks (Fig. 3). The application source consists of Unity 3D assets and C# scripts. We have decoupled the logic of the scripts from the creation of new digital content, to enable extensibility.

Table 1: Children and families involved in the study

ID	Gender	Age	Diagnosis	Parent ID	Accompanying parent
Child 1	Male	11	Autism Spectrum Disorder	Familiar 1	Father
Child 2	Male	11	Autism Spectrum Disorder	Familiar 2	Father
Child 3	Male	10	Autism Spectrum Disorder	Familiar 3	Mother
Child 4	Female	11	Autism Spectrum Disorder	Familiar 4	Mother

4 METHODOLOGY

4.1 Participants

A total of eight experts (F=8) (Table 2 in Appendix A) and four children (F=1, M=3) (Table 1) participated in the study. Currently, one group of four professionals works in a special education school for the care of autistic children and adolescents, and the other group of four professionals works in a Centre of Child Development and Early Attention (CCDEA), where they care for children with developmental difficulties between 0 and 6 years old, including autistic children. The professionals involved in the study are specialized in psychology (n=3), pedagogy (n=3), speech therapy (n=1), and special education (n=1). For the workshop sessions, four children and one parent of each child, participated in the study. These participants were recruited from an autism association in the city of Seville, Spain. According to the 5th Edition of Diagnostic and Statistical Manual of Mental Disorders (DSM-V) [4] all participants had an autism diagnosis level 1 that includes verbal communication skills and motivation to interact but with occasional difficulties.

4.2 Research design

We used PD to explore the potential of AR in improving vocabulary learning in autistic children, and inform design practices on how to design an AR solution that accounts for the children's needs, learning abilities and preferences. To do so, we organised focus groups with experts in the field and conducted individual workshops with autistic children and their families. The inclusion of autistic children, their parents, and domain experts was intended to empower them in the design process and provide them with a sense of ownership of a solution that takes into account their needs, experience, and preferences.

The focus groups with experts consisted of two phases. First, we conducted a semi-structured interview with professionals on how they teach vocabulary to children with autism, including the mechanisms and methodologies they use. Second, we presented cARd and asked professionals to interact with the toolkit and identify its potential for facilitating vocabulary learning. We elicited their requirements and ideas for AR-enhanced vocabulary learning, based on three main aspects: in accordance with the physical cards, interaction with AR and the 3D content, and general questions

Figure 3: The cARd prototype

about the use of the AR prototype. Three researchers guided the sessions, one as a moderator of the interview, the second researcher moderated the demo prototype, and the third researcher, as an observer. Each session of focus group would last between one hour and one-hour and a half.

The participation in the workshops for the children and their families consisted of a collaborative design phase in which they made used of the cARd toolkit. We proposed two dynamics. First, the evaluators hid the cards around a room, gave the mobile device to the child, and asked them to look for all the animals (cards) they could find in the room, scan them with the device and return them to the table. This was intended to observe how they would manipulate the mobile device and interact with the AR content. Second, we laid out all the cards on the table, so that they could interact with them while sitting on a chair. We also provided cARd to the accompanying parent. We then conducted a short semi-structured interview with both the child and the family member to get their ideas about what would be relevant for the AR prototype, and to allow them to express what they would like to see as 3D models or what they would use it for. The sessions would last from 20-30 minutes.

4.3 Procedure

After obtaining the approval of the Bioethics Committee of the University of Seville to carry out this study, we have recruited experts working in the field of autism, along with autistic children and their families. For the focus group sessions with experts we collected individually signed consent forms. Parents gave consent for participation, recording and photography for both themselves and their child. The children also assented to participate in the activity. In total, we formed two focus groups with 4 professionals in each and 4 individual workshops for children and their families. The first focus groups were carried out in a special education centre for autism and the second focus group in a room set up in the Faculty of psychology. Three familiar-child workshops were carried out in Aspiro Sevilla association, and one workshop session was conducted in a room set up in the Faculty of psychology. A group of collaborating students transcribed the recordings for further analysis.

4.4 Data Analysis

To address the three research questions we analysed the content of the collected qualitative data inductively. First, we identified what content we expected to find in each of the questions asked in both the focus groups and the workshops. Secondly, a coder reviewed one of the transcripts from the focus groups and one from the workshops. This coder also reviewed the literature to establish and define initial codes. Then, we established that the unit of content analysis of the transcripts for both the practitioner group and the family workshops would be: a) verbalisations given that matched the description of the pre-established code; b) participants' behaviours while interacting with cARd.

Next, three coders corresponding to three authors of this paper analysed the content of the two focus groups and the four family-child workshops independently, to mitigate errors and bias. At this point, the coders met to compare the results, review the codes and discuss until a consensus was reached. Finally, we drafted guidelines and recommendations for the design of an AR application to support vocabulary learning in autistic children.

5 FINDINGS

Below we report the four themes that emerged from our PD study with the domain experts, the children, and the families.

Mechanisms and difficulties in vocabulary learning in autism

The experience of professionals was clear on how the learning of new vocabulary occurs. As they stated on numerous occasions, they perceive autistic children to perform word-reference mapping on the basis of association mechanisms, confirming findings from research. They explained children understand the learning of new words as occurring in two ways. First, by repeatedly showing the relationship of a word with its real referent or meaning, as Professional 5 said when she mentioned an example: *"I hear 'give me water, give me water, give me water', and I say 'give me water' because I repeat, I repeat as it is, I repeat the sound I am hearing and then I give it the meaning"*. Second, mapping the word-reference relationship through visual support (images, drawings, pictograms) as the same Professional 6 commented: *"The other aspect is to learn with images, for example, to see a duck and learn that what I am seeing in an image is called a duck"*.

However, after asking about how autistic children learn new concepts, Professional 1 commented that *"well, for the bad things, also that associative thinking"* suggesting that this was a barrier to overcome in order to make progress in vocabulary learning. They mentioned other difficulties such as *"they have no communicative intention or interest in relating, they have no motivation for interaction"* according to Professional 6, or even that restricted interests are also a barrier, as mentioned by Professional 5: *"If my interest is, I don't know, cars, I learn the vocabulary of cars, (...) of any other subject maybe they don't participate because it is not of their interest"*.

On the other hand, practitioners stated that it is not only restricted interests that impede vocabulary learning but that there are specific cognitive biases that are influencing such as weak core coherence. Professional 1 mentioned: *"everything that has to do with central coherence is what makes it very difficult for them to obtain vocabulary, the acquisition of concepts in general"* and explained *"they focus on specific aspects that do not necessarily have to be relevant to a particular material or object, so it is very difficult for them to extract the relevant information from that and realise why we call a chair a chair"*. In turn, they related that this difficulty impeded the formation of concepts or even the generalisation of vocabulary between different reference environments of the same category, as Professional 4 commented *"they acquire a concrete vocabulary of the real life in which they handle, they are objects that they are manipulating, but they do not have the global concept"*. They even mentioned that *"many times there is that vocabulary, the question is (...) when to use it and in what contexts (...) because they have a lot of difficulties in generalising from one context to another"*.

A complementary approach of both technological and non-technological devices is used to teach vocabulary in autism
The findings on the different devices experts use to teach vocabulary was clear-cut. The two groups of experts indicated they teach vocabulary to children with autism using both tools (i.e. technological devices and non-technological devices). Experts use physical tools, including songs, games, toys, images or photographs, pictograms, since they represent real and tangible objects used to make associations. Moreover, experts mentioned technological devices such as computers, tablets, mobile phones and agree that they all use, and have easy access to, videos on YouTube, specific apps, and PowerPoint presentations. However, in the workshop with the families, when researchers asked parents if they use technological devices to teach vocabulary to their children, three parents stated they do not use technological devices to teach vocabulary. The parents, however, have an iPad or computer at home, which is used by children for other purposes (e.g. reading). One parent stated she uses technology to teach new concepts as is remarked by Familiar 3 *"If by technological we understand, YouTube videos, online exercises. If that usually works very well"*. Nonetheless, families use non-technological devices to teach vocabulary such as, boards, drawings, books but mostly they teach new words verbally using synonyms or definitions stated by Familiar 2 *"Usually with verbal language. If he wants to understand it, he catches it on the fly"*.

Furthermore, noteworthy experts agreed that electronic and non-electronic tools complement each other. Both tools complement each other by using them for different activities, for example, professional 5 remarked *"I do use a lot of pencil and paper for certain children, for example, to establish a schedule, anticipate what we are going to play, sequence and so on, because it is much better than putting it in an app"* and electronic tools to motivate and encourage learning for example, experts start from the premise of the child's interest, Professional 4 stated: *"it is true that they are much more attracted to technological material, we start from a prior interest in technological material"*. In one focus group, participants mentioned that the usability of the tool depends on the characteristics of the child and the difficulties children might have to produce associations, as is remarked by professional 5 *"I believe that everything has its moment, and I believe that in the beginning, it does not make sense to introduce a Tablet. But when I already know he knows how to make associations, classify and do some things, and I have manipulated it, it is much more functional learning"*. Lastly, experts argued about the use of different tools would also depend on personal and professional convenience professional 3 stated: *"But because I feel more comfortable, perhaps and I feel safer because of what I have studied. Maybe it's the way I apply it"*.

The experts also mentioned numerous activities used to teach vocabulary. Among them was a list of imitation and modelling tasks, classification, simulation, repetition, and intruder search. In addition, they commented that it is very important to reinforce and use their interests to motivate children to learn a certain vocabulary. Furthermore, they mentioned that the strategies used should be systematic. They also explained that the training should have a practical application and should be done in different contexts. For example, Professional 2 mentioned that *"association with daily life routines, especially in the functionality of those learning, of that vocabulary that is used, the practical application"*, or Professional 5 emphasised that it is necessary to train *"in different contexts with different situations and give them many models"* and with the involvement of the whole environment of the child, both school, family and therapies. In addition, as mentioned Professional 4, they carried out vocabulary training with the aim of forming new concepts and categories in the following way: *"Along with the word we tell them what it is for, where it is, how it is used, to create associations and build more complex categories"*.

A realistic visual design of the learning content enhances vocabulary acquisition
The findings of our investigation converged on a joint agreement on the visual design of both the cards and the corresponding 3D assets. The assets that populate the content of cARd have been designed using both cartoonish and realistic elements. The experts argued that to effectively enhance vocabulary learning in autistic children, the use of both realistic images and 3D assets would be more effective to introduce new concepts. For instance, both Professional 5 and Professional 6 argued that *"Using both realistic images and realistic 3D assets is recommended because they facilitate generalization and contextualization of words"*. However, the experts mentioned that to reinforce previously acquired vocabulary, cartoons, drawings and pictograms may be appropriate. In addition, the use of animations for the 3D assets is crucial. Professional 4 stated that *"I think that use of animations is important to explain actions. Having only static content wouldn't represent the action itself"*. On the same line Professional 4 argued *"Having both static and animated content would be helpful, so that we can provide multiple exemplars of the same concepts and provide a more realistic learning experience"*. Furthermore, complementing the visual AR content with auditory stimuli

can be effective to enhance learning. The participants agreed that having representative sounds of some objects (e.g., the roar of a lion) or spelling the name of a word could benefit the children in understanding the meaning.

Multiple interaction modalities with the AR-enhanced learning content are required
Content interaction involves several elements, including cards, 3D assets, AR interaction paradigms through mobile devices and different ways of image detection. The participants discussed the difficulty of recognizing a 3D object at first glance, due to its position the AR space. Professional 4 and Professional 3 stated *"It would be better to scan the picture/card vertically to better see the horizontal profile of the 3D model instead of seeing it from the top.. it is not always easy to rotate the device"*. Moreover, cARd allows for rotation around the z-axis of the 3D assets. Familiar 1 pointed out *"In my opinion it would be better to rotate an object using two fingers.. that's what I am used to with my iPhone"*. The participants suggested that further interactions with the 3D content can facilitate the learning process, including the possibility of dragging and moving the content, and resizing it. Concerning card detection, some participants highlighted that the detection of some cards was not immediate, which could lead to frustration in the children. On the same line, cARd does not allow for multiple image tracking. Professional 5 and Professional 6 argued that *"Multiple image tracking could allow to recreate "cause-effect" actions"*. Similarly, Child 1 pointed out *"If for example I drag the apple next to the wolf, I would expect to see the apple being eaten"*. By observing how children interacted with the AR prototype, we realized that they all tried to interact with the digital content using their hands instead of using touch-screen input. They argued that *"It feels more natural to touch the object"*. Moreover, Child 2 and Child 3 used the tablet as a visualization tool and interacted with the digital content by holding the physical card. Child 3 suggested *"It would be nice that when I take the card and rotate it, to see the 3D object rotate as well"*.

6 DISCUSSION

The main purpose of our study was to investigate how to design a mobile AR application to enhanced the vocabulary learning skills of autistic children. Our findings are in line with previous literature, but also present new insights based on a collaborative approach that involved the participation of different stakeholders.

6.1 Learning factors considered by experts in vocabulary learning among autistic children

According to the experts interviewed, autistic children learn by matching a word with images of different characteristics, or with its referent when it is presented to them repeatedly. This is consistent with studies related to statistical learning whose results show that autistic children can establish reliable object-referent relationships if presented with multiple trials, situations, even when the correspondence of a word-referent is ambiguous [20]. It is worth mentioning that professionals train vocabulary in different contexts, and by associating the word with different visual aids to encourage the generalisation of these concepts, given the observed difficulties that autistic children have in this respect. In general, research shows that one of the main barriers in autism is the lack of generalisation of acquired knowledge and learned skills [47]. Specifically, in the area of language, the literature explains that, in general, children at 24 months use the shape of objects as a cue to apply a label to a novel object, rather than other features [24]. However, autistic children do not seem to show this preference for shape to generalise vocabulary [19]. Professionals mentioned other dimensions that might be influencing vocabulary learning. They perceive a lack of motivation for social interaction or relationships as a barrier influencing vocabulary learning, as children are often unwilling to learn concepts about issues that do not interest them. In addition, practitioners also noted that children with autism display a specific attentional bias called weak central coherence, as discussed in [18]. This bias might cause autistic children not to process objects and words in a global way, but to focus on details that are sometimes irrelevant for extracting a concept. However, this is not entirely clear [38]. One theory that seems to shed more light on vocabulary learning difficulties is the auditory-visual misalignment theory [43]. This proposes that language learning occurs when the referent is aligned in time and attentional focus, i.e., that the child attends to the referent when presented with the word and is aware of the relationship between the two. Therefore, if the autistic child is not motivated by the interaction or is attending to irrelevant details of the referent at the time of training, the word-referent relationship may not be adequately established.

6.2 Methodologies that experts rely on to teach vocabulary to autistic children

Based on the results, experts rely on the need to use both non-technological and technological devices to facilitate vocabulary learning, as they complement each other. Since professionals have not actually worked with mobile AR app for children with autism before, we asked for their opinion and expectations on using the app to learn vocabulary with autistic children during the focus group, the professionals stated they could use the AR mobile app into their one-on-one therapy sessions with the children. The experts use technology depending on the different activities they perform, as well as children's needs, abilities, and preferences. All professionals stated the use of technological tools with autistic children could have an added value, mostly to encourage motivation, as they are attracted to technology [13]. If the student prefers technology, the therapy session would begin by showing technological devices; starting from a previous interest in technology and then exploiting the motivation for the learning environment. Moreover, it has been shown in extant research that the more attention and motivation towards the task, the greater the interest in learning [28]. The preference for technology to encourage motivation is under exploited at the home, as evident in families' responses to the use of technological devices. Despite one parent remarking that her child liked using technology for learning, the other three families reported children use of technology for other reasons than vocabulary acquisition. Parents appear to rely more on non-technological devices (e.g. verbal language) to teach vocabulary rather than technology. Further, experts stated that before using technological devices with autistic children, it is important that abilities such as association are covered, and professionals could use AR mobile app as it will help them to have more personalized and extensive materials to apply for each child. Other methodologies used by professionals are classification, simulation, repetition and reinforcement; using those methodologies in different contexts can allow faster or more efficient generalization.

6.3 Design features of a mobile AR application to enhance vocabulary learning in autistic children

Our study shows that design features should address the visual design of the AR content, how this content would be presented, and how children should interact with it. According to our findings, the visual design of an AR solution should include realistic images and realistic 3D assets to effectively enhance vocabulary learning in autistic children. Experts agreed that realism of content can facilitate generalization and contextualization of new words. Moreover, evidence-based research shows that the more a learning content resembles reality, the more iconicity (degree of similarity between a symbol and its referent), the more transparent the symbol. Studies [10] showed that minimally-verbal children with autism have greater accuracy when learning from coloured realistic pictures compared to cartoons. This indicates that they benefit from greater iconicity of visual stimuli when learning words. Therefore, since the 3D content used in this application can be more iconic than a 2D visual image, children with autism could benefit equally in learning new vocabulary. Nonetheless, experts and children believe that using non-realistic content can be useful for reinforcement learning. Based on this, our AR application would enable the visualization of both realistic and non-realistic content, and the teacher would choose which one to use to initiate a learning activity. In addition, the realism of digital content must be also achieved using auditory stimuli, as it can be effective to enhance learning according to the domain experts. The user interface (UI) of the mobile application should allow hearing the word that a child is learning, and, when possible, a representative sound of the referent object (e.g., the meow of a cat). Moreover, the unique capability of marker-based AR is that it allows users to scan cards and see their 3D representation in AR. However, the current state of our prototype allows the visualization of one 3D object at a time. As Professional 4 pointed out, for every word a child is learning, multiple exemplars of it should be displayed. For instance, when showing the AR representation of a cup, multiple exemplars should appear with different colours and shapes, to facilitate generalisation and contextualization, which is consistent with findings from research [15, 40]. In addition Engelmann and Carnine [15] mention that it is ideal to use different examples of a referent that differ in some non-nuclear characteristic (e.g. labeling a cat as an animal with four legs, pointed ears, and a long tail regardless of color). Hence, the UI of the AR application should allow the users to switch among different 3D models representing the same object to better achieve generalization.

Concerning the interaction design with the learning content, our results show that using different gestures to manipulate the content of cARd can support the learning process of the children. The experts pointed out that the opportunity to manipulate a 3D object using rotation and translation can facilitate learning and increase visual attention. The current state of the prototype allows only the interaction using touch-screen input with one-finger manipulation to rotate a 3D object, which stimulates the mental rotation abilities of autistic children. In addition, our observational study revealed that it is instinctive for the children to interact with digital content using either their hands (hand tracking), ignoring the use of the touch screen or using a hybrid approach (combination of device rotation and multi-touch input). The mobile device only serves as a tool to visualise the content, not to interact directly with it. This suggests that the use of hand tracking can make the learning experience more engaging and natural for users. Evidence in the literature suggests benefits in using hand-tracking to interact with 3D content for learning using AR [46]. Moreover, studies show that the use of a hybrid approach offers the best results in terms of usability and interaction with the AR content [26]. As a result, including different interaction gestures for interaction can match the different needs and capabilities of the children, allowing them to interact with the AR content based on their personal preferences.

6.4 Limitations and future works

One limitation was the small sample size of children involved in this study. Besides, applied studies using the AR prototype in practice are needed to deliver more insight into the extent to which the experts' expectations match real-life experience with the technology. Moreover, a controlled experimental study is recommended to assess the efficacy of the AR solution in enhancing vocabulary learning in autistic children.

7 CONCLUSION

Our study addressed three RQs adopting a PD approach, to investigate which dimensions experts consider relevant for vocabulary acquisition in autistic children, what methodologies are used to teach vocabulary and what design features should a mobile AR application have to enhance vocabulary learning in autistic children. As a result, a mobile AR application to enhance vocabulary learning in autistic children should: (1) include realistic content to facilitating generalization and contextualization, (2) complement the visual content with auditory stimuli, (3) provide multiple interaction modalities to enhance learning and visual attention and (4) include learning activities based on association, classification, simulation and repetition. Moreover, the AR solution is not intended to replace teaching methods of vocabulary, but should be used as a complementary tool to encourage motivation and attention in the children.

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A APPENDIX

Table 2: Domain experts involved in the study

ID	Gender	Occupation	Population they work with	Current workplace
Professional 1	Female	Pedagogist	Autism from 7 to 13 years old	Special education school for the care of autistic children and adolescents
Professional 2	Female	Speech therapist	Autism from 0 to 16 years old	Special education school for the care of autistic children and adolescents
Professional 3	Female	Pedagogist	Autism from 11 to 17 years old	Special education school for the care of autistic children and adolescents
Professional 4	Female	Pedagogist	Autism from 16 to 21 years old	Special education school for the care of autistic children and adolescents
Professional 5	Female	Special education teacher	Autism, other neurological conditions and neurodevelopmental disorders from 0 to 6 years	Centre of Child Development and Early Attention
Professional 6	Female	Psychologist	Autism, other neurological conditions and neurodevelopmental disorders from 0 to 6 years	Centre of Child Development and Early Attention
Professional 7	Female	Psychologist	Autism, other neurological conditions and neurodevelopmental disorders from 0 to 6 years	Centre of Child Development and Early Attention
Professional 8	Female	Psychologist	Autism, other neurological conditions and neurodevelopmental disorders from 0 to 6 years	Centre of Child Development and Early Attention