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Review

Mobile Augmented Reality Technologies for Autism Spectrum Disorder Interventions: A Systematic Literature Review

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Abstract: Over the past decade, enhanced computing capabilities and mobile technologies have begotten the upsurge of innovative mobile health (mHealth) solutions, and many research efforts have occurred recently in the area of technology-based interventions (TBI) for autism spectrum disorders (ASD). Mobile augmented reality (MAR) refers to AR systems that use the handheld mobile device medium (mobile phones, tablets or smart glasses). This article reports the results of a systematic review undertaken on the use of MAR for ASD-related skills learning from the year 2010. It aims to provide an insight into the current state of research on MAR interventions and to provide guidance to relevant designers and researchers. We searched seven databases and retrieved 625 articles initially. After exclusion and screening, 36 articles were reviewed reporting on using MAR to improve various skills of children and adolescents with ASD, and 10 research questions related to PICO (P: Population, I: Intervention, C: Comparison, O: Outcomes) were addressed. This study identifies challenges that still exist in the research efforts towards the development of applications exploiting the MAR for ASD interventions: technology issues, research design consideration, subjective assessment etc. The studies examined suggest researchers should focus on users and improve the quality of the MAR app. In addition, more effective research methods and evaluation methods could be involved in future studies to facilitate the development of MAR intervention applications.

Keywords: augmented reality; autism spectrum disorder; intervention; research design; smartphone; social communication; tablet; app design

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1. Introduction

Autism spectrum disorder (ASD) is a neurodevelopmental disability varying in severity across the spectrum with two main characterized symptoms: (1) impaired communication and social interaction and (2) repeated activities and interest [1]. The World Health Organization (WHO) reports that approximately 1 in 160 children has been identified as having ASD, which affects the entire range of daily living activities from a very young age, restricting social participation of individuals and even need lifelong care [2]. Due to increasing attention to autism and increased awareness of clinical screening, the relevant data may increase significantly. According to the fifth edition of the Diagnostic and statistical manual of mental disorders (DSM-5), all different subtypes, including autism, disintegrating diseases in children, Asperger syndrome, Rett Diseases and generalized developmental disorders are classified as one diagnosis: autism spectrum disorder (ASD) [3].

Early Intensive Behavioral Intervention can improve the defect of autism to a certain extent [4]. However, the materials of some traditional media intervention methods, such as Video Modeling (VM), are usually too long and have no interaction mechanism [5–7]. It is difficult to dynamically adjust their attention focus and switch their attention position. Over the last years, information and communication technologies (ICTs) have been widely utilized to help the healthcare industry [8]. In the field of autism rehabilitation, technology-based interventions (TBI) include social robots [9], computer-based interventions [8,10–12], VR [13,14], tablet computers [15], serious games [16,17] and other TBI interventions [18,19].

As a new type of human-computer interaction (HCI) technology, augmented reality (AR) has evolved drastically over the years, which can combine real scene information and virtual information to provide rich visual information and diverse interactive experiences [20–23]. Evidence supports that people with autism are keen to process visual information and use digital devices, and AR provides new ideas for improving their learning experience [24–26]. Their parents also report that technology, including smartphones and tablets, plays a key role in addressing these behavioral challenges [27,28]. MAR applications make the treating process more interesting [29–33] and affect the academic achievement of children with ASD in a positive way [34–40].

Several literature reviews have been published about the use of augmented reality technologies in interventions with children and adolescents with ASD. Marto et al. have conducted a systematic literature review (SLR) of 16 primary studies on the use of AR for the rehabilitation of people diagnosed with ASD [41]. However, only eight studies on MAR were included. The authors in reference [42] reviewed 10 preliminary studies published from 2012 to 2016 and put forward some suggestions for future development and evaluation. Similarly, there are only six studies of MAR in the collection. In 2018, Adnan et al. [43] listed the development and research routes of AR in the field of autism intervention, while the search for literature was inadequate. Khowaja et al. [44] have conducted an SLR of primary studies published in 2005–2018 on the use of AR to learn different skills for children and adolescents with ASD and proposed the research classification of ASD; however, their study did not address MAR, and the research timeframe needs to be updated. Berenguer et al. [45] carried out an evaluation of the effectiveness of AR technologies on ASD. In this paper, we conduct an SLR of the use of MAR for ASD-related interventions from 2010 to 2020 and address ten research questions (RQ) related to PICO in order to identify current trends, future prospects and possible gaps related to the mobile AR technologies in the field of autism spectrum disorder.

2. Methods

According to Kitchenham [46], a systematic literature review (SLR) is a method of identifying, evaluating and interpreting all available research relevant to a topic area, or particular research question. We conduct this research in accordance with the PRISMA guidelines [47], and we follow recommendations outlined by Kitchenham.

2.1. Research Questions

A total of ten research questions (RQ) were formulated following the PICO framework to implement a comprehensive review of the topic [48]. In this study, the Population (P) is composed of autistic individuals enrolled in the intervention process; The Intervention (I) considered is the use of AR applications for ASD; The Comparison (C) is not applicable since the aim of this study is to describe the application of MAR; Finally, the Outcomes (O) refers to the main outcomes obtained. As a result, we elaborated ten RQs that guide the purpose of the study, as shown in Table 1.

Table 1. Research questions.

No.	Research Questions	Data Extraction Process
RQ1	What channels are used to publish research articles in ASD interventions exploiting AR technology?	Venue and year of publication is required.
RQ2	What device was used?	The used technological devices are required.
RQ3	What are the targeted population?	Characteristics of participants should be defined.
RQ4	For what purposes have been applied the proposed solution?	The targeted skills of selected studies should be extracted.
RQ5	What research designs are used in the studies?	The research design of selected studies should be defined.
RQ6	What methods are used to evaluate the performance of participants with the provided AR technology intervention?	The assessment methodology should be presented.
RQ7	What are the outcomes obtained by the application of the proposed solutions?	The major outcomes of the study should be presented.
RQ8	Which settings are used in the primary studies?	Details on the setting (classroom, home, controlled research environment, etc.) are required.
RQ9	How sustainable the outcome of the intervention is?	Detailed information about maintenance.
RQ10	How generalized the intervention result is?	Detailed information about generalization.

In RQ1, the channel refers to the demographic information of the primary studies, such as the published years, article types, and quality we assessed. In RQ8, the setting refers to the environment in which the intervention is implemented. In RQ9, sustainable means keeping the skills learned over time, and in RQ10, generalization refers to the transfer of skills learned from one situation to a new situation.

2.2. Search Strategy

A search of peer-reviewed published literature was implemented in February 2020 for articles related to the use of MAR technologies in ASD interventions. The search process was conducted using keywords that link to our topic, and the keywords combined by the Boolean operators are determined as follows: ("Autism*" OR "Autism Spectrum Disorder" OR "ASD") AND ("Mobile augmented reality" OR "AR" OR "Augmented reality") AND ("Mobile" OR "Tablet" OR "Smartphone" OR "Phone" OR "Smartglass").

The following inclusion criteria were used:

- Articles published after 2010;
- Studies published in English;
- Research from peer-reviewed journals or conferences, books and lecture notes;
- Articles focused on mobile AR applications for ASD people;
- Articles must be a full or short version (not an abstract).

Seven online databases linked to the scientific fields relevant to both technologies and ASD interventions were selected to search primary studies for this review. These databases include Web of Science, Scopus, ACM Digital Library, ScienceDirect, IEEE Xplore, SpringerLink, PubMed and Google Scholar. The search and selection process is described in Figure 1, with the following steps:

1. A separate search was carried out in the identified online databases, and search results were manually imported to EndNote for further screening;

2. Individually check and remove the incorrect references (such as abstracts or contents, etc.) from the EndNote;
3. To remove all the duplicates studies;
4. To check the research title, abstract, introduction and conclusion, and exclude documents that do not meet the inclusion criteria;
5. Add the research we missed from other review paper;
6. Perform a full-text review to delete non-mobile AR studies (such as device used computer or Kinect, etc.).

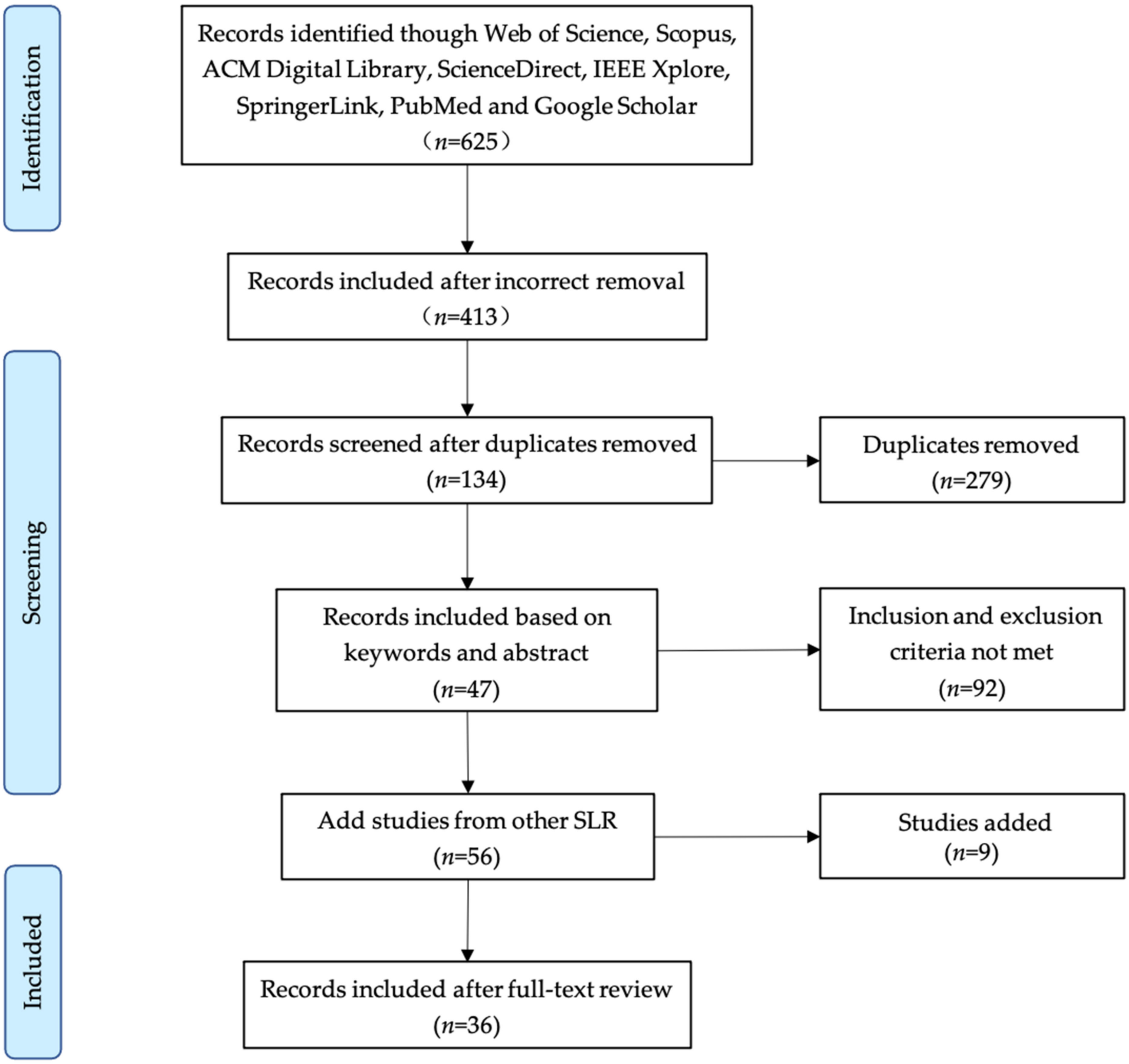

Figure 1. Literature search and selection process.

2.3. Quality Assessment

The importance of the selected articles was weighted for quality assessment, and the eight quality assessment questions were used together with their weight to evaluate the completeness and content relevance of the primary studies. CORE Conference Ranking 2020 [49] and Journal Citation Reports (JCR) 2019 [50] were used accordingly for conferences/workshops and the journal index papers. The criteria used, along with their weight, are presented in Table 2.

Table 2. Quality assessment criteria.

No.	Quality Assessment Question	Weight
QA1	Are the demographic information of the participants clearly stated?	Yes (+1), Partially (+0.5), No (+0)
QA2	Are the data collection methods adequately described?	Yes (+1), Partially (+0.5), No (+0)
QA3	Is the paper published in a recognized source?	Conferences: CORE A * or A (+1.5), CORE B (+1), CORE C (+0.5), not included in CORE ranking (+0). Journals: ranked Q1 (+2), ranked Q2 (+1.5), ranked Q3 or Q4 (+1), no JCR ranking (+0) Other sources: (+0)
QA4	What is the number of participants in the evaluation phase?	≥20(+3), 10–20 (+2), 6–9 (+1.5), 3–5 (+1), 1–2 (+0.5), 0 or not specified (+0)
QA5	Is AR-based solution clearly defined?	Yes (+1), Partially (+0.5), No (+0)
QA6	Are future works mentioned?	Yes (+1)/No (+0)

2.4. Data Extraction

The data extraction process aims to identify relevant information from the primary studies in depth and explain all research questions related to SLR. The process was stood by the RQs and Data extraction process defined in Table 1, and the review results are shown in Tables 3 and 4.

Table 3. This is the QA score and paper types and venues of the selected studies.

Ref.	Authors (Year)	Venues	Type	QAS
[51]	Keshav et al. (2017)	JMIR MHEALTH AND UHEALTH	Journal	8
[52]	Sahin et al. (2018)	Journal of Clinical Medicine	Journal	8
[53]	Antao et al. (2020)	Cyberpsychology Behavior and Social Networking	Journal	8
[26]	Escobedo et al. (2014)	IEEE Pervasive Computing	Journal	7.5
[54]	Singh et al. (2019)	ACM SIG International Conference on Computer Graphics and Interactive Techniques	Conf	7.5
[55]	Liu et al. (2017)	Frontiers in Pediatrics	Journal	6
[56]	Escobedo et al. (2012)	ACM Annual Conference on Human Factors in Computing Systems	Conf	5.5
[57]	Vahabzadeh et al. (2018)	JMIR MENTAL HEALTH	Journal	5.5
[58]	Lee et al. (2018)	Asia-Pacific Education Researcher	Journal	5.5
[59]	Cihak et al. (2016)	Journal of Special Education Technology	Journal	5
[60]	Lee (2019)	Interaction Studies	Journal	5
[61]	McMahon et al. (2015)	Journal of Research on Technology in Education	Journal	5
[62]	McMahon et al. (2015)	Journal of Research on Technology in Education	Journal	5
[63]	Vahabzadeh et al. (2018)	Behavioral Sciences	Journal	5
[64]	Sahin et al. (2018)	JMIR HUMAN FACTORS	Journal	5
[65]	Keshav et al. (2019)	Children	Journal	5
[66]	Dragomir et al. (2018)	ACM SIGACCESS Conference on Computers and Accessibility	Conf	5
[67]	Lee, et al. (2018)	State of the Art Virtual Reality and Augmented Reality Knowhow	Chapter	5

Table 3. *Cont.*

Ref.	Authors (Year)	Venues	Type	QAS
[68]	Lorenzo et al. (2018)	Education and Information Technologies	Journal	5
[69]	Sahin et al. (2018)	Frontiers in Education	Journal	4.5
[70]	Wang et al. (2019)	Eurasian Conference on Educational Innovation	Conf	4.5
[51]	Keshav et al. (2018)	JMIR HUMAN FACTORS	Journal	4
[71]	Nuraini et al. (2019)	International Journal of Engineering and Advanced Technology	Journal	3.5
[72]	Abou et al. (2019)	International journal of online and biomedical engineering	Journal	3.5
[73]	Taryadi et al. (2018)	Journal of Physics: Conference Series	Conf	3.5
[70]	Wang et al. (2019)	Eurasian Conference on Educational Innovation	Conf	3.5
[74]	Nubia et al. (2015)	Workshop on Engineering Applications—International Congress on Engineering	Conf	3.5
[75]	Quintana et al. (2012)	Iberoamerican Congress on Pattern Recognition	Conf	3
[76]	Vullamparthi et al. (2013)	IEEE Fifth International Conference on Technology for Education	Conf	3
[77]	Xu et al. (2015)	Asia-pacific Signal & Information Processing	Conf	2.5
[78]	Brandão et al. (2015)	International Conference on E-Learning in the Workplace	Conf	2
[79]	Chung & Chen (2016)	Advances in Intelligent Systems and Computing	Journal	2
[80]	Daniel et al. (2019)	International Conference on Digital Technology in Education	Conf	2
[81]	Juhlin et al. (2019)	International Conference on Human-Computer Interaction	Conf	1
[82]	Tang et al. (2019)	International Conference on Innovation in Artificial Intelligence	Conf	1
[83]	Pradibta et al. (2017)	International Seminar on Application for Technology of Information & Communication	Conf	1

Conf: Conference; QAS: Quality Assessment Scores; Ref.: References.

Table 4. Summary of selected studies (n = 36).

Authors (Year)	Target Skill	Participants	Intervention Setting	Research Design	Outcome Measurement	Outcomes
Brandão et al. (2015)	Facial Expressions and Emotion	-	D: Mobile device (tablet, smartphone or laptop)	-	-	An innovative AR Game Book has been developed
Escobedo et al. (2012)	Social skill practice	3 ASD child + 9 NT child 8–11 y.o	D: Smartphone P: School T:7 weeks	Multiple condition design	Behavioral observations: video transcript coding analysis Interviews	Increased social interaction and reduced social and behavioral errors
Escobedo et al. (2014)	Attention	12 ASD child 3–8 y.o, 7 Teachers	D: Smartphone P: School T: 8 weeks	Single subject with multiple condition design	Behavioral observations: video sequential analysis	Improved continuous attention and engagement
Cihak et al. (2015)	Brush teeth	3 (M) ASD child 6–7 y.o	D: iPod touch P: School T: Single session	Multiple probe across participants design	Performance: percentage of independent implementation steps Questionnaire on social effectiveness Follow-up surveys	Increased independent performance
McMahon et al. (2015)	Literacy	1 ASD + 3 ID adult 19–25 y.o.	D: iPad (3rd generation) P: Lab	Multiple probe across behaviors/skills design	Vocabulary tests Likert-type survey	Increased number of correct responses
McMahon et al. (2015)	Navigation	1 ASD adult 21 y.o + 3 ID adult	D: iPhone 4s P: Community	Adapted alternating treatment single- subject design (ATD)	Percentage of independent navigational checks Correct responses rate	More independent navigation decisions when using the AR navigation tool
Chung & Chen, (2017)	Social reciprocate	-	D:Laptop	-	-	A prototype for the social skill "greeting"
Keshav et al. (2017)	Social Communication	21 ASD child + adult 11.9 y.o 4.4–21.5	D: Google Smartglasses P:Lab	Single-case experimental design	Observations: caregiver report Likert scale	Well tolerated and usable of the provided BPAS system
Sahin et al. (2017)	Social Communication	18 ASD child + adult 12.2 y.o 4.4–21.5	D: Google Smartglasses P: Lab	Single-case experimental design	Structured interviews	No significant negative effects
Sahin et al. (2018)	Social Communication	1 (M) ASD adult (fully-verbal) 13.92 y.o	D: Google Smartglasses P: School T: 3 weeks	Case study incorporating elements of a single-case Design	Social Responsiveness Scale 2 (SRS-2)	No result in adverse behaviors
Vahabzadeh et al. (2018)	Behavior	8 ASD child + adult 15 y.o 11.7–20.5	D: Google Smartglasses P: Lab T: 2 days	Single-case experimental design	Aberrant Behavioral Checklist (ABC-H) scores	Decreased ABC-H score
Vahabzadeh et al. (2018)	Social Emotional; Behavior	4 (M) ASD 7.5 y.o 6.7–8.8, 3 Educators	D: Google Smartglasses P: School T: 6 weeks	Single-case experimental design	Aberrant Behavioral Checklist (ABC-I; ABC-H; ABC-L/SW) Likert scale	Reduced irritability, hyperactivity, and social withdrawal

Table 4. *Cont.*

Authors (Year)	Target Skill	Participants	Intervention Setting	Research Design	Outcome Measurement	Outcomes
Sahin et al. (2018)	Social Communication	8 (7M; 1F) ASD 11.7 y.o 6.7–17.2, Caregivers	D: Google Smartglasses P: Lab	Single-case experimental design	Semi-structured interview	The children successfully used smartglass and did not feel the pressure
Keshav et al. (2018)	Attention	1 (M) ASD 13 y.o	D: Google Smartglasses P: School T: 2 weeks	Single-case experimental design	Digital logs and In-person interviews	Practical and feasible of the system, improved social interaction
Keshav et al. (2019)	Social Communication	7 (6M; 1F) ASD 15.6 y.o 14–18	D: Google Smartglasses P: School T: 1 weeks	Single-case experimental design	Aberrant Behavior Checklist (ABC-H) the combined ADHD subscale of the TRF	Game performance is related to the severity of ADHD symptoms
Liu et al. (2017)	Behavior treatment/usability	2 ASD (M) child 8–9 y.o	D: Google Smartglasses P: School T: 1 session	Single-case experimental design	Aberrant Behavior Checklist (ABC) Post-intervention interview	improved nonverbal communication, eye contact, and social engagement
Abou et al. (2019)	Social Communication; Behavior	3 ASD	D: Mobile device (tablet, smartphone or laptop)	Single-case experimental design post-test	Questionnaire Likert scale	A framework was developed
Daniel et al. (2019)	Emotion Recognition; Attention	-	D: Tablet	-	-	Developed an AR app
Dragomir et al. (2018)	Pretend play	7 (6M; 1F) ASD 8–14 y.o	D: Tablet P: School T: 5 weeks	Single-case experimental design pre-post test	Video analysis Feedback	Significant increased mean frequency of pretend play acts
Juhlin et al. (2019)	Language skill; Navigation		D: Mobile device		-	Three high level concepts were developed
Lee et al. (2018)	Social reciprocate	3 (2M; 1F) ASD 8.8 y.o 8–9	D: Tablet P: School	Single-subject research with a multiple-baselines across-subject design	SST test, Correct rate, Likert scale Questionnaires and interviews Parental reports	Increased target responses of the SST test
Lee et al. (2018)	Social reciprocate	3 (2M; 1F) ASD 7.73 y.o 7–9	D: Laptop P: School T: 6 weeks	Single subject in a multiple baseline across subject design pre-post-test	Social Story trial (SSTs) tests 5-point Likert scale Social behavior experts' score Parents questionnaires and interview feedback reports	Decreased error rate. Increased overall role-playing score

Table 4. *Cont.*

Authors (Year)	Target Skill	Participants	Intervention Setting	Research Design	Outcome Measurement	Outcomes
Lorenzo et al. (2018)	Social communication	11 (10M; 1F) ASD 3.99 y.o 2–6	D: Smartphones P: Community	Pre-Post test design with control group AR vs. non-AR	Autistic Spectrum Inventory Whitney U test Wilcoxon Signed-Rank Test Mann-Whitney U test	No statistically significant differences found, improved attention and motivation
Singh et al. (2019)	Learning; Usability	12 (6M; 6F) ASD 10.3 y.o 9–12	D: Laptop P: School T: 1 session	Single-case experimental design	Observations Subjective questionnaire	Longest time in understanding instructions when using the AR mode, while the in-person mode was the fastest.
Tang et al. (2019)	Literacy	TD child + adult	D: Smartphone P: University campus	-	Observations	Attracted attention of children
Taryadi & Kurniawan, (2018)	Social communication	12 ASD	D: Smartphone P: Lab T: 15 sessions	Single subject experimental design	Behavioral observations, interview	significant improvement in the autistic children's communication ability
Anta et al. (2020)	Motor skill	48 ASD child + 48 TD child	D: Laptop P: Institute	Control experiment ASD vs. TD	Mann–Whitney U test, Wilcoxon signed-rank test	improved in reaction times, Improved ability to identify numbers
Wang et al. (2019)	Social communication	3 (2M; 1F) ASD	D: Laptop/smartphone P: School	Multiple case studies and withdrawal designs	Observations	improved correct judgment rate and situational understanding rate
Quintana et al. (2012)	Learning	-	D: Tablet/smartphone	-	-	An AR system-MOBIS has been developed
Nubia et al. (2015)	Social communication	6 (5M; 1F) ASD 3–9 y.o	D: Smartphone P: Clinic T: 1 session	Control experiment AR vs. non-AR	Questionnaire Observations	increase in the attention process and appearance of verbal language.
Pradibta et al. (2017)	Daily Prayers	-	D: Smartphone	-	-	Augmented Reality Flash Cards (ARDOA) app has been developed
Vullamparthi et al. (2013)	Learning	Parents	D: Smartphone P: School	-	Interview	An AR system has been developed and has appreciated by parents
Xu et al. (2015)	Job interview	Researcher	D: Google Glass Smartglasses P: Lab	-	Observations	demonstrated an acceptable level of performance

Table 4. *Cont.*

Authors (Year)	Target Skill	Participants	Intervention Setting	Research Design	Outcome Measurement	Outcomes
Lee et al. (2019)	Social cues	3 ASD	D: Tablet P: School	Multiple-baselines across-subject design	Questionnaire Observations	increased answer correct rate and higher rate in the maintenance phase
Wong et al. (2019)	Learning	4 ASD + 1 SpeEdu teacher	D: Tablet/smartphone P: School	Pre-post experimental research design	Performance (success) Observation	higher achievement scores than BLS (Static graphic)
Nuraini et al. (2019)	Bakery	10 (9M; 1F) ASD	D: Smartphone P: School	Single subject experimental design	Questionnaire	excellent responses

NT: Neurotypical children; TD: Typically Developing; y.o: Years old; M: Male; F: Female; D: Devices used; P: Intervention conducted place; T: Intervention time.

3. Results

Among the 625 articles extracted from online database search results, we identified 491 incorrect and duplicates references. The 134 remaining papers were then checked for inclusion on the basis of the abstract and keywords, and there were 47 potential papers for inclusion. A further 20 references were eliminated after a full-text review, and 36 articles were included in the end. According to the results of the quality assessment, three papers got the maximum score of 8, three scored 7.5, and one paper scored 6 (see Table 3). Most of the reviewed papers (65%) are above half of the total score. This fact confirms that the reviewed papers are appropriate for the research conducted.

3.1. RQ1: What Channels Are Used to Publish Research Articles in ASD Interventions Exploiting AR Technology?

According to the review results, studies are published in different channels. Figure 2 shows the number and type of papers per year. The reviewed articles were published from 2011 onwards, with 61.1% (n = 22) of them being published after 2018. More than one-half (58.3%) were reported in journals, while 38.8% is published in conference proceedings, only 2.7% is published in books. Almost half (47.2%) of the sources are recorded in technology-related journals or conference proceedings. The remaining papers were published in educational, medical conferences and journals. Journal of Research on Technology in Education appeared two times [59,60], while the rest of the articles are distributed in 19 journals, 14 conferences and 1 book. 37.5% (n = 9) of publications presented in the JCR ranking, and 21.4% (n = 3) of conferences listed in CORE rankings. As for the active researchers, it was found that the author Keshav and Sahin both have three studies as the first author and McMahon, Chung, Lee, Vahabzadeh and Escobedo have two studies as the first author each.

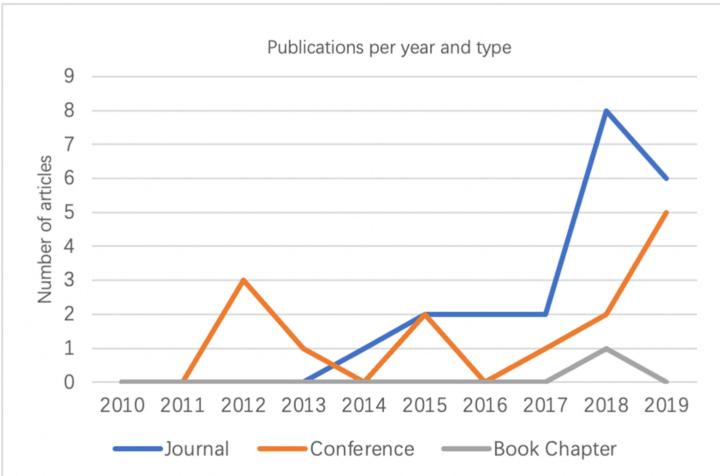

Figure 2. Publications per year and type.

3.2. RQ2: What Mobile Device Was Used?

Researchers have used different devices in the intervention, and the technologies and devices used in each project include mobile smartphones, laptops, iPads, smart glasses and iPod touch was listed in Table 4. More than one-half (55.6%) of research intervention projects use mobile smartphones (n = 10) and smart glasses (n = 10). The proportion of iPad and tablet used is 19.4% (n = 7) and 13.9% (n = 5) each. It was reported that they could use any mobile device (tablet, smartphone or laptop) in three studies, and iPod appeared one time.

3.3. RQ3: What Are the Targeted Population?

Figure 3 presents their distribution. As we can see, less than 5 people participated in most of the studies (55.6%, n = 20), while 13.9% had 6–9 subjects and 25% (n = 9) recruited 10–20 participants. The number of participants in the research conducted by Keshav et al. [51] and Antao et al. [53] is more than 20. Furthermore, the brief overview of the basic demographic characteristics of participants of each study was demonstrated in Table 4. In total, 36.1% of the studies (n = 13) did not report the demographic information of participants in detail or even not recruit participants in the least, while four papers briefly present the number of participants. For instance, Lee et al. [58] used intelligence quotient (IQ) scores to test participants to determine whether they are suitable for participating in project research. The last studies (n = 19) described participants' inclusion criteria and demographic characteristics in detail. In 14 studies included a total of 77 participants stated the proportion of male and female participants, male accounted for 81%. Only one study reported parental involvement.

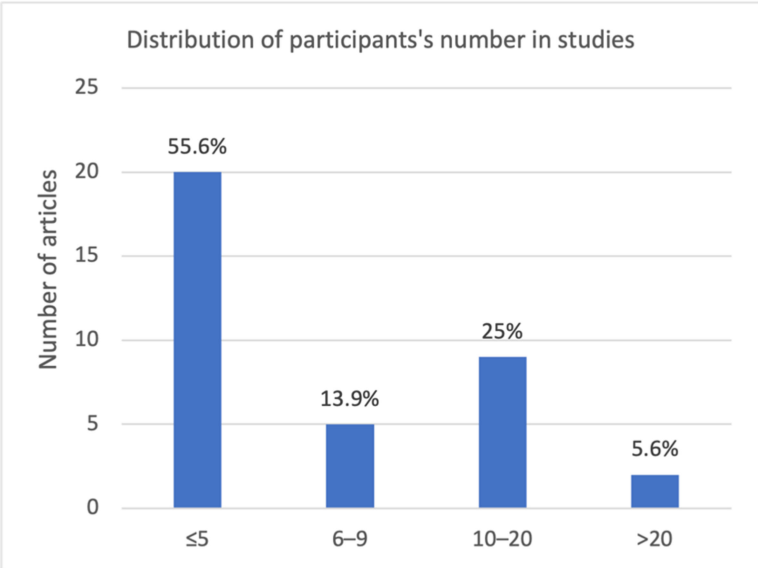

Figure 3. Distribution of participants' number in studies.

3.4. RQ4: For What Purposes Have Been Applied the Proposed Technology Solution?

Figure 4 shows the classification of the target skills in the primary studies, and 16 main categories were identified, including social communication, behavior, learning, social reciprocity, facial expressions and emotion, attention, navigation, literacy, language skill, social skills practice, pretend play, motor skill, job interview, daily prayers, brush teeth and bakery. The majority of research conducted was related to improving social communication skills (31%), followed by behavior (11.1%) and learning (11.1%), while the remaining skills are used in two or one study each. There are four studies in which authors have used two or more skills [63,72,80,81]. The studies related to social communication and behavior were briefly described below.

A series of research has been conducted on the smart glasses systems Brain Power Autism System (Empowered Brain system), which uses AR and emotional artificial intelligence to assist the social communication of autistic children and adults. Keshav et al. [51] evaluated the tolerance and usability of the Empowered Brain system with ASD. Sahin et al. [52] investigated the safety and negative effect of EBS along with its effectiveness and usability in a classroom environment.

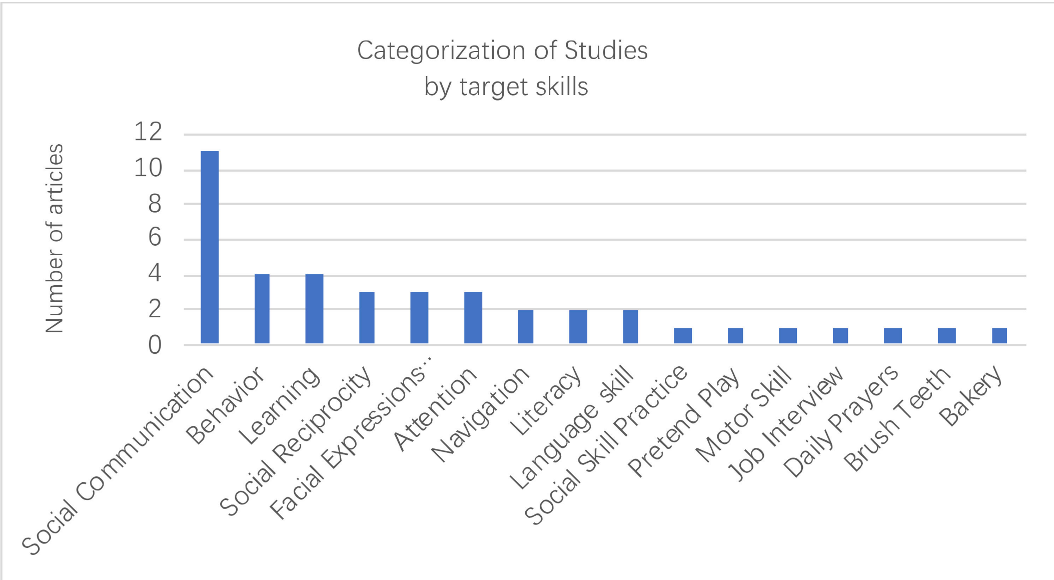

Figure 4. Publications per year and type.

Lorenzo et al. [68] have conducted a study to assess the effectiveness of AR training programs named Quicker Vision app to improve social skills with autism. Taryadi et al. [73] have combined the use of AR with the PECS method (Picture Exchange Communication System) in training the communication ability of children with autism. The prototype developed by the authors called Multimedia AR app uses images, video and sounds that allow an individual to work with PECS by just scanning a QR code instead of selecting an image in traditional PECS. Lee [60] presented a report about an augmented reality coloring book (ARCB) to teach ASD children how to recognize and understand some specific social signals. This is the only study that has been found about augmented reality coloring books. ARCB can keep the participants' attention and maintain the positive intervention results to the maintenance stage. Nubia et al. [74] have reported the use of an AR app to improve the communication field in children with autism. The goal is to investigate whether AR intervention will increase the attention process and speech expression.

Wang et al. [70] have conducted a study to enhance the effectiveness of autistic children's request for help and expression functions. The authors developed the Auto Organizational Menu (AOM), which combined augmented reality (AR) with video of key parts with action (KPV) and evaluated it through the observation method. Abou et al. [72] developed a framework to support children with ASD and ID study in an enhanced education environment to improve social communication and behavior, while the users of the designed system are parents and teachers, which may reduce the engagement of autistic children. Regarding the skill of behavior, Vahabzadeh et al. [57] have investigated the changes in ADHD-related symptoms in children, adolescents, and young adults with ASD immediately after the use of the Empowered Brain system. The authors used the ABC-H scale to test the participants and grouped them according to their scores. Likewise, Vahabzadeh et al. [63] presented the behavioral and social-emotional effects of using the Empowered Brain on students with ASD to assess the feasibility and efficacy. They conducted a study to investigate if EBS reduces the irritability and hyperactivity of the users. Liu et al. [55] performed one session intervention in school and reported a lower ABC score in the post-test, which improved nonverbal communication, eye contact and social participation.

3.5. RQ5: What Research Designs Are Used in the Studies?

According to the data extraction results (see Table 4), a quarter (25%) of the published articles are no-experimental design, which is characterized by no random assignment design, no control group and no multiple measures. Two-thirds of the research was conducted with a single-case experimental design, and 8.3% (n = 3) reported a quasi-experimental design with a control group. Lorenzo et al. [68] conducted a pre-posttest control group design, which grouped 11 individuals (10 male and 1 female) into control (n = 5) and experimental group (n = 6). It is not a random assignment experiment, for they used a non-probabilistic intentional sampling method. Nubia et al. [74] and Antao et al. [53] presented a posttest control group design, which compared the evaluation of different groups of participants at the end of the evaluation.

In addition to the simplest pretest-posttest single-case experimental design, there also includes a multiple baseline single-case design that increases the internal validity by testing multiple baselines, alternating treatment single-subject design and withdrawing single-case designs.

3.6. RQ6: What Methods Are Used to Evaluate the Outcomes?

The outcome measurement method is used to record the results or outcomes in the mobile AR intervention. According to William M.K. Trochim, there are four main types of measurement: survey research, scaling, qualitative research and unobtrusive measures [84]. Among the primary studies, four main outcome measurement methods have been used, and these methods include an interview, questionnaire, observation and scaling. In total, 36.1% of the papers utilized a combination of different methods for measurement, while 16.7% of the studies did not report it, and the others used a single measurement method. More specifically, 17 studies used survey research (8 for questionnaires and 9 for interviews) along or with other measurement methods, 11 studies applied qualitative observation research, and 14 applied scaling. Survey research includes the design and implementation of interviews and questionnaires, and scaling involves consideration of the main methods of formulating and implementing scales. Qualitative research outlines a wide range of non-numeric measurement methods.

3.7. RQ7: What Are the Outcomes Obtained by the Application of the Proposed Solutions?

Table 4 depicts the major outcomes of the primary studies. In total, 22.2% of them reported results of the development of an app, prototype framework and concept, while did not conduct user studies [72,76,78–80,83]. The majority of research (42%, n = 15) shown an improvement of participant's ability and performance. In the study conducted in [51,56,73], the qualitative analysis shows that participants enhanced their social interaction and communication skills. Of the studies, 16.7% found that they have improved continuous attention and engagement [26,54,55,70,73,74,82]. In the studies conducted by Cihak et al. [59] and McMahon et al. [62], the authors found that all participants were more independent after the AR training. The statistical analysis in [57] shows a reduction in irritability of ASD children. The results of [68] revealed no statistically significant differences between control and experimental groups with or without using AR-based intervention; however, the qualitative feedback provided by the researchers revealed an improvement in the focus of attention and motivation among children through AR, which can provide fruitful results in the development of skills for children with ASD. The quantitative analysis using tests in [58,60,62,70] shows that the test score of all the participants was improved, while Vahabzadeh et al. [57] revealed that the outcome is the decreased ABC-H score. Furthermore, in the study conducted in [52,69,71,85], the authors found that the usability of the applied mobile AR application. Keshav et al. [65] explored the relationship between student performance and validated clinical measures and then demonstrated game performance is related to the severity of ADHD symptoms.

3.8. RQ8: Which Settings Are Used in the Primary Studies?

From the primary studies, there are three types of environment for primary research, including school environment, community environment and laboratory environment. The majority of research was conducted in a school environment (50%, n = 18), followed by the lab (22.2%). In the study conducted in [62,68], the setting used was community environment, and Nubia et al. [74] conducted their research in a clinic, while seven studies did not mention the setting environment.

3.9. RQ9: How Sustainable the Outcome of the Intervention Is?

The durability effects of MAR have rarely been investigated, and only six studies assessing near/far effects. In [58,60,67], participants performed the same tasks as in the baseline phase procedure 6 weeks after the intervention, and the results were similar in immediate and delayed post-tests, indicating that the enhanced correct rate was maintained after the intervention. Cihak et al. [59] conducted the maintenance phase 9 weeks after the intervention, and Escobedo et al. [26,56] began the maintenance phase after 1 week. Taryadi and Kurniawan [73] mentioned the maintenance phase but did not describe much.

3.10. RQ10: How Generalized the Intervention Result Is?

From the primary studies, only one study by Lee et al. [58] conducted generalization probes at various instances (baseline, intervention and maintenance) of their research, but they did not present the generalization results.

4. Discussion

Authors should discuss the results and how they can be interpreted from the perspective of previous studies and of the working hypotheses. The findings and their implications should be discussed in the broadest context possible. Future research directions may also be highlighted.

The diversity of the publication sources could be explained due to the high adaptability of the emerging mobile augmented reality technology, which allows them to be applied in different fields. The research team includes Keshav, Sahin, Vahabzadeh and Liu, and it is more active than the others, which have published a quarter of the primary studies (n = 9) on using the Empowered Brain on students with ASD. As for the researchers, McMahon and Cihak are also slightly more active than others, followed by Lee (n = 3) and Escobedo (n = 2). Initially, researchers mainly published their results through conferences, while after the year 2013, journals are preferred by researchers as being the most "prestigious" and impactful source to publish their studies. Increasingly advanced mobile devices provide fertile soil for applying mobile AR solutions to solve real-life problems of the ASD population. In view of the results, research related to the use of mobile AR technology for developing interventions in autism is expected to undergo an important increase in the coming years.

As far as the population is concerned, MAR studies were widely conducted with children rather than adolescents. This agrees with Marto et al. [41], who conducted the research on applying AR for autist patients with 16 studies. Their parents tend to provide intensive treatment for them at younger ages, which may be related to the golden period of the intervention; however, it has no evidence. Participants also have large deviations between male and female, almost for 4:1, that may be caused by the different prevalence rates of male and female with autism and the difficulty of recruiting participants. It is a common problem of the small sample size, which possibly due to the difficulty of recruiting participants. Further studies should address teen years for covering their needs, recruit more participants of different ages and reduce participants' gender bias. Furthermore, the limited participation of parents in the examined studies could also be related to privacy and security issues.

As for the selection of devices in intervention, the cost of technology is one of the essential factors to consider [86]. Handheld devices, such as smartphones (11 studies) and tablets, have become an obvious choice for use because they are getting cheaper and cheaper and widely available. The use of smart glasses (9 studies covering the Empowered Brain system) has also increased these years due to their size, portability and flexibility.

Regarding the target skill, most parts of these studies (n = 11) presented social communication as the variable to improve with the AR technology, which may be because social disorders are one of the most significant characteristics that affect the lives of people with autism. The last target skills are related to defect repair and skills learning as well, which is different from the educational assistance of typically developed students. In the future, we can design products that meet their need to improve the user's satisfaction.

With regard to the research design, these studies are devoted to examining whether the intervention method or project causes some outcomes or results. Research design can combine research projects (participants, measurements, interventions, etc.) and can be used to organize research to show how the research projects solve the research problem together. Among the primary studies, two research design methods have been used, including the quasi-experimental design and non-experimental design, and the quasi-experimental design divided into single case design and quasi-experimental design with a control group. The single-case design, also known as single-subject design, refers to a research design that can only use one subject in the research process. Although there is only one subject, it can also clearly determine whether there is a causal relationship between variables. However, all the studies did not use the randomized experiment design. This is because individual differences are normally large along the autism disorder spectrum and have different performances in each; therefore, treatment usually focuses only on a single individual's development rather than a group. Multiple baselines across subject design are regarded as a standard and evidence-based method in many computer-based treatments used in special education. It is a fundamental experimental method for research in the field, and, in actual practice, it does not require control groups or many participants. Based on this, maybe it is better to design a multiple baseline across subject design than a posttest or pretest-posttest single-case design. In the study conducted by Lorenzo et al. [68], the author used different evaluators before and after the test, and the sample size is too small. The number of participants and the factors that may affect reliability during the research process should be considered. In addition, studies without research design are also a major issue for the research effectiveness in this area.

Measurement methods are also the main concerns in research projects. In the methods used in these studies, both survey research and qualitative research require human participation, and it will increase the error rate and reduce the effectiveness and reliability of the measurement if observers are not adequately trained. Comprehensive training of observers before the intervention, calculating the data multiple times, or using a computer-assisted data collection method can reduce the inadvertent introduction of personnel errors. Furthermore, eye tracking is a technique used to measure a person's eye movements when interacting with a stimulus [87]. Greene et al. [88] examined the utility of eye-tracking as an outcome measure and stated that it has the potential to function as a valid treatment outcome measure for use with individuals with ASD of varying ages and levels of impairment. Eraslan et al. [89] assessed the ability to search for web information in individuals with high-functioning autism. Rezae et al. [90] assessed visual preferences for mobile device interfaces in individuals with autism. Yaneva et al. [91] applied eye-movement tracking to the diagnosis of high-functioning autism in adults using web stimuli. However, there is still a gap that directly uses eye-tracking technology to measure the AR intervention outcomes. Based on the current findings, future studies could investigate eye-tracking technology as a measure in pre-and post-intervention to track responses to intervention in individuals with ASD.

The outcomes reveal that the application of mobile AR in the field of autism intervention is successful to a certain extent. All the studies report a positive result related to target skills. From the perspective of target skills, the achievements are all related to the education of defect repair and improvement of basic life skills of the autistic population. It is to be noted that the research on defect repairment and is much larger than the research on education. This is consistent with the core goal of autistic population interventions, which is to reduce core symptoms or related defects, achieve self-care in life, improve quality of life and reduce family stress, rather than pursuing academic success [92]. From the perspective of outcome measurement methods, studies using survey and qualitative research measurement methods both report better various performances and the improvement of participants' capabilities, and studies using scaling give the scores improvement of participants. The studies without user research only mention the usability of related apps.

Regarding the research setting, most of the research is conducted in a school and laboratory, and two studies are in the community environment, while some studies do not mention the setting. To a certain extent, the social skills of autistic children and adolescents may be improved with training in a laboratory setting, but their core issue (social) still needs to be practiced in a real social environment. The ultimate goal of the intervention is to integrate them into society and family, while there is no family environment mentioned. It should be emphasized that school and institutional research settings are very important because there has peer participation. However, special education teachers can only accompany autistic children for a few years, and they will eventually return to their families and enter society. Future research can involve more family interventions, enable parents to participate more and guide their children to live an active life. More family environments can involve and enable parents to participate more and be their mentors.

The analysis results of the MAR durability effects showed that most of the studies conducted their research without the far effects of AR, which may be due to the limitation of research time. Part of the articles studied the durability effects of MAR in a short period (up to 9 weeks), while other articles focusing on long-term effect research have reported half a year to one year. It is almost a blank area. Research on generalization and maintenance is still in the infant stage. The long-term effect and generalization of mobile augmented reality can push the evidence-based practical research on mobile augmented reality further. The application of learned skills to other environments, such as expressing greetings learned in the lab to strangers in society which is also a major issue for persons with ASD.

However, like every other review, this paper has some limitations such as the keywords, inclusion and exclusion criteria we chose contain subjective elements, which might affect the number of selected primary studies. Furthermore, regarding the studies we reviewed, we can summarize the major problems and limitations faced by the studies.

- Small sample;
- Research design issues;
- Not generalizable results;
- Short intervention time;
- Participants are not differentiated by age;
- No use of control groups;
- Difficult in recruiting participants;
- Lack of gender parity of the sample;
- App design issues;
- Internet connection issues.

Many of the existing mobile AR applications for people with ASD are not considered very practical due to insufficient functionality. Designers must focus on users and design products that have high interactivity, quality and meet user needs to improve user satisfaction and make mobile AR become widely accepted. As for the issue of internet connection, which is a considerable indicator in most mobile AR-related user experience studies, the solutions can be focused on the selection of mobile devices and intervention locations. Furthermore, the studies on internet stability and speed, especially in a rural area, are still in the infant stage, and more effort should be put into this particular area.

The main issue related to the evaluation of mobile AR in people with ASD may point to the research design method, sample and the intervention period. Currently, there is no research report on randomized experiments in this field; thus, the effectiveness of randomized experiments research design still needs to be investigated. The most mentioned in the studies are the small sample size and short intervention time. The determination of the participants' number is related to the research design method, region, and many other factors. Recruiting more participants, establishing inclusion criteria and conducting strict screening can improve the accuracy of the research. The distribution of participants between females and males reveals an extremely limited gender bias, and more female autistic participants can be recruited to solve this issue.

Intervention time also had been added as one of the future directions while solutions can be focused on extending the research period. The long-term impact research is helpful to verify the stability of mobile AR in the intervention with autism and is more conducive to the promotion of this technology.

Technology assessment is very challenging and time-consuming but a necessary task in any research effort. Focusing on mobile AR applications, the evaluation is even more challenging since there is no gold standard. Researchers can use the combination of quantitative and qualitative measurement methods to further optimize technology usability and user studies to improve the stability and effectiveness of research. On another hand, due to the study on generalization, there is one more issue to be focused on that can help the research of evidence-based practices; researchers can improve their design by taking account of durability and generalization of mobile AR effects. The most notable feature of mobile AR is that it is portable. For related research, it should be verified in a wider variety of participants and diverse environments instead of only in the experimental setting.

Although mobile AR technologies have not been a novel issue, they still keep a broader development space for autism treating. The use of mobile AR applications in an educational environment is a relatively recent development, and there is a need for further studies designing scientific intervention process in combination with the existing effective evidence-based teaching methods to maximize the impact of technology.

5. Conclusions

Early findings indicate that mobile augmented reality has a positive effect on ASD and has great potential to help teachers and parents intervene more effectively early on. Despite the promising results reported by almost all well-conducted studies, we must be mindful of the existing issues. As an emerging interdisciplinary area of research, future studies should follow systematic experimental research methods and rigorous evaluation processes if possible. For instance, physiological assessment methods, such as eye-tracking, can be used to improve the validity of the measurements. In addition, gender bias needs to be minimized for the selection of participants. We should also be aware that when it comes to intervention studies that focus on the development of a single individual, the larger the number of participants is not better. Furthermore, it is important to design MAR systems with a user-centered approach, involving more family members and de-signing products that meet their needs in order to improve the learning outcomes obtained during the intervention and to increase user satisfaction. Finally, research on the long-term effects and diffusion of MAR should be conducted to further promote evidence-based practice research on mobile augmented reality.

Overall, this systematic review presents the use of mobile AR technology in autism spectrum disorder interventions and answers 10 research questions to provide MAR-based solutions for skill learning for individuals with ASD and gives directions for research in this area to make MAR better for individuals with autism. It is hoped that this review could provide useful insight and guidance for researchers, educators and those who are concerned with ASD.

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