Int. J. Human–Computer Studies 178 (2023) 103085

Contents lists available at ScienceDirect

International Journal of Human - Computer Studies

journal homepage: www.elsevier.com/locate/ijhcs

Evaluating user interface of a mobile augmented reality coloring application for children with autism: An eye-tracking investigation

Xiaojie Lian [a,b], Mohd Shahrizal Sunar [a,b,*], Qingqing Lian [c], Mohd Khalid Mokhtar [a,b]

[a] Department of Emergent Computing, Faculty of Computing, Universiti Teknologi Malaysia, 81310, Skudai Johor, Malaysia
[b] Media and Game Innovation Centre of Excellence, Institute of Human Centered Engineering, Universiti Teknologi Malaysia, 81310, Skudai Johor, Malaysia
[c] Handan Special Education Center, Handan, 056000, Hebei, China

ARTICLE INFO

Keywords:
Accessible user interface
Mobile augmented reality app
Eye tracking
Autism children
Coloring augmented reality

ABSTRACT

Mobile augmented reality (AR) solutions are increasingly being used to facilitate learning and skills training for children with autism spectrum disorder (ASD). Derived from the fact that mobile AR systems can be embedded with multimedia effects, such as 3D animations, sounds or personalized images, with potential benefits for learning and engagement. Many mobile AR-based applications have been developed over the past decade; however, little is known about how children with autism interact with mobile AR application interface elements, which limits the accessible user interface (UI) design of such applications. In this study, we conducted an eye-tracking experiment to examine how children with autism interact differently with the UI of mobile AR coloring apps compared to typically developing (TD) children. Both quantitative and qualitative data suggest that 1) icons and images were more attractive to ASD children and could facilitate their understanding of the task more effectively; 2) a richer interface makes participants with autism focus more on irrelevant elements; and 3) the size and position of icons affected their speed of information processing. We recommend that UI be designed to suit the characteristics of children with autism. For example, visual stimuli such as icons or images should be meaningful; screen elements need to be simple and clear; background distractions should be avoided; and text also needs to be brief and precise. This study is expected to inspire researchers to provide AR apps with accessible UIs in the future and improve the user experience (UX) of children with autism.

1. Introduction

Autism Spectrum Disorder (ASD) can be defined as a lifelong developmental disability that affects how people perceive the world and interact with others, with problems or peculiarities in domains of social interaction, communication, and attention (Hobson, 2019). People with autism have atypical social functioning, tending to have a reduced range of activities and interests (Frazier et al., 2012). In addition, ASD tends to respond differently to sensory stimulation (American Psychiatric Association, 2013; Robertson and Baron-Cohen, 2017; Robertson and Simmons, 2013). Such characteristics may lead to peculiar modalities of visual preference and make it challenging for people with autism to interact with the user interface (UI) of technological products.

While symptoms cannot be cured, they will improve with early intervention and support (Dawson et al., 2012; Eldevik et al., 2009). Over the past decade, Human-Computer Interaction (HCI) and overall computing communities have shown an increased interest in designing, developing, and evaluating technologies targeted at autistic children (Williams and Gilbert, 2020; Alessandrini et al., 2014; Chien et al., 2015; Mazon et al., 2019; Spiel et al., 2020). Technology-based interventions (TBI) have been widely utilized to support the development of various skills for individuals experiencing autism, including social robots (Pennisi et al., 2016), computer-based interventions (Khowaja and Salim, 2013; Ramdoss et al., 2011; Lopezherrejon et al., 2020), VR/AR (Dalim et al., 2016; Lorenzo et al., 2019; Khowaja et al., 2020; Williams et al., 2022; Yusof et al., 2016), serious games (Noor et al., 2012) and so on. Of these, as a novel technology in HCI communities, augmented reality (AR) technology can combine real scene information with virtual information to provide rich visual information and diverse interactive experiences (Brandão et al., 2015; Chen et al., 2015; Ismail et al., 2015; Lee, 2020). It coincides with the avid processing of visual information and the use of digital devices by children with autism and is increasingly being used to facilitate their learning and foster skills (Escobedo et al., 2014; Quill, 1997). Evidence suggests that AR can promote sustained

* Corresponding author at: School of Computing, Faculty of Engineering, Universiti Teknologi Malaysia, Skudai, 81310, Johor Malaysia.
E-mail address: shahrizal@utm.my (M.S. Sunar).

https://doi.org/10.1016/j.ijhcs.2023.103085
Received 30 April 2022; Received in revised form 1 June 2023; Accepted 3 June 2023
Available online 4 June 2023

attention and learning interest in children with autism to some extent (Escobedo et al., 2014; Lian and Sunar, 2021; Lorenzo et al., 2019; Vahabzadeh et al., 2018).

Despite the positive findings, however, questions about the design and deployment remain (Williams et al., 2019). Collecting self-reported data directly from children with autism has often been avoided by researchers due to the absence of shared modes of communication. Most of these studies follow an indirect perspective of assessment, such as performance (as defined by therapists, parents, and researchers), task success or classical usability, or interpretation of the child's experience through observation, without providing the opportunity to create more appropriate and acceptable technology (Spiel et al., 2020). More specifically, ASD children are rarely included in the interface design evaluation of those AR solutions.

The UI is the communication window between the user and the mobile software application (Stone et al., 2014). Accessible UIs are available when all people can perceive and understand each UI element (e.g., buttons, text, navigation) and operate the software in an easy way (Kamaruzaman et al., 2016). According to Mankoff et al. (2010), well designed interfaces benefit from early and frequent creative evaluation. Eraslan et al. (2019) performed an eye-tracking study with high-functioning autistic adult and neurotypical participants to examine whether people with autism have different processing strategies with web pages. The findings revealed that people with autism tend to look at more elements on a web page than neurotypical participants and proposed improvements to the existing web accessibility guidelines. It is unusual to assume that recommendations for the web are entirely applicable to mobile solutions (Aguiar et al., 2022). Rezae et al. (2020) evaluated the UI of a mobile navigation software for adults with autism through eye movement analyses, showed that autistic users interact differently with UIs than non-autistic users and made recommendations to improve UI design. According to Pavlov (2014), a complex and difficult to use interface can confuse users and lead them to abandon the software despite its many benefits.

It is thought that children with autism also have different processing strategies when accessing mobile applications but limited empirical evidence to support this. In this study, we aimed to investigate differences in the way ASD children and typically developing (TD) children search for information in the UI of mobile AR applications and to improve the accessible interface design. To achieve our aim, we conducted an eye-tracking study on 23 children with ASD and 26 children with TD and performed an in-depth statistical analysis. We carried out a statistical analysis of the eye movements of these two groups on the user interface of a mobile AR coloring application, focusing on the differences in eye gazed fixation data, task success rate, and user ratings on the questionnaire for user interaction satisfaction (QUIS).

The subsequent parts of the article begin with a review of related work in Section 2. We explain the eye-tracking study methodology in Section 3 and present statistical analyses in Section 4. The discussion of the results and the implications of these results for improving the accessibility interface of mobile augmented reality coloring apps for children with autism is then in Section 5. Section 6 presents the study limitations and future work, and Section 7 concludes this study.

2. Related research

People with ASD perceive the world differently from others, meaning their attention patterns and responses to sensory stimuli differs (Robertson and Baron-Cohen, 2017; Robertson and Simmons, 2013; Frith, 2003). Some environmental features that TD individuals can process quickly and that many individuals with autism may feel overwhelmed by (Robertson and Baron-Cohen, 2017). These features may manifest as challenges when individuals with autism use technology. At the same time, people with autism are interested in using technology (Putnam and Chong, 2008), particularly augmented reality which can lead to rich visual stimulation. While there is much research discussing the difficulties that people with autism may have when interacting with technology (Yaneva et al., 2019), little is known about how children with autism interact with the interface of mobile augmented reality applications, particularly how they deal with the visual elements of the interface, such as icons, text, and labels. In the following sections, we first discuss existing research on AR-based interventions for children with autism, then discuss accessibility guidelines for autism and explain how eye tracking can be used to understand the difficulties experienced by people with autism.

2.1. AR intervention for children with autism

Traditional early intervention approaches are simple and repetitive, using materials with little visual content (Axe and Evans, 2012). It tends to bore children, fails to maintain their attention, and does not directly stimulate their interest in learning (Mcconnell, 2002). Augmented reality technology can provide rich visual information and novel multi-modal interactive experiences that have been proven by researchers to improve social, behavioral, learning and attention skills in children with autism (Tang et al., 2019; Taryadi and Kurniawan, 2018; Brandão et al., 2015; Escobedo et al., 2014; Singh et al., 2019; Taryadi and Kurniawan, 2018; Vahabzadeh et al., 2018). A systematic review of AR interventions for children with autism also showed positive outcomes for children with autism using AR (Khowaja et al., 2020).

Lee et al. (2018) developed the AR with concept maps (ARCM) training system using AR technology combined with concept maps (CM) to teach children with ASD how to respond when greeting others. This study reported increased target responses on the Social Story trial (SSTs) tests following the intervention. To help children with autism identify and understand some specific social cues and improve their social skills, Lee et al. (2019) examined an AR coloring book (ARCB). They found that the ARCB maintained the attention of children with autism and sustained the positive intervention effects for longer than traditional paper-based materials.

Escobedo et al. (2012) proposed using an AR mobile assistive app to help children with autism practice social skills in real-life situations. The results showed that the AR app improved the quantity and quality of social interactions and reduced social and behavioral errors in children with autism. Then they investigated the effects of the AR Moving Object Recognition System (Mobis) on the emotions and attention of children with autism before and after its use, with a single case multiple baseline study approach (Escobedo et al., 2014). The study found that using Mobis had a positive effect as it improved sustained attention and increased engagement in children with ASD.

Taryadi and Kurniawan. (2018) developed "Augmented Reality Multimedia" by combining AR with the Picture Exchange Communication System (PECS) method to train communication skills in children with autism. Using images, video, and sound, "Augmented Reality Multimedia" allows individuals to work with PECS by scanning a QR code rather than selecting an image from a traditional PECS. The study reported an increase in communication skill levels after the intervention. Vahabzadeh et al. (2018) examined changes in ADHD-related symptoms in children, adolescents, and young adults with autism immediately after using the Empowered Brain system (EBS). They tested participants using the ABC—H scale and demonstrated the effects of EBS on the social-emotional and behavioral aspects of children with autism.

Only limited empirical studies have investigated whether augmented reality systems are appropriate and acceptable for children with autism. Keshav et al. (2017) evaluated the acceptance and usability of Brain Power Autism System (BPAS), a new smart glasses AR face play system for people with ASD. The results showed that the BPAS is well tolerated and can be used for people with ASD of different ages and severity. However, this is only one study based on wearable AR glasses. Another empirical study was conducted by Singh et al. (2019), who assessed the feasibility of an augmented reality application to enhance learning experiences for children with autism. They found that children with autism

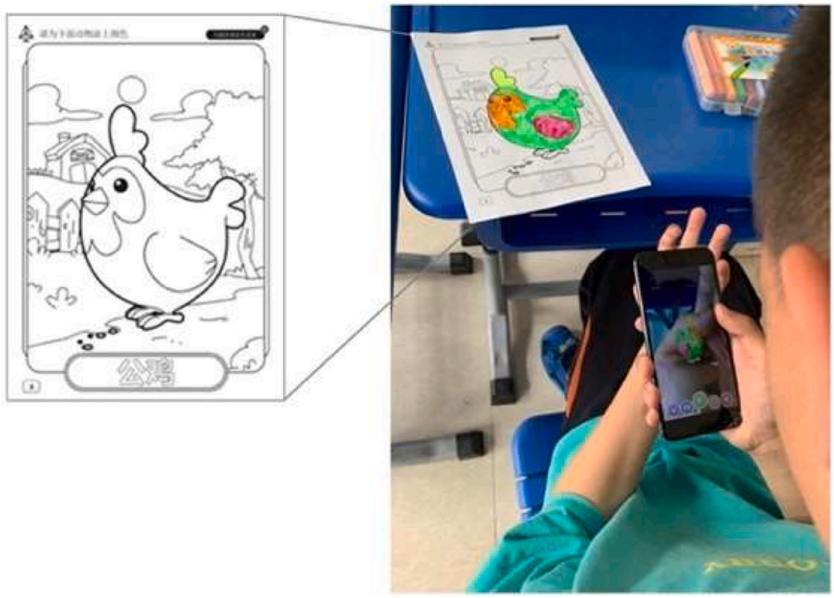

Fig. 1. An ASD child uses wARna to scan and interact with an AR model after coloring.

Table 1
Demographic characteristics of participants.

	ASD ($N = 23$)	TD ($N = 26$)	T	p value
Age (years)	11.17 (1.94)	8.96 (1.28)	6.048	.001
Mental Age	10.71 (1.62)	9.96 (1.31)	1.788	.080
Total IQ	98.87 (12.19)	107.27 (9.01)	−2.765	.008
Verbal IQ	97.04 (13.9)	109.58 (8.85)	−3.809	.001
Performance IQ	105.22 (16.37)	110.1 (9.04)	−1.241	.221
CARS	32.31 (3.49)	15.27 (0.53)	24.559	.000
Sex, M: F	17:6	12:14		

Table 2
Experimental task.

Task	Description	Page
1	Find “Help”.	1–3
2	Take a picture of the AR animal, Change the background, and exit the current page.	4–6
3	Find “my album”.	7–9
4	Share the picture taken in task 2 with your WeChat friend, then delete it.	10–13

took the longest to understand instructions using the AR mode, possibly due to the inappropriate features of the system that caused their cognitive load. However, the purpose of these studies was not to assess the accessibility of the system empirically.

These studies focus on the evaluation of specific tools or apps for users with autism and provide few accessibility recommendations (Pavlov, 2014). If multimedia elements (e.g., interface graphics, animations, and text) are not designed appropriately, they can be barriers to the interaction processes of ASD children (Kao et al., 2019). For instance, they distract children with autism, interfere with manipulative processes, reduce comprehension, or induce cognitive overload (Takacs et al., 2015). Therefore, it is essential to conduct accessibility research on augmented reality technology intervention systems.

2.2. Accessibility studies for autism

Accessibility is about ensuring that people with disabilities have an equivalent user experience. For mobile applications, accessibility means that people with disabilities can perceive, understand, navigate, and interact with applications and tools (Dattolo et al., 2017).

Many accessibility guidelines can be used to guide designers in making systems more accessible to people with disabilities (Harper and Yesilada, 2008). One of the most commonly used is the Web Content Accessibility Guidelines (WCAG), developed by the Web Accessibility Initiative (WAI) of the World Wide Web Consortium (W3C) (Caldwell et al., 2008). The audience for this guideline is all disability groups.

Some studies focus on accessibility guidelines for people with autism. Pavlov (2014) outlined the reading-comprehension difficulties for people with ASD and the presentation methods that can be used to overcome these difficulties. Yaneva et al. (2015) used eye-tracking technology to evaluate text documents for autistic adults. They provided the preferences of autistic individuals in text presentation and synthesized a set of guidelines, such as “illustrate the main ideas in text paragraphs through the insertion of relevant images to the meaning of the paragraph” and “if a relevant image is unavailable or the idea of the text is too abstract to be depicted as an image, do not put anything.”

Britto and Pizzolato (2016) collected and analyzed existing web interface guidelines related to ASD from different countries. They then categorized these 28 guidelines into engagement, affordance, customization, redundant representation, multimedia, feedback, system status,

Table 3
Summary of metrics considered in the experiments.

	Metric	Description	Format
Gaze-Based	Number of fixations (NF)	Number of fixations generated in an AOI	Count
	Time to First Fixation (TFF)	How long it takes before a test participant fixates on an AOI for the first time	Sec
	Total duration of fixation (TDF)	The sum of the duration for all fixations within an AOI	Sec
	Percentage of Fixation (PF)	Compare the total fixation duration on an AOI divided by the total visit duration of the overall screen	%
Non-Gaze	QUIS	9-point questionnaire for user interaction satisfaction	Points
	Task Success	The score of correct response to the tasks	Points

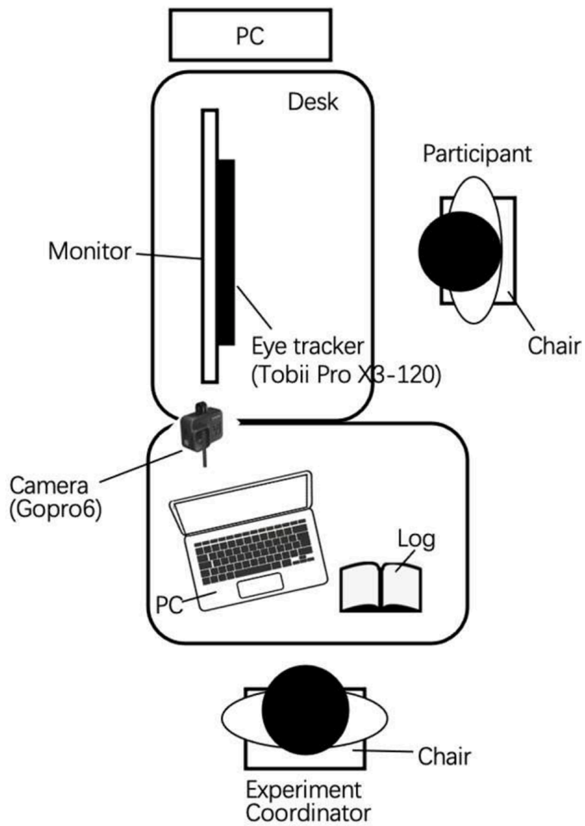

Fig. 2. The physical setup: an LCD monitor, an eye tracker, a camera facing the user, the PC and notebook for experiment coordinator.

navigability, and interaction with a touch screen. However, the guidelines examined were based on a literature review of existing guidelines rather than empirical research on people with autism (Friedman and Bryen, 2007). Dattolo et al. (2017) defined specific recommendations in three macro-areas (graphical layout, structure and navigation, and language) for the design of tourist websites for ASD individuals through reviewing existing guidelines literature for designing a usable and accessible user interface for people with cognitive disabilities and people with ASD. Raymaker et al. (2019) utilized a community-based participatory research (CBPR) approach to drawing lessons from the development and evaluation of a website designed for healthcare for adults with autism. They developed recommendations for web accessibility guidelines to increase the physical, intellectual, and social accessibility of websites for use by autistic adults. The guidelines overlap with those recommended by WCAG.

Aguiar et al. (2022) collected and analyzed existing guidelines related to software solutions for ASD using a systematic literature review approach. These guidelines were then categorized into 11 categories according to the Ergonomic Criteria for the Evaluation of Human-Computer Interfaces. In terms of mobile device user interfaces, recommendations were made to address the challenges that people with ASD may encounter, such as “provide a clear, simple and minimalist interface that avoids irrelevant information (audio, images, text)” and “the interface style should be consistent across all its components (layout, consistency in interactions, navigation elements)”.

Eraslan et al. (2019) performed an eye-tracking study with high-functioning autistic adults and neurotypical participants to examine whether people with autism have different processing strategies with web pages. The findings revealed that people with autism tend to look at more elements on a web page than neurotypical participants and make more transitions between the elements. This is the first study to examine whether people with autism tend to use different information-seeking strategies when processing web pages, indicating that the content of web pages needs to be improved to accommodate these differences better.

Rezae et al. (2020) evaluated the UI of a public transport trip-planning mobile application, OrienTrip, for people on the autism spectrum through an eye-tracking experiment. They revealed that adults with autism process icons and images faster than text through eye-movement analysis and that icons and text with unclear relationships can confuse users, suggesting improvements to user interface design. However, these empirical studies focus on the differences between adults with autism and TD individuals when interacting with applications.

The existence of many design guidelines for people with autism highlights the importance of developing web or application interfaces that meet the needs of this specific population. Some studies used technology such as eye-tracking to empirically examine how information should be presented to adults with autism (Eraslan et al., 2020; Eraslan et al., 2019, 2017; Yaneva et al., 2019, 2015; Rezae et al., 2020). To the best of our knowledge, the experiment conducted by Rezae et al. (2020) is the only existing experiment for investigating the differences

Fig. 3. A participant searches the interface provided by the wARna and eye movement data was recorded by the eye tracker (the boy is doing task 1).

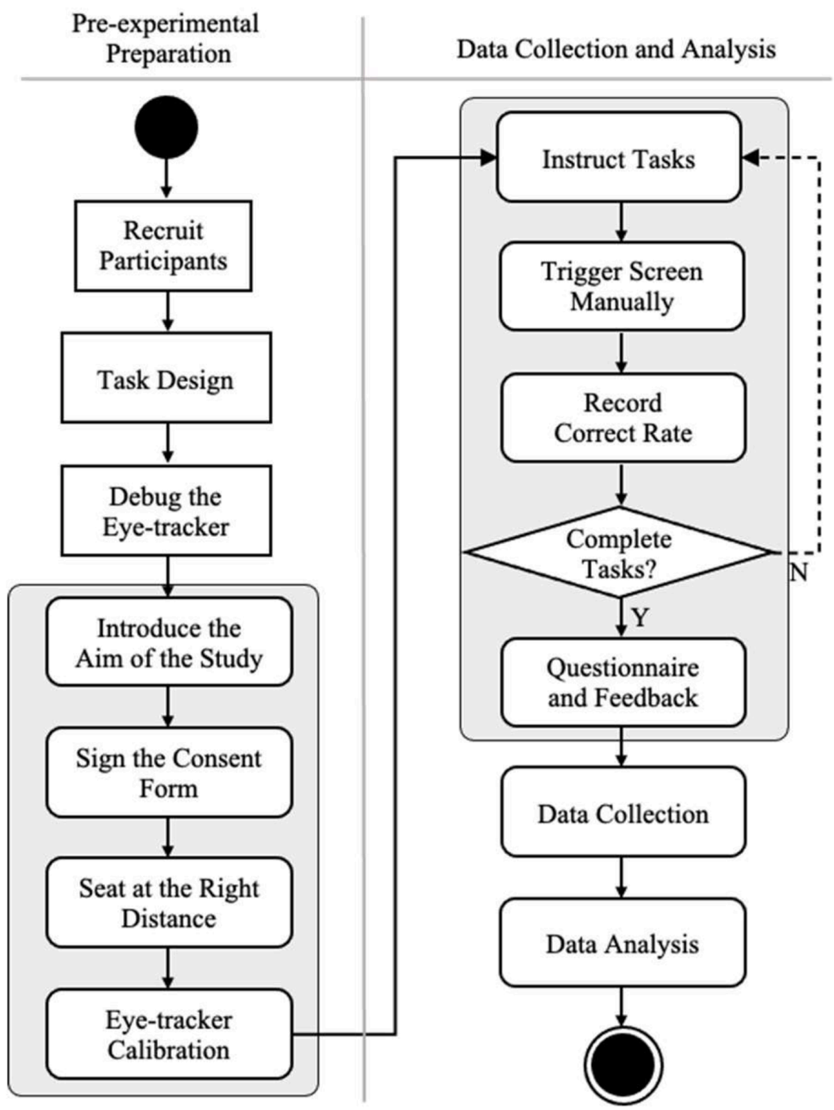

Fig. 4. Research process.

between users with and without autism in processing mobile applications. Nevertheless, this research focuses on autistic adults. Few studies have investigated how children with autism differ from TD children when interacting with mobile applications. We aim to provide some empirical understanding of the eye fixation preferences of children with autism concerning mobile AR application interfaces through eye tracking.

2.3. Eye tracking

Eye-tracking is a technique used to measure eye movement data when a person interacts with the stimulus (Mintz and Joseph, 2013; Sun et al., 2016). Eye gaze is an objective and quantifiable behavior, and through eye movement experiments, researchers can know where a person is looking at a given time and how long their eyes are gazing (Mintz and Joseph, 2013; Pierce et al., 2016).

Eye-tracking techniques can be used for early identification and clinical assessment of autism (Mcconnell, 2002; Pierce et al., 2016; Yaneva, 2018). Yaneva et al. (2020) conducted an eye-movement experiment to test for differences in visual processing between adults with and without high-functioning autism. The results showed visual processing differences between the two groups when processing web pages and that it is feasible to use this method to detect autism.

Eye tracking can also be used to assess the accessibility of software user interfaces. An empirical study by Eraslan et al. (2019) demonstrated that people with autism have different processing strategies than TD people when searching for information on web pages. Yaneva et al. (2019) investigated the accuracy and efficiency with which high-functioning web users with autism and a control group of neurotypical participants obtain information from web pages. They found that both groups had similar levels of accuracy, but the autistic group was less efficient, suggesting that the autistic group put more cognitive effort into achieving the same results as their neurotypical counterparts. Rezae et al. (2020) evaluated the UI of navigation software for autistic adults using eye-tracking technology. According to Kwon et al. (2019) and Ramakrisnan et al. (2012), it is feasible to use eye-tracking technology to measure visual preferences in children with ASD. However, to our knowledge, no eye-tracking studies have assessed how children with autism interact with mobile application interfaces.

Eye-movement research provides valuable insights into how people interact with screens and can facilitate greater accessibility of technology for users with autism. Many mobile AR applications are being developed for children with ASD, but the evaluation of the UI is rarely given much attention. In this paper, we aim to provide empirical support for accessible UI design by using eye-tracking technology to understand how children with autism interact with mobile application interfaces.

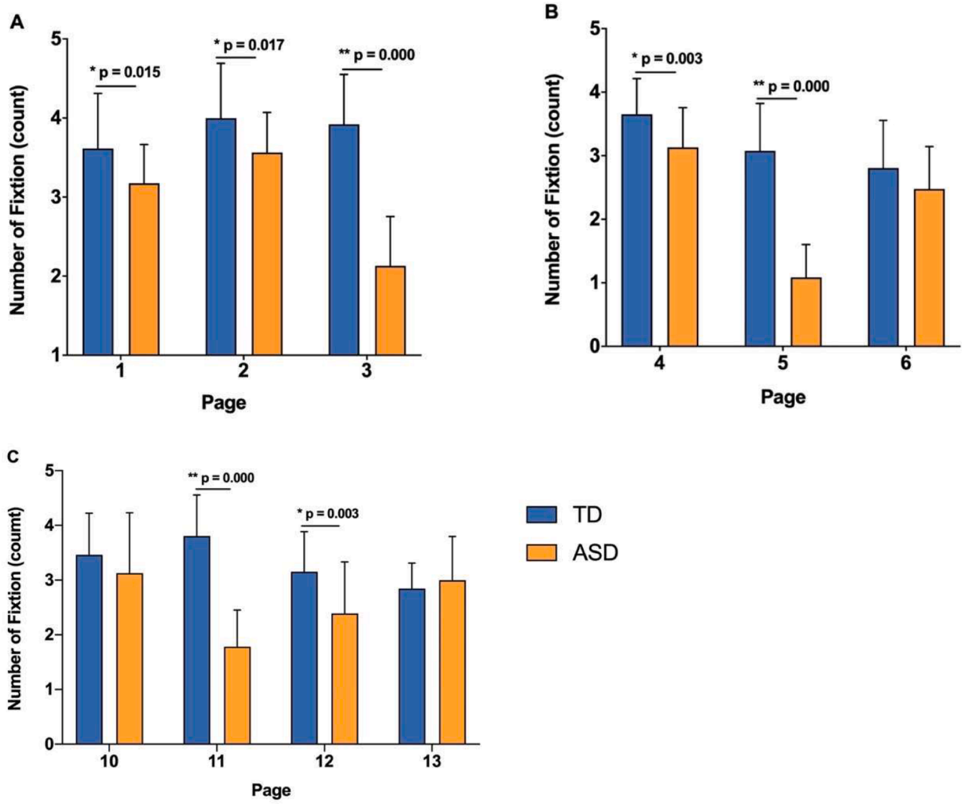

Fig. 5. NF between the ASD and control group in: (A) task 1; (B) task 2; (C) task4.

Table 4
Summary statistics analyze of NF between two groups.

Pages	TD group (N = 23)		ASD group (N = 26)		*t*-test/U-Test		
	Mean	SD	Mean	SD	t/Z	Sig.	Cohen's *d/r*
1	3.62	0.70	3.17	0.49	**−2.29**	**0.02**	**0.35**
2	4.00	0.69	3.57	0.51	2.48	0.02	0.72
3	3.92	0.63	2.13	0.63	9.99	0.00	2.91
4	3.65	0.56	3.13	0.63	3.09	0.00	0.90
5	3.08	0.74	1.09	0.52	10.75	0.00	3.13
6	2.81	0.75	2.48	0.67	1.62	0.11	0.47
7	3.23	0.43	3.00	0.67	1.45	0.16	0.42
8	3.50	0.65	3.22	0.67	1.50	0.14	0.44
9	4.23	0.95	3.52	0.59	**−2.66**	**0.01**	**0.41**
10	3.46	0.76	3.13	1.10	**−1.02**	**0.31**	**0.10**
11	3.81	0.75	1.78	0.67	9.91	0.00	2.89
12	3.15	0.73	2.39	0.94	2.71	0.00	0.79
13	2.85	0.46	3.00	0.80	**−0.73**	**0.47**	**−0.11**

Bolded finding is the result of *U test*.

3. Method

3.1. Overview of the AR coloring app "wARna"

wARna is a mobile AR coloring app created for children which can interactively play with colored 2D coloring book pages by visualizing them in 3D on the user's mobile devices (Mokhtar et al., 2018). It is used with the coloring book to encourage children to focus more on the coloring activity. The markers (coloring pages) are used to display animal AR interactive models to learn word spellings (most popular critters such as chicken, sheep, and rabbit). The markers are A4 size with a resolution of 300 pixels per inch and are used to print companion books where the animal's name, the outer outline of the animal, and the interactive animal object are bold at 8 points wide, and the background image and the internal outline lines of the animal are 4 points wide. The current version of Mandarin wARna provides the following functionalities:

- User can scan the book pages after coloring them
- Users can use mobile devices for 3D visualization
- User can interact with the AR 3D models (move, zoom in and out)
- User can take a picture of the 3D models
- User can change the background of the interaction (turn off the real scene)
- Users can review the photos taken and share or delete them

When the camera is pointed at the complete image that the user has colored in, an animation of the colored 3D model is automatically played on the smartphone (Fig. 1). In this study, we evaluated the relevant UI elements of wARna.

3.2. Participants

Fifty-five children (28 ASD, 27 TD), ages 6–12 years, participated in this study. All participants with autism were recruited through a public special education school in the city of Handan, where they had to provide a copy of their formal diagnosis to access the educational services of the school. The participants without autism were recruited through another regular public primary school in Handan.

The inclusion criteria for participants were ages ranging from 6 to14 years and normal or corrected-to-normal vision. The experimental group needs to have a formal diagnosis of autism. The exclusion criteria were the presence of any degree of intellectual disability in their diagnoses. In addition, none of the TD children should have exhibited any features of autism.

All participants completed the Wechsler Intelligence Scale for Children Revised in China (WISC-RC) and the Childhood Autism Rating Scale (CARS Chinese version). The WISC-RC is a measure of Intelligence

Table 5
Summary statistics analyze of TFF between group.

Pages	TD group ($N = 23$) Mean	SD	ASD group ($N = 26$) Mean	SD	*t*-test/U-Test t/Z	Sig.	Cohen's *d/r*
1	1255.43	382.50	1542.58	383.65	−2.62	0.01	−0.76
2	1426.61	328.30	1356.05	294.79	0.79	0.46	0.23
3	1877.17	327.29	2449.18	289.92	−6.35	0.00	−1.87
4	1365.46	366.51	1651.60	519.55	−2.25	0.03	−0.66
5	1715.65	279.21	2369.13	342.99	−7.26	0.00	−2.14
6	1234.16	302.34	1315.29	247.11	−1.02	0.31	−0.29
7	1037.98	305.78	1114.47	187.52	**−2.06**	**0.39**	**−0.15**
8	987.34	189.44	1050.64	148.86	−1.29	0.20	−0.38
9	1346.11	330.98	1426.11	320.31	−0.86	0.39	−0.25
10	1187.78	331.65	1351.24	299.82	−1.80	0.08	−0.53
11	1630.30	348.23	1969.62	304.79	−3.61	0.00	−1.05
12	1496.38	291.53	1710.57	327.33	−2.42	0.02	−0.71
13	1170.80	295.92	992.20	208.22	2.35	0.02	0.71

Bolded finding is the result of *U test*.

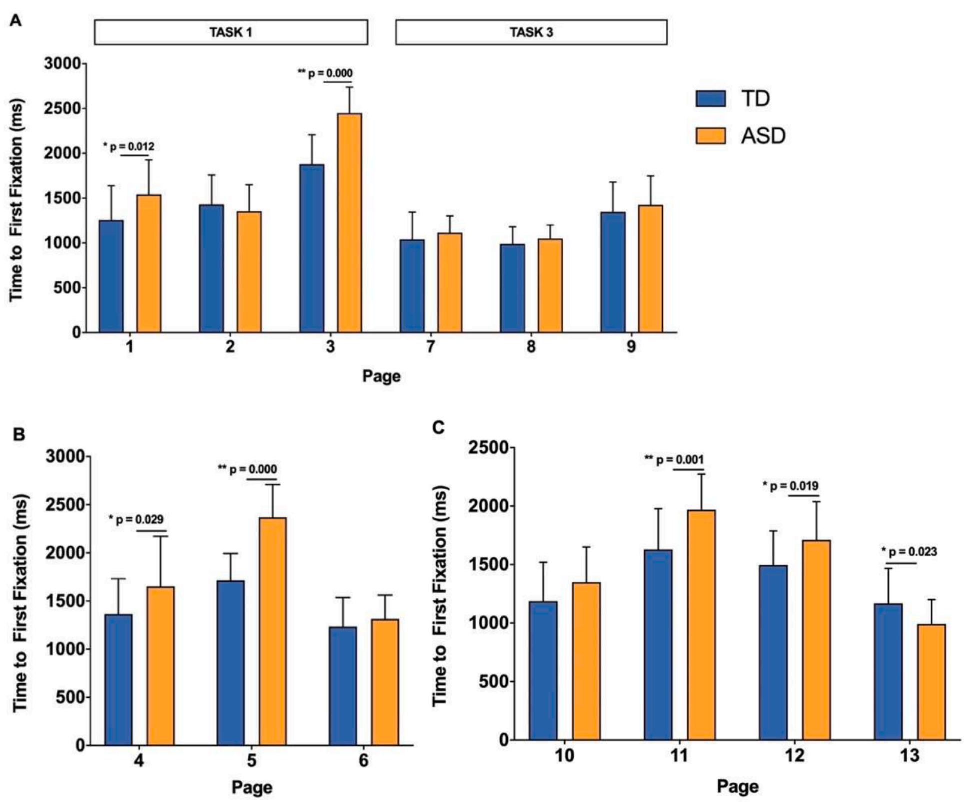

Fig. 6. TFF between the ASD and control group in: (A) comparison of task 1 and 3; (B) task 2; (C) task4.

Quotient (IQ), including verbal and performance IQ, ensuring that participants understood the experiment instructions. The CARS are tested for checking the autism features of the TD group. Participant information and t-tests of group differences are shown in Table 1.

The mean age of the autism group was $m = 11.17$ with a standard deviation of SD $= 1.94$, whereas the mean age was $m = 8.96$ with SD $=1.28$ for the control group. Participants did not differ regarding mental age ($t = -2.765$, $p = 0.080$) or performance IQ ($t = -1.241$, $p = 0.221$). Although there were differences in total IQ ($m = 98.87$) and verbal IQ ($m = 97.04$), the scores for the ASD group were within the normal range (Bianco et al., 2018). None of the control participants included in the study had a CARS score higher than 30, meaning they all did not exhibit any features of autism. Due to low sampling rates in eye-tracking experiments, five children with ASD and one TD child were excluded from the analyses. Ethical approval was sought and obtained from the Municipal Health Committee Ethics Committee prior to the recruitment of participants.

3.3. Apparatus

We recorded eye movements with the Tobii Pro-X3–120 Eye Tracker, a non-invasive eye tracker that uses infrared pupil position detection and corneal reflection to track eye movements. The sampling rate was 120 Hz, the measurement accuracy in the gaze direction was 0.24, and the freedom of head movement was approximately 50 cm x 40 cm. We attached it to a 22″ widescreen monitor for eye tracking of physiological objects. The participants' eyes were approximately 70 cm from the display during the experiment, and they were free to move their heads within a specific range while looking at the screen. The system was calibrated at five points by asking the participant to look at a set of points on the screen. The binocular data of each participant was recorded and then transmitted wirelessly to a computer. The Tobii Pro-lab

Fig. 7. Heat map of the ASD group (left) and control group (right) of pages 13 in task 4 (confirm photo deletion).

Fig. 8. Heat map of the ASD group (left) and control group (right) of pages 9 in task 3, (find my album) showing ASD children paying more attention to icons.

Table 6
Summary statistics analyze of PF between groups.

Pages	TD group (N = 23)		ASD group (N = 26)		t-test/U-Test		
	Mean	SD	Mean	SD	t/Z	Sig.	Cohen's d/r
1	0.63	0.12	0.55	0.10	2.51	0.02	0.73
2	0.56	0.09	0.49	0.11	2.37	0.02	0.69
3	0.60	0.12	0.36	0.08	7.88	0.00	2.29
4	0.61	0.09	0.54	0.12	2.36	0.02	0.69
5	0.61	0.11	0.28	0.07	12.22	0.00	3.56
6	0.61	0.11	0.57	0.10	1.53	0.13	0.45
7	0.66	0.09	0.63	0.11	0.95	0.35	0.28
8	0.66	0.09	0.62	0.11	**−1.56**	**0.12**	**0.19**
9	0.61	0.13	0.53	0.13	2.19	0.03	0.64
10	0.58	0.18	0.56	0.15	0.43	0.67	0.13
11	0.57	0.14	0.41	0.11	4.19	0.00	1.22
12	0.54	0.12	0.37	0.08	5.68	0.00	1.66
13	0.52	0.11	0.56	0.10	−1.20	0.24	−0.35

Bolded finding is the result of *U test*.

was used for subsequent data analysis.

3.4. Experimental task

The eye movement experimental study consists of four tasks and 13 screens with varying visual complexity (Appendix A). The translucent-colored geometric shapes on the interface highlight the Areas of Interest (AOI). These tasks required participants to locate a specific AOI (element or area) on the application interface.

Task 1 consisted of three pages, and the two groups of subjects were asked to find the item "How to Use" (Figs. A.1–A.3). This action would trigger wARna's help screen, which instructed the user to operate the application. The AOI on page 2 is a "triangle" icon with the text "Please press the triangle for two seconds" below it (Fig. A.2). Page 3 is the menu page for the application, and the AOI is the fourth item on the menu board, with the text "How to Use" and the corresponding question mark icon (see Fig. A.3).

Task 2 required participants to identify the correct icon (take a picture, change the background, and exit). The AOI on page 4 is a "camera" icon used to take a picture, on page 5 is a "picture" icon indicating a change of background, and on page 6 is an "exit" icon. See Figs. A.4–A.6.

Task 3 was to "Find my album" on the menu page. The interfaces for this task were identical to those for task 1, and the first two screens had the same instructions (Figs. A.7 and A.8). The AOI on page 9 (Fig. A.9) is the second item on the menu board, the album icon, and the text "My Album".

Task 4 consisted of 4 screens and was to find the photo taken in Task 2 in an album, share it on WeChat and then delete it. The AOI of page 12 (Fig. A.12) is the icon of the social media application WeChat. The AOI on page 13 consists of a green "YES" and a tick mark icon. At the top of this screen are two lines of text, "Are you sure you want to delete this photo permanently?" with a "NO" and a fork symbol on a red background at the bottom right.

There are two reasons for using these four tasks. Firstly, to give participants an idea of the core features of wARna, which we expect users to use when using the application in the real world. Secondly, to introduce participants to the core UI elements of wARna and to assess how they interact with these elements to complete a given task. We collected metrics such as the number of fixations, the time to first fixation, and the percentage of fixation.

Users were required to interact with one or more of wARna's screens to complete the tasks. For data analysis, each screen consists of one or more AOIs. The AOIs on each screen have been carefully selected. Specifically, elements that the user must interact with or view (e.g., buttons, icons, and labels) are selected as target AOIs to obtain specific information or complete tasks. These tasks are listed in Table 2.

3.5. Measurement

The monitor-based eye-tracking study provides initial insights into the evaluation of user interfaces for mobile coloring applications. The use of a computer screen allows for better control of experimental conditions and environments, more precise timing, and consistent data collection. However, it is also recognized that factors such as screen size and touch interaction can influence user behavior and preferences, so to gain a comprehensive understanding of how children with autism manipulate the user interface, we supplemented the eye-tracking data with real-time interaction analysis on actual mobile devices. This involves recording success rates in completing tasks and user interaction satisfaction ratings, collecting feedback, and observing interactions to understand the specific needs and preferences of autistic children. Table 3 lists the dependent variables measured, as defined below:

Number of fixations (NF). Repeated fixations may indicate a lack of significance or visibility of the target region (Ehmke and Wilson, 2007). It means that the ASD group may have spent more time trying to understand the recognition area compared to the control group. It could also be argued that the higher number of fixations reflected an interest in the region. We will therefore analyze the difference in NF in conjunction with other metrics.

Time to First Fixation (TFF). The time in seconds when an AOI was first fixated measured from the moment the page was presented on screen. This metric correlates with the level of interest of the individual.

Total duration of fixation (TDF). It represents possible differences

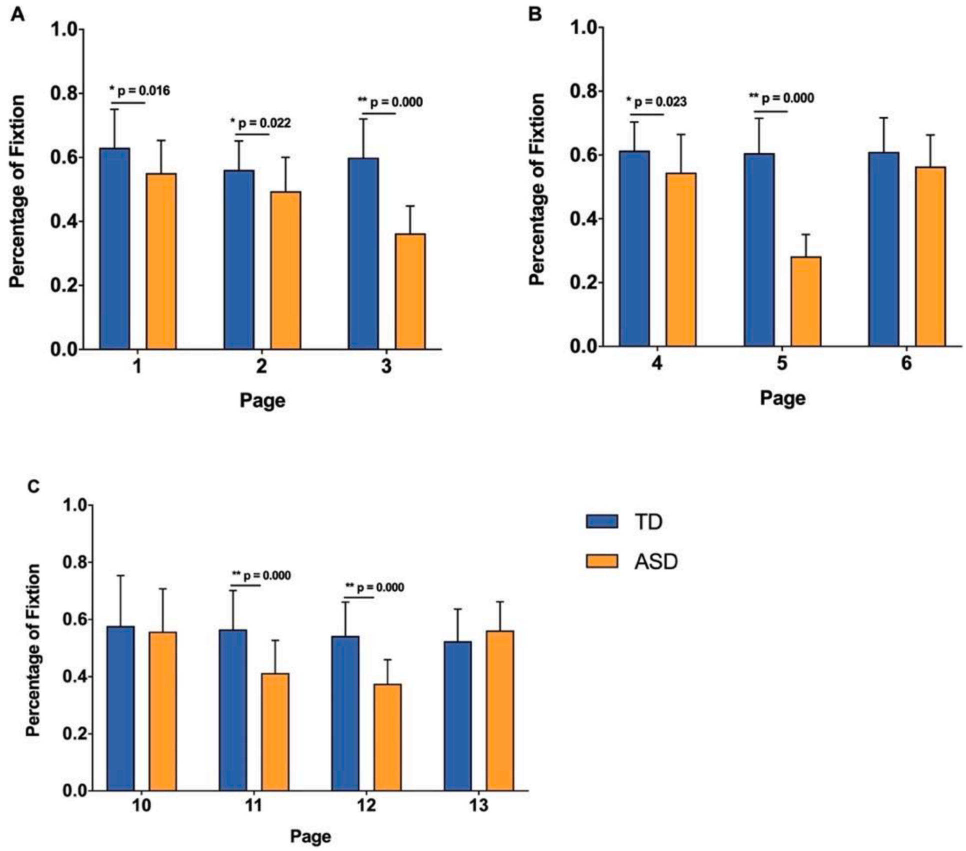

Fig. 9. PF between the ASD and control group in: (A) task 1; (B) task 2; (C) task4.

Table 7
The responses of the ASD and control groups to the tasks.

Task	TD group (N = 26)		ASD group (N = 23)	
	Mean	SD	Mean	SD
1	2.92	0.27	2.78	0.52
2	2.77	0.43	2.70	0.56
3	2.92	0.27	2.87	0.34
4	3.73	0.53	3.57	0.59

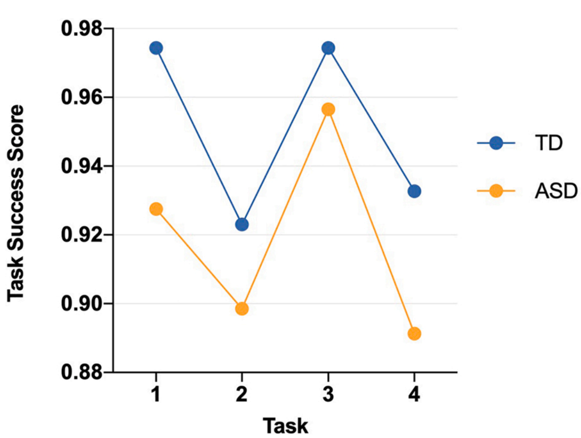

Fig. 10. Task success rate of ASD and TD group.

in information processing between ASD and TD children. According to (Follet et al., 2011), the TDF metric is usually associated with information processing.

Percentage of Fixation (PF). This metric is defined as the TDF within each AOI divided by the total looking time. Differences in PF between the two groups were examined using an independent sample t-test or an M-W U test.

Task success. The task's score is to investigate whether people with autism experience practical difficulties in performing system manipulations (searching for specific information) in a limited time compared to TD children. In this study, a task success checklist was developed. We recorded each participant's correct or incorrect behavior after receiving the task instructions and scored 1 point if the participant responded correctly within the time limit. Otherwise, a score of 0 was recorded. The checklist was organized according to the flow of the study and the sequence of tasks.

User Interaction Satisfaction. User interface satisfaction was measured by responses to the questionnaire to understand the participants' overall assessment of the app interface. We adopted the QUIS developed at the human-computer interaction laboratory at the University of Maryland in 1998. It has been proven reliable and valid by Catani and Biers (1998). The QUIS contains a measure of overall app satisfaction along six scales and specific interface factors such as screen, terminology, system information, learning, and system capabilities. Each area measures the user's overall satisfaction on a 9-point scale. For example, children were asked the questions: reading the text on the screen (0-difficult to 9-easy); operating the system (0-difficult to 9-easy). Participants with autism will complete the scale with the support of special education teachers.

3.6. Procedure

The experiment was chosen to take place in a quiet classroom in a special education school, with the participation of researchers, teachers, or their parents, in order to avoid environmental discomfort for people with autism. First, the participants were asked to sit at a table, and the

Table 8
Questions about user interface satisfaction in the questionnaire and statistics of the averages scores of TD and ASD group.

No.	Question	TD Mean	SD	ASD Mean	SD	p
A. Overall reaction to the system						
1	(terrible/wonderful)	6.71	1.04	7.09	1.31	
2	(difficult/easy)	6.5	0.83	5.86	1.21	*
3	(frustrating/satisfying)	6.63	0.92	6.18	1.11	
4	(inadequate power/adequate power)	5.33	1.01	6.14	1.52	*
5	(dull/stimulating)	6.96	1.12	7.73	1.16	*
6	(rigid/flexible)	6.88	0.99	6.5	1.30	
B. Screen						
7	Reading characters on the screen (hard/easy)	7.04	1.30	4.05	1.43	**
8	Icons simplifies task (not at all/ very much)	6.04	1.23	7.00	1.21	*
9	Organization of information (confusing/very clear)	6.92	1.32	6.00	1.72	*
10	Sequence of screens (confusing/ very clear)	6.13	1.42	5.91	1.23	
C. Terminology and system information						
11	Use of terms throughout system (inconsistent/consistent)	6.75	1.26	4.55	1.06	**
12	Terminology related to task (never/always)	5.04	1.23	6.00	1.58	*
13	Position of messages on screen (inconsistent/consistent)	6.13	1.30	4.82	1.33	**
D. Learning						
14	Learning to operate system (difficult/easy)	6.63	1.31	5.77	1.54	*
15	Remembering names and use of commands (difficult/easy)	6.46	1.32	4.77	1.07	**
16	Performing tasks is straightforward (never/always)	6.58	1.18	6.18	1.18	
17	Help messages on the screen (unhelpful/helpful)	7.46	1.10	7.23	1.11	
E. System capabilities						
18	System speed (too slow/fast enough)	5.63	1.21	5.68	1.58	
19	System reliability (unreliable/ reliable)	5.54	1.02	5.14	1.08	
20	System tends to be (noisy/quiet)	6.38	1.25	6.14	2.01	
21	Systems help learning (never/ always)	6.63	0.88	7.36	1.41	*
22	Designed for all levels of users (never/always)	6.33	1.24	5.86	1.64	

* $p < 0.05$; ** $p < 0.001$.

researcher introduced them to the purpose and procedure of the experiment. After becoming familiar, they all signed a consent form. Demographic data regarding their age, gender, and diagnosis was then collected with the help of their caregivers.

Then the participants were asked to sit at the proper distance (around 70 cm), and a five-point eye tracker calibration was performed. After successful calibration, the coordinator manually triggered the first screen of wARna from a different computer, and the remaining screens were displayed in sequence. The coordinator dictated the task instructions before the screens were displayed. The participants were given 6 s to complete the search task on each page. When participants took less than 6 s to complete the task on a given page, they moved directly to the next page. The experiment coordinator recorded the task success score of each participant during the eye-tracking session.

The eye tracker was placed at the base of the primary monitor on the desk, which displayed the task screen. The coordinator delivered instructions and made observations at another table to the left side of the participant (see Figs. 2 and 3). After completing the eye tracking session, the participants were asked to fill out the QUIS (with the assistance of caregivers if necessary). We also asked some questions that allowed for free-form responses to gather feedback, such as “Which aspects did you find challenging to use?” and “What improvements do you suggest for the wARna interface?”. All the participants could take a break whenever they felt tired. Fig. 4 shows the overall experiment workflow, with shaded boxes showing the steps that participants need to repeat.

Fig. A.1. Menu button on home screen.

3.7. Data analyses

Analyses were performed using IBM SPSS Statistics 26, with the significance level set at $P < 0.05$. Participants' eye gaze data were entered for analyses of variance to test for the effects of the dependent variables. In between-group analyses, an independent samples T-test or its non-parametric alternative, the Mann-Whitney U test, was performed for all dependent variables. Independent samples t-tests were used when Levene's test for homogeneity of variance was not significant in each case (all $P > 0.05$) and when the normality of any dependent variable was not significantly different. Otherwise, the Mann-Whitney U test was used to compare the two groups of participants. Task success scores and QUIS data were entered into a t-test to test for differences in sample means. For brevity, only those results that were considered significant ($p < 0.05$) are discussed.

Fig. A.2. Security verification interface.

Fig. A.3. Menu interface with target AOI – "How to use" button.

4. Results

Our analysis investigated whether participants in the children with autism and TD groups had different visual preferences for each page, and the more subtle interaction features that arose when the two groups manipulated the application. We present the results of the eye-gaze based metrics and the task success and QUIS data. The effect sizes of Cohen's d for independent T-tests were classified into small (> 0.2), medium (> 0.5), and large (> 0.8) (Cohen, 1988), and r for Mann-Whitney U-tests were classified into small (> 0.1), medium (> 0.3), and large (> 0.5) (Pallant, 2020).

4.1. Number of fixations

We compared the means of NF of participants using independent samples t-tests. Levene's test for homogeneity of variances was not significant ($p > 0.05$) in each case except on pages one, nine, ten, and thirteen, and there was no significant difference in the normality of any of the dependent variables. As shown in Fig. 5, apart from page thirteen in task 4, children with autism had a lower mean NF in comparison with TD children while searching for information. Appendix A illustrates our detailed statistical analysis, including the mean, the standard deviation of the mean NF of the ASD and control groups on all pages, and the independent T-test or Mann-Whitney *U test* results. As shown in Table 4, the number of fixations on the AOI revealed differences between the two groups, with a large effect size on pages three ($t = 9.99$, $p < 0.001$, $d = 2.91$), four ($t = 3.09$, $p < 0.001$, $d = 0.90$), five ($t = 10.75$, $p < 0.001$, $d = 3.13$), and eleven ($t = 9.91$, $p < 0.001$, $d = 2.89$). A statistically significant medium effect was found between group for page one ($Z = -2.53$, $p < 0.05$, $r = 0.35$), page two ($t = 2.48$, $p < 0.05$, $d = 0.72$), page nine ($Z = -2.66$, $p < 0.01$, $r = 0.41$), and page twelve ($t = 2.71$, $p < 0.01$, $d = 0.75$). There were no overall group differences found for the last five pages.

4.2. Time to first fixation

To assess whether there were differences across the two groups in the TFF on an AOI, an independent T-test with a 95% confidence interval or its non-parametric alternative, the Mann-Whitney U-Test, was conducted. There was no overall group difference, $p = 0.267$. However, the mean number of fixations on 13 pages for the ASD and TD control groups and the results of the *t*-test revealed that there was a significant effect on page three, with a large effect size ($t = -6.35$, $p < 0.001$, $d = -1.87$), as well as on page five ($t = -7.26$, $p < 0.001$, $d = -2,14$) and page eleven ($t = -3,61$, $p < 0.01$, $d = -1.05$). There was also a significant effect, with a medium effect size for page one ($t = -2.62$, $p < 0.05$, $d = -0.76$), page

Fig. A.4. Camera button to take pictures.

Fig. A.5. Image button to change the background.

twelve ($t = -2.42$, $p < 0.05$, $d = -0.71$), and page thirteen ($t = -2.35$, $p < 0.05$, $d = 0.71$), details in Table 5. Fig. 6A shows the comparison of the TFF on the same interface for task 1 and task 3. The participants could operate correctly in a shorter time when searching the same interface for the second time, whether in the TD or ASD groups. It is also worth noting that, in the ASD group, participants have a lower TFF on pages 2, 4, and 13.

4.3. Percentage of fixation

PF is defined as the total fixation duration on an AOI divided by the total visit duration of the overall screen. We first analyzed the total fixation duration with an independent T-test. This resulted in a significant effect of total fixation duration between the groups for page 13 with a medium effect size ($t = 1.89$, $p = 0.04$, $d = 0.55$), and the heat map shows the ASD group has a larger total fixation duration on AOI "YES" than TD (seen Fig. 6). There were no statistically significant differences found on page nine ($t = 1.01$, $p = 0.24$, $d = 0.29$), although the TD group was more concentrated on AOI "my album" than ASD (see Fig. 7). In addition, the heat map also revealed that ASD looks more at icons and TD looks more at text.

The percentage of time spent fixating on the AOI revealed differences between the two groups on page three, with a large effect size ($t = 7.88$, $p < 0.001$, $d = 2.29$), as well as on page five ($t = 12.22$, $p < 0.001$, $d = 3.56$), page eleven ($t = 4.19$, $p < 0.001$, $d = 1.12$), and twelve ($t = 5.68$, $p < 0.001$, $d = 1.66$). In addition, a significant difference was detected with a medium effect size for page one ($t = 2.51$, $p < 0.05$, $d = 0.73$), page two ($t = 2.37$, $p < 0.05$, $d = 0.69$), page four ($t = 2.36$, $p < 0.05$, $d = 0.69$), and page nine ($t = 2.19$, $p < 0.05$, $d = 0.64$). Detailed statistical results are presented in Table 6, and the data in Fig. 8 illustrate the differences between the two groups for each task.

4.4. Task success

To examine whether people with autism experienced practical difficulties when searching for specific information on the app page in a limited amount of time compared to the TD group, we compared participants' responses to specific tasks. Table 7 shows the mean and standard deviation of each group's response scores to each task, and we can note that the ASD group had more minor success scores in each task than the TD group. A total score was calculated (the highest score for one participant was 13) and then tested statistically. Although the ASD group ($M = 11.91$) was less successful in finding the correct information on the page compared to the control group ($M = 12.35$), a t-test showed that the difference between these two groups was not significant ($t = 1.606$, $p = 0.115$, $d = 0.47$). The task success rate of the ASD and TD

Fig. A.6. Exit button to quit the current scan screen.

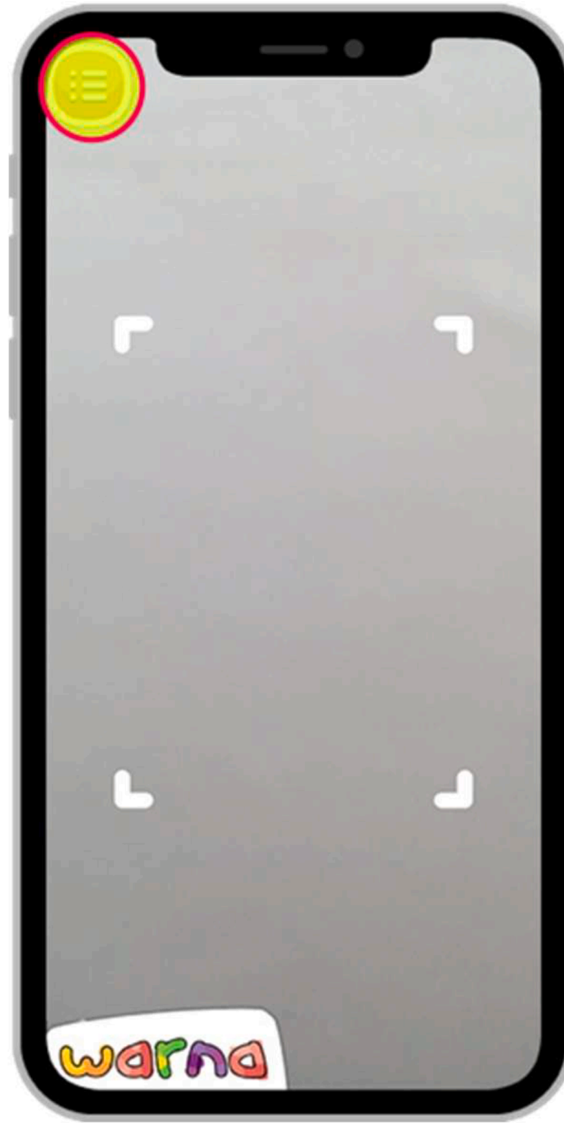

Fig. A.7. Menu button on home screen.

groups is shown in Fig. 9.

4.5. User interaction satisfaction

Table 8 shows the user interface satisfaction scores based on the "questionnaire for user interaction satisfaction". Scores were compared with an independent *t*-test, and Levene's homogeneity of variance assumption was met ($p > 0.05$). As can be seen from the table, most mean ratings were moderately high. On the 9-point QUIS scale, the mean scores ranged from 5.04 to 7.46 for the TD group and from 4.05 to 7.73 for the ASD group. The overall mean score of the overall reaction (A) to the system was 6.5 for TD and 6.58 for ASD, and no significant difference was observed between the two groups ($t = -0.596$, $p > 0.05$), as well as the aspect of (E) system capabilities (TD = 6.10, ASD = 6.01, $t = 0.558$, $p > 0.05$). These facts indicate that, in general, the users considered the app to be sufficiently good.

Conversely, the statistical results of the data on B, C, and D (screen, terminology, and system information and learning) prove significant differences in the scores of the two groups. We therefore conducted a statistical test for each question, and the QUIS scores revealed differences between the two groups, with a large effect size for No. 7 ($t = 7.44$, $p < 0.001$, $d = 2.91$), No. 11 ($t = 6.39$, $p < 0.001$, $d = 1.93$), No. 13 ($t = 3.37$, $p < 0.05$, $d = 1.02$), and No. 15 ($t = 4.74$, $p < 0.001$, $d = 1.43$).

5. Discussion

The AR coloring app wARna enables participants to scan and interact with the generated AR model after coloring. In this way, it makes the coloring process more engaging. In this paper, we evaluated the interface design of the app using eye-movement technology, investigated which elements of the coloring app interface might influence the interaction process between participants and the interface, and conducted a user interface satisfaction survey to supplement the study.

5.1. Main results

Among adults with autism, there is a preference for visual stimuli such as icons over long texts (Rezae et al., 2020). As investigated in this study, children with autism also show a preference for images and icons compared to TD children. According to the eye-tracking literature, the higher number of gazes implies that the participants may have spent more time trying to understand the highlighted AOIs or reflects the participants' interest in the area (Ehmke and Wilson, 2007; Follet et al., 2011; Pierce et al., 2016; Rezae et al., 2020). Pierce et al. (2016) suggest

Fig. A.8. Security verification interface.

Fig. A.9. Target AOI – “My album” label.

that the percentage of fixation can be used to represent the fixation duration. Children with autism do not maintain attention on the screen for long periods of time, and the total visitation time may differ between the two groups. The fixation percentage may be a more robust indicator.

On page 2 of task 1, both NF and PF were lower in the autistic group than in the control group and showed a significant difference with a medium effect size between the two groups. The lower NF and PF suggest that they could not maintain attention for long periods and had weaker information-processing skills than the control group. Although there is no statistically significant difference, the mean TFF for the autism group is also smaller than that of the control group. This suggests that for the AOI on page 2, the autistic group might focus on the shape (triangle) first compared to the TD group, which will comprehend the text first. In order to improve interaction with the interface of mobile applications for autistic children, it is crucial to consider the preferences of children with autism for icons in the design phase.

The target AOI of 13 pages was first observed in the autism group compared to the control group. Through observations and feedback, we learned that this was because the control group read the text at the top of the screen first to aid comprehension, whereas the autistic group was drawn to the icons as soon as they heard the instructions. The “tick” marked icons helped the ASD group quickly search for the target area. The heat map in Fig. 6 shows that the autistic group looked more at the “YES”, while several participants in the control group incorrectly paid attention to the “NO” option on the right. This is because some TD children, who over-understood the text above, were confused and thought that the red “fork” and “NO” indicated deletion. In contrast, more children in the autistic group did not pay too much attention to the text, understood the instructions directly, and made the correct choice.

These results have practical implications for the accessibility of UIs for children with autism. We mentioned above that interface design should consider the preference for icons in children with autism, where the relationship between icons and task guidance is more prominent. This is because visual stimuli can effectively facilitate their understanding of the task, reduce the cognitive effort required to scan the interface for people with autism, and optimize their task completion time (Eraslan et al., 2019).

Previous research has shown that individuals on the autism spectrum pay more attention to irrelevant elements on web pages than non-autistic individuals (Britto and Pizzolato, 2016; Eraslan et al., 2019; Yaneva, 2018). On page 3, participants in the control group seemed to be better able to exclude certain irrelevant visual elements or follow organizational cues. The TFF results show that the autistic group spent more time looking for the AOI, and NF and PF were lower than the

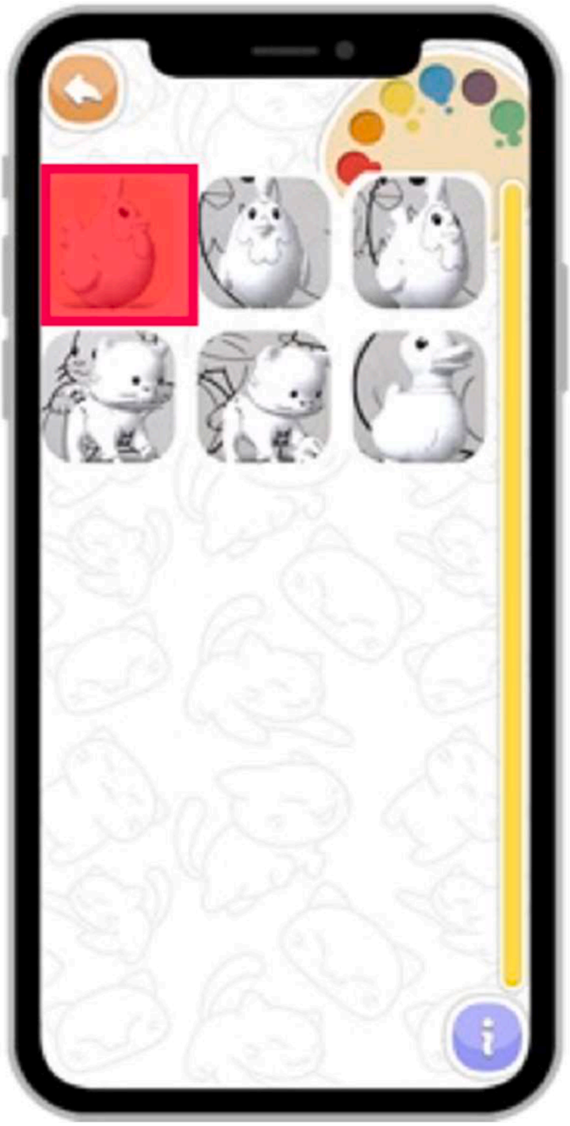

Fig. A.10. Target AOI - the picture.

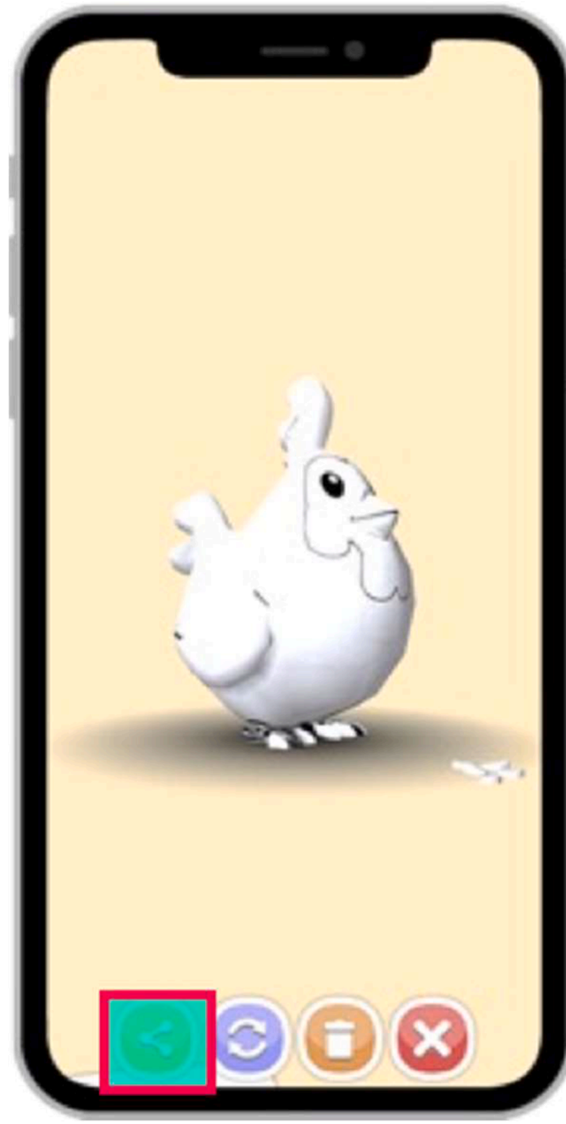

Fig. A.11. Sharing button.

control group. Combined with the user feedback, this can be interpreted that a richer interface with more information can cause children with autism to focus more on irrelevant elements, affecting their attention distribution and reducing the speed of information processing. Focusing on irrelevant elements may explain the poor performance of children with autism in this task. However, further work is needed to confirm this.

For the TFF on page 9, which has the same interface as page 3, no statistically significant differences were observed, and both groups were able to find the target area very quickly. We analyzed this as possible since the icons aided the ASD group's comprehension, allowing them to observe the target AOI more quickly. As can be seen in the heat map of Fig. 7, the ASD group focused more on the icons located on the left of the AOI. This finding validates that 1) icons can help children with ASD understand the task and search for the target area quickly, and 2) children with ASD prefer icons. Furthermore, this gaze distribution heat map supports, and 3) the autistic group focused more on irrelevant elements compared to the control group. In future designs, to improve the processing of interfaces for people with autism, consideration needs to be given to keeping screen elements simple and clear, avoiding extraneous background distractions, and making them more accessible to children with autism.

The results on pages 7 and 8 show that when looking for the target area on the same screen a second time, there was no significant difference between the two groups, although the NF and PF of the autistic group were still lower than those of the TD group. This suggests that under our research context, once children with autism understood the task and became familiar with the interface, they performed better and could even reach the same level of task search as the control group. However, this may not be the case for children with autism in other settings. No significant differences in TFF were found, suggesting that participants were able to operate the interface correctly in less time the second time they operated the same interface, regardless of whether they were TD or ASD children, indicating that, overall, the app was learnable and easy to operate.

On page five, both groups of participants showed statistically significant differences for larger effects on NF, TFF, and PF, reflecting the lower level of attention to this area in the autistic group. One reason is that the icon is not the common background photo icon. Our entire design is in a more child-appealing cartoon style, and the icons in the application interface are colored in a more rounded design. The rounded "picture" icon resulted in some participants with autism not being able to understand its meaning. We would modify this design as previous research on user interface design for people with autism has also shown

Fig. A.12. WeChat icon.

Fig. A.13. Confirm text and button.

that icons should be easily recognizable (Hussain et al., 2016; Raymaker et al., 2019). From the results of the questionnaire and feedback, we learned that the icons are small in shape and positioned downwards, which is also making it difficult for users with autism to search (Pavlov, 2014).

On the AOI “Share” on page 11, the TFF statistics show that the autistic group needed more time to observe because most children with autism did not recognize the icon. This is also evident from the feedback of parents and teachers during the experiment. Furthermore, the NF and PF data also showed statistical differences between the two groups, with the autistic group showing lower levels of attention on the “share” AOI, which also suggests that the AOI is not a commonly used icon, lacks meaning, does not capture the attention of children with autism, and is difficult to understand (Ehmke and Wilson, 2007; Yaneva et al., 2020). It may be easier for children with ASD to understand by replacing it with a “forward” icon with an arrow.

The autistic group showed significantly less PF on the WeChat AOI of page 12, and they focused more on irrelevant elements of the interface (Britto and Pizzolato, 2016; Rezae et al., 2020). There are icons on the page, such as “Add to Collection”, “Convert to PDF” and “Bluetooth”, which are difficult for ASD children to understand. The uncommon icons lack of meaning confuses them. In order to improve the processing of pages by children with autism, the interface should be designed with the involvement of children with autism, and iterative improvements should be performed. We will simplify the interface by setting up only one or two common applications to reduce distraction for children with autism.

During the experiment, there was no statistical difference between the two groups, although, in terms of the overall score, the ASD group ($M = 11.91$) had a lower success score in finding the correct information in a limited time than the control group ($M = 12.35$). The statistics for individual tasks also showed no significant difference between the two groups, suggesting that, overall, participants in both groups were able to understand the interface settings of the application and did not encounter greater barriers when interacting with it. Participants were less successful on tasks 2 and 4 than on tasks 1 and 2 because there were uncommon icons in the target area of tasks 2 and 4 that reduced the recognition rate. Moreover, the success rates of children with autism on the tasks improved to a great extent after they became familiar with the interface, which also indicated an increase in their information processing speed. Our app is easy to use, learnable, and can be understood more deeply by children with autism to some degree if there are no uncommon icons or other elements.

The user interface satisfaction questionnaire showed that the overall score for the autistic group was slightly lower than the control group. Participants were asked to answer the question “Reading characters on the screen" (0 = hard, 9 = easy) to give us an understanding of their perceptions of the textual design of the interface. The control group found it very easy to read the text on the screen, whereas the autistic group found it more challenging to read the text, possibly because children with ASD do not comprehend well and do not enjoy reading text themselves. Two children with ASD and one parent commented that there was "too much text on the menu pages", which also suggests that the autistic group was not very interested in long text or had difficulty perceiving it. Similarly, for the question "Terminology related to task" (0 = never, 9 = always), there was a significant difference in scores between the two groups. Some TD children reported that although they could understand the meaning of the interface, they "could add more text to describe the task". The assessment of scores for "Position of messages on screen" (0 = inconsistent, 9 = consistent) showed that the autistic group was more likely to find the text-picture setting confusing and that the long text setting affected the autistic group's understanding of the interface. There was feedback from autistic parents that "the icons in task 2 were somewhat small and less significantly positioned". In contrast, the control group perceived the picture-text setting to be more consistent and that the text-picture facilitated comprehension of each other. This supports the results of the eye-movement experiment that, in future user interfaces designed for children with autism, long text descriptions could be reduced, and meaningful icons could be used more.

Although there were significant differences, parents of ASD children reported that the app was easy to learn and use and that their children were proficient independently the second and third times around. In addition, children with ASD were more consistent in finding the "help" function of the system useful. In the experiment, one parent of a child with autism said that their child liked things with sound, and he was excited about the system and wished he could download the app to his phone. A participant in the control group commented that the system was fun but not very flexible and that more features could be developed. In addition, regarding the "System reliability", although both groups reported that the system was stable, we observed that the mobile device needed to be far away from the marker before the participants could scan the AR model. In addition, we found that most children can understand and operate the system more easily with the coordinator's task instructions, but when using the app independently, they are sometimes overwhelmed. The survey results have practical implications for the accessibility of the wARna interface for people with autism.

Based on the issues identified, there are changes we can make the app more suitable for children with autism, such as making the book smaller or creating a wall-mountable coloring board, adding voice guidance functions with voice prompts for actions to be taken (with the option to turn it off). Although the participants in this study are only a few representatives of a broad and diverse group of children with autism, they can help to illuminate what the researcher was unable to understand, and they may be more familiar with the experiences of others with similar conditions (Mankoff et al., 2010). In the future, we could develop more child-based materials or involve users in the design to enrich the user experience.

5.2. Impact on user interface accessibility

The discussion of the results in the previous section provides evidence of information-seeking strategies for children with ASD in the mobile application interface. In this section, within the context of this study, the following accessibility design recommendations are summarized for children with ASD:

Make key elements big: Consider the significant impact of the size and placement of elements within the UI on information capture for children with autism. It is crucial to make important elements, including buttons and interactive components, sufficiently large to attract their attention. Additionally, strategic positioning of these elements can facilitate intuitive navigation and interaction within the UI.

Minimize visual distractions: Acknowledge that complex interfaces can impact the information processing speed of children with autism. Strive for simplicity by minimizing the number of elements in the interface. This includes reducing visual distractions like an abundance of buttons, icons, or text, which can overwhelm children with autism. Prioritize a clean and uncluttered design that fosters ease of understanding.

Keep the text brief and concise: Recognize that children with autism generally prefer visual stimuli over textual information. Therefore, it is recommended to utilize simple and concise sentences to convey instructions or information. Emphasize the use of visual elements, such as images and icons, as they are more effective in communicating concepts and instructions, reducing the reliance on text.

Use clear and simple elements: Consider the confusion that unfamiliar or uncommon icons may cause for children with autism. Instead, priority should be given to clear and universally recognized icons that are easy to understand. To ensure that visual elements are clear and simple, it is beneficial to conduct usability tests with children with autism and their caregivers.

Provide customization options: Acknowledge that children with autism may have specific sensitivities and preferences. In order to meet their individual needs and promote a personalized and comfortable user experience, it is recommended that customization options be available within the application. This could include allowing users to adapt sound effects, visual settings, or other features to their preferences. By providing customization options, the app can be better adapted to the different sensory needs of children with autism, improving their overall engagement and usability.

Minimize auditory distractions: Recognize that excessive noise or loud auditory cues can be overwhelming for children with autism. Minimize the impact of auditory distractions and create a more comfortable user experience by reducing background noise or using gentle, non-intrusive sound cues where necessary. Ensure that the sounds chosen are soothing rather than overstimulating.

Include interactive features: Utilize augmented reality (AR) technology, simple games, or interactive tests in mobile apps to effectively engage children with autism. These interactive features stimulate curiosity, increase engagement, and provide opportunities for learning, skill development and enjoyment, creating a holistic and fulfilling experience for children with autism.

6. Limitations and future research

Given the heterogeneity of the population, the sample in this study does not reflect the general visual preferences of children with ASD for mobile AR applications, and more research should be conducted to provide conclusive evidence. Thirteen UIs of the wARna app were evaluated in the eye tracking study and all participants were able to cope with this number of pages and tasks. Future studies could use eye-tracking experiments to evaluate more mobile app UI pages with varying levels of content complexity in order to validate the findings of this study.

Another limitation of this study is the experimental setup. The real-world use of the interaction occurred on a mobile device, but since accurate eye-tracking technology is not yet available for mobile devices, screenshots of the mobile AR app wARna's interface, were displayed on a 22-inch widescreen monitor to measure the eye movement data of the participants. Factors such as screen size and actual interaction could influence the preferences of children with autism. On the other hand, the monitor magnifies the application interface elements, which may enable better control of the experimental conditions and maintain data consistency. Future research could attempt to restore the natural interaction environment while satisfying measurement accuracy. The suggested guidelines may be somewhat general, but provide a direction for research. In the future, more in-depth research on visual preferences could be carried out by cutting into one of these aspects.

Furthermore, using eye movements to study the effects of mobile AR systems on the interest and attention of users with children with autism may also be a promising direction. Future research can also try to access the eye movement data of children with autism when interacting with AR models. According to Eraslan et al. (2021), the legibility of mobile application interface elements may also be related to the visual complexity of the interface. Future research can be conducted focusing on the visual complexity of UI and investigating its relationship with the visual perception of children with autism to further contribute to the evolution of accessible UI for mobile AR applications.

7. Conclusion

Autism spectrum disorder is a developmental disability that affects communication and social interaction, and people with ASD have differences in attention, cognitive processing, and sensory integration from the TD population. Such characteristics may lead to peculiar modalities of visual preference and make it challenging for people with autism to interact with the user interface (UI) of technology products. Existing relevant research aims to develop mobile augmented reality intervention systems as well as evaluate usability. Some studies have evaluated the process of interacting with computer web pages for adults with autism, suggesting design guidelines to make web pages more accessible to them. However, gaps remain in evaluating the UI for mobile AR systems for children with autism.

In this study, we investigated the visual differences between children with autism and TD children when searching for information in mobile application interfaces and whether certain interface elements distracted participants with autism. We present an eye-tracking study involving 23 participants with children diagnosed with autism and 26 control participants with TD children. All participants were asked to view 13 interfaces of the mobile AR application across four tasks and find specific information or items on each interface.

We found that child participants with autism tend to look at more irrelevant visual elements and prefer visual stimuli such as icons to long text. The results also showed that visual stimulus elements not only captured the attention of the participants in the ASD group to a greater extent but also facilitated their comprehension of the task, and the size and position of icons, as well as uncommon icons, affected the processing speed of children with ASD. The QUIS and task success scores imply that the mobile AR coloring app was usable for both groups of participants, but children with ASD tended to adopt a different information-seeking strategy when processing the mobile app interface. Therefore, the user interface design and content need to be improved to better accommodate these differences. Based on the visual preferences of children with ASD, we made some suggestions to help design user interfaces that are more appropriate for them.

Overall, the visual processing differences obtained through the eye-movement experiment, QUIS results, and task success rate can provide practical insights into the UI design of mobile AR applications, effectively helping researchers to design or improve accessible mobile AR application UI for people with autism. The present study is one of the first to examine the interaction process of mobile interfaces in AR coloring apps using eye-tracking. We hope that future similar studies will benefit from this empirical study.

Author statement

XL conceived of the study, participated in the design and coordination of the study, performed analyses, and drafted the manuscript. MSS and QL conceived of the study, participated in its design, coordination, and analyses, and revised the manuscript. MKM participated in the design. All authors read and approved the final manuscript.

Informed consent

Informed consent was obtained from all individual participants included in the study.

CRediT authorship contribution statement

Xiaojie Lian: Conceptualization, Methodology, Investigation, Data curation, Visualization, Writing – original draft. **Mohd Shahrizal Sunar:** Supervision, Software, Validation, Conceptualization, Project administration, Writing – review & editing. **Qingqing Lian:** Investigation, Data curation, Writing – review & editing. **Mohd Khalid Mokhtar:** Software, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no conflict of interest.

Data availability

Data will be made available on request.

Appendix

Appendix A. Mobile app screens

Task 1 - Find “Help”. (Figs. A.1–A.3)

Task 2 - Take a picture of the AR animal, Change the background, and exit the current page. (Figs. A.4–A.6)

Task 3 - Find “my album”. (Figs. A.7–A.9)

Task 4 - Share the first picture to you WeChat friend then delete it. (Figs. A.10–A.13)

References

American Psychiatric Association, 2013. Diagnostic and Statistical Manual of Mental Disorders DSM-5.

Aguiar, Y.P.C., Galy, E., Godde, A., Trémaud, M., Tardif, C., 2022. AutismGuide: a usability guidelines to design software solutions for users with autism spectrum disorder. Behav. Inf. Technol. 41, 1132–1150. https://doi.org/10.1080/0144929X.2020.1856927.

Alessandrini, A., Cappelletti, A., Zancanaro, M., 2014. Audio-augmented paper for therapy and educational intervention for children with autistic spectrum disorder. Int. J. Hum. Comput. Stud. 72, 422–430. https://doi.org/10.1016/j.ijhcs.2013.12.001.

Axe, J.B., Evans, C.J., 2012. Using video modeling to teach children with PDD-NOS to respond to facial expressions. Res. Autism Spectr. Disord. 6, 1176–1185. https://doi.org/10.1016/j.rasd.2012.03.007.

Brandão, J., Cunha, P., Vasconcelos, J., Carvalho, V., Soares, F., 2015. An augmented reality gamebook for children with autism spectrum disorders. In: Proceedings of the International Conference on E-Learning in the Workplace. New York, New York, USA, pp. 1–6.

Britto, T., Pizzolato, E., 2016. Towards web accessibility guidelines of interaction and interface design for people with autism spectrum disorder. In: ACHI 2016: the ninth international conference on advances in computer-human interactions, pp. 1–7. https://doi.org/10.13140/RG.2.1.4881.0321.

Catani, M.B., Biers, D.W., 1998. Usability evaluation and prototype fidelity: users and usability professionals. In: Proceedings of the Human Factors and Ergonomics Society Annual Meeting, p. 19. https://doi.org/10.1177/154193129804201901.

Caldwell, B., Cooper, M., Reid, L.G., Vanderheiden, G., 2008. Web content accessibility guidelines 2.0. W3C. http://www.w3.org/TR/WCAG20/.

Chen, C.H., Lee, I.J., Lin, L.Y., 2015. Augmented reality-based self-facial modeling to promote the emotional expression and social skills of adolescents with autism spectrum disorders. Res. Dev. Disabil. 36, 396–403. https://doi.org/10.1016/j.ridd.2014.10.015.

Chien, M.-E., Jheng, C.-M., Lin, N.-M., Tang, H.-H., Taele, P., Tseng, W.-S., Chen, M.Y., 2015. iCAN: a tablet-based pedagogical system for improving communication skills of children with autism. Int. J. Hum. Comput. Stud. 73, 79–90, 10. 1016/j.ijhcs.2014.06.001.

Cohen, J., 1988. Statistical Power Analysis For the Behavioral Sciences, 2nd ed. Hillsdale, New Jersey.

Dalim, C.S.C., Dey, A., Piumsomboon, T., Billinghurst, M., Sunar, S., 2016. TeachAR: an interactive augmented reality tool for teaching basic english to non-native children. In: 2016 IEEE International Symposium on Mixed and Augmented Reality, pp. 82–86. https://doi.org/10.1109/ISMAR-Adjunct.2016.0046.

Dattolo, A., Luccio, F.L., 2017. Accessible and usablewebsites and mobile applications for people with autism spectrum disorders: a comparative study. EAI Endorsed Trans. Ambient Syst. 4 e510.4108/eai.17-5-2017.152549.

Dawson, G., Jones, E., Merkle, K., Venema, K., Lowy, R., Faja, S., Kamara, D., Murias, M., Greenson, J., Winter, J., 2012. Early behavioral intervention is associated with normalized brain activity in young children with autism. J. Am. Child Adolesc. Psychol. 51, 1150–1159. https://doi.org/10.1016/j.jaac.2012.08.018.

Ehmke, C., Wilson, S., 2007. Identifying web usability problems from eye-tracking data. In: BCS-HCI '07 Proceedings of the 21st British HCI Group Annual Conference on People and Computers: HCI...but Not as We Know It, pp. 119–128.

Eldevik, S., Hastings, R.P., Hughes, J.C., Jahr, E., Eikeseth, S., Cross, S., 2009. Meta-analysis of early intensive behavioral intervention for children with autism. J. Clin. Child Adolesc. Psychol. 38, 439–450. https://doi.org/10.1080/15374410902851739.

Eraslan, S., Yaneva, V., Yesilada, Y., Harper, S., 2017. Do web users with autism experience barriers when searching for information within web pages?. In: Proceedings of the 14th International Web for All Conference, pp. 1–4. https://doi.org/10.1145/3058555.3058566.

Eraslan, S., Yaneva, V., Yesilada, Y., Harper, S., 2019. Web users with autism: eye tracking evidence for differences. Behav. Inf. Technol. 38, 678–700. https://doi.org/10.1080/0144929X.2018.1551933.

Eraslan, S., Yesilada, Y., Yaneva, V., Ha, L.A., 2021. Keep it simple!": an eye-tracking study for exploring complexity and distinguishability of web pages for people with autism. Univers. Access Inf. Soc. 20, 69–84. https://doi.org/10.1007/s10209-020-00708-9.

Escobedo, L., Nguyen, D.H., Boyd, L.E., Hirano, S.H., Rangel, A., Garciarosas, D., Tentori, M., Hayes, G.R., 2012. MOSOCO: a mobile assistive tool to support children with autism practicing social skills in real-life situations. In: Proceedings of the SIGCHI conference on human factors in computing systems, pp. 2589–2598. https://doi.org/10.1145/2207676.2208649.

Escobedo, L., Tentori, M., Quintana, E., Favela, J., Garciarosas, D., 2014. Using augmented reality to help children with autism stay focused. IEEE Pervas. Comput 13, 38–46. https://doi.org/10.1109/MPRV.2014.19.

Follet, B., Le Meur, O., Baccino, T., 2011. New insights into ambient and focal visual fixations using an automatic classification algorithm. iPercept 2, 592–610. https://doi.org/10.1068/i0414.

Frazier, T.W., Youngstrom, E.A., Speer, L., Embacher, R., Law, P., Constantino, J., Findling, R.L., Hardan, A.Y., Eng, C., 2012. Validation of proposed DSM-5 criteria for autism spectrum disorder. J. Am. Child Adolesc. Psychol. 51 https://doi.org/10.1016/j.jaac.2011.09.021, 28-40.e23.

Friedman, M.G., Bryen, D.N., 2007. Web accessibility design recommendations for people with cognitive disabilities. Technol. Disabil. 19, 205–212. https://doi.org/10.3233/TAD-2007-19406.

Harper, S., Yesilada, Y., 2008. Web Accessibility: a Foundation For Research. Springer.

Hussain, A., Abdullah, A., Husni, H., Mkpojiogu, E., 2016. Interaction design principles for edutainment systems: enhancing the communication skills of children with autism spectrum disorders. Rev. Téc. Ing. Univ. Zulia. 8, 45–50, 10.21311/001.39.8.06.

Hobson, R.P., 2019. Autism and the Development of Mind. Routledge.

Ismail, A.W., Sunar, M.S., 2015. Multimodal fusion: gesture and speech input in augmented reality environment. In: Computational Intelligence in Information Systems: Proceedings of the Fourth INNS Symposia Series on Computational Intelligence in Information Systems, pp. 245–254. https://doi.org/10.1007/978-3-319-13153-5_24.

Kamaruzaman, M.F., Rani, N.M., Nor, H.M., Azahari, M., 2016. Developing user interface design application for children with autism. Procedia - Soc. Behav. Sci. 217, 887–894. https://doi.org/10.1016/j.sbspro.2016.02.022.

Kao, Y.M., Chiang, X.Z., Foulsham, T., 2019. Reading behavior and the effect of embedded selfies in role-playing picture e-books: an eye-tracking investigation. Comput. Educ. 136, 99–112. https://doi.org/10.1016/j.compedu.2019.03.010.

Keshav, N.U., Salisbury, J.P., Vahabzadeh, A., Sahin, N.T., 2017. But will they even wear it? Exploring the tolerability of social communication coaching smartglasses in children and adults with autism. JMIR Mhealth. Uhealth. 5, e140. https://doi.org/10.2196/mhealth.8534.

Khowaja, K., Salim, S.S., 2013. A systematic review of strategies and computer-based intervention (CBI) for reading comprehension of children with autism. Res. Autism. Spectr. Disord. 7, 1111–1121. https://doi.org/10.1016/j.rasd.2013.05.009.

Kwon, M.K., Moore, A., Barnes, C.C., Cha, D., Pierce, K., 2019. Typical levels of eye-region fixation in toddlers with autism spectrum disorder across multiple contexts. J. Am. Acad. Child Adolesc. Psychiatry. 58, 1004–1015. https://doi.org/10.1016/j.jaac.2018.12.011.

Lee, I.J., Chen, C.-H., Wang, C.-P., Chung, C.-H., 2018. Augmented reality plus concept map technique to teach children with ASD to use social cues when meeting and greeting. Asia-Pac. Educ. Research. 27, 227–243. https://doi.org/10.1007/s40299-018-0382-5.

Lee, I.J., 2020. Kinect-for-windows with augmented reality in an interactive roleplay system for children with an autism spectrum disorder. Interact. Learn. Environ. 29, 688–704. https://doi.org/10.1080/10494820.2019.1710851.

Lee, I.J., 2019. Augmented reality coloring book: an interactive strategy for teaching children with autism to focus on specific nonverbal social cues to promote their social skills. Interact. Stud. 20, 256–274. https://doi.org/10.1075/is.18004.lee.

Lian, X., Sunar, M.S., 2021. Mobile augmented reality technologies for autism spectrum disorder interventions: a systematic literature review. Appl. Sci. 11, 4550. https://doi.org/10.3390/app11104550.

Lopez-Herrejon, R.E., Poddar, O., Herrera, G., Sevilla, J., 2020. Customization support in computer-based technologies for autism: a systematic mapping study. Int. J. Hum-Comput. Int. 36, 1273–1290. https://doi.org/10.1080/10447318.2020.1731673.

Lorenzo, G., Gómez-Puerta, M., Arráez-Vera, G., Lorenzo-Lledó, A., 2019. Preliminary study of augmented reality as an instrument for improvement of social skills in children with autism spectrum disorder. Educ. Inf. Technol. 24, 181–204. https://doi.org/10.1007/s10639-018-9768-5.

Mankoff, J., Hayes, G.R., Kasnitz, D., 2010. Disability studies as a source of critical inquiry for the field of assistive technology. In: Proceedings of the 12th international ACM SIGACCESS conference on Computers and accessibility, pp. 3–10. https://doi.org/10.1145/1878803.1878807.

Mazon, C., Fage, C., Sauzéon, H., 2019. Effectiveness and usability of technology-based interventions for children and adolescents with ASD: a systematic review of reliability, consistency, generalization and durability related to the effects of intervention. Comput. Hum. Behav. 93, 235–251. https://doi.org/10.1016/j.chb.2018.12.001.

Mcconnell, S.R., 2002. Interventions to facilitate social interaction for young children with autism: review of available research and recommendations for educational intervention and future research. J. Autism Dev. Disord. 32, 351–372. https://doi.org/10.1023/A:1020537805154.

Mintz, Joseph, 2013. Additional key factors mediating the use of a mobile technology tool designed to develop social and life skills in children with Autism Spectrum Disorders: evaluation of the 2nd HANDS prototype. Comput. Educ. 63, 17–27. https://doi.org/10.1016/j.compedu.2012.11.006.

Mokhtar, M.K., Mohamed, F., Sunar, M.S., Arshad, M.A.M., Sidik, M.K.M., 2018. Development of mobile-based augmented reality colouring for preschool learning. In: Proceedings of the IEEE Conference on e-Learning, e-Management and e-Services (IC3e).

Noor, H.A.M., Shahbodin, F., Pee, N.C., 2012. Serious game for autism children: review of literature. In: Proceedings of World Academy of Science, Engineering and Technology. World Academy of Science, Engineering and Technology. https://doi.org/10.5281/zenodo.1333272.

Pallant, J., 2020. SPSS Survival Manual: A step By Step Guide to Data Analysis Using IBM SPSS, 5th ed. Berkshire, England.

Pavlov, N., 2014. User interface for people with autism spectrum disorders. J. Softw. Eng. Appl. 2014 https://doi.org/10.4236/jsea.2014.72014.

Pennisi, P., Tonacci, A., Tartarisco, G., Billeci, L., Ruta, L., Gangemi, S., Pioggia, G., 2016. Autism and social robotics: asystematic review. Autism. Res. 9, 165–183. https://doi.org/10.1002/aur.1527.

Pierce, K., Marinero, S., Hazin, R., Mckenna, B.S., Barnes, C.C., Malige, A., 2016. Eye tracking reveals abnormal visual preference for geometric images as an early biomarker of an autism spectrum disorder subtype associated with increased symptom severity. Biol. Psychiatry. 79, 657–666. https://doi.org/10.1016/j.biopsych.2015.03.032.

Putnam, C., Chong, L., 2008. Software and technologies designed for people with autism. In: Proceedings of the 10th International ACM SIGACCESS Conference on Computers and Accessibility - Assets '08. ACM Press, New York, USA. https://doi.org/10.1145/1414471.1414475. New Yorkpp. 3.

Quill, K.A., 1997. Instructional considerations for young children with autism: the rationale for visually cued instruction. J. Autism Dev. Disord. 27, 697–714. https://doi.org/10.1023/A:1025806900162.

Ramakrisnan, P., Jaafar, A., Razak, F., Ramba, D., 2012. Evaluation of user interface design for leaning management system (LMS): investigating student's eye tracking pattern and experiences. Procedia - Soc. Behav. Sci. 67, 527–537. https://doi.org/10.1016/j.sbspro.2012.11.357.

Ramdoss, S., Lang, R., Mulloy, A., Franco, J., O'Reilly, M., Didden, R., Lancioni, G., 2011. Use of computer-based interventions to teach communication skills to children with autism spectrum disorders: a systematic review. J. Educ. Behav. 20, 55–76.

Raymaker, D.M., Kapp, S.K., McDonald, K.E., Weiner, M., Ashkenazy, E., Nicolaidis, C., 2019. Development of the AASPIRE web accessibility guidelines for autistic web users. Autism Adulth. 1, 146–157. https://doi.org/10.1089/aut.2018.0020.

Rezae, M., Chen, N., McMeekin, D., Tan, T., Krishna, A., Lee, H., 2020. The evaluation of a mobile user interface for people on the autism spectrum: an eye movement study. Int. J. Hum. Comput. Stud. 142, 102462 https://doi.org/10.1016/j.ijhcs.2020.102462.

Robertson, C.E., Baron-Cohen, S., 2017. Sensory perception in autism. Nat. Rev. Neurosci. 18, 671–684. https://doi.org/10.1038/nrn.2017.112.

Robertson, A.E., Simmons, D.R., 2013. The relationship between sensory sensitivity and autistic traits in the general population. J. Autism Dev. Disord. 43, 775–784. https://doi.org/10.1007/s10803-012-1608-7.

Singh, K., Shrivastava, A., Achary, K., Dey, A., Sharma, O., 2019. Augmented reality-based procedural task training application for less privileged children and autistic individuals. In: Proceedings of the International Conference on Virtual-Reality Continuum and Its Applications in Industry. Brisbane, QLD, Australia, pp. 14–16. https://doi.org/10.1145/3359997.3365703.

Spiel, K., Gerling, K., Bennett, C.L., Brulé, E., Williams, R.M., Rode, J., Mankoff, J., 2020. Nothing about us without us: investigating the role of critical disability studies in HCI. In: Extended Abstracts of the 2020 CHI Conference on Human Factors in Computing Systems, pp. 1–8. https://doi.org/10.1145/3334480.3375150.

Stone, D., Jarrett, C., Woodroffe, M., Minocha, S., 2014. User Interface Design and Evaluation. 1st ed.

Sun, Q.C., Xia, J.C., Nadarajah, N., Falkmer, T., Lee, H., 2016. Assessing drivers' visual-motor coordination using eye tracking, GNSS and GIS: a spatial turn in driving psychology. Spat. Sci. 61, 1–18. https://doi.org/10.1080/14498596.2016.1149116.

Takacs, Z.K., Swart, E.K., Bus, A.G., 2015. Benefits and pitfalls of multimedia and interactive features in technology-enhanced storybooks: a meta-analysis. Rev. Educ. Res. 85, 698–739. https://doi.org/10.3102/0034654314566989.

Tang, T.Y., Xu, J., Winoto, P., 2019. An augmented reality-based word-learning mobile application for children with autism to support learning anywhere and anytime: object recognition based on deep learning. In: Proceedings of HCII: Universal Access in Human-Computer Interaction. Multimodality and Assistive Environments, pp. 182–192. https://doi.org/10.1007/978-3-030-23563-5_16.

Taryadi, Kurniawan, I., 2018. The improvement of autism spectrum disorders on children communication ability with PECS method Multimedia Augmented Reality-Based. J. Phys. Conf. Ser. 947, 012009 https://doi.org/10.1088/1742-6596/947/1/012009.

Vahabzadeh, A., Keshav, N.U., Salisbury, J.P., Sahin, N.T., 2018. Improvement of attention-deficit/hyperactivity disorder symptoms in school-aged children, adolescents, and young adults with autism via a digital smartglasses-based socioemotional coaching aid: short-term, uncontrolled pilot study. JMIR Ment. Health 5. https://doi.org/10.2196/mental.9631 e25.

Williams, R.M., Gilbert, J.E., 2020. Perseverations of the academy: a survey of wearable technologies applied to autism intervention. Int. J. Hum. Comput. Stud. 143, 102485 https://doi.org/10.1016/j.ijhcs.2020.102485.

Williams, R.M., Alikhademi, K., Gilbert, J.E., 2022. Design of a toolkit for real-time executive function assessment in custom-made virtual experiences and interventions. Int. J. Hum. Comput. Stud. 158, 102734 https://doi.org/10.1016/j.ijhcs.2021.102734.

Yaneva, V., 2018. Autism and the web: using web-searching tasks to detect autism and improve web accessibility. SIGACCESS Access. Comput. 2 https://doi.org/10.1145/3264631.3264633, 1–2:1.

Yaneva, V., Ha, L.A., Eraslan, S., Yesilada, Y., 2019. Adults with high-functioning autism process web pages with similar accuracy but higher cognitive effort compared to controls. In: Proceedings of the 16th International Web for All Conference, pp. 1–4. https://doi.org/10.1145/3315002.3317563.

Yaneva, V., Le, A.H., Eraslan, S., Yesilada, Y., Mitkov, R., 2020. Detecting high-functioning autism in adults using eye tracking and machine learning. IEEE Trans. Neural Syst. Rehabil. Eng. 28, 1254–1261. https://doi.org/10.1109/TNSRE.2020.2991675.

Yaneva, V., Temnikova, I., Mitkov, R., 2015. Accessible texts for autism: an eye-tracking study. In: Proceedings of the 17th International ACM SIGACCESS Conference on Computers & Accessibility (ASSETS '15). New York, NY, USA. ACM, pp. 49–57. https://doi.org/10.1145/2700648.2809852.

Yusof, C.S., Bai, H., Billinghurst, M., Sunar, M.S., 2016. A review of 3D gesture interaction for handheld augmented reality. J. Teknol 78, 2. https://doi.org/10.11113/jt.v78.6923. -2.