Effect of sensory-based technologies on atypical sensory responses of children with Autism Spectrum Disorder: A systematic review

LINGLING DENG

University of Nottingham Ningbo China

PRAPA RATTADILOK

University of Nottingham Ningbo China

GABRIELLE SAPUTRA HADIAN

University of Nottingham Ningbo China

HAOYANG LIU

University of Nottingham Ningbo China

ABSTRACT

Atypical sensory responses are one of the most common issues observed in Autism Spectrum Disorder (ASD), affecting the development of a child's capability for social interaction, independent living and learning. In the past two decades, there has been a growing number of studies of technology-based interventions for atypical sensory responses of individuals with ASD. However, their effects and limitations have not been fully examined. This systematic review investigates the effects of sensory-based technologies (SBTs) on atypical sensory responses of children with ASD. Publications that report on the use of a SBT as an intervention tool were retrieved from four academic databases: "PubMed", "IEEE Xplore", "ACM Digital Library" and "Web of Science". The search finally yielded 18 articles. The results indicated an emerging trend of studies investigating the effects of SBTs on atypical sensory responses over the past decade. Challenges and limitations were found in studies, mainly because the literatures adopted different methods and indicators, small sample sizes, and varying experimental designs. Findings were that the use of SBTs could effectively improve auditory and visual recognition, and some other behavioural outcomes such as attention in children with ASD. Future development of SBTs could further integrate more advanced techniques, such as machine learning, in order to widen the scope of SBTs usage to help more ASD children.

CCS CONCEPTS • Human-centered computing~Accessibility~Accessibility technologies • Applied computing~Life and medical sciences~Health informatics • Social and professional topics~User characteristics~People with disabilities

Additional Keywords and Phrases: Autism Spectrum Disorder, sensory-based technology, atypical sensory responses, systematic review

1 INTRODUCTION

1.1 Atypical sensory responses in Autism Spectrum Disorder

Autism Spectrum Disorder (ASD) is a neurological and developmental disorder, beginning early in childhood and lasts throughout an individual's life [25]. Sensory processing impairments, often displayed as atypical sensory responses to stimuli, are one of the most common issues observed in ASD and have been incorporated into most systems for the diagnosis of ASD [36, 37]. Evidence from previous studies suggests that atypical sensory responses affect more than 90 percent of individuals with ASD [30, 48]. According to the Diagnostic and Statistical Manual of Mental Disorders [2], atypical sensory responses in ASD involve hyper-or hypo-sensitiveness to sensory input or unusual interest in sensory aspects of the environment. The behavioural output of atypical sensory responses could be very different across individuals with ASD. Clinical data indicated that having difficulty paying attention, appearing to not listen when being spoken to, and seeking sensory input yielded the highest frequencies of atypical sensory responses in the ASD group [48]. There are some other important atypical sensory features of ASD that are easily neglected, which include difficulties in coping with novel situations, circumscribed interests, and problems of distractibility and behaviour control [19]. For example, the distress caused by sensory stimuli may lead to self-injurious and aggressive behaviours in children with ASD [22]. Atypical sensory responses are usually manifested quite early in the development process of children with ASD, for example, by 9 to 12 months of age [5], profoundly affecting the development of a child's capability for social interaction and participation, self-regulation, independent living and learning in the long term.

Despite the overwhelming prevalence of atypical sensory responses in ASD, less attention was paid to sensory-related issues compared to other developmental problems in ASD [48]. One possible barrier in addressing the issue would be that sensory processing is complex and idiosyncratic in individuals with ASD, which would require highly customised solutions. Previous research efforts have endeavoured to develop sensory interventions targeting the sensory problems in children with ASD. Over the past decades, dominant interventions to help ASD children enhance their sensory ability and self-regulation include clinic-based, child-centred sensory integration therapy [8]; followed by school-based, teacher-directed approaches and home-based, parent-mediated interventions such as serious game, music therapy, and massage. These interventions to address atypical sensory responses should be requested by caregivers of children with ASD through professional services. However, in many areas, especially in remote regions of developing countries, there are still very limited services to support the sensory experience in ASD [12]. In addition to conventional therapy methods, researchers and practitioners have made efforts to change and improve this situation by promoting collaborations among technology developers, engineers, and various stakeholders in the ASD community [7]. Technology-based intervention methods have been widely adopted in order to provide effective, accessible and inclusive solutions for families of children with ASD.

1.2 Technology-based interventions for atypical sensory responses in ASD

With the rapid development and innovation of healthcare technologies, there has been a growing number of studies on technology-based interventions for individuals with ASD. Technology-based interventions have been designed to work on diverse aspects of daily lives affected by the disorder, which range from the most basic aspect, such as sensing of the environment, to socialising with others. Although using innovative technologies as supporting tools have become a trend in ASD research, previous literature on the technologies have indicated that most technologies for ASD intervention concentrated mainly on physio-social activities such as communication and social cognition, whilst only a handful have targeted improvements in atypical sensory responses [3, 6, 22]. Nevertheless, over the past two decades, innovative sensory-based technologies have increasingly emerged to assist ASD children in utilising different sensory modalities. Advanced sensing technologies and enhanced computing capabilities have contributed to the increasing utilisation of sensors in technologies for addressing atypical sensory responses. For example, as part of the interventions, wearable devices such as smart glasses were found to be effective in improving the sensory ability of individuals with ASD by providing real time feedback [6]. In addition to wearable devices, there was an upsurge of interest in exploring the role of robots in ASD therapies, as robots are usually equipped with interesting characteristics such as human-like appearance, sensors and prompts that make them useful as tools to help children with ASD to sense, imitate, and interact [12].

Although technologies targeting atypical sensory responses serve a more and more important role in interventions for ASD nowadays, their effects and limitations have not been fully understood. Therefore, the aim of this study is to review the technologies that have been used as interventions that target atypical sensory responses in ASD and to analyse their efficacy. However, there is a lack of clear definition and classification for these technologies designed specifically to address atypical sensory responses in ASD. “Sensory device”, “sensor technology”, “sensing technology” are some of the general descriptions and categories [24, 44], which may hinder the literature review from locating relevant articles by keyword search. In order to lead onto clearer research questions and protocol for the systematic review, the researchers tend to use the term “sensory-based technologies” (SBTs) in this study to specify the technology-based interventions for atypical sensory responses in ASD.

1.3 Defining sensory-based technologies

Aligned with the basic definition of sensory devices, SBT in this study refers to the technologies that are designed to work on one or more sensory modalities (i.e. audition, touch, smell, taste, and vision) to address ASD individuals’ atypical sensory responses by controlling sensory stimuli [12]. To serve this purpose, early standard SBTs are usually embedded with sensors, signal processing components and user interface. Sensors receive information about an object and transform it into electrical signals, which will be processed by the signal processing components [44]. The user interface allows effective operation and control of the device from the users’ end. Early prototypes include listening devices to augment sound and filter background noise for children with ASD [42]. With the rapid evolution of smart devices, SBTs can be easily built on off-the-shelf mobile devices which equipped with a range of built-in sensors and microprocessors. Benefiting from smart computing technologies such as Internet of Things (IoTs) and machine learning, SBTs nowadays employ intelligent capabilities to facilitate identification of issues, self-assessment and self-regulation functions which early standard SBTs do not [44].

Due to the novelty and interdisciplinary nature of SBTs in ASD interventions, most literature tend to focus more on the feasibility and potential of the technology than its effect [17]. Small number of participants in individual studies usually made it hard to generalise results for demonstrating the effectiveness of the technology [17, 23]. In order to obtain insights into the effects of SBTs in helping ASD children with their atypical sensory issues, the researchers proposed to conduct this systematic review following the PRISMA Statement

[28], a guideline to gauge the quality of a systematic review. This systematic review has the following specific research questions:

1. What SBTs have been used as interventions that impact sensory processing in ASD with children?
2. What is the efficacy of the SBTs in helping with sensory processing in ASD children?
3. Apart from impacts on sensory processing, what other outcomes (on children with ASD) are obtained by the application of SBTs?

2 METHODS

Researchers conducted a systematic literature search in four online academic databases covering the areas of the research topic: (1) “PubMed” which covers publications in medical and life sciences; (2) “IEEE Xplore” which covers publications in electrical engineering, computer science and electronics; (3) “ACM Digital Library” which covers publications in computer science; and (4) “Web of Science” which contains publications across multiple disciplines, including numerous proceeding papers submitted to international conferences. Only articles that were peer-reviewed and published after 2000 were included in order to gain a comprehensive and most recent understanding of the research topic.

2.1 Search strategy

Keywords were used to search and locate the most relevant articles. Boolean operators were used to combine the possible search terms in order to locate as many relevant articles as possible. As agreed by all researchers, the final search string was: (Autism OR Autistic OR “ASD” OR "Autism Spectrum Disorder") AND ("sensory based technology" OR "sensor technology" OR "sensing technology" OR smartphone OR wearable OR application OR sensor OR device OR mobile) AND ("sensory processing" OR "sensory modulation" OR "sensory regulation" OR sensation OR audition OR auditory OR vision OR visual OR touch OR tactile OR haptic OR oral OR taste OR olfactory OR smell). Filters were applied in the initial search to include peer-review papers only. Following the initial search, one researcher conducted the screening of the articles’ title and abstracts for primary inclusion. Thereafter, two independent researchers read the full text of included articles to determine eligibility based on the exclusion and inclusion criteria. Other resources include seven clinical trials retrieved from the “Cochrane Library”, a leading database for systematic reviews in healthcare [10]. The researchers also searched the reference sections of these eligible articles in order to find more resources. Decisions as to which of these resources were to be included were settled by discussion and consensus between the two researchers and then validated by the third researcher.

2.2 Selection criteria

Both exclusion and inclusion criteria were applied at different stages of the search. Articles written in English and published in a peer-reviewed journal or in conference proceedings from or after 2000 were included. The participants of each study were checked, so that only studies that examined the effects on ASD individuals were primarily included. Studies were included if the sample involved children under the age of 18 who had been diagnosed with ASD. Besides, the technology used in the included article must be for intervention purposes and should conform to the definition of SBT, that is, the technology should be designed to deal with ASD children’s sensory issues with audition, touch, smell, taste, or vision by controlling or affecting sensory stimuli. Correspondingly, studies that did not meet the inclusion criteria or were irrelevant to the research were excluded. For example, an article should be excluded if it only discussed the design and test of the technology but did not examine the effect on a particular sensory issue. Articles that used technology as a diagnosis tool or merely for assessment were excluded as well.

2.3 Data extraction and analysis

Two researchers independently extracted characteristics of eligible studies, including general information on technology, participants, targeted sensory modalities, experiment design, measures, as well as key findings. A "Characteristics of Included Studies" table (Table 1) was used for recording the descriptive information extracted from all included studies. Quantitative and qualitative data extracted from included studies were managed in Review Manager Version 5.3 [34], a software mainly used to support preparing and maintaining systematic review, for data analyses.

Based on the data extracted, the researchers noticed a diversity in study designs and outcome measures. Firstly, not all studies employed control group designs. Most of the studies only did the experiment on children with ASD and other developmental disorders (DD) (n = 14), whilst a few studies made comparison between ASD/DD group and another control group of children without ASD (n=4). Secondly, since atypical sensory responses include a variety of symptoms, different studies usually have different focuses which make the outcome measures vary from one study to another. Tools used in the literature for the outcome measures range from Children's Auditory Performance Scale (C.H.A.P.S.), Aberrant Behaviour Checklist (ABC), Child Behaviour Checklist (CBCL), to a number of self-defined assessment tools (e.g. questionnaires). Due to heterogeneity in study designs and outcome measures reported, it was unlikely to perform meta-analysis over all studies. Data analyses and comparisons were made by structured and thematical review using both quantitative and qualitative data. For those single-subject studies which adopt pre-post or ABAB (alternating no-intervention and intervention trials) design, the researchers opted to use the statistical data from ASD groups. Means, standard deviations (SD) and number of ASD participants in pre-intervention trials and post-intervention trials from studies with same measures were entered into the Review Manager for computing the mean difference and effect size for outcomes. This will have data from typically developing (TD) groups excluded from statistical analyses, however, comparison between ASD and TD groups will be made descriptive to probe into the effect of SBTs on corresponding sensory symptoms in ASD.

Before implementing the statistical analysis, the methodological quality of included studies was examined by two independent researchers using the Single-Case Experimental Design (SCED) Scale [47]. The reason to choose this rating scale is that, currently a number of SBTs studies where ASD participants were involved did not employed a randomised controlled trial (RCT). Due to limited sample size and high diversity in patient characteristics, most included studies employed the single-subject design instead. SCED Scale is an 11-item rating scale which was developed for evaluating the reliability of single-subject experiments [47]. The purpose of the quality assessment was to facilitate the understanding of potential limitations and enhance the validity of results, so the quality assessment will not exclude any article from the review.

3 RESULTS

After removing duplicates and papers that are abstract-only or are published in a language other than English, a total of 3355 studies were identified, and 3271 were excluded after screening the title and abstract.

The remaining 84 articles were assessed by reading the full texts, and 18 studies were finally included in this review. Figure 1 provides detailed information about the results and selection criteria at each stage.

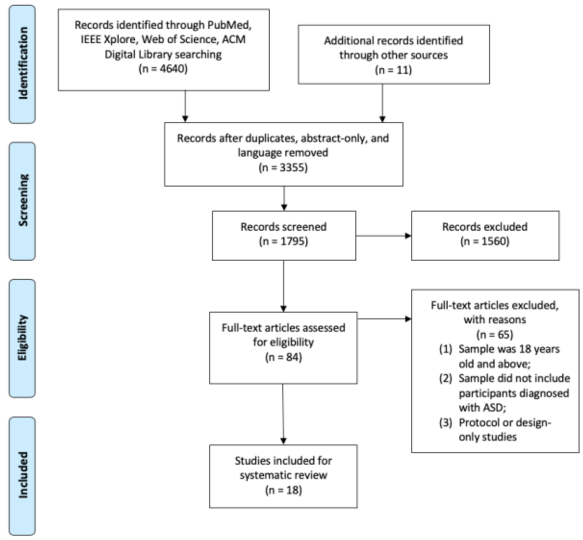

Figure 1: PRISMA flow diagram of search results (Latest search date: 31 April 2021)

All included studies used specific SBT as an intervention tool for children who had been diagnosed as ASD. Table 1 describes authors, publication years, use of technologies, sample, experiment design, measures and findings of each of the studies. The first study identified dates back to 2002 and 16 out of the 18 studies were published in or after 2010, which indicates an emerging trait of studies investigating the effect of SBTs on ASD children over the past decade.

3.1 Study quality

As shown in Table 2, 16 quantitative studies were assessed by using the SCED Scale; Whilst two articles were considered as observational and were not included in the quality assessment as they did not suit the criteria for the assessment tool. Most of the studies included have provided critical demographical and clinical information of the research subject (n=13). All studies identified a precise repeatable and operationally defined target behaviour. Although most quantitative studies statistically compared the results over the study phases (n=13), three studies provided processed data merely, rather than complete raw data. Two studies were lacking clinical history, baseline information, independence of assessors and statistical results, therefore scored the lowest among all studies appraised using the SCED Scale. Additionally, the majority of studies failed to demonstrate the functional utility of the intervention in extending beyond the target behaviour or intervention environment into other areas of the individual's life. Overall, most studies assessed by SCED present a moderate to high methodological quality. 12 articles were rated from a score of 7 to a maximum score of 10. However, there are four articles scored lower than 7, indicating challenges and limitations still existed in some studies on SBTs for children with ASD.

3.2 Use of SBTs

This section presents the usage of SBTs in previous studies by categories to answer research question 1: what SBTs have been used as interventions that impact sensory processing in ASD with children? The range of SBTs among studies is diverse, containing listening devices, robots, augmented reality (AR) devices, computer-assisted applications, tactile prompting devices, IoTs, and multimodal systems (see Table 1). Around one forth (27.8%, n=5) of the included studies used listening devices for the improvement of auditory processing difficulties of children with ASD. The listening devices used include ear-level remote-microphone devices, and classroom amplification systems. Schafer et al. [38, 39, 40] conducted a series of investigations using a remote-microphone device. The device consists of a sound sensor, a transmitter and a receiver, to enable the voice of the teacher to be sent directly to the children with ASD in class. Following the initial pilot study by Schafer et al. [39], Rance et al. [33] tested the remote-microphone device on a larger sample to evaluate the effects on children with ASD. Rance et al. [32] further compared the effects of the remote-microphone device with another SBT intervention, a classroom amplification system, which amplifies sound signal via strategically placing loudspeakers in the listening space.

Around one forth (27.8%, n=5) of the included studies used social robots as assistive tools which give affective stimuli to children to reduce the atypical sensory responses of children with ASD. One widely-used social robot is NAO. NAO robot is a humanoid and programmable robot equipped with cameras, microphones and tactile sensors [43]. A recent study conducted by Ali et al. [1] programmed NAO to give three different kinds of sensory stimuli (i.e. visual, auditory and motion) to engage children with ASD. KASPAR is another child-sized humanoid robot equipped with tactile sensors [11]. Costa et al. [11] designed interactions between a KASPAR robot and eight boys diagnosed with ASD. Another study used a facial display robot (FACE) which equips with an eye tracking and facial expression recognition system to track the subjects' attention towards the robot [31]. Giannopulu [15] conducted a pilot study with five children with ASD using a movable animal-shaped robot (POL) to incite the child to engage in interaction and express language. Another study conducted by Arpaia et al. [4] employed a robotic therapy in their study using a SanBot Elf robot. Similar to the previous study conducted by Giannopulu [15], the purpose of the robot was to provide movement cues. In addition to the robotic intervention, Arpaia et al. [4] employed AR smart glasses to render the visual stimuli, and a wearable Brain-Computer Interface (BCI) to monitor brain activities of children with ASD in the therapy. AR technologies are becoming popular for ASD interventions due to its advantages of creating controlled and real environments, which helps researchers understand how children with ASD are challenged by a sensory overload and aversion to a variety of visual and tactile stimuli [3]. Another study conducted by Liu et al. [26] used AR smart glasses to help children with ASD with emotional understanding, face directed-gaze, eye contact and self-control.

Four studies worked on computer-assisted applications, which are designed to be used on computers, tablets or mobile telephones. Main purpose of these applications is to enhance ASD children's sensitivity and attention to a variety of stimuli and tasks. An audiovisual speech perception application (Listening to Faces) was designed by Irwin et al. [20] to improve ASD children's perceptual sensitivity to speech by presenting monosyllabic words in varying levels of auditory noise. SIGUEME is a mobile application for sensory training which consists of six phases with different exercises at each phase, ranging from gathering visual attention to classification games [49]. Besides, Mir and Khosla [27] developed a Kinect-based counting game to provide sensory training to children with ASD. A more recent study conducted by Hu et al. [18] used a personal computer

(PC) laptop and a Leap Motion controller to develop a visual matching game for children with ASD and other developmental disorders.

Other SBT solutions reported in the literature include a tactile prompting device, an IoT-based system, and a multimodal system. The tactile prompting device can be placed in the participant's pocket and vibrate when activated by a remote control, which acts as an unobtrusive prompt to increase ASD children's responses to social interactions initiated by their TD peers [41]. IoT is a type of Internet application which enables the sharing of information on a global scale, and thus becomes popular in health informatics. The IoT-based system designed by Sula et al., [46] can monitor the sensory environment around children with ASD and send information about the children state in real time to therapists using Peer to Peer (P2P) technology and also allow children to interact with their friends and parents. Ringland et al. [35] designed a multimodal sensory system which combines sensor technologies with traditional sensory integration therapies in order to augment traditional therapies and balance children's attention between sensory stimuli and their own bodies. The system has tangible interfaces which provide auditory and visual stimuli and allow children to paint on a large display to reduce their symptoms of atypical sensory responses.

3.3 Reported efficacy of the SBTs

Research using listening devices demonstrated that the technology significantly enhanced the children's capability of auditory recognition [32, 33, 38, 39, 40]. Rance et al. [32, 33] identified that remote-microphone systems not only reduced physiological stress levels but also ameliorated listening performance, increasing ASD children's responses for the speaker's voice in class. This result is consistent with studies conducted by Schafer and colleagues in 2013, 2016 and 2019, which used similar remote-microphone systems to help ASD children sense auditory stimuli. Data from 21 pre- and post-intervention events in studies by Schafer et al. [39, 40] were recorded and the overall result showed a large effect size ($z = 6.98$, $p < 0.00001$), reinforcing the evidence for the effectiveness of the SBT on auditory recognition. The most recent study conducted by Schafer et al. [38] also demonstrated same findings. In addition to listening devices, Irwin et al. [20] evaluated the efficacy of the audiovisual speech perception application with four children with ASD. They found that all four children showed improved performance on an auditory noise assessment after using the application, suggesting that the application may be helpful for children with ASD in auditory recognition.

Some studies witnessed an improvement in the performance of visual recognition in ASD children when the SBT was used [1, 18, 49]. The SIGUEME study identified enhanced performance of visual recognition in ASD children in the post-intervention results [49]. Vélez-Coto et al. [49] concluded that the change is connected with the use of this SBT, suggesting that the technology provided additional stimuli for ASD children, which could have facilitated the learning and therefore, improved recognition. Ali et al. [1] compared three different sensory stimuli (i.e. visual, auditory and motion) in a robotic therapy. The visual stimuli were tested on 12 ASD children by presenting different colors and blinks in eight sessions. The results indicated that visual stimuli are more effective compared to auditory and motion stimuli as children with mild ASD all became more responsive to visual stimulation. Moreover, the assessment of computer-assisted application with two children with ASD showed a significant increase of correct responses to visual matching tasks in the intervention [18].

Touch plays a very crucial role in ASD children's social interactions [9]. Studies using the sense of touch attempted to enhance children's touch perception and encourage tactile interactions [11, 15, 35, 41]. Shabani et al., [41] reported increased responses to peer initiations among all three ASD participants when the tactile prompt was activated by the device. Giannopulu [15] examined the tactile interactions between children and the robot. However, the results were partially presented and insufficient to demonstrate effects on tactile interactions. In the qualitative data reported by Ringland et al. [35], although a few ASD children presented aversion to the tactile system “SensoryPaint”, therapists and parents still reported overall positive impacts in children’s responses to somatosensory inputs. This multimodal system was likely to have calming effect on children with ASD and decrease their inappropriate behaviours in tactile interactions. Another study tested whether the robot KASPAR with tactile sensors can enhance appropriate tactile interactions in children with ASD [11]. The quantitative results reported no typical pattern in the data from eight ASD children regarding tactile interaction. However, there were significant differences between the gentle and harsh touches towards the robot. The number of harsh touches toward the robot was lower than the gentle tactile interaction, suggesting that the robot can be a useful tool to encourage children with ASD to perform appropriate tactile activities.

Sula et al. [46] investigated how children with ASD moved their hand to show responses to the sensory stimuli controlled by the IoT-based system. The result showed that the average response time of hand movement is increased when the device is used. However, the authors failed to point out whether the increased movement was positive or not, considering many ASD children may have stereotyped behaviours in their daily lives. Ringland et al. [35] clearly indicated that the use of appropriately designed multimodal systems could increase motor functioning for children with ASD. Similar findings were demonstrated by Mir and Khosla [27]. The ASD participants’ motor skills were improved with the help of Kinect-based game. Unfortunately, there was a lack of sufficient statistical evidence to support the conclusion.

Table 1: Characteristics of included studies (in order of publication year)

Reference	Technology type	Device used	Sample	Design	Measures (data type)	Outcomes when the technology is used
[41]	Tactile prompting device	JTECH vibrating pager	ASD N=3 [n.d.] Age: 6-7 y	ABAB	Verbal initiations and responses (Quantitative, qualitative)	Increased verbal initiations and responses
[31]	Robot	Artificial head, eye tracking and facial expression recognition device	ASD N=1 [1 male] Age: 7 y TD N=1 [n.d.] Age: 8 y	Time series	Heart rate (Quantitative, qualitative)	Less rapid increase or oscillation of heart rate compared to TD child
[15]	Robot	n.d.	ASD N=5 [4 males] Age: 7-8 y	Time series	Child-robot interaction, including eye contact, touch, manipulation and posture; expressive language (Quantitative)	More frequent expressive language; Results related to other measures were not explicit

Reference	Technology type	Device used	Sample	Design	Measures (data type)	Outcomes when the technology is used
[39]	Remote-microphone system	Microphone, receiver, transmitter	ASD N=7 [7 males] Age: 9-11 y ADHD N=4 [2 males] Age: 10-12 y TD N=11 [n.d.] Age: 9-12 y	Pre-post, ABAB	Auditory performance (Quantitative, qualitative)	Improved speech recognition in noise, on-task behaviours, and listening behaviours
[46]	IoT-based system	JXTA-Overlay platform, SmartBox device	ASD N=1 [1 male] Age: n.d.	Time series	Hand movement (Quantitative)	Improved response time and concentration
[33]	Remote-microphone system	Microphone, receiver, transmitter	ASD N=20 [17 males] Age: 8-15 y TD N=20 [17 males] Age:8-15 y	ABAB, control group	Auditory performance (Quantitative)	Improved speech recognition in noise, social interaction and educational outcomes
[35]	Multimodal system	Multi-sensory environment	ASD N=19 [19 males] Age: 4-14 y	ABAB	Interaction modes, attention, engagement, body awareness, motor functioning, sensory skills, socialisation (Qualitative)	Improved engagement, attention, and sensory skills
[11]	Robot	KASPAR robot	ASD N=8 [8 males] Age: 6-9 y	Pre-post, time series	Child-robot interaction, including eye gaze, touching performance, imitation (Quantitative, qualitative)	Significant differences between gentle and harsh touches towards the robot; improved engagement
[20]	Computer-assisted application	iPad tablet	ASD N=4 [4 males] Age: 8-10 y	Pre-post, time series	Performance on auditory noise assessment (Quantitative)	Improved performance in auditory noise assessment

Reference	Technology type	Device used	Sample	Design	Measures (data type)	Outcomes when the technology is used
[40]	Remote-microphone system	Microphone, receiver, transmitter	ASD N=12 [n.d.] Age: 5-17 y	Pre-post	Auditory performance (Quantitative)	Less difficulty with auditory filtering and sensitivity after using the technology; Improved speech recognition in noise
[26]	AR	Brain Power System AR smart glasses	ASD N=2 [2 males] Age: 8, 9 y	Pre-post	Behavioural symptoms (Quantitative, qualitative)	Decreased irritability, lethargy and hyperactivity
[32]	Remote-microphone system, classroom amplification system	Microphone, receiver, transmitter, speaker	ASD N=26 [20 males] Age: 6-16 y	Pre-post	Listening-related stress (Quantitative)	Improved listening, communication and social interaction; Reduced physiological stress levels
[49]	Computer-assisted application	Android tablet, iPad tablet, PC	ASD N=65 [n.d.] Age: 3-16 y LFD N=37 Age: 3-16 y	Pre-post, control group	Confirmatory factor analysis, including attention, recognition, association, catergorisation, interaction, communication (Quantitative)	Improved attention; Effects on other outcomes were small
[27]	Computer-assisted application	Kinect device, PC	ASD N=3 [n.d.] Age: n.d.	Time series	Game performance, motor and sensory skills (Quantitative)	Improved motor, sensory and memory skills
[38]	Remote-microphone system	Microphone, receiver, transmitter	ASD N=15 [10 males] Age: 7-21 y	Pre-post	Auditory performance (Quantitative)	Improved speech recognition and acceptance of background noise
[1]	Robot	NAO robot	ASD N=12 [11 males] Age: 4-10 y	Time series	Response to stimuli, including eye contact time and performance (Quantitative)	Children are more responsive towards visual stimulus (color variation) compared to auditory and motion stimulus.

Reference	Technology type	Device used	Sample	Design	Measures (data type)	Outcomes when the technology is used
[4]	Robot, BCI, AR	Moverio BT-200 AR smart glasses, EEG sensors, SanBot Elf Robot	ASD N=3 [n.d.] Age: 8-10 y	Time series	Acceptance and attentional performance (Qualitative)	Positive feedback on device acceptance and attentional performance
[18]	Computer-assisted application	PC laptop, Leap Motion controller	ASD N=2 [1 male] Age: 9, 10 y Other DD N=2 [2 males] Age: 10, 11 y	ABAB	Response accuracy; task engagement (Quantitative)	Improved response accuracy in visual matching task; Improved task engagement (Effects: CAI>TII)

n.d.: Not defined
ASD: Autism Spectrum Disorder
TD: Typically Developing
DD: Developmental Disorder
LFD: Low Functioning Disorder

Table 2: Quality assessment of studies, rated by SCED Scale [47]

Reference	[41]	[31]	[15]	[39]	[46]	[33]	[11]	[20]	[40]	[26]	[32]	[49]	[27]	[38]	[1]	[18]
Clinical history		✓	✓	✓		✓	✓	✓	✓	✓	✓	✓		✓	✓	✓
Target behaviours	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Design	✓			✓		✓	✓	✓	✓	✓	✓	✓		✓		✓
Baseline	✓			✓		✓	✓		✓	✓	✓	✓		✓		✓
Sampling behaviour during treatment	✓			✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Raw data record	✓	✓		✓	✓	✓		✓	✓	✓	✓		✓	✓	✓	✓
Inter-rater reliability	✓	✓	✓	✓			✓		✓							✓
Independence of assessors		✓	✓	✓			✓		✓		✓	✓				
Statistical analysis	✓		✓	✓		✓	✓	✓	✓	✓	✓	✓		✓	✓	✓
Replication	✓		✓	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Generalisation			✓		✓		✓			✓						✓
Score	8	5	7	10	3	8	10	7	10	9	9	8	4	8	6	10

4 DISCUSSION

Because of its high prevalence and complex symptoms, atypical sensory responses in ASD have become a major concern which needs early-childhood intervention to reduce difficulties related to the issue. Technology-based interventions were found to be affective on a range of outcomes associated with ASD individuals, including social problem-solving and facial and emotional processing skills [50]. However, discussion on the effect of SBTs on atypical sensory responses is still limited [6]. Therefore, the researchers need to identify the effects of SBTs in helping ASD children with atypical sensory responses, in order to support and become source of information for future technological development.

Although this systematic review interpreted the findings of included studies by presenting statistical data and descriptive information, several limitations including small sample sizes, varying experimental designs, unknown characteristics of conditions, and selection bias should be admitted. Since significant methodological heterogeneity threatened the validity of meta-analysis [45], the researchers chose a thematical way to summarise the results. Based on existing literature, it is evident that ASD children have more and unique sensory barriers compared to TD children, but the use of SBT interventions could lead to some positive outcomes for ASD children with atypical sensory issues, such as auditory and visual recognition. Apart from these impacts on sensory processing, researchers identified that there are other behavioural outcomes commonly reported in the studies which are related to the benefit of SBTs. The following discussions are around the additional behavioural outcomes aiming to answer the last research question: Apart from impacts on sensory processing, what other outcomes (on children with ASD) are obtained by the application of SBTs? The final section will discuss the implications of these findings for the future development of SBTs for children with ASD.

4.1 Attention and engagement

From the several atypical sensory responses in ASD identified by the previous literature, deficits in attentional focusing seem to be paramount [42]. Children with ASD showed poorer performance on attention, even in a quiet environment, when compared to performance of TD children. The issue restricts children's participation in everyday activities and therefore impacts on their social engagement [22]. Extensive articles have observed children's engagement, attention or both throughout the use of SBTs. The study conducted by Schafer et al. [39] proved that the device was efficient in enhancing ASD children's auditory attention. Strengthened attention on sensory events and engagement were identified in the study conducted by Ringland et al. [35] using multimodal systems. Sula et al. [46], Costa et al., [11], and Arpaia et al. [4] all demonstrated similar results. Mir and Khosla [27] used the Kinect-based learning game to provide sensory training for three ASD children for 10 days. No robust evidence showed that the game could improve the basic attention, but authors suggested that overall the participants' performance was improved. More desirable results might be obtained if the sample size could be larger and the intervention could be continuous for a longer term. Vélez-Coto et al. [49] recruited a relatively large sample with 47 ASD children in the study of the tablet-based application SIGUEME. The mean difference of attention levels between pre- and post-intervention was 0.33 with a 95% confidence interval (CI = 0.05 - 0.61). The result revealed that the SBT intervention was efficient in improving ASD children's attention and participation in watching, listening and guessing activities by providing visual and auditory stimuli, such as moving images and music.

4.2 Anxiety and stress

On the other hand, ASD children with sensory avoiding or sensitive characteristics are susceptible to high levels of anxiety and stress, particularly when confronted with social situations [32]. Pioggia et al. [31] compared the heart rate of a child with ASD with another TD child during the intervention. It was found that when requested to focus on the robot, ASD child did not suffer a rapid increase or oscillation of cardiac frequency as the TD child did. This result suggests that it is likely that the use of the robot can relax ASD children. The studies of Rance et al. [32] and Liu et al. [26] both evidenced that SBTs had positive impacts on atypical stress responses in children with ASD. In the study conducted by Rance et al. [32], comparisons between pre- and post-intervention results supported their hypothesis that auditory amplification devices could reduce listening stress in children with ASD. Firstly, some parents of ASD children reported that their child's anxiety levels were considerably lower after using the remote-microphone device. Physiological data (cortisol concentrations) used for indicating stress levels only reflected a non-significant difference. The mean difference of parent-reported anxiety was 7.6 with a 95% confidence interval (CI = -13.87 - 29.07) and the mean difference of cortisol concentrations was 0.15 with a 95% confidence interval (CI = -0.58 - 0.88). In another experiment with the classroom amplification system, the cortisol concentration values for participants showed a significant decrease, illustrating effective improvement with the provision of SBT intervention. Moreover, the study conducted by Liu et al. [26] demonstrated that AR smart glasses could also significantly reduce the anxiety levels of children with ASD. The overall mean difference for both studies is 4.43 with a 95% confidence interval (CI = 0.76 - 8.10). The overall effect size ($z = 2.37$, $p = 0.02$) indicates that the results support the effectiveness of SBTs on reducing the anxiety and stress levels in children with ASD.

4.3 Implications for future development of SBTs

Overall, the way current SBTs address atypical sensory responses has two preferred forms: stimulation amplification and interaction. For stimulation amplification, SBTs usually act as a medium between stimuli sender and receiver to augment sensory input and to facilitate ASD children to sense (e.g. AR, remote-microphone system). The studies showed indication of increased attention and recognition for ASD children who had used these devices when compared to a non-intervention condition. Studies of Schafer et al. [39] and Vélez-Coto et al. [49] proposed that one possible explanation for the positive effect on attention and recognition may be that additional stimuli wake the responses of individuals who are hypo-sensitive to sensory stimuli and facilitate their learning, hence improve attention and recognition. Despite the positive effect of such SBTs on hypo-sensitive or high threshold children in the literature, one of the possible challenges could be that the application of such SBTs may be limited to ASD children with high threshold sensory patterns. On the contrary, SBTs through interaction, were identified to be not limited to specific sensory patterns. These SBTs generally take advantage of multimodal system and intelligent User Interface (UI) to make the intervention adaptive, interactive and attractive, capturing the attention of ASD children and evoking their interest to participate in the interactive activities. Moreover, given the fact that children with ASD prefer interactions with systems that include animations and sounds [29], most of SBTs through interaction were found to be supplied with visual or auditory characteristics. Some were even humanoid or animal-like that seem to provide a real-world object for ASD children to "sense".

Although SBTs through stimulation amplification and interaction were both found to be effective in helping children with ASD, especially in terms of social interactions, communication skills, and expressing their emotions, it is not yet proven that SBT is useful for all ASD children having different sensory patterns [3]. This further leads to research and development gaps that enable all types of atypical sensory issues to be targeted and treated appropriately in ASD children.

Thus, for addressing the gaps, future development of SBTs could integrate both stimulation amplification and interaction function and use mature technology of machine learning and sensors to decrease the barriers in identifying each user's sensory pattern and atypical sensory symptoms. Additionally, tactile hypersensitivity sometimes can be a significant barrier for ASD children in using wearable SBTs. It is necessary for researchers to consider this effect and future SBTs could look beyond the wearable SBTs to avoid causing stress for ASD individuals. Moreover, it is identified that SBT interventions were usually used in three settings: school, home or clinic centres. The use of SBTs in different settings may be associated with a variety of effects, therefore, further research might need to evaluate the effects of SBTs in different settings and investigate how optimal strategies could be adapted according to settings.

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