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ORIGINAL ARTICLE

# Advances in Eye-tracking Methods for Detection of Autism Spectrum Disorder in Children: A Systematic Review

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**ABSTRACT** - Eye-tracking uniquely bridges brain functioning and real-world behaviours in individuals with autism spectrum disorder (ASD), offering insights that neither biological nor behavioural studies alone can achieve. Its non-invasive nature makes it ideal for infant studies, as it require neither complex motor responses nor verbal communication. During the first year of life, reduced gaze duration toward faces and social stimuli, coupled with difficulty disengaging attention, serve as early behavioural markers of ASD. Intervention efficacy depends on early detection, highlighting the critical importance of identifying ASD in early childhood. This urgency has driven a surge in research focused on early ASD detection during childhood. Eye-tracking technology serves as a powerful tool for investigating gaze patterns in infants. Despite three decades of active research and significant advancements, technical challenges persist, including individual ocular variations, occlusions, and variability in scale, spatial positioning, and lightning conditions. Data on ocular positioning and movement dynamics have broad applications, proving essential in face detection, biometrics, human-computer interaction, and clinical diagnostics. This systematic review examines recent advancements in eye-tracking technology for early ASD detection in children. It underscores the critical need for rapid, effective screening tools, as current methods are typically time-consuming and resource-intensive. The review evaluates diverse eye-tracking methodologies, their clinical applications, and the potential benefits of integrating these technologies into routine developmental screenings. The review highlights eye-tracking's diagnostic precision and clinical practicality while outlining future research priorities and implementation strategies for healthcare integration.

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## INTRODUCTION

Autism spectrum disorder (ASD) is a brain-based disorder manifesting in behavioural and cognitive impairment, causing delays in social interaction skills alongside restricted or repetitive behaviours and interests with the usual onset in early childhood [1; 2] with a global prevalence of 1 in every 100 children [3]. Naturally from birth, humans tend to have a prolonged gaze at favourite stimuli and a much longer gaze at facial expressions of emotion, especially happy faces. While abnormal gaze patterns to social stimuli are indicative of ASD [4]. ASD as a neurodevelopmental illness is differentiated by difficulty in social communication, recurrent behaviours, and sensory activities [5] with common comorbidities that include anxiety, epilepsy, and mood disorders [6]. The most dominant sense organ in humans is the eye, by virtue of the visual cortex being the largest sensory processing area in the brain [4]. A study by [7] posited that atypical eye gaze patterns in infants are attributable to ASD. A similar study by [8] also found that infants with ASD had a longer time to first fixation than did typically developing controls when searching for targets in pictures of real-world scenes, implying that finding the search targets took more time for infants with ASD. These are further corroborated by findings of the meta-analysis study [7] reveals that infants with ASD highly exhibit impaired eye gaze fixation when viewing the eyes thereby

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suggesting that lack of fixation of eye gaze to the eye region may signify a biomarker indicative of the onset of ASD. Some of the methods that are used for gaze tracking include shape-based, feature-based, appearance-based, and hybrid methods [9].

The onset of ASD is usually between 6 - 24 months after birth [10]. It manifests within the first 36 months [11] with a considerable inhibiting effect on the cognitive and mental health of children and also imposes a heavy economic and psychological burden on both immediate families and society at large due to its proneness to disability, poor prognosis, and the need for continuous rehabilitation [12]. The study by [13] focuses on early symptoms of developmental abnormalities that can be discovered as early as 14 months old by analysing the developmental trajectories of children who are at high risk of ASD. Differences in early vocalisations at 14 months can predict later ASD diagnoses. Infants with canonical vocalisations and their directed use are less likely to be diagnosed with ASD [14]. While one-third of children diagnosed with ASD at 18 months were identified through the Modified Checklist for Autism in Toddlers (M-CHAT), many early signs are evident by 14 months, emphasising the need for early screening [15]. [16] argued that the significant variability in symptom trajectories from 14 to 36 months highlights the importance of early and repeated assessments to track developmental changes and initiate prompt interventions. Functional neuroimaging at 6 months can predict ASD diagnosis at 24 months with high accuracy, suggesting that early brain anomalies can inform early interventions before behavioural symptoms fully manifest [17]. Although ASD accounts for less than one percent of all neurodevelopmental diseases that are diagnosed worldwide [18], its rising prevalence has made it a matter of public health concern globally [19]. According to [20], ASD is more prevalent than was once believed, even though environmental and hereditary variables have a role in the development of these conditions, however, specific genes and exposures remain unknown. As posited by [21], early identification of ASD in children has remained one of the primary global child health issues of the 21st century.

Despite significant advancements in eye-tracking technology for ASD detection, several challenges remain. One key limitation is the lack of standardized protocols and validation across diverse populations, which limits the generalizability of findings [112]. Additionally, while eye-tracking methods have demonstrated promise in differentiating ASD from typically developing children, current studies often rely on small sample sizes and controlled laboratory settings, which may not reflect real-world applications [113]. Moreover, most eye-tracking research focuses on facial and social stimuli, but there is still a need to explore other gaze-based biomarkers that could enhance diagnostic accuracy [114]. Addressing these gaps is crucial for making eye-tracking a more accessible, scalable, and cost-effective tool for ASD screening.

Timely identification of ASD is essential for implementing prompt therapies that can greatly enhance long-term outcomes for children affected by the condition [2; 22]. Nevertheless, existing screening techniques sometimes rely on subjective assessments, are labour-intensive and time-consuming, and demand substantial resources [2]. Eye movements are crucial in communicating a person's needs, wants, cognitive functions, emotional states, and interpersonal relationships [9]. Eye movement pattern abnormalities have been established as highly correlated with and constitute a high-risk factor for ASD in children [23]. Eye-tracking is a precise and non-intrusive technology that enables accurate digital capturing of where and when a person looks. It allows researchers to understand how people process information and behave, by analysing recorded eye movements. This technology has been widely applied in ASD screening [24; 25].

According to [26], the integrated early detection programme makes it possible to identify ASD at an earlier stage, particularly in children with poor intrinsic intelligence. Early detection of ASD in children before the age of 24 months, provides these children with the best possible long-term advantages and assists in reducing the anxiety that families experience throughout the process of diagnosis [27]. The early diagnosis of ASD is extremely important; given previous studies with siblings who are at "high risk" reveal a more favourable outcome [28].

Research by [29] shows that a video that is only ten seconds long and features a female speaker can effectively differentiate between children with ASD and children who are growing normally, with an accuracy of classification of 85.1%. As reported in [30], the eye-tracking algorithm based on tablets provides a portable and fairly cost-effective screening tool for ASD by accurately measuring gaze preference among children with or without ASD. It has been established that the early indicators of autism in young children, such as reduced face-gazing time and focus issues, can be identified using eye-tracking technology [24]. According to [31], it is possible to use eye-tracking technology in a non-invasive manner without requiring complex motor responses or language. This paper assesses the potential of eye-tracking technology to overcome these constraints by providing a quick, unbiased, and non-intrusive screening tool.

This paper contributes to the growing body of research on eye-tracking technology as a diagnostic tool for Autism Spectrum Disorder (ASD) by addressing key gaps in the field. It synthesizes existing evidence on the correlation between atypical gaze patterns and ASD, highlighting eye-tracking as a non-invasive, efficient, and objective screening method that can aid early diagnosis. The study identifies limitations in current research, such as the lack of standardized protocols, small sample sizes, and a predominant focus on social stimuli, and proposes expanding gaze-based biomarkers to enhance diagnostic accuracy.

Additionally, this paper evaluates recent advancements in eye-tracking methodologies, including their integration with machine learning and portable screening tools, which can increase accessibility and affordability in diverse settings. By emphasizing the importance of early detection, it underscores how timely interventions can improve long-term outcomes for children with ASD and reduce the burden on families. Finally, this study provides valuable insights for future research and clinical applications, advocating for the development of standardized, multimodal, and cost-effective eye-tracking technologies to enhance ASD screening and diagnosis.

## OVERVIEW OF EYE-TRACKING TECHNOLOGY

Eye-tracking in early autism is an essential component for comprehending human visual activity and cognitive processes. Through the presentation of a variety of eye-tracking methods, [32] highlighting the importance of data quality in enabling researchers to maximise data accuracy and critically evaluate the work of others. Sensory processing, particularly visual processing, is often perturbed in individuals with ASD. Research indicates that understanding visual processing is essential to diagnosing the entire ASD population accurately, particularly those with intellectual disabilities, which are often co-morbid with ASD [33].

Modern eye-tracking uses video technology to monitor eye movements. They employ an invisible infrared light that reflects off the cornea, enabling the software to locate the eye's centre and pupil. Before tracking, a calibration process ensures accuracy by having participants focus on specific points on the screen. Once calibrated, the tracker can accurately determine the participant's gaze by analysing the relative positions of the pupil and corneal reflection. An eye tracker functions to quantify where, how and in what sequence the eye view is focused when performing a task (reading, watching). The structure of the eye confines high-acuity vision to a small portion of the visual field, making it necessary to move the eyes so that the fovea is aligned with the stimulus being viewed. This phenomenon, known as the eye-mind link [34], evidencing the effectiveness of eye-tracking as a tool for studying the allocation of visual attention [35].

Cognitive processes such as attention, perception, memory, language, and decision-making influence where we look, and for how long. Although there is a strong dependency between where the eyes are focused and what the mind is processing, this relationship is not perfectly aligned or guaranteed. However, it is generally accurate that the eyes tend to reflect the mental processing of whatever we are focused on at any given moment [36]. Eye-tracking is a powerful method for investigating mental processes, providing immediate insights into cognitive activities. By capturing rapid eye movements, it offers a comprehensive view of how thoughts and decisions develop. Additionally, since eye movements are mostly involuntary, they serve as a dependable indicator of underlying cognitive processes, even when individuals are unaware of their viewing patterns [37]. Because eye movements are controlled by an extensive and distributed system, make them highly prone to disruption as a result of brain damage [38]. Disruptions in the brain's eye movement control network generate distinct and measurable indicators, making eye movements valuable for identifying the location and extent of lesions [39]. Hence, the potential of eye movement as a diagnostic measure [40; 41].

Impaired cross-modal (auditory-visual) modulation is linked to socio-communicative deficits in ASD. Studies show that atypical visual cortex activity during auditory processing is associated with autism symptomatology, highlighting the importance of visual and cognitive process integration [42]. The interaction between gaze processing and neural activities mediates cognition. Research using EEG and eye-tracker signals shows that cognitive processing in ASD is influenced by visual and neural dynamics, supporting the importance of understanding these processes for diagnosing and treating ASD [43]. Studies indicate that adults with ASD show impairments in social and non-social cognitive domains. These findings contribute to understanding cognitive functioning patterns in ASD and assist in identifying targets for cognitive interventions [44]. Regulation of visual attention is crucial for learning about the environment. Infants at high risk of developing ASD exhibit impairments in regulating visual attention, which later impacts cognitive outcomes. This underscores the significance of early visual attention in diagnosing and intervening in ASD [45].

Eye-tracking is an approach researchers use for observing and analysing eye movements (where people look, and for how long) and gaze patterns during various activities. Fundamentally, it is a tool for understanding how individuals process information visually [46]. An eye tracker concurrently measures the location of the eye and tracks its movement over time to monitor and record eye movements. Consequently, it can identify the direction and point of focus when an eye scans its environment or fixes its attention on an object. Eye-tracking systems are used to detect areas in which the viewer's interest is focused by tracking the eye position, movement, and pupil size at a given moment [47]. Eye-tracking offers an invaluable empirical tool for real-time cognitive processing and information transfer research. The two main areas of eye-tracking applications are interactive and diagnostic. Diagnostic eye-tracking provides a quantitative and objective means of recording the point of focus of a viewer's gaze [9] aimed at identifying abnormalities.

According to [48], this technology offers significant new insights into the cognitive processes of humans as well as their levels of visual attention, especially the visual impaired. The SMI RED-M portable remote eye-tracker and the SMI eye-tracking spectacles are two examples of eye-tracking equipment used in psychological research. These devices enable researchers to better examine how humans absorb visual information. According to [49], these strategies allow one to gain insights into cognitive processes by monitoring the direction of visual attention and eye movements regardless of the environment in which they are being observed. The use of eye-tracking as a research method has gone through three primary phases throughout the course of history.

The work by Charles Bell 1823 which linked eye movements to brain function, categorised different types of eye movements and explained their role in visual attention laid the foundation of eye-tracking. Through his work, a crucial connection between the eyes and the brain is established affirming the fact that eye movements can provide insights into cognitive processes [50]. Subsequent centuries witnessed the development of various techniques to measure eye movements objectively. Early methods, which included plaster-of-Paris rings and corneal reflections, were cumbersome and expensive. This limited the widespread use of eye-tracking in research due to the significant time and resources [46]. In its early form, it referred to the practice of monitoring eye movements while reading throughout the Victorian era. Film recordings, which allowed for non-intrusive eye motion tracking, were the product of later improvements in cinematic technology. According to [51], by the 1970s, the central focus had turned to the practical use of eye-tracking in several research fields.

Quantifying eye movements and positions is one of the ways that eye-tracking technology contributes to the analysis of human activity. According to [52], applications can be found for it in a wide variety of study fields. Enhanced precision, stability, and sample rates are the results of rapid technological advancements. These advancements have resulted in the creation of new prospects and applications in a variety of sectors, including human-computer interaction, virtual reality, neurology, and cognitive-behavioural research [53]. The usage of various types of eye-tracking equipment, including mobile, head-mounted systems and fixed, screen-based systems, can be found in a variety of research settings. The various systems and the pragmatic use of those systems are highlighted in [32]. In a similar vein, [54] examines advanced eye-tracking technologies such as head-mounted, glass, table-mounted, and embedded systems, as well as the applications that are associated with each of these types of eye-tracking systems [54].

Modern-day eye-tracking usually uses a high-resolution camera and near-infrared technology to follow an individual's gaze. By aiming the light at the centre of the eyes, this technique creates reflections on the cornea. The reflections are recorded by a camera, which enables the technology to ascertain the location of the eyes' focus ("gaze points"), the duration of, if the gaze was fixed on any particular item ("fixation"), and the movements between fixations (referred to as "saccades") [55].

The study by [56] explored the use of eye-tracking to assess visual attention to social stimuli in children with ASD. They examined the ability of visual attention as a biomarker for the identification of ASD in children. Performance measures include Dwell Time (DT), Fixation Count (FC), and First Fixation Time (FFT) obtained using EyeLink 1000 Plus eye tracker as children viewed social scenes from the Autism Diagnostic Observation Schedule (ADOS). The results show that children with ASD displayed reduced fixation duration on faces compared to those with neurotypical controls indicative of autism symptoms. This suggests that measuring visual attention to social stimuli is a valid biomarker in the diagnostic process for ASD. However, a larger sample size is required for validating the approach. A novel method for diagnosing ASD using eye-tracking scan paths and deep learning techniques is proposed in [57]. The research explored a convolutional deep neural network model - T-CNN-ASD to classify children's datasets into ASD and typically developing (TD) groups based on eye movement patterns. ASD datasets are obtained through SMI Experiment Center Software remote eye tracker. The research used visual stimuli which include videos to attract the attention of children. The T-CNN-ASD model attained a classification accuracy of 95.59%. This research findings demonstrate that extracted eye-tracking data analysed through T-CNN can be used as an effective and non-invasive tool for early ASD diagnosis. This work represents a significant step toward developing reliable, automated tools for early ASD detection, which could have profound implications for clinical practice and public health.

Research by [58] adopt a live interaction paradigm to assess the gaze pattern of infants with a high risk of ASD. The study used Tobii TX300 eye tracker to measure the difference in gaze congruency comparing infants' gaze-following accuracy across the two conditions. The study reveals that there exists a stronger reliance on head movement for gaze following among high-risk infants. The implication of this is that infants at risk for ASD are most likely to rely excessively on head cues as against eye cues in interpreting gaze direction. A novel approach towards understanding visual exploration in children with ASD is presented by [59]. An RGBD sensor i.e., a Microsoft Kinect is used to develop a non-invasive, calibration-free gaze estimation framework. The approach comprises head pose estimation and pupil localisation, allowing the tracking of gaze trajectories and finding points of interest (POI). The tool enables a natural observation of children's visual processing activities during toy selection tasks in a therapeutic setting. The observation is free of intrusive equipment or a pre-study calibration process. The study laid the foundation for the development of a low-cost, naturalistic tool to aid in the early detection and monitoring of ASD-related behaviours.

The efficacy of the JAKE® system in detecting and measuring ASD symptoms is evaluated in [60] across nine sites in the United States. To monitor a wide range of physiological and behavioural data, the JAKE® system integrates digital phenotyping through My JAKE and biosensors through JAKE Sense. The pros of My JAKE were ease of use for caregivers and sensitivity in detecting differences in ASD symptoms compared to traditional measures. Despite these promising results, there is a need for further validation of JAKE Sense biosensors as reliable ASD biomarkers across other U.S.-based sites. [61] explores the potential of combining eye-tracking technology with deep learning algorithms for early detection of ASD. Deep learning models—specifically CNN, RNN, LSTM, CNN-LSTM, GRU, and BiLSTM are leveraged in analysing gaze patterns in children diagnosed with ASD and the typically developing (TD) peers. The study utilised an eye-tracking dataset comprising over 2 million data points obtained using RED mobile eye tracker. Out of all the models considered, the LSTM model emerged as the most effective, achieving an accuracy of 98.33%. The findings underscore the importance of early detection as a precursor to timely and effective interventions for ASD while also demonstrating the efficacy of DLM in ASD diagnosis. However, to enhance the generalisability of the result, calls for expanding the sample size and diversity.

Using a Tobii X2-30 remote-based eye tracker, [62] conducted a study to monitor the eye-gaze behaviour of two autistic and two typically developing (TD) children while reading and answering comprehension questions. The study aimed to explore the relationship between eye-gaze patterns and reading comprehension in students with ASD. The study focused on mean fixation durations during question-answering as performance measures to examine whether these durations impacted comprehension accuracy. Although, the autistic participants exhibited longer mean fixation times, however, their comprehension accuracy is equal or superior compared to their TD counterparts. This finding negates the assumption that longer fixations are associated with poorer comprehension. [63] explores the use of eye-tracking technology to assess the receptive verb vocabulary of late talkers and autistic children. Dynamic scenes depicting actions were presented to the Participants who were prompted to identify the referent of a target verb. Eye-gaze measures: accuracy (proportion of looking time to the target scene) and latency (time to first look at the target), are used to evaluate the children's receptive verb knowledge. The study found that late talkers required more time to demonstrate their knowledge, while the accuracy and latency of autistic children are predictable by their receptive language abilities.

The study by [64] focused on using a low-cost eye-tracking device *to identify autism risk factors* in *preschoolers* in Ecuador. Two types of stimuli—human versus object movements and dynamic speaking faces are employed in exploring visual preferences. Additional data on the adaptability of the eye-tracking technology was obtained through a parental questionnaire. The study found a persistent visual preference for human movements over object movements. Also, a higher fixation on the mouth region exists relative to the eyes. Feedback from parents reveals a general acceptance of the eye-tracking method, suggesting its potential use in clinical settings for early ASD risk identification in low- and middle-income contexts. A similar study, [65] investigates attention control and learning in preschool children with and without ASD in New Delhi, India using portable eye-tracking technology. The study aims to assess cognitive processes related to visual attention, using the antisaccade task, which measures the ability to inhibit eye movements toward a distracting stimulus and anticipate looks toward a reward as performance measures. The key measures included the proportion of prosaccades (eye movements toward a distractor) and antisaccades (eye movements toward a target), captured using a Tobii X2-60 eye tracker at 60Hz. The results of the study reveal that children with ASD had a reduced ability to inhibit prosaccades and a decreased rate of learning to anticipate looks toward the target, relative to the typically developing groups. This suggests the reduced ability to learn to anticipate targets could be a trait more specific to autism. The summary of related studies is provided in Table 1.

The reviewed studies in Table 1 provide a broad examination of eye-tracking applications in ASD research, highlighting its potential for early detection, behavioural assessment, and intervention. The studies collectively demonstrate that individuals with ASD exhibit distinct visual attention patterns, such as reduced fixation on social stimuli, longer reaction times in gaze following, and variations in attention control mechanisms. Several studies employed deep learning models to enhance the predictive accuracy of ASD classification, with some achieving accuracies exceeding 95% [57; 61]. Others explored non-invasive tracking solutions, such as computer vision-based gaze tracking [59], which can facilitate real-world applications outside laboratory settings.

However, a key limitation across these studies is ambiguity in the definition and application of eye-tracking metrics. Measures such as fixation duration, dwell time, and gaze congruency are frequently reported [56; 58; 62], but the studies lack uniformity in how these parameters are defined, calculated, and interpreted. This lack of standardization raises concerns about reproducibility and cross-study comparability. For instance, while fixation duration is often used as an indicator of social preference, its threshold and measurement conditions vary across different studies. Similarly, gaze congruency as a predictor of ASD risk is inconsistently applied, making it difficult to establish a universal benchmark for early diagnosis.

To enhance the reliability of eye-tracking as an ASD diagnostic tool, future research should prioritize standardized methodologies, ensuring that eye-tracking parameters are defined in a reproducible and comparable manner. Establishing universal benchmarks for gaze fixation patterns, response time to social stimuli, and visual exploration behaviours will be crucial in translating these findings into clinical and real-world applications.

**Table 1.** Summary of Related Studies

| Author | Focus | Stimuli | Methodology | Measures | Eye tracker | Findings |
|---|---|---|---|---|---|---|
| [56] | Eye-tracking of ADOS tasks for visual attention to social stimuli. | ADOS Description of a Picture Task | Eye-tracking during free viewing of social scenes selected from the ADOS. | Dwell Time, Fixation Count, First Fixation Time, SCQ subscale scores, Conners' Rating Scales | EyeLink 1000 Plus | Fixation duration to faces was reduced in infants with ASD+ADHD |
| [57] | Eye-tracking scan paths to predict ASD | Animated videos characters | Deep learning model (T-CNN-ASD | Accuracy, classification performance | SMI remote eye tracker | T-CNN-ASD achieved 95.59% accuracy, |
| [58] | Infants Gaze following for ASD risk | Objects gazing | Eye-tracking of 10-month-old infants | Difference score (DS) of gaze congruency | Tobii TX300 | Gaze following correlated with ASD |
| [59] | Visual exploration in children with ASD | Toys in a natural setting | Computer vision-based gaze | Gaze trajectories, sequence of POI, number of gaze hits | Microsoft Kinect (RGBD sensor) | The system allows for non-invasive eye-tracking |
| [60] | Explore Janssen Autism Knowledge Engine (JAKE®) | Traditional ASD symptom measures | Observational, non-interventional, study at 9 U.S. sites | ASD symptoms, caregiver feedback, physiological data | JAKE | JAKE detected differences in ASD |
| [61] | Early detection of ASD using eye-tracking and deep learning | Static images and dynamic videos | Deep learning models (CNN, RNN, LSTM, CNN-LSTM, GRU, BiLSTM) | Accuracy, sensitivity, specificity, F1 score | RED mobile eye tracker | LSTM achieved 98.33% accuracy. |
| [62] | Eye gaze patterns and reading comprehension | Texts from WIAT-II | Eye-tracking during reading text and comprehension | Mean fixation duration and comprehension accuracy | Tobii X2-30 remote-based eye tracker | Found no correlation between longer fixation durations & ASD |
| [63] | Assessing receptive verb vocabulary in late talkers and ASD | Dynamic scenes depicting verbs | Eye-tracking dynamic viewed scenes | Proportion of looking time, time to first look at target | Eye-tracking | Late talkers require longer to demonstrate verb knowledge |
| [64] | Preschoolers' Visual preference towards socially salient stimuli | Dynamic speaking faces | Eye-tracking & parental questionnaire | Mean fixation times | EyeTribe | Consistent visual preference for human over object movements |
| [65] | Attention control and learning in ASD children | Visual stimuli (antisaccade task) | Portable eye-tracker technology | Proportion of prosaccades and antisaccades | Tobii X2-60 (60Hz) | Attention Control Challenges in ASD Children |

## OFTEN APPLIED EYE-TRACKING MEASURES/METRICS

In ASD research, eye-tracking technology has grown to be an indispensable tool since it enables the exact measurement of several variables that reveal the cognitive and behavioural traits of people with ASD. Researchers used different performance measures/metrics to evaluate the performance of eye-tracking devices. According to [66] the amount and quality of data collected represent an important metric. Other important metric is user experience obtained through the Exit Survey or informal communication [66]. In evaluating the performance of Tobii Pro glasses, [67] use three eye gaze metrics from the centre of the area of interest (AOI): Total visit duration, total visit count, and first fixation duration. Similarly, [68] applies gaze indices: average normalised fixation counts and average normalised fixation duration towards the different AOIs of the screen to evaluate the performance of the Tobii 4c tracker. [68] uses four metrics: the number of fixations; the total fixation time; the latency of the first fixation within a specific area; and fixation duration to evaluate the performance of a remote R6 system.

Typical eye-tracking measures are gaze patterns, saccades, and fixation length [1]. These measures enable scientists to have a better grasp of personal attention to and visual processing of information. For example, [69] developed and validated eye-tracking metrics to evaluate ASD risk and quantify symptom levels by means of gaze duration and fixation patterns. Similarly, [70] demonstrated atypical gaze patterns in children with ASD, highlighting differences in how they visually explore their environment. Focusing on the time spent looking at target versus non-target images, [71] also measured speech comprehension in children with ASD using eye-tracking equipment. This approach aligns with findings from [72], who reported that children with ASD exhibit different fixation patterns when viewing faces, affecting their ability to interpret social cues.

Early autism studies have found that early signs of ASD, especially in young toddlers and infants, have included reduced gazing time at individuals and faces as well as problems with disengagement of attention [31]. Further research by [73] supports this, showing that infants later diagnosed with ASD display notable difficulties in disengaging attention. Several eye-tracking activities can expose differences in social attention and motivation among children with ASD. [74] demonstrated how various stimuli impact social attention in ASD, showing distinct gaze patterns compared to typically developing children. [75] also identified that visual social attention varies with perceptual load, offering insights into the underlying cognitive mechanisms of ASD.

In evaluating the performance of eye-tracking devices, researchers adopt numerous eye-tracking metrics to assess visual attention and cognitive processes for ASD diagnosis in children. Dwell Time (DT) and Fixation Count (FC) are used by [56] to duration how long and the frequency of participants' fixation on specific stimuli mostly faces in social scenes. [56] also used First Fixation Time (FFT) to track the time it takes for a participant to first fixate on a specific AOI, such as face. Gaze Congruency which measures the accuracy of gaze following in infants in distinguishing between conditions where the infants used both eye and head movements versus just eye movements was employed as a metric in [58]. [62] adopts mean fixation durations during reading and comprehension tasks as a measure of performance in examining the relationship between reading and comprehension accuracy in autistic and TD children. The frequency of eye movements toward Prosaccades (distractors) and antisaccades (targets) was investigated as a metric by [65] to investigate visual attention control by ASD infants. The accuracy and latency of eye movements in response to verb prompts were used as performance measures to provide insights into receptive language abilities in the work [63]. These measures/metrics enable researchers to evaluate the efficacy of the eye-tracking devices, models, and methodology. It also provides a means of benchmarking different research works.

## RELEVANCE OF METRICS FOR ASD BEHAVIOURS AND SYMPTOMS

Eye-tracking measures have a great bearing on ASD symptoms and behaviours. For instance, [76] underlined those measures of treatment success in children with ASD can be derived from eye-tracking metrics including social attention and face scanning patterns, which are linked with language and adaptive communication skills. Particularly in evaluating gaze allocation and goal-directed looking behaviour in new-borns and young children, [77] underlined the need for eye-tracking measures in the early detection of ASD. Using eye-tracking data, machine learning techniques have also been used to classify ASD in infants, therefore attaining great accuracy in detecting ASD, particularly in preschool-aged children [78]. Using eye-tracking, [79] investigated predictive reasoning skills and visual expectation in children with ASD, therefore exposing diagnostic variations in goal-based visual predictions. An automated tool for quantifying responding to joint attention (RJA) behaviours using eye-tracking data was developed in [80]. The tool [81] demonstrated that eye-tracking combined with virtual reality and machine learning can achieve high accuracy in recognising ASD, highlighting the potential for these technologies in diagnostic applications. [82] found that visual scanning and pupillary responses to different stimuli could serve as early indicators of ASD, providing additional metrics for early diagnosis.

## METHODOLOGICAL DEVELOPMENTS IN EYE-TRACKING FOR ASD IDENTIFICATION

### IMPROVEMENTS IN HARDWARE AND SOFTWARE

Recent developments in eye-tracking technologies greatly increase ASD detection's accuracy and dependability. High-resolution cameras, such as those included in the eye-tracking system built using a Raspberry Pi 4 and Noir camera, have improved the accuracy of visual attention assessments in children with ASD. The exact mapping of pupil coordinates to screen coordinates made possible by this approach guarantees data quality improvements [83]. Furthermore, as shown in [30], advanced algorithms for data processing have made it feasible to create simple but powerful eye-tracking systems free from head holding or calibration. These methods greatly increase the feasibility of ASD screening in many environments and precisely estimate gaze preference [30]. The utilisation of innovative experimental designs, such as dynamic and adaptable stimuli, has significantly improved the dependability of eye-tracking data. Uniform protocols guarantee consistent data acquisition, which is crucial for comparing findings across different studies [77].

Adaptive optics, integrated with pupil tracking, significantly improves high-resolution retinal imaging [84]. This technology enables accurate eye movement compensation, which is crucial for medical applications in retinal imaging. The approach of using default cameras for alignment minimises cost and complexity, making high-resolution imaging more accessible [85].

Utilising graphics processing units (GPUs) to parallelise pupil tracking algorithms allows for high-speed, high-resolution eye-tracking. This technology enables real-time processing at frequencies up to 530 Hz, significantly enhancing the accuracy and speed of eye-tracking systems, which is vital for various research and clinical applications [86].

Novel foveating cameras use micro-electromechanical systems (MEMS) mirrors to dynamically adjust the viewpoint, allowing for high-angular resolution and wide-field-of-view imaging. This technology enhances the performance of remote eye-tracking systems, making them suitable for applications requiring high precision and adaptability [87]. Real-time eye and iris tracking using smart cameras integrated with LabVIEW software demonstrates the feasibility of developing compact, efficient, and cost-effective eye-tracking systems. These systems are highly adaptable for various applications, including user studies, medical research, and human-computer interaction [88; 89]. Likewise, using high-definition cameras for binocular pupil and gaze detection improves the accuracy and resolution of eye-tracking systems. This technology allows for precise measurement of eye movements, which is essential for clinical diagnostics and research involving visual processing [89]

In addition, affordable eye-tracking solutions have emerged, allowing more researchers to conduct eye-tracking studies. For example, [90] explored the use of low-cost eye trackers in web design, indicating the potential for broader applications in different fields. The use of eye-tracking in virtual reality (VR) environments is another notable advancement. By combining eye-tracking with VR, researchers can create immersive environments to study visual attention and behaviour. For instance, [91] discussed the integration of eye-tracking in mixed reality systems to enhance user interaction and experience. Additionally, open-source solutions like EyeLoop have been developed to provide high-speed, closed-loop eye-tracking at a lower cost, making advanced eye-tracking more accessible [92]. Numerous types of eye-tracking devices distinguishable by cost, accuracy, size and portability are available to researchers and practitioners. EyeLink 1000 Plus is used by [56] due to its ability to provide high-precision measurements of visual attention in social scenes. Tobii Eye Tracker is used in several studies such as [58; 62; 65] as a result of its versatility and ability to capture a wide range of visual behaviours. [57] employed SMI Experiment Center Software Remote Eye Tracker to capture scan paths in dynamic visual stimuli for deep learning analysis. Microsoft Kinect (RGBD Sensor) is used in [59] as a non-invasive, calibration-free approach to tracking gaze trajectories in naturalistic settings. JAKE Sense Biosensors which are part of a broader system integrating digital phenotyping with eye-tracking data were used in the study by [60].

## INNOVATIONS IN EXPERIMENTAL DESIGN

Experimental design innovations have greatly aided eye-tracking techniques for ASD identification. Ensuring the dependability and comparability of eye-tracking data across research depends on standardised techniques. The importance of standardised protocols can never be overemphasised as inconsistent data collection can be promoted by variances in visual stimuli and paradigms [77]. Furthermore, enhancing the efficacy of eye-tracking paradigms is guaranteed by the inclusion of dynamic and adaptable stimuli. [93] for instance, presented a video-based eye-tracking paradigm including several scenarios aiming at various facets of ASD. This dynamic and flexible technique captures a wider spectrum of behaviours, thereby improving the screening process. The development of space-time cube visualisation in combination with clustering techniques allow for the analysis of eye movement data with dynamic stimuli, such as videos and animated graphics. This method enables the identification of attentional trends and focuses on enhancing the reliability of eye-tracking data across different time sequences and spatial contexts [94]. REMoDNaV, an event classification algorithm, is suitable for both static and dynamic stimuli. This algorithm classifies saccades, post-saccadic oscillations, fixations, and smooth pursuit events with high accuracy, even under suboptimal conditions, thereby improving the dependability of eye-tracking data in dynamic environments [95]. Innovations such as the Vision Egg library allow for real-time generation of arbitrary visual stimuli, from sinusoidal gratings to naturalistic 3D scenes. This adaptability in stimulus presentation enhances the accuracy and ecological validity of eye-tracking experiments [96].

Also, the integration of synchronised laser modulation in adaptive optics scanning laser ophthalmoscopes (AOSLO) allows for precise delivery of adaptive optics-corrected stimuli to the retina. This method significantly improves the measurement of visual acuity and the reliability of retinal image data [97]. New methods for automatically generating AOIs in videos, especially for moving stimuli, reduce the labour-intensive process of manual AOI construction. This innovation enhances the efficiency and accuracy of eye-tracking data analysis in studies involving dynamic stimuli [98]. [99] employed a novel technique called Sparsely Grouped Input Variables for Neural Networks (SGIN) to select the most effective experimental stimuli from a large set, thereby optimizing the diagnostic process for ASD through targeted eye-tracking measures. The use of Compact Convolutional Transformers (CCT) in visualizing eye-tracking patterns for early autism detection, achieving high classification accuracy and demonstrating the potential of advanced deep learning models in experimental design was explored in [100].

Several stimuli were used across the reviewed studies. Studies [56; 58] uses social stimuli that include faces, gaze following, and interactions. These studies investigate differences in attention to socially relevant stimuli by individuals with ASD compared to TD individuals. Aimed to observe more naturalistic behaviours and preferences of ASD infants, [63] explore dynamic scenes and naturalistic settings such as actions depicted in videos or toy selection tasks. The study by [64; 65] investigates contrast stimuli of human vs. object movements. The studies employ stimuli that contrast human actions with object movements or other non-social stimuli for determining visual preferences and attention control of children with ASD. Deep learning models are used in [61] on both static and dynamic visual stimuli to capture detailed gaze patterns to diagnose ASD in infants.

## INTEGRATION WITH OTHER TECHNOLOGIES

Combining eye-tracking technology with other diagnostic instruments has created new paths for in-depth ASD diagnosis. Eye-tracking combined with EEG, fMRI, and motion trackers show the potential to improve ASD tests' depth and accuracy. Reviewing the integration of eye-tracking with these technologies, [101] underline their possibilities to offer a more complete knowledge of ASD symptoms and behaviours. Moreover, the analysis of data using machine learning has transformed the interpretation of eye-tracking data. Based on eye-tracking data, [78] performed a meta-analysis showing the great accuracy of machine learning algorithms in identifying ASD and visually impaired people, thus highlighting the possibilities of these algorithms to improve early identification and screening efforts. [102] also investigated the use of neural networks and machine learning to examine eye-tracking data for automatic ASD detection, attaining excellent classification accuracy and proving the effectiveness of these sophisticated computational approaches.

## KEY STUDIES DEMONSTRATING EYE-TRACKING METHODOLOGIES

Eye-tracking equipment has been used extensively in many studies on ASD. [29] for instance, measured focus times of children with ASD and normally developed (TD) children using a 10-second video of a girl speaking. With a classification accuracy of 85.1%, the study revealed notable decreases in fixation time in children with ASD, especially in the mouth and body parts. Likewise, [93] presented a novel video-based eye-tracking paradigm with ten video scenarios, each aimed at various facets of ASD, demonstrating a non-invasive and practical technique for early ASD screening. In another experiment, [103] used a convolutional neural network in eye-tracking for visual representations to identify participants. High classification accuracy of this method shows the possibility of merging advanced data processing methods with eye-tracking. Reviewing eye-tracking research targeted at young children with ASD, [31] noted changed gazing patterns across facial areas and limited orienting to biological motion as early ASD symptoms.

## COMPARATIVE ANALYSIS OF DIFFERENT METHODOLOGICAL APPROACHES

Eye-tracking studies have evaluated several methodological techniques to see how well they identify ASD. A somewhat cheap screening tool, [30] created a basic eye-tracking algorithm free of head holding or calibration. Based on accurate measurement of gaze preference, this tablet-based method separated children with and without ASD. By means of a meta-analysis on the application of machine learning to eye-tracking data, [78] discovered great accuracy in detecting ASD, particularly in preschool-aged children. The paper highlighted how well machine learning techniques might improve the diagnosis procedure.

Several case studies have demonstrated how well eye-tracking equipment detects ASD. To assess limited and repetitive behaviours (RRBs) in children with ASD, [104] for instance coupled electroencephalography (EEG) with eye-tracking technology. This combined technique proved to show strong links between eye-tracking measures and ASD degree, so offering a strong early diagnosis tool. In a study of children between 2- and 4-year-old with ASD, [105] considered visual scanning and face recognition. The study found that abnormalities in face processing were clear early and became more noticeable with age. These results imply that social and cognitive deficits linked with ASD can be clearly found through eye-tracking technologies.

## IMPLICATIONS FOR CLINICAL PRACTICE

The integration of eye-tracking technology in clinical ASD screening offers a non-invasive, objective, and scalable method for early diagnosis. Unlike traditional behavioural assessments, eye-tracking allows for precise measurements of gaze behaviour, enabling earlier detection of ASD risk in infants and toddlers [115]. This could lead to timely interventions such as speech therapy and behavioural training, improving long-term outcomes [116].

Advancements in machine learning have further enhanced the accuracy of eye-tracking-based ASD diagnosis. Additionally, portable, cost-effective eye-tracking solutions could make ASD screening more accessible, especially in low-resource healthcare settings [116]. However, clinical adoption faces challenges. Lack of standardized protocols, data privacy concerns, and cost barriers remain key issues

[117]. Additionally, clinician training is needed to properly interpret eye-tracking data alongside behavioural assessments.

## ETHICAL CONSIDERATIONS IN EYE-TRACKING RESEARCH FOR ASD DETECTION

The use of eye-tracking technology for detecting ASD presents ethical challenges that must be carefully addressed to ensure responsible and fair implementation. While this technology has significant potential for early diagnosis and intervention, concerns related to data security, privacy, informed consent, bias, and potential misuse must be critically examined.

One of the most pressing concerns is data security and privacy risks, as eye-tracking technology collects highly sensitive biometric data, including gaze patterns, facial responses, and cognitive engagement indicators. Given the biometric nature of these data, the risk of unauthorized access, data breaches, and misuse is substantial. Ensuring robust data encryption, anonymization techniques, and secure storage is crucial to protect individuals' privacy. Moreover, compliance with international data protection laws such as GDPR (General Data Protection Regulation) and HIPAA (Health Insurance Portability and Accountability Act) is necessary when handling eye-tracking data, particularly for children.

Since children with ASD are often the primary participants in eye-tracking research, obtaining informed consent is a critical ethical issue. Researchers must ensure that parents or guardians fully understand how the data will be collected, stored, and used, while also considering children’s assent whenever feasible to respect their autonomy. Ethical research conduct demands that all studies undergo rigorous review by Institutional Review Boards (IRBs) or Ethics Committees to guarantee adherence to ethical standards.

Another major concern is the potential for bias and discrimination in eye-tracking-based ASD detection systems. If datasets used to train deep learning models lack diverse population representation, it may lead to misdiagnosis or biased assessments, particularly among underrepresented ethnic, racial, or socioeconomic groups. Studies have shown that current models often rely on limited demographic diversity, raising concerns about algorithmic fairness and the risk of reinforcing disparities in ASD diagnosis. Addressing data diversity and ensuring that eye-tracking models are validated across varied demographic and cultural backgrounds is essential for fair and equitable diagnosis.

Beyond research settings, there is growing concern that eye-tracking data could be misused in non-clinical environments such as surveillance, commercial exploitation, or employment screening. Unauthorized entities could potentially profile individuals based on cognitive or behavioural traits, leading to privacy violations, discrimination, or stigma. Ethical guidelines must clearly define the intended use cases of eye-tracking data and implement strict access controls to prevent misuse by third parties.

Psychological and social implications must also be considered when applying eye-tracking for early ASD detection. While early diagnosis can improve intervention outcomes, misclassification or false positives could lead to unnecessary stress, stigma, and financial burdens for families. Transparent communication about diagnostic limitations and ensuring that eye-tracking results are interpreted alongside other clinical assessments is vital to prevent misdiagnosis and undue anxiety.

While eye-tracking technology holds immense promise for early ASD diagnosis and research, its ethical implications cannot be overlooked. Ensuring data security, informed consent, transparency, and fair application is critical to prevent privacy breaches, bias, and unintended consequences. Ethical frameworks, policy regulations, and multidisciplinary oversight must guide the development and deployment of eye-tracking-based ASD detection tools to safeguard both scientific integrity and human rights.

## CHALLENGES AND LIMITATIONS

Despite significant advancements in eye-tracking technology for ASD detection, several key challenges persist, particularly in uncontrolled environments, ethical considerations, machine learning reliability, standardization, and real-world deployment. Addressing these challenges is essential to ensuring its effective adoption in clinical and research settings.

One of the primary challenges is the need for precise calibration, which affects data accuracy and usability. [30] posited that conventional eye-tracking systems often require intensive calibration and stable head positioning, making them difficult to use with young children, particularly those with ASD who may struggle with sustained attention or sensory sensitivities. To improve usability, adaptive calibration techniques and gaze estimation algorithms should be further explored to reduce setup complexity while maintaining accuracy.

Another major challenge is participant response variability, which leads to inconsistent findings across studies. Individuals with ASD exhibit diverse eye-gaze behaviours, influenced by cognitive load, attention differences, and environmental factors. [106] observe that individual variations in visual attention and the variety of visual traits can hamper the characterisation of visual attention in every group (ASD vs. TD) and hence influence diagnosis accuracy. Research by [109] found that while machine learning-based classification of ASD using eye-tracking can be highly effective, its performance is affected by inconsistencies in gaze responses across individuals. Future studies should focus on developing adaptive machine learning models trained on diverse datasets to ensure diagnostic algorithms can accommodate a wide range of ASD-related gaze behaviours.

Beyond technical constraints, ethical concerns and data privacy pose significant challenges. While eye-tracking is non-invasive, issues related to informed consent, data privacy, and psychological impacts on participants must be carefully considered. There is also concern over over-reliance on AI-driven diagnostic systems, which could potentially replace human expertise in clinical decision-making. Future research must develop clear regulatory frameworks that balance automation with human oversight, ensuring ethical and accurate diagnosis.

Real-world deployment remains another limitation, as most eye-tracking studies are conducted in controlled laboratory environments. Translating findings to clinical, educational, and home settings requires eye-tracking systems to function reliably under varied lighting conditions, participant movement, and distractions. The feasibility of live eye-tracking was recently demonstrated in a study by [111], showing that toddlers with ASD exhibit different gaze patterns even in face-to-face interactions with caregivers. However, real-world tracking still requires more robust algorithms that can adapt to naturalistic settings without compromising data accuracy.

Lastly, cost and accessibility remain barriers to widespread adoption. High-precision eye-tracking systems are often expensive and resource-intensive, making them less accessible in low-income or rural areas. While cost-effective, tablet-based eye-tracking tools have shown promise, their accuracy and scalability across diverse populations remain an open question. A review by [110] suggests that integrating eye-tracking with other diagnostic tools, such as EEG, could enhance diagnostic precision while reducing costs. Future research should explore scalable, portable, and low-cost eye-tracking solutions to ensure global accessibility in ASD diagnosis.

By addressing the challenges like calibration complexity, participant variability, ethical concerns, real-world adaptability, and accessibility barriers. Eye-tracking can become a more reliable and scalable tool for ASD detection. Future research must prioritize standardization, ethical considerations, and technological advancements to bridge the gap between laboratory research and practical clinical applications.

## FUTURE DIRECTIONS

Recent advancements in deep learning and eye-tracking integration have significantly enhanced the accuracy and reliability of ASD screening. Studies such as [107] have demonstrated the efficacy of advanced deep learning models, including convolutional neural networks (CNN) and recurrent neural networks (RNN), in classifying ASD-related gaze patterns with high precision. However, despite these promising results, there remains a critical need for hybrid computational frameworks that integrate deep learning with traditional diagnostic tools to enhance accuracy and minimize biases associated with machine learning models. Future research should focus on refining these models to address issues of overfitting, data dependency, limited generalization and potential biases introduced during training, particularly in diverse populations. More successful ASD screening techniques are being made possible emergence of innovative technologies and approaches in eye-tracking studies. To assist the ASD screening process, [103] investigated how eye-tracking combined with data visualisation and machine learning might be used. This method showed the possibility of simplifying and improving ASD screening accuracy by converting eye-tracking scan paths into visual representations and applying deep learning models for classification

Beyond machine learning, the integration of eye-tracking with complementary diagnostic technologies such as electroencephalography (EEG) and physiological sensors has shown potential in capturing a more holistic view of ASD-related behaviours. For instance, [104] demonstrated that combining eye-tracking with EEG can effectively measure limited and repetitive behaviours (RRBs) in ASD children, strengthening the link between eye-movement patterns and ASD severity. Future work should explore standardized multi-modal diagnostic approaches, where eye-tracking data is analysed alongside brain activity, heart rate variability, and behavioural assessments to enhance diagnostic reliability.

Scalability and accessibility remain crucial challenges in real-world deployment. While high-end eye-tracking systems provide precise measurements, they are often expensive and require controlled environments. More cost-effective, portable solutions such as tablet-based screening tools have emerged as promising alternatives, as demonstrated by [30]. These tools offer a calibration-free, easy-to-use screening method, making them more suitable for primary healthcare settings and low-resource environments. Future research should focus on validating the effectiveness of these low-cost tools in real-world clinical settings, ensuring they maintain accuracy while remaining accessible.

Additionally, methodological standardization is essential to improve the comparability and reproducibility of eye-tracking studies. Despite widespread calls for consistency, variations in data collection, gaze metrics, and analysis techniques remain a challenge. Establishing global standards for defining and applying metrics such as fixation duration, dwell time, and gaze congruency will be critical in ensuring that eye-tracking data is interpreted consistently across different research settings. Developing open-access eye-tracking datasets and collaborative research frameworks will further facilitate cross-validation and scalability of these diagnostic techniques.

Lastly, ethical considerations and privacy concerns must be addressed as eye-tracking technology becomes more widespread. While the technology is non-invasive, issues related to data privacy, consent, and the psychological impact on children and families require deeper exploration. Future studies should establish guidelines for secure data storage, ethical use of eye-tracking in paediatric diagnostics, and mechanisms to prevent misuse or over-reliance on automated classifications without human oversight.

By addressing these challenges, machine learning refinement, multi-modal integration, real-world validation, standardization, and ethical considerations. Eye-tracking technology can transition from an experimental tool to a widely accepted and clinically viable method for early ASD detection.

## CONCLUSION

Autism Spectrum Disorder (ASD) is a neurodevelopmental condition characterized by deficits in communication, social interaction, and repetitive behaviours. Among the various diagnostic approaches, eye-tracking technology has emerged as a promising, non-invasive, and efficient tool for early ASD detection, given its strong correlation with eye movement patterns in individuals with ASD. The integration of high-resolution cameras, advanced algorithms, and adaptive experimental designs has significantly improved the reliability and accuracy of eye-tracking data. Moreover, the combination of eye-tracking with EEG and machine learning further enhances diagnostic precision, making it a powerful tool for early screening. Future advancements should focus on refining these technologies and clinical protocols to maximize their utility in real-world clinical settings, thereby enhancing early diagnosis and intervention outcomes for children with ASD. Despite these advancements, challenges remain. The widespread adoption of eye-tracking for ASD detection requires affordable and accessible solutions for the general populace. Additionally, due to the heterogeneous nature of ASD, future research should move beyond binary classifications (ASD vs. non-ASD) and instead explore a broader spectrum of ASD subtypes. Expanding the scope of biomarkers in eye-tracking studies will be crucial in differentiating ASD phenotypes more accurately. Ultimately, continued innovation in eye-tracking technologies has the potential to revolutionize ASD screening, offering early and accurate detection, leading to more timely interventions and improved support for individuals and their families. This review aims to encourage further research into non-invasive, multimodal, cost-effective, and highly accurate eye-tracking solutions for ASD diagnosis, paving the way for more effective and inclusive diagnostic tools.

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## CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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