Journal of
Computer Science and Software Development

Research Article Open Access

Gamified Vision Screening: A Promising Tool for Early Detection of Eye Disorders Using Eye-tracking Innovations

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Received Date: October 19, 2024 **Accepted Date:** November 19, 2024 **Published Date:** November 22, 2024

Citation: David Lim, Alan Huong Yong Ting, Abdulwahab Atanda (2024) Gamified Vision Screening: A Promising Tool for Early Detection of Eye Disorders Using Eye-Tracking Innovations. J Comput Sci Software Dev 3: 1-22

Abstract

This literature review examines the effectiveness of the current pediatric vision screening methods. It explores the potential of integrating eye-tracking technology with gamified elements for engagement among children as a means of enhancing the accuracy of vision screening. The review identifies several gaps in conventional vision screening practices, including issues with engagement, accuracy, and the need for specialised equipment and training. The conventional methods often fail to maintain the attention of young patients, rely heavily on subjective assessments, and require extensive training and specialised equipment, limiting their use in diverse settings. The proposed computerised vision screening tool addresses these challenges by incorporating consistent setup parameters, non-invasive eye-tracking technology, and gamified children-friendly interfaces. This tool aims to standardise the screening process, eliminate the discomfort associated with other technologies like VR, and make the process more engaging for children. By transforming vision screening into a more interactive and enjoyable experience, the tool promises to improve both the accuracy and the efficacy of pediatric vision screening. The integration of eye-tracking and gamification is expected to provide objective measurements that enhance diagnostic precision, reduce reliance on subjective interpretations, and increase patient engagement. This novel approach has the potential to revolutionise pediatric vision screening by making it more accessible, accurate, and engaging, thereby improving early detection and treatment outcomes for visual impairments in children.

Keywords: Gamification; Eye-tracking; Pediatric Vision Screening; Visual Impairment Detection; Child-Friendly Interfaces; Early Detection

Introduction

Vision development is a pivotal aspect of early childhood, profoundly impacting educational achievements and social interactions [1,2]. Several types of visual impairments ranging from blurry vision to loss of peripheral vision encompassing conditions like refractive errors, cataracts, presbyopia, glaucoma, diabetic retinopathy, and others can cause permanent blindness if not early detected, treated, and with regular checkups [2]. Early treatment and regular eye screening can help prevent irreversible blindness from these significant visual impairments [3]. Early and effective vision screening during the formative years is crucial, as early detection and treatment of visual impairments can lead to significantly better developmental and educational outcomes [4]. Early, documented, and disclosed diagnosis serves as a cornerstone of effective healthcare delivery, benefiting patients, healthcare providers, and healthcare systems alike by enabling timely intervention, empowering patients, optimising resource allocation, promoting coordination of care, and upholding legal and ethical standards in healthcare practice [5].

In a study that examines the effectiveness of vision screening for visual disorders in newborns, infants, and young children, it was observed that although evidence is limited for children under three, there is moderate certainty that vision screening between three to five years provides moderate net benefits. This screening is important for detecting conditions like amblyopia and its risk factors, which are linked to better treatment outcomes and improvements in visual acuity, school performance, and overall quality of life [6].

Conventional methods of vision screening, while effective to a degree, often do not engage children effectively, potentially leading to inaccurate results or lower screening compliance [7,8]. The authors compared conventional screening techniques with instrument-based methods.

They found that conventional methods were less time-efficient and did not demonstrate a significant difference in detecting visual acuity needs compared to instrument-based screening. This supports the notion that conventional methods might not engage children effectively or lead to the most accurate screening results [9]. The conventional devices for testing eye disorders include various perimetry devices like the Humphrey Visual Field Analyzer and Goldmann perimetry. Aside from being costly, these devices are uncomfortable, time-consuming, and available only in a few special clinics [10]. Other testing techniques such as visual acuity tests by reading optotype charts can be boring for children with the likelihood of incorrect assessment [8]. Equally, the need for constant monitoring by clinicians at clinics leads to a lack of motivation for frequent testing in various age groups in conventional testing methods. The patient's attention during these tests decreases continuously due to the non-comfortability of the test resulting in fixation errors or false positives [11].

As technology advances, the integration of innovative tools such as eye-tracking technology and gamification presents a novel opportunity to enhance pediatric vision screening [12]. Eye-tracking technology, which has been utilised effectively in various fields for its precision and reliability, offers a non-invasive, engaging way to assess how children perceive and interact with visual stimuli. This technology provides objective data on visual function without requiring verbal feedback, which is ideal for use with young children [9].

The advent of eye-tracking technology presents a novel opportunity to revolutionise vision screening through gamification. For eye-tracking technology and its advent in various fields including vision screening, the paper by [13] discusses the development and application of eye-tracking technology, emphasising its use in diverse contexts such as rapid targeting on fighter planes and medical applications like vision screening. Several studies have shown the efficacies of eye-tracking technology in the screening and possible identification of eye disorders and other related diseases such as dyslexia [7,9,13].

Children's vision screening poses difficult challenges for clinicians as children may not be literate enough to read eye chart letters or mature for letter-based tests [9]. Hence, the usage of nonverbal approaches such as the observation of eye movements tracking or symbol matching for children's vision screening. Aside from being time-consuming, the nonverbal approach also requires the efforts of an experienced clinician. Children are bored and easily lose interest due to visual dryness and the uninspiring nature of the test. Making repeatability of the tests almost impossible [9,14]. Arousing and maintaining patient attention is critical for improving the accuracy of pediatric health screening [9]. Gamification which involves the application of game design elements to non-game contexts is being widely used in pediatric health screening. Gamification is employed to enlist voluntary participation with otherwise difficult visual challenges and provide the fundamental impetus for the sustained utilization of the screening devices. The effectiveness of gamification in encouraging users to conduct voluntary activities, especially among children has been confirmed experimentally [15-17] emphasizing its effectiveness in enhancing user interaction and engagement in health platforms [18].

In Malaysia, where specific data on pediatric visual impairments and the efficacy of current screening methods are limited, there is a compelling need to adopt these innovative technologies. This literature review aims to assess the effectiveness of current vision screening methods and explore the potential of integrating gamified elements with eye--tracking technology to enhance children's engagement during vision screening as a means of attaining high screening accuracy. By examining existing methodologies and the innovative application of eye-tracking in gamified environments, this review seeks to highlight how such technologies could address the limitations of current practices while offering a more engaging, accurate, and child-friendly approach to vision screening.

Literature Review

The potential of gamified eye-tracking technology in vision screening to improve child engagement and screening accuracy has been explored by several studies. The outcomes of these studies suggest promising results, highlighting the benefits of gamification in children's vision screening. Recent developments in eye-tracking technology have shown promising potential in transforming the landscape of vision screening. Eye-tracking technology allows for precise measurement and analysis of eye movements and gaze patterns without relying on verbal responses, making it particularly suitable for use with young children and individuals with communication difficulties [5,6]. This technology has been successfully applied in various fields, including neuroscience, psychology, and human-computer interaction, demonstrating its versatility and reliability in capturing detailed visual behaviour data [8,13].

Studies [9,19,20] explored the potential of gamified approaches for vision assessment in children, focusing on conditions that can be challenging to assess with conventional methods. [19] investigated a game-based approach specifically designed to measure Contrast Sensitivity Function (CSF) in young children with amblyopia. The gamified test showed promise in differentiating between healthy and amblyopic eyes, even with potential limitations introduced by the game format. Another study [9] explored a mobile game designed to assess visual acuity in young children. While not targeting a specific disorder, this research suggests that gamified approaches can improve engagement and potentially accuracy in general pediatric vision assessments. Likewise, the study [20] examined the feasibility of self-administered contrast sensitivity tests for children, including a gamified iPad app, among participants with varying vision conditions, including normal vision, amblyopia, and bilateral impairment. This approach has the potential to improve access to vision screening for a wider range of pediatric eye conditions. Overall, these findings highlight the promise of gamified approaches for improving pediatric vision assessment, particularly for conditions that can be difficult to assess with conventional methods due to a lack of patient cooperation [9,19,20].

Analysing eye movement patterns during reading can provide insights into how children process written language. Studies by [21] and [12] investigates the potential of eye-tracking for identifying dyslexia in children and adults. Dyslexia is a common learning disability characterized by difficulties with reading fluency and accuracy [12]. Both studies propose using eye-tracking technology to analyse eye movements during reading as an objective measure for dyslexia screening. Machine learning models applied in [12] to eye-tracking data and achieved promising accuracy in differentiating individuals with dyslexia from control groups with an accuracy of 80.18%. These findings highlight the potential of eye tracking as a fast, non-invasive, and potentially cost-effective tool for dyslexia screening in both research and clinical settings.

The Beynex app, a self-administered cognitive assessment tool designed for the early detection of cognitive decline was investigated for screening dementia in [5]. The Beynex app utilizes gamified tests to assess cognitive performance and generates a score. The study demonstrates the app's potential as a user-friendly tool for self-monitoring cognitive health, particularly for individuals hesitant to seek professional help. The Beynex app utilizes gamified tests to assess cognitive performance across seven domains and generates a Beynex Performance Index (BPI) score. Researchers compared the BPI score with the Montreal Cognitive Assessment (MoCA) test, a standard clinical tool, in over 300 participants. The analysis showed a moderate correlation between BPI scores and MoCA ratings, indicating Beynex's potential for cognitive screening. Additionally, the Beynex app demonstrated good internal consistency and test-retest reliability, suggesting users perform consistently over time.

The potential of Extended Reality (XR) for developing gamified applications for vision function testing was explored [3]. XR encompasses Virtual Reality (VR), Mixed Reality (MR), and Augmented Reality (AR) that offer a promising alternative to conventional testing by creating realistic virtual environments and integrating game mechanics, potentially improving engagement and accessibility. The review analyses 59 research papers on XR applications for visual function testing, focusing on devices used, accuracy compared to conventional methods, usability, and game mechanics. The authors highlight the promise of XR technology for developing engaging and accessible visual function testing methods, potentially improving early detection and management of vision problems. The authors [22] propose a gamified online test combined with a machine-learning model for dyslexia screening. Their model achieved over 80% accuracy in detecting dyslexia among more than 3,600 participants. The method's robustness was further validated using a different dataset and testing environment (tablets instead of desktops). This approach offers promise for improving access to dyslexia screening in populations where conventional methods might be less effective. Overall, the study demonstrates the potential of machine learning combined with gamified testing for dyslexia screening in languages with transparent orthographies. This approach has the potential to improve access to dyslexia identification and facilitate early intervention.

The reviewed literature comprehensively explores the emerging applications of gamification and eye-tracking technology in vision and cognitive assessments. The authors effectively highlight the potential of these advancements for improving child engagement, screening accuracy, and accessibility. Studies employing gamified approaches in vision assessment [9,19,20] demonstrate promise for assessing challenging conditions like amblyopia and improving access to broader pediatric eye care. Similarly, research on eye tracking for dyslexia screening [12,21,22] suggests its potential as a fast, objective, and non-invasive tool. The Beynex app [5] exemplifies gamification for cognitive screening, showing promise for early detection and self-monitoring. The inclusion of Extended Reality (XR) [3] explores a future direction for creating more engaging and accessible vision testing methods. Overall, this review effectively summarises the growing body of research on gamification and eye-tracking technologies in vision and cognitive assessments, highlighting their potential to revolutionize screening methods, particularly for pediatric populations. Table 1 presents the summary of the reviewed literature.

This summary of the literature review as presented in Table 1 encapsulates a range of innovative research endeavours aimed at advancing early detection and assessment methods for visual and cognitive conditions across different populations. Studies employing gamified approaches [9,19,20] illustrate their efficacy in enhancing engagement and accessibility in assessing conditions like amblyopia and contrast sensitivity function impairments, despite existing challenges such as platform validation and environmental variability. Similarly, advancements in eye-tracking technology [12,22,23] highlight their promise as objective tools for dyslexia screening, achieving significant accuracy rates and demonstrating robustness across diverse populations and testing environments. Moreover, the integration of gamification in cognitive screening through applications like the Beynex app [5] shows promise for early detection of cognitive decline, though further validation in varied clinical settings remains imperative. Looking ahead, Extended Reality (XR) technologies [3] offer innovative approaches to vision testing, emphasizing enhanced engagement and accessibility, yet requiring standardized integration into clinical practice. Overall, these advancements underscore a pivotal shift towards more effective, engaging, and accessible screening methods in pediatric healthcare, while emphasizing the ongoing need for rigorous validation and standardization across diverse clinical and demographic contexts.

Table 1: Summary of Literature Review

Reference	Purpose	Method	Outcome	Gap
[9]	Assess gamified approach for visual acuity in children	Mobile game- based assessment	Improved engagement and potential accuracy in pediatric visionassessment	Limited specificity to particular disorders
[19]	Measure Contrast Sensitivity Function (CSF)in amblyopic children	Game-based CSF test	Differentiation between healthy and amblyopiceyes	Potential limitations of game format
[20]	Evaluate self-administered contrast sensitivity tests inchildren	Gamified iPad app	Enhanced accessibility to vision screening	Variability in device and environmentusage
[23]	Identify dyslexia througheye-tracking analysis	Eye-trackingtechnology	Objective dyslexiascreening method	Validation acrossdiverse populations
[12]	Utilize eye-tracking and machine learning fordyslexia screening	Machine learning models on eye-tracking data	High accuracy in dyslexia detection	Standardization across differentenvironments
[24]	Investigate Beynex app for cognitive decline screening	Gamified cognitive tests	Moderate correlation with MoCA ratings	User demographic diversity and clinicalvalidation
[3]	Explore XR for visionfunction testing	XR technologyapplications	Enhanced engagementand accessibility	Standardization andclinical integration
[22]	Develop gamified onlinetest with machine-learning for dyslexia screening	Online gamifiedtest with ML model	Achieved over 80%accuracy in dyslexia detection	Validation acrossdifferent datasets and environments

The literature review from Table 1 highlights promising advancements in early detection and assessment methods for visual and cognitive conditions using innovative technologies such as gamified self-check systems, eye tracking, and machine learning. However, a critical gap exists regarding the implementation proof of these technologies in clinical practice. Many studies emphasize initial positive outcomes but lack sufficient evidence of their efficacy and reliability when applied in real-world healthcare settings. Furthermore, the non-generalizability of findings due to smaller sample sizes limits the broader applicability of these methods across diverse populations. Moreover, there is minimal discussion on the cost-effectiveness or feasibility of scaling these technologies for widespread use, essential considerations for their practical adoption in healthcare. Addressing these gaps is crucial to fully realize the potential benefits of these technological innovations and to guide their integration into routine clinical practice

Visual Impairments

Visual impairments in children, notably refractive errors, amblyopia, and strabismus, represent significant barriers to normal development and quality of life. Refractive errors, such as myopia (nearsightedness), hyperopia (farsightedness), astigmatism, distorted visual perception and are the most common forms of visual impairment among children. These conditions significantly impact the academic performance and the future life of a child [25,26]. Amblyopia, often referred to as lazy eye, is due to the brain and the affected eye not working properly together, which can lead to permanent vision loss if not treated timely. This condition has been shown to negatively influence school readiness and is associated with poorer cognitive performance during early schooling, particularly when combined with strabismus [27]. Strabismus, characterised by misalignment of the eyes, can lead to amblyopia as well as challenges with depth perception. The structural changes in the eye associated with strabismus, such as alterations in the nerve fibre layer and ganglion cell complex, underscore its impact on the visual system [28].

The consequences of untreated visual problems in children extend far beyond simple vision impairment. Academically, children with unresolved vision issues, such as uncorrected refractive errors, may struggle with tasks that are visual in nature, such as reading and writing. This can lead to decreased academic performance and heightened frustration in school settings, as shown in a study that found diminished vision was more common in students not participating in school health programs, affecting their learning outcomes [29]. Socially, poor vision can hinder the ability to navigate and interact with peers effectively, potentially resulting in poor social integration and diminished participation in group activities. This is highlighted by research emphasizing the importance of early and regular vision screenings to prevent such irreversible consequences, which have significant social, academic, and financial implications [30]. Overall, untreated visual impairments can drastically affect a child's quality of life, leading to disadvantages that extend into adulthood, such as limited job opportunities and social challenges. These significant impacts underscore the importance of timely and effective vision screening and correction to mitigate the far-reaching effects of visual impairments.

Early vision screening plays a critical role in preventing the detrimental effects of unaddressed visual impairments in children. Common childhood vision problems like refractive errors, amblyopia, and strabismus can significantly impact a child's development if left untreated [25-27]. These conditions can lead to academic difficulties, hindering performance in reading and writing tasks [29]. Furthermore, poor vision can pose social challenges by hindering peer interaction and limiting participation in activities [30]. Research emphasises the importance of early and regular vision screenings to prevent these lasting consequences, which can have significant social, academic, and even financial implications throughout a child's life [29,30]. Timely detection and correction of vision impairments are crucial to ensure a child's healthy development and quality of life.

Current Screening Methods in Pediatric Vision Care

The assessment of vision in children has conventionally employed a range of established screening tools, each designed to target specific aspects of visual function. Among the most commonly used are the Amsler Grid [31], the TNO Stereotest [32], and various visual acuity tests [9,33]. The Amsler Grid is a straightforward diagnostic tool, that assists in detecting visual disorders related to retinal abnormalities, especially in the macula. Patients using the Amsler Grid observe a grid pattern and report any distortions or blank areas, which could indicate conditions such as macular degeneration [34]. In a systematic review and meta-analysis, [35] assessed the Amsler Grid's accuracy in diagnosing neovascular age-related macular degeneration (AMD). Despite its widespread recommendation for self-assessment to promote early diagnosis, the findings reveal that the Amsler Grid displays variable sensitivity and specificity, underscoring its importance in-home monitoring and the necessity for routine ophthalmic examinations.

The TNO Stereotest utilises red-green glasses and a series of patterned cards to evaluate depth perception, where the ability to perceive these patterns in three dimensions indicates the level of the patient's stereoscopic vision [36]. A recent study by [37] specifically examined the validity of the TNO cards stereopsis test as a screening tool for defects of binocularity in children. This study is particularly relevant as it investigates how effectively the TNO test identifies binocular vision defects such as amblyopia, strabismus, and refractive errors. The findings revealed that while the TNO test demonstrates high sensitivity and specificity in screening for amblyopia and strabismus, it is less effective at detecting refractive errors. Consequently, it is recommended that the TNO test be used alongside other vision assessments to ensure a comprehensive screening approach.

Lastly, visual acuity tests using the Snellen chart measure the clarity of sight from a fixed distance by requiring patients to read letter rows, with the smallest accurately discernible row determining their visual acuity [38]. A study by [39] delves into the effectiveness of the Snellen chart in clinical settings, discussing how Snellen visual acuity measurements are converted to the LogMAR scale for precise evaluation, particularly in larger studies. The study underscores the Snellen chart's widespread acceptance owing to its simplicity and ease of use, making it a staple in routine ophthalmic assessments. However, it also points out the challenges associated with its subjective nature and its potential inconsistencies in measurements emphasizing the importance of more standardised tools.

Despite the widespread use of these methods (Amsler Grid, the TNO Stereotest, and various visual acuity tests), they present several limitations that may hinder their effectiveness, particularly in pediatric populations. One significant issue with conventional vision screening methods is their invasiveness and the discomfort they may cause, which can be particularly challenging for young children who may not cooperate fully during the screening [40]. Addressing this, a study by [41] discussed the development and evaluation of a novel, non-invasive vision screening method that utilises smartphone technology which is designed to be less invasive and more comfortable for children. This smartphone-based approach allows for quick, effective screening with minimal discomfort for the child. The study highlights how this method proved to be a viable alternative in resource-limited settings, where the conventional and more invasive screening tools might be less practical or too uncomfortable for young children. This means that conventional, and more invasive screening tools can potentially lead to resistance or inaccurate test results [42]. Additionally, conventional vision screening methods often depend on subjective responses from the patient [23], such as reporting distortions seen in the Amsler Grid or describing their perception of depth in the TNO stereotype. This reliance on subjective feedback can lead to variable results, particularly in children who lack the necessary communication skills or attentiveness for accurate testing. Addressing these limitations, a study by [43] explored the low accuracy of conventional subjective methods commonly used in vision screening. The research highlights how subjective methods are heavily dependent on individual feedback, which can vary greatly. To enhance the precision of these assessments, the study investigated the use of weighted scales that incorporate objective measurements like eye-tracking, demonstrating that such methods can significantly improve the accuracy of conventional subjective vision screenings. Moreover, the potential for examiner bias is an inherent drawback of the conventional screening methods, where the interpretation of results can be subtly influenced by the examiner’s prior experiences and expectations, and manual test administration may lead to inconsistencies in how tests are conducted and results are interpreted [44]. Supporting this, [45] addresses the subjective limitations of conventional vision detection methods, which can be influenced by the uneven distribution of medical resources and the examiner's subjective biases. The authors propose an innovative, automatic, and objective vision screening system using Electroencephalogram (EEG) signals that analyses individuals' visual state without medical staff involvement, significantly reducing examiner bias and enhancing the objectivity and consistency of the screening process.

These challenges highlight the urgent need for advancements in vision screening technologies. Integrating eye-tracking technology with gamified elements represents an innovative approach that could transform pediatric vision screening. This integration offers a non-invasive, engaging, and unbiased method to evaluate visual function, promising more accurate and reliable outcomes for the early detection and management of visual impairments in children.

Technological Advances in Vision Screening

Recent years have witnessed significant technological innovations in the field of visual screening, which have broadened the scope and enhanced the precision of diagnostic methods. One of the most prominent advancements in eye health assessment is the adoption of digital tools and artificial intelligence (AI) [46]. This shift has been thoroughly explored in recent research, with significant contributions like the work by [47]. Their study reviews the pivotal role of AI in transforming ophthalmic care, highlighting how the application of deep learning techniques to diagnose and screen for diabetic retinopathy (DR) achieves an accuracy exceeding 95%. The evolution of AI in ophthalmology represents a major shift towards more precise and automated methods of disease detection and management, demonstrating the transformative impact of these technologies in eye care. Building on this technological advancement, the gradual transition from conventional to digital methods in healthcare, particularly in vision screening, calls for a measured approach. According to a study by [48], there is a notable readiness among healthcare professionals and students to embrace digital health tools in patient care, suggesting a favourable shift in attitudes toward modern technologies in healthcare sectors. Their study explores the factors influencing this willingness, finding a strong inclination towards adopting these innovations. The result advocates for comprehensive digital health education programs that not only prepare current and future healthcare professionals with necessary digital competencies, but also ensure seamless integration of these tools into patient care. Such educational initiatives are crucial for ensuring that the healthcare workforce is fully prepared to make the most of digital advancements, thus supporting a careful and informed transition to more modern screening methods.

Integration of technologies in vision screening particularly through automated systems and AI, is revolutionising accessibility and engagement in eye care, much like the potential application of gamified eye-tracking tools [49]. [50] Conducted a study demonstrating that automated diabetic retinopathy detection with AI could achieve high diagnostic performance, showing 90.8% sensitivity with a conventional fundus camera and 94.1% sensitivity with a white LED confocal scanner. This underscores the potential of automated systems to enhance diabetic retinopathy screening accuracy in various settings, including underserved areas. Similarly, [51] evaluated a community-based screening using an offline AI system on a smartphone, which proved effective in remote areas lacking ophthalmological services. This mobile, non-mydriatic approach aligns with efforts to make screening not only more accessible but also more engaging, offering a scalable method to detect eye diseases. Additionally, [52] highlighted the successful implementation of an automated vision screening system in a primary care setting, significantly improving follow-up adherence in a low-income patient population, and demonstrating how AI-assisted screenings can enhance outcomes in resource-limited environments. These examples vividly illustrate how technological advancements in vision screening can be paralleled by innovations like gamified eye-tracking, aiming to boost engagement and effectiveness across diverse populations.

Eye-tracking technology has emerged as a groundbreaking tool in medical diagnostics, transcending its conventional applications in psychology and market research [53]. In vision screening, eye-tracking offers several benefits over conventional methods. It provides objective, quantitative data on eye movements, crucial for diagnosing a range of disorders from common refractive errors to more complex neurological conditions such as nystagmus or strabismus. A comprehensive study by [1] illustrates the increasing utilisation of eye-tracking technologies in vision screening. Their research reveals the expanding role of eye-tracking in diagnosing varieties of eye-related disorders, affirming its advantages over conventional methods by providing more precise and objective measurements. Furthermore, the study [54] demonstrates how eye-tracking technology can significantly enhance the reading experiences of low-vision individuals by recognising fine-grained gaze behaviours. This capability not only assists in medical diagnostics but also offers substantial improvements in the usability of visual aids, showcasing the technology's extended application in patient-centred care. The integration of eye-tracking into vision screening protocols not only enriches the diagnostic process, but also paves the way for more accessible and effective eye care solutions across diverse populations.

Eye-tracking technology works by measuring either the reflection of infrared light off the retina or the image of the eye, captured by high-resolution cameras [55]. This allows the continuous monitoring of eye positions and movements without physical contact. Making it especially suitable for use with children who may struggle to remain still or follow verbal instructions during conventional screenings.

Research by [56] has shown that retinal image-based eye motion measurement from scanned ophthalmic imaging systems, such as scanning laser ophthalmoscopy, can achieve precise real-time eye tracking at sub--micron resolution. This technology aside from capturing most of the eye motion across image sequences also minimises image distortions induced by eye movements, facilitating accurate measurement of fixational eye movements in various diagnostic applications. Additionally, [57] developed a high-resolution, ultrafast, wide-field retinal eye--tracking system that measures eye displacements with exceptional accuracy. Their system, which uses a 2D MEMS scanner for high frame rate image acquisition, demonstrates the clinical capabilities of detecting microsaccades and other subtle features of ocular motion that are crucial for identifying biomarkers of neurodegenerative diseases. These advancements underline the significant potential of eye-tracking technology in enhancing the effectiveness and patient comfort of vision screenings, particularly in pediatric settings.

Eye-tracking technology, particularly beneficial in dynamic assessments where patients interact with visual stimuli on a screen, provides critical insights into how patients perceive, process, and respond to visual information. For instance, in vision therapy, eye-tracking has proven instrumental in developing personalized training sessions that enhance eye coordination and visual attention. The use of eye--tracking in therapy for amblyopia, or "lazy eye," demonstrates significant improvements in patients. A notable study by [58] explores the use of eye-tracking-aided VR system for amblyopia treatment in children. This system dynamically adjusts the difficulty of tasks based on real-time eye-tracking data, ensuring that the therapy is both engaging and appropriately challenging, thus maintaining intrinsic motivation throughout prolonged treatment periods. Additionally, the study [59] involves a system that uses eye-tracking to enhance the management of amblyopia through interactive, binocularly balanced visual tasks. This treatment is shown to be effective in improving visual acuity and binocular function in a home-based setting, reflecting significant advancements in non-invasive, technology-driven therapeutic approaches for amblyopia. These studies exemplify how modern eye-tracking technology not only supports the integration of gamification with eye-tracking technology but represents a novel more accurate and detailed assessment that enriches treatment protocols, making them more adaptive and responsive to individual patient needs in real-time.

Gamification in Pediatric Vision Screening

Gamification involves the use of game-like elements, such as points, challenges, rewards, and story-driven tasks, in non-game settings to increase user motivation and engagement [94]. In the context of vision screening, gamification provides a structured approach to evaluate visual functions while making the process fun and enjoyable for young patients [19]. This approach allows clinicians to assess how well children track visual targets by incorporating interactive games, ensuring that children stay focused and engaged throughout the screening [41]. Through game elements, children's eye movements are tracked more consistently and with better compliance, which helps gather more accurate data about their visual capabilities [19].

The eye-tracking component is integrated seamlessly with the game [95]. As the child interacts with the game visually, the system monitors where and how they look at various elements [96]. Points are awarded based on successful interactions, such as accurately following a moving target or focusing on specific visual cues at the right times [97]. This feedback mechanism ensures that children stay focused and their eye movements are consistently measured [98]. By quantifying interactions, such as how long the child focuses on a specific target or how smoothly they track a moving object, gamified tasks provide an engaging yet highly informative way to assess eye-tracking behavior [99].

The integration of gamification into eye-tracking technology for vision screening is a transformative advancement that leverages game design elements to make health assessments more engaging and interactive [60]. Gamification involves using video game elements in non-game contexts, which has been shown to improve motivation and compliance, particularly in pediatric patients [61]. By incorporating elements such as point scoring, competitions, and interactive storylines into the vision screening process, children are more likely to remain engaged and cooperative throughout the diagnostic process. [62] emphasises enhancement of these processes through an innovative data analysis pipeline that makes eye-tracking assessments more interactive. Additionally, [63] underscores the importance of high-quality eye-tracking data in ensuring accurate and engaging health assessments. Meanwhile, [64] highlights the accessibility and scalability of smartphone-based eye-tracking, which broadens the reach and engagement of vision screening. Further, [1] discusses how the growth of eye-tracking technology in vision screening has been particularly enhanced by gamification and visualisation techniques that captivate children's interest. Lastly, [54] explores technological improvements that optimise the interaction experience, likening the eye-tracking process to gaming scenarios found in virtual reality applications, thus enriching the screening experience for young patients. This comprehensive approach to integrating eye-tracking with gamification elements demonstrates a significant shift towards more engaging, interactive, and effective methods in pediatric vision screening, ensuring that children remain attentive and responsive throughout the diagnostic process.

This approach aside from making the screening process more enjoyable, it also increases the accuracy of the data collected, as children are more responsive to the tasks. For instance, the study by [19] demonstrated how gamification in vision screening keeps children's interest high, improving both enjoyment and the quality of clinical data collected. Additionally, gamified eye-tracking tasks can adapt in real-time to the child's skill level, ensuring that the screening remains challenging but achievable, which is key to maintaining engagement. [65] showed that adaptive gamification methods can significantly enhance user engagement by tailoring game mechanics to individual user profiles.

Gamification in vision screening represents a promising frontier that can revolutionize how young patients perceive and participate in preventative health measures, leading to earlier detection and more effective management of visual impairments. Studies [66], [67] underscore the effectiveness of personalized gamification techniques in increasing patient engagement and compliance, which are crucial for pediatric vision screening. [68] highlights the need for engaging screening methods to ensure better compliance and effective early detection. Similarly, studies [69], [70] show that gamification boosts motivation and participation, which is essential for engaging children in educational contexts. Finally, [71] discusses the benefits of adaptive gamification in e-learning, suggesting that similar strategies can be mirrored in pediatric vision screening to maintain children's interest and participation.

Gamification also plays a crucial role in enhancing the diagnostic accuracy of pediatric vision screening. By creating an engaging environment, gamified elements such as point scoring, adaptive challenges, and interactive storylines help maintain the attention and motivation of young patients throughout the assessment process. Increased engagement means children are more likely to comply with visual tasks, reducing incomplete or inconsistent data. This improved compliance translates into higher-quality diagnostic data, leading to more reliable screening results. Studies have shown that gamified health assessments result in better participation and attention, which are key factors in ensuring accurate outcomes [100], [101], [102], [103], [104], [105], [106]. Additionally, gamified vision screening can adapt to each child's performance, maintaining an optimal level of challenge to sustain interest, further contributing to consistent and reliable eye-tracking measurements.

The strategic integration of gamification with eye--tracking technology in vision screenings for children not only enhances the screening experience but also substantially improves the outcomes. By making the process interactive and adaptive, this approach ensures higher levels of engagement and cooperation from young patients, facilitating more accurate and early diagnosis of potential visual impairments. By integrating these advanced technologies, particularly eye-tracking and gamification, into visual screening protocols, medical professionals can offer more precise, efficient, and patient-friendly assessments. This not only aids in early detection and treatment of visual impairments but also contributes to better long-term outcomes in patient vision and quality of life.

Critical Analysis of Eye-Tracking and Gamification Approaches

Despite significant advancements in eye-tracking technologies, several limitations still exist. One notable limitation is the variability in results, often influenced by differences in participants' eye anatomy, such as eye color, eyelashes, or glasses, which can interfere with the accuracy of the measurements [107]. Additionally, dependence on calibration accuracy is another significant factor that affects the reliability of the data gathered [108]. Effective calibration requires that the subject remains still and focuses accurately on calibration points, which can be challenging, particularly with young children [109]. Failure to achieve precise calibration can lead to less accurate tracking data, reducing the effectiveness of the screening tool [110].

While gamified approaches have shown promise in improving engagement and participation in vision screening, they also present certain ethical concerns [100]. The positive experience generated by gamified elements, such as interactive storylines, rewards, and point scoring, may lead to misconceptions about health outcomes [101]. Children and their guardians may develop unrealistic expectations, potentially giving children a false sense of reassurance regarding their health status [102]. This risk highlights the importance of maintaining transparency about the limitations and purpose of these assessments [106].

Limitations in Pediatric Vision Screening

In pediatric healthcare, vision screening is a pivotal component that ensures early detection and management of visual impairments in children. Effective screening during the early years is essential for mitigating potential developmental and educational setbacks. However, conventional methods of pediatric vision screening often fall short in terms of engagement, accuracy, and accessibility, particularly in diverse and resource-limited settings [15,72]. The advent of computerised tools, incorporating technologies like eye-tracking and gamification, presents an opportunity to transcend these limitations, offering a more standardised, objective, and engaging approach to vision screening [24,73].

One of the critical shortcomings of conventional vision screening methods is their failure to engage young patients effectively. Conventional screenings often lack interactive elements that capture and maintain children's attention, decreasing cooperation and focus [3]. This lack of engagement can lead to unreliable test results, as children may not respond accurately or consistently to the tasks required. A computerised screening tool, especially one enhanced with gamified elements, can revolutionise this aspect by turning the screening process into an enjoyable activity [15,24]. Such tools are designed to hold a child's interest through interactive and visually appealing tasks, ensuring more accurate and reliable outcomes. For example, the game "Space Vision" developed by [60] uses a gamified approach to improve the visual acuity testing process, making it more enjoyable and engaging for children. Additionally, the smartphone-based solution by [41] has been shown to enhance screening accuracy and efficiency in resource-limited settings by engaging children through digital interaction. Moreover, the AI-based system discussed by [74] uses digital tools to make vision screenings more effective and child-friendly. These innovations demonstrate the potential of gamified and computerised tools to transform vision screening into a more effective and enjoyable process for young patients, leading to better diagnostic outcomes.

Conventional vision screenings often rely on subjective assessments by clinicians and the verbal responses of children, both of which can introduce significant variability and inaccuracies [23]. This is particularly problematic when assessing non-verbal or less cooperative children, where misinterpretations can lead to incorrect diagnoses [3]. Computerised tools can mitigate these issues by utilising eye-tracking technology that provides objective, quantitative data on visual function. This technology reduces the reliance on subjective interpretations and verbal feedback, enhancing the precision of the screening results. For example, [62] discusses the use of eye-tracking data to provide objective metrics and visual representations that enhance the accuracy of vision screening, particularly in contexts where children may not be able to give consistent verbal feedback. Additionally, [63] provides an extensive overview of eye-tracking technology, explaining how it delivers high-quality, quantitative data that reduces reliance on subjective assessments by clinicians. Furthermore, a bibliometric study by [75] reviews the application of eye-tracking technologies in vision screening, highlighting its role in reducing subjectivity and improving diagnostic precision. These innovations demonstrate the potential of gamified and computerised tools to transform vision screening into a more effective and enjoyable process for young patients, leading to better diagnostic outcomes.

Another significant challenge with conventional screening methods is the dependency on specialised equipment and trained personnel [24]. This requirement can be a substantial barrier in resource-limited settings or regions with a scarcity of trained professionals, limiting the reach and frequency of effective screenings [3]. Computerised visual screening tools can be designed to be user-friendly and require minimal training, making them accessible to a broader range of operators and settings. This accessibility can significantly expand the reach of vision screening programs, especially in underserved areas. For instance, the development of "Chart Reader," discussed by [76], showcases how visualization tools can be designed to be accessible and require minimal specialized training, making them suitable for a wide range of users. Similarly, the research by [77] on accessible web development emphasizes the importance of creating tools that are easy to use, further supporting the feasibility of employing computerised screening tools in various settings. Moreover, [78] illustrates how interfaces can be designed to accommodate users with minimal training, which is crucial for deploying these tools in environments with limited professional training. These innovations demonstrate the potential of computerised tools to transform vision screening into a more effective and accessible process for diverse populations.

Conducting widespread and regular vision screenings is logistically challenging with conventional methods, particularly in large, diverse populations [21]. The variability in testing conditions and the interpretation of results across different examiners and locations can further compromise the consistency and reliability of the screenings [7]. A computerised tool offers a solution by standardising the screening process across different settings, ensuring that all children are evaluated under consistent conditions. This standardisation not only improves the reliability of the screenings, but also enhances their scalability, making it feasible to implement large-scale screening initiatives. For instance, the development of a streamlined children's vision screening solution based on smartphone imaging, as discussed by [41], demonstrates how such tools can efficiently be deployed across various settings without need for specialised equipment or highly trained personnel, significantly improving the scalability of vision screenings. Moreover, the systematic review by [48] on deep learning-based algorithms for diabetic retinopathy screening, further supports the use of automated systems to reduce variability and standardise diagnostics across different examiners and settings. These computerised tools thus present a viable solution to overcome the logistical challenges associated with conventional vision screening methods, offering a more standardised and scalable approach.

The limitations inherent in conventional pediatric vision screening methods underscore the pressing need for innovative approaches that provide more reliable, efficient, and engaging screenings. Computerised visual screening tools, particularly those incorporating eye-tracking technology and gamification, offer promising solutions to these challenges. By enhancing engagement, accuracy, and accessibility, these tools have the potential to transform pediatric vision screening practices, ensuring that more children receive the timely and effective care they need for optimal developmental outcomes.

Need for a Computerized Tool

Vision screening in pediatric populations is a critical healthcare practice that significantly influences a child's developmental and academic success. Conventional methods, however, often struggle with issues of engagement, accuracy, and practicality, particularly in diverse and resource-limited settings [22]. The integration of computerised tools in vision screening, incorporating advanced technologies such as eye-tracking and gamification, promises to revolutionise this field. These tools can provide standardised, objective, and engaging screening processes that are both efficient and accessible [5].

One of the foremost benefits of a computerised vision screening tool is its ability to standardise the screening process. Conventional methods can vary significantly depending on the equipment used and the professional administering the test, leading to inconsistent results. A computerised tool standardises the assessment conditions and criteria for all children, thereby reducing variability and increasing the reliability of the screening outcomes. This consistency is crucial for accurate screening across various settings, ensuring that all children receive equal and unbiased access to vision care. For example, a study by [79] discusses a virtual reality approach to visual field screening that provides a standardised user experience across different demographic groups, ensuring consistent testing conditions without need for extensive training or specialised equipment. Additionally, the study by [80] on implementation of a standardised vision screening guideline in a pediatric inpatient rehabilitation unit shows how standardising vision screenings can improve the quality and consistency of screenings, thereby increasing their reliability and effectiveness. These advances highlight the critical role of computerised tools in enhancing the standardisation and reliability of vision screenings across diverse settings.

Computerised vision screening tools utilise eye-tracking technology and automated analysis algorithms to provide objective data on a child's visual function. This technology minimises the reliance on subjective interpretations and the need for verbal feedback from children, which can often be unreliable due to communication barriers or lack of cooperation. By providing a clear and quantifiable measure of visual performance, these tools enable more accurate diagnoses, thereby facilitating early detection of potential issues which might otherwise go unnoticed. For instance, the study by [81] discusses how eye-tracking supports children's vision screening, especially useful in cases where children cannot provide reliable verbal feedback. Additionally, [63] elucidates the principles of eye-tracking technology, emphasising its capacity to yield objective and quantitative data that bypasses the need for subjective judgment. Moreover, the systematic review by [82] highlights the implementation of eye-tracking in optometry, showing its effectiveness in providing precise measurements that enhance diagnostic accuracy. These advancements underscore the critical role of computerised tools in transforming vision screening into a more reliable and inclusive process, particularly beneficial in pediatric care.

Integrating gamification into vision screening transforms a routine medical assessment into an interactive and enjoyable experience for children. This approach significantly enhances children's engagement and cooperation during the screening process. Gamified elements such as scoring, rewards, and interactive gameplay keep the child focused and motivated, resulting in enhanced accuracy of the collected data. This not only improves the screening experience but also ensures that the results are reflective of the child's true visual capabilities. For instance, [19] explores the feasibility of a gamified contrast sensitivity function measure, finding that such engaging methods can effectively sustain a young child's interest and improve the accuracy of vision assessments. Similarly, the "ColourSpot" test, developed by [83], uses gamified tasks on a tablet to diagnose color vision deficiencies in young children, which is enjoyable and effective in maintaining children's attention throughout the screening process. These innovations demonstrate the potential of gamification to enhance the effectiveness of vision screenings by making them more appealing and engaging for young patients.

The design of computerised vision screening tools prioritises user-friendliness, requiring minimal training for operators. This ease of use expands the tool's accessibility, allowing it to be deployed effectively in different settings—from urban schools to remote community centres. By simplifying the operational requirements, these tools can be utilised by a broader range of healthcare providers, educators, and even volunteers, significantly increasing the reach of essential vision screening services to underserved populations. For instance, a scoping review by [84] examines various eHealth tools that facilitate the self-testing of visual acuity. The review notes that while these tools can be deployed effectively with minimal training, they often lack validation and regulation, posing potential risks and confusion for users. This highlights the need for validated, standardised, and computerised tools. Additionally, a systematic review by [85] discusses portable hardware and software technologies that address ophthalmic health disparities, emphasising how technological advancements in vision screening tools enable easy deployment and operation across varied and remote settings, thus broadening their accessibility and utility. These advancements demonstrate how integrating thoughtfully designed technologies in vision screening tools can make essential health services more accessible and effective for all and sundry.

Computerised tools streamline the vision screening process, making it much faster than conventional methods. This efficiency is crucial for conducting high-throughput screenings, particularly in large-scale public health initiatives where time and resources are often limited. For example, a study by [86] describes an interactive desktop autostereoscopy vision test that significantly accelerates the screening process by enabling the simultaneous assessment of visual acuity, colour vision, stereo vision, and binocular balance within just a few minutes. This rapid screening process reduces the burden on healthcare systems and ensures that a larger number of children can be assessed promptly, facilitating timely interventions. Such advancements in computerised vision screening tools greatly enhance the scalability and effectiveness of public health efforts, especially in settings that require swift and reliable evaluations.

The development of computerised vision screening tools represents a significant advancement in pediatric healthcare. By addressing the limitations of conventional methods through standardisation, objectivity, and enhanced engagement, these tools offer a superior alternative that is both more effective and accessible. The incorporation of eye-tracking technology and gamification does not only improve the quality and accuracy of the screenings, but also makes the process more appealing and less intimidating for children. As such, computerised vision screening tools are poised to make a profound impact on the early detection and treatment of visual impairments, contributing to better. health outcomes and brighter futures for children worldwide.

Potential of the Computerised Vision Screening Tool

Vision screening is an essential part of pediatric healthcare, pivotal for detecting early signs of visual impairment that could affect a child's development and learning. However, conventional methods often face challenges such as low engagement from children, inconsistent test conditions, and subjective results. To address these challenges, a new computerised vision screening tool is proposed. This tool integrates advanced features such as consistent setup parameters, eye-tracking technology, and gamified, child-friendly interfaces, aiming to transform the screening process into an effective and enjoyable experience for young patients.

The proposed computerised vision screening tool is designed with innovative features to enhance the accuracy and convenience of pediatric eye assessments. Unlike conventional methods, this tool ensures a consistent setup by maintaining a fixed distance between the user and the screen. This is critical for obtaining reliable and standardised results. For example, a study by [87] demonstrates how device-embedded cameras used for eye tracking in cognitive assessments provide a consistent and standardised data collection method. This approach, while focusing on cognitive metrics underscores the potential of eye-tracking technology to ensure fixed and precise testing conditions in vision screenings, thereby enhancing the reliability of the results. This example illustrates how eye-tracking technology can be leveraged to maintain a controlled and consistent environment crucial for accurate assessments. Furthermore, the computerised vision screening tool employs eye-tracking technology superior to virtual reality (VR) alternatives that might cause dizziness and are often cumbersome for small children. Although a study by [88] suggests that young children can tolerate immersive VR gameplay well, with 6% of participants discontinuing the VR play after the first 10 minutes, due to discomfort such as eye strain, fatigue, or motion sickness. Even the presence of this small percentage, experiencing discomfort underscores the potential challenges and limitations of using VR technologies in pediatric screenings. This suggests that for sensitive applications such as vision screening, eye-tracking technologies, which do not involve immersive environments that might cause disorientation, could be more suitable and comfortable for small children. Their study supports the claim that eye-tracking technologies, devoid of the immersive encapsulation that VR necessitates, are a better fit for children's vision screening due to their non-invasive and less disorienting nature. Eye-tracking provides a non-invasive, direct measurement of eye movements, offering precision without physical discomfort. Additionally, the computerised vision screening tool incorporates engaging gamification elements with child-friendly interfaces. These interfaces are intuitive and designed to capture and maintain children's attention by making the screening process similar to playing a game, thus reducing anxiety and increasing cooperation. For example, a study by [89] explores the use of gamified mobile mental health interventions, which have been shown to significantly improve user engagement and reduce attrition rates, demonstrating the potential of gamification to make health-related screening tasks more engaging for users. Similarly, research by [90] investigates the integration of gamification into eHealth interventions, finding that gamified features can substantially increase user engagement and compliance, particularly in settings that might otherwise be stressful or uninteresting for children.

By integrating these features, significant improvements in the screening process are anticipated. The accuracy of the screenings will increase due to the precise data captured by eye-tracking technology, which eliminates the guesswork and variability of manual assessments. For instance, a study by [45] validates the spatial accuracy of an eye--tracking system used to measure radiologists' visual fixations during CT image examinations, demonstrating how eye-tracking can precisely monitor and record visual search processes. This technology offers precise, objective data that reduces the variability associated with manual assessments, that directly applicable to improving the standardisation and reliability of vision screenings. Additionally, a study by [91] highlights how eye-tracking technology surpasses manual annotation methods in accuracy, especially in clinical decision support applications where precise data collection is critical. This further substantiates the advantage of eye--tracking in ensuring high reliability and consistency in diagnostic assessments, including vision screenings. These advancements show that eye-tracking technology is crucial for improving the standardisation and accuracy of vision screenings. The objectivity provided by automated analyses ensures that the results are consistent and unbiased, which is critical for accurately diagnosing and tracking the progression of visual impairments. Most importantly, the engagement level of children is expected to rise significantly. The gamification of the screening process, aside from holding the interest of young participants also encourages active participation, which is crucial for accurate diagnostics. For example, a study by [92] on early childhood education through gamification shows how making learning environments interactive and enjoyable greatly enhances children's willingness to engage and participate. This approach can be directly applied to vision screenings, where gamified elements ensure the process is less intimidating and more engaging for young participants. Additionally, [93] discusses the psychological benefits of gamification in learning, including increased engagement and motivation. By incorporating game elements into tasks children find them more appealing and enjoyable. This is crucial for maintaining cooperation and participation during vision screenings. These studies collectively underscore the effectiveness of gamification in transforming potentially stressful or mundane tasks into enjoyable and interactive activities that appeal to children, thereby facilitating more accurate and effective vision screenings.

The proposed computerised vision screening tool represents a significant advancement in pediatric healthcare, specifically in the early detection and treatment of visual impairments. The combination of consistent setup conditions, non-invasive eye-tracking technology, and gamified elements within a child-friendly interface. This tool is set to overcome the limitations of conventional vision screening methods. It promises to deliver more accurate, objective, and engaging assessments, making the process more enjoyable and less intimidating for children. Ultimately, this tool is expected to lead to better health outcomes by facilitating the early identification and treatment of visual issues, ensuring that children have the best possible support for their visual and overall developmental needs.

Conclusion

This review comprehensively explored the critical role of vision screening in childhood, highlighting its impact on educational attainment and social development. It identified limitations of current methods, particularly in engaging young children and providing objective assessments. The emergence of computerised tools, integrating eye-tracking technology and gamification, presents a promising solution. Unidentified visual impairments such as refractive errors, amblyopia, and strabismus can significantly hinder a child's development and quality of life. These conditions not only affect academic performance but also limit social interaction and participation, potentially impacting career opportunities and overall well-being in adulthood. Early detection and intervention are crucial to mitigating these impacts, underscoring the importance of comprehensive screening programs.

While traditional methods like the Amsler Grid, TNO Stereotest, and Snellen chart have been instrumental, they have limitations. These include subjectivity, potential for examiner bias, and challenges in engaging young children. This necessitates advancements in vision screening technologies to better serve pediatric populations. The integration of eye-tracking technology and gamification marks a significant leap forward in pediatric healthcare. Eye-tracking offers objective, quantitative data on eye movements, enabling more precise diagnoses. Gamification transforms the screening experience into an interactive and enjoyable process, fostering sustained engagement and compliance. This synergy enhances accuracy, efficiency, and supports early detection and intervention, crucial for optimising visual outcomes.

Looking ahead, continued research and development are essential to refine and validate these technologies further. Future studies should aim to validate these findings through controlled clinical trials involving diverse pediatric populations. These trials should be designed to evaluate the diagnostic accuracy and engagement benefits of gamified eye-tracking screening tools. Metrics for evaluation should include engagement levels, compliance rates, and diagnostic accuracy, measured through comparisons with traditional screening methods. By focusing on both short-term diagnostic outcomes and long-term impacts on visual health, these trials will provide the necessary evidence to support the widespread clinical adoption of these innovative screening approaches. Additionally, research on the cost-effectiveness and integration of these technologies into existing pediatric care workflows will be crucial for maximizing their potential. Ultimately, the integration of advanced computerised technologies in pediatric vision screening has the potential to transform clinical practice, ensuring early detection and improving lifelong visual health outcomes for children worldwide.

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