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Remote monitoring of social behavior in children with autism: The role of digital phenotyping in public programs

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Abstract

Autism Spectrum Disorder (ASD) is characterized by social and behavioral challenges, making early identification and continuous monitoring crucial for effective intervention. Traditional methods of monitoring social behavior in children with ASD often face limitations, particularly in resource-limited settings. The advent of digital phenotyping—using data from smartphones, wearables, and other digital tools to track behaviors—presents new opportunities for remote monitoring. This review examines the role of digital phenotyping in ASD care, focusing on its integration into public health programs. It explores key technologies for remote monitoring, the advantages of digital phenotyping in tracking social interactions, and the challenges posed by privacy and data security concerns. Additionally, the review discusses the policy implications and potential for large-scale adoption in public programs. Finally, it highlights emerging trends, such as AI integration, which could enhance the effectiveness of digital phenotyping in diagnosing and treating children with ASD. The review underscores the potential of digital phenotyping to revolutionize ASD monitoring, enabling more personalized, data-driven approaches in public healthcare systems.

Keywords: Remote; Monitoring; Social Behavior; Children; Autism; Digital Phenotyping; Public Programs

1. Introduction

1.1. Background on Autism Spectrum Disorder (ASD)

Autism Spectrum Disorder (ASD) is a neurodevelopmental condition characterized by persistent deficits in social communication, interaction, and restricted, repetitive patterns of behavior, interests, or activities (American Psychiatric Association [APA], 2013). ASD manifests early in childhood and affects individuals differently, with symptoms ranging from mild to severe. Recent studies estimate that ASD affects 1 in 54 children, making it a significant public health concern (Maenner et al., 2020). The complexities of ASD arise from a combination of genetic, epigenetic, and environmental factors that influence brain development, leading to atypical neural connectivity and functioning (Tick et al., 2016).

Figure 1 shows a young child in a classroom environment, seated at a red table with colorful markers and paper in front of him. He appears visibly distressed, covering his ears and squinting his eyes tightly, indicating discomfort. In the background, other children are engaged in activities, seated on green chairs, seemingly unaffected by the environment.

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The child's reaction suggests he may be experiencing sensory overload, a common occurrence for some children with Autism Spectrum Disorder (ASD) when faced with loud noises, bright lights, or busy environments. The setting highlights the challenges that sensory sensitivities can pose in group or classroom settings, impacting focus and comfort.



Figure 1 Classroom Sensory Overload in Autism (Nurturing Parenting, 2023)

A core feature of ASD is the difficulty in social interactions and communication. Children with ASD often exhibit delayed language development, impaired ability to engage in reciprocal conversations, and challenges in understanding non-verbal cues such as facial expressions and body language (Lord et al., 2020). These social deficits can impact their educational progress, peer relationships, and overall quality of life. Furthermore, many children with ASD also demonstrate repetitive behaviors and intense interests in specific activities, which may further hinder their social integration (Hodges et al., 2020).

Given the heterogeneity of ASD, early diagnosis and intervention are essential for improving outcomes. Numerous studies indicate that early intervention programs focusing on behavioral therapies can significantly enhance social, cognitive, and language skills in children with ASD (Zwaigenbaum et al., 2015). However, traditional methods of diagnosing and monitoring ASD rely heavily on clinical observations and parent-reported assessments, which may not fully capture the nuances of the disorder, particularly in real-world settings. This limitation has prompted the exploration of new technologies, such as digital phenotyping, to provide more objective and continuous monitoring of social behaviors in

children with ASD (Jiang et al., 2020). The growing interest in digital phenotyping represents a shift toward leveraging digital tools to track behavioral patterns, offering a more comprehensive understanding of how ASD manifests in daily life. By utilizing smartphones, wearables, and other digital devices, digital phenotyping can capture data on social interactions, movement, and environmental factors, providing valuable insights into the social challenges faced by children with ASD. This emerging approach holds promise for enhancing early detection, personalized interventions, and long-term monitoring, particularly in public health programs aimed at supporting children with ASD.

1.2. Importance of Early Identification and Intervention in ASD

Early identification and intervention in Autism Spectrum Disorder (ASD) are crucial for optimizing developmental outcomes and enhancing quality of life for children affected by the disorder. Research consistently demonstrates that early detection of ASD, typically before the age of three, allows for timely intervention that can significantly improve cognitive, social, and adaptive skills (Dawson et al., 2020). Children who receive early intervention, such as Applied Behavior Analysis (ABA) or speech and language therapies, often show marked improvements in communication, social interaction, and the reduction of problematic behaviors associated with ASD (Zwaigenbaum et al., 2015).

Early identification is particularly important because the brain's plasticity is highest during the first few years of life. This period provides a critical window of opportunity for intensive interventions that can reshape neural circuits, fostering the development of social and communicative competencies that might otherwise remain underdeveloped (Landa, 2018). Studies show that the sooner intervention begins, the more likely children with ASD are to develop essential skills that enhance their ability to engage with peers, succeed academically, and participate in daily life activities (Estes et al., 2015).

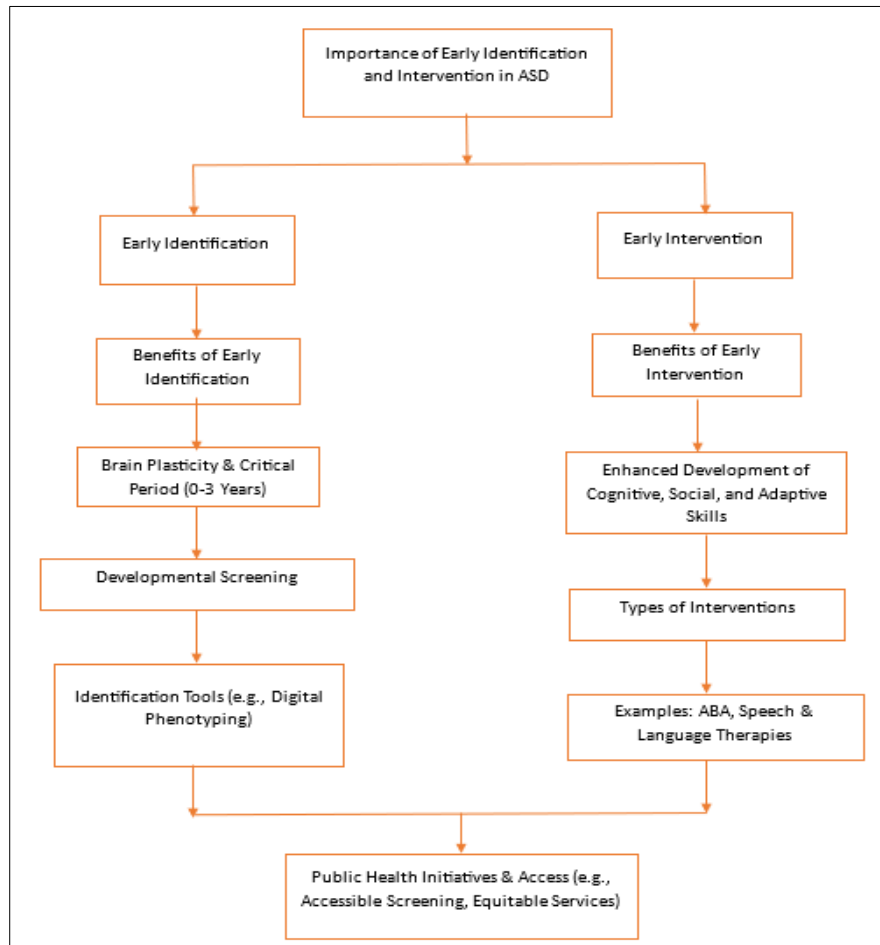


Figure 2 Pathways to Optimizing Developmental Outcomes through Early Identification and Intervention in ASD

Figure 2 illustrates the interconnected pathways highlighting the importance of early identification and intervention in Autism Spectrum Disorder (ASD). Early identification, often achievable through developmental screening and digital tools like phenotyping, enables timely detection during a critical period of brain plasticity in early childhood (typically before age three). This early detection allows for intervention methods—such as Applied Behavior Analysis (ABA) and speech therapy—to be implemented during this optimal developmental window. The result is enhanced growth in cognitive, social, and adaptive skills, which helps children improve communication, social interactions, and behavioral management. Public health initiatives, which emphasize accessible and equitable screening, aim to extend these benefits to underserved populations, ensuring that early support is broadly available. This model underscores the value of both early detection and structured intervention in fostering better developmental outcomes for children with ASD.

However, the process of early identification can be complex due to the heterogeneous presentation of ASD symptoms. While some children exhibit clear signs of social and communicative delays by the age of two, others may not be diagnosed until they are older, when difficulties in social relationships and behaviors become more evident (Landa, 2018). This variability underscores the importance of regular developmental screenings and the use of innovative tools, such as digital phenotyping, to monitor social behavior in real-time, facilitating earlier diagnosis and personalized intervention strategies (Jiang et al., 2020).

Given the significant impact of early intervention on developmental trajectories, public health initiatives increasingly emphasize the need for accessible and equitable screening programs. These programs aim to reach children in underserved communities who may otherwise face barriers to diagnosis and treatment. By incorporating technologies like digital phenotyping, public programs can enhance early detection efforts, enabling continuous monitoring and early identification of social and behavioral challenges in children with ASD.

1.3. Challenges in Monitoring Social Behavior in Children with ASD

Monitoring social behavior in children with Autism Spectrum Disorder (ASD) presents unique challenges due to the complex and heterogeneous nature of the disorder. Social deficits, such as difficulties in forming relationships, interpreting social cues, and engaging in reciprocal communication, are hallmark features of ASD (Lord et al., 2020). These impairments manifest differently in each child, making standardized monitoring methods difficult to apply universally. Traditional observation-based assessments, while valuable, are often time-consuming, resource-intensive, and may fail to capture the full spectrum of social behaviors across different contexts (Capp, 2020).

Figure 3 shows young children engaging in various activities at a classroom table. One child is focused on drawing or coloring, while other children are interacting in the background, engaging with materials on the table. This setting is ideal for observing natural social interactions and behaviors, particularly relevant in Autism Spectrum Disorder (ASD) monitoring. Such environments allow researchers and clinicians to observe how children with ASD engage in social settings, assess their interactions with peers, and identify specific behavioral patterns in a comfortable, familiar context. In ASD care, monitoring behaviors in naturalistic environments, like a classroom, provides a realistic view of social and communicative behaviors that may differ from clinical observations, thus supporting more accurate assessments and tailored interventions.



Figure 3 Observing Social Engagement in Natural Settings to Support ASD Monitoring (ConnectABILITY.ca. 2012)

One of the primary challenges in monitoring social behavior is the variability in how children with ASD interact with their environment. Social interactions may differ significantly based on the setting—home, school, or public spaces—and are often influenced by external factors such as sensory sensitivities or anxiety, which can mask or exaggerate certain behaviors (Kasari et al., 2012). Additionally, many traditional assessment tools rely heavily on caregiver reports or structured clinical observations, which may not provide an accurate picture of the child's behavior in naturalistic settings (Jeste et al., 2020). Another significant challenge is the reliance on sporadic, in-person evaluations that may not capture the dynamic and evolving nature of social behaviors in children with ASD (Jiang et al., 2020). Social behaviors can fluctuate throughout the day, and behaviors that are problematic in one situation may not occur in another, making it difficult to obtain a comprehensive assessment through periodic clinical visits alone (Constantino et al., 2014).

Furthermore, the gap between clinical assessments and real-world experiences can result in delays in diagnosis and treatment, particularly for children with milder or more nuanced social impairments.

Table 1 Enhancing Social Behavior Monitoring in Children with ASD: Challenges and Solutions

Aspect	Challenges	Traditional Approach	Limitations of Traditional Approach	Potential Solutions
Complexity and Heterogeneity	Social deficits vary widely, affecting relationship formation, social cue interpretation, and communication	Standardized assessments	Difficulty in capturing individual differences	Develop adaptable monitoring tools for personalized assessments
Standardization Issues	Diverse manifestations of social behaviors in each child make universal standards challenging	Generalized scales and metrics	Often fails to capture unique social patterns	Create flexible tools for individualized social interaction tracking
Observation-Based Assessments	Traditional methods are time-consuming, resource-intensive, and context-limited	In-person behavioral observations	Limited scope, may miss behaviors that occur outside clinical settings	Use continuous monitoring tech to capture a broader, more representative range of behaviors
Environmental Influences	Social behaviors differ significantly across settings (e.g., home, school, public spaces)	Standardized observations within a single setting	Lack of context-specific data	Context-sensitive monitoring tools that adjust to different environments
Influence of External Factors	Factors like sensory sensitivities and anxiety can alter or mask social behaviors	Static observation during clinical assessment	Unable to account for fluctuating external influences	Systems that incorporate external factor tracking (e.g., anxiety levels)
Reliance on Caregiver Reports	Reports or structured observations may not reflect naturalistic behavior	Caregiver surveys and feedback	Subject to bias, may lack accuracy in different contexts	Real-time, objective digital phenotyping for unbiased data
In-person Evaluations	Periodic evaluations may not capture fluctuations in behavior across time and situations	Scheduled in-person clinical visits	Snapshot approach; may miss variations in behavior over time	Remote, continuous monitoring for real-time data collection
Gap Between Clinical & Real-World	Behaviors in clinical settings can differ significantly from those in daily life, impacting diagnosis accuracy	Controlled clinical environment assessments	Clinical setting may not elicit natural social responses	Use of wearable or mobile devices for real-world data collection
Technological Integration	Accessibility, privacy, and usability challenges with digital monitoring tools	Limited implementation of digital solutions due to various barriers	High implementation and accessibility hurdles	Develop user-friendly, secure, accessible tools that prioritize both usability and privacy
Cultural Sensitivity & Adaptability	Monitoring tools often overlook socio-economic and cultural diversity among children with ASD	Generalized monitoring tools with limited cultural customization	Tools may not meet the diverse needs of all children with ASD	Design culturally sensitive and adaptable technologies for diverse ASD populations

Table 1 outlines the key challenges in monitoring social behavior in children with Autism Spectrum Disorder (ASD) and examines both traditional assessment methods and their limitations, while proposing potential solutions through innovative technology and adaptable approaches. Due to ASD's complexity, social deficits such as challenges in forming relationships and interpreting cues vary widely, complicating standardized monitoring. Traditional assessments, which often rely on in-person evaluations or caregiver reports, provide valuable insights but are limited by time constraints, subjective bias, and their inability to capture dynamic behavior changes across different environments and daily settings. Environmental influences, such as sensory sensitivities, can further complicate assessments, as behaviors may differ significantly between clinical and naturalistic settings, leading to delays in diagnosis or ineffective interventions. Digital phenotyping and continuous remote monitoring tools offer promising solutions, enabling real-time data collection that captures the dynamic nature of ASD social behaviors in everyday settings. By integrating culturally adaptable, user-friendly, and privacy-sensitive technology, these advancements aim to provide a more accurate, accessible, and individualized approach to monitoring social behavior, addressing gaps left by traditional methods and enhancing care for children with ASD.

Technology offers potential solutions to some of these challenges by enabling continuous and objective monitoring of social behavior. However, integrating these technologies into everyday life presents its own set of hurdles, including issues of accessibility, data privacy, and the need for user-friendly interfaces that can be utilized by both clinicians and caregivers (Capp, 2020). Despite these challenges, advances in digital phenotyping and remote monitoring hold promise for providing more accurate, real-time assessments of social behavior in children with ASD, which could lead to earlier and more effective interventions (Jiang et al., 2020).



Figure 4 Comprehensive Data Integration for Enhanced ASD Monitoring and Care (Brus 2019)

Figure 4 represents the integration of diverse data sources to provide a holistic approach to Autism Spectrum Disorder (ASD) monitoring and care. At the center, individuals with ASD are supported by various data streams that capture both clinical and behavioral information. Key sources like electronic medical and health records, lab/biomarker data, and hospital data provide insights into the physiological and clinical aspects of ASD. Meanwhile, wearables can monitor movement patterns, stress levels, and social interactions, offering real-time data on behaviors typical of ASD. Non-traditional data sources, like social media activity, survey data, and consumer data, can help track social engagement, preferences, and external influences on behavior. By bringing together pharmacy data, claims data, and mortality data, healthcare providers and public health programs can identify patterns, personalize interventions, and address comorbid conditions. This integrative approach ensures a comprehensive understanding of each individual's needs, supporting early diagnosis, tailored interventions, and continuous monitoring to improve the quality of life for individuals with ASD.

Figure 5 illustrates a therapeutic session commonly used in the assessment and support of children with Autism Spectrum Disorder (ASD). The child is actively engaged with the therapist, who is observing and taking notes on the child's gestures, expressions, and communication style. Such sessions are crucial in ASD care, as they allow clinicians to assess social interaction, non-verbal communication, and behavioral responses in a structured but welcoming environment. The child-friendly setting, with colorful elements like the hoop and small furniture, helps the child feel at ease, encouraging natural behaviors that provide valuable insights into their social and communicative skills. Through careful observation in these sessions, therapists can identify specific challenges and strengths related to ASD, enabling them to develop personalized intervention strategies that address the child's developmental needs and support their social and communication skills.



Figure 5 Autism Spectrum Disorder Evaluation and Assessment (Panter & Schulman 2012)

The integration of digital tools into ASD monitoring also highlights the importance of developing culturally sensitive and adaptable technologies that consider the diverse needs of children with ASD across different socio-economic backgrounds. As the field progresses, overcoming these challenges will be crucial in improving the accuracy and accessibility of social behavior monitoring, thereby enhancing the quality of care for children with ASD.

1.4. Emergence of Digital Phenotyping in Healthcare

The emergence of digital phenotyping represents a transformative shift in healthcare, particularly in the realm of behavioral health and neurodevelopmental disorders such as Autism Spectrum Disorder (ASD). Digital phenotyping refers to the moment-by-moment quantification of human behavior through data collected from personal digital devices, such as smartphones and wearables, providing a continuous and objective measure of an individual's physical and social interactions (Jain et al., 2015). This approach offers unprecedented opportunities to monitor real-time behaviors and environmental contexts, providing clinicians with a more holistic view of a patient's condition, particularly for disorders like ASD, where symptoms can vary significantly across contexts and over time (Insel, 2017).

Traditionally, phenotyping in healthcare relied on clinical observations, genetic testing, and patient-reported outcomes, which can be limited by subjective biases and infrequent monitoring. Digital phenotyping, by contrast, allows for the passive collection of large volumes of behavioral data without interfering with a patient's daily routine (Onnela & Rauch, 2016). This continuous data stream offers a more dynamic and nuanced understanding of conditions like ASD, where behaviors such as social interaction, language use, and motor activities fluctuate across different settings (Miller et al., 2021). For example, digital tools can track speech patterns, facial expressions, and movement, providing insights into a child's social behavior over time (Mohr et al., 2020).

In ASD care, the use of digital phenotyping has the potential to address some of the key challenges in monitoring social behavior. By capturing data in real-world environments, digital phenotyping can complement traditional clinical

assessments, offering a more comprehensive picture of a child's social interactions across different settings (Jiang et al., 2020). Moreover, the continuous nature of data collection can help detect subtle behavioral changes that might otherwise be missed during periodic clinical visits, enabling earlier intervention and more personalized treatment plans (Saeb et al., 2015).

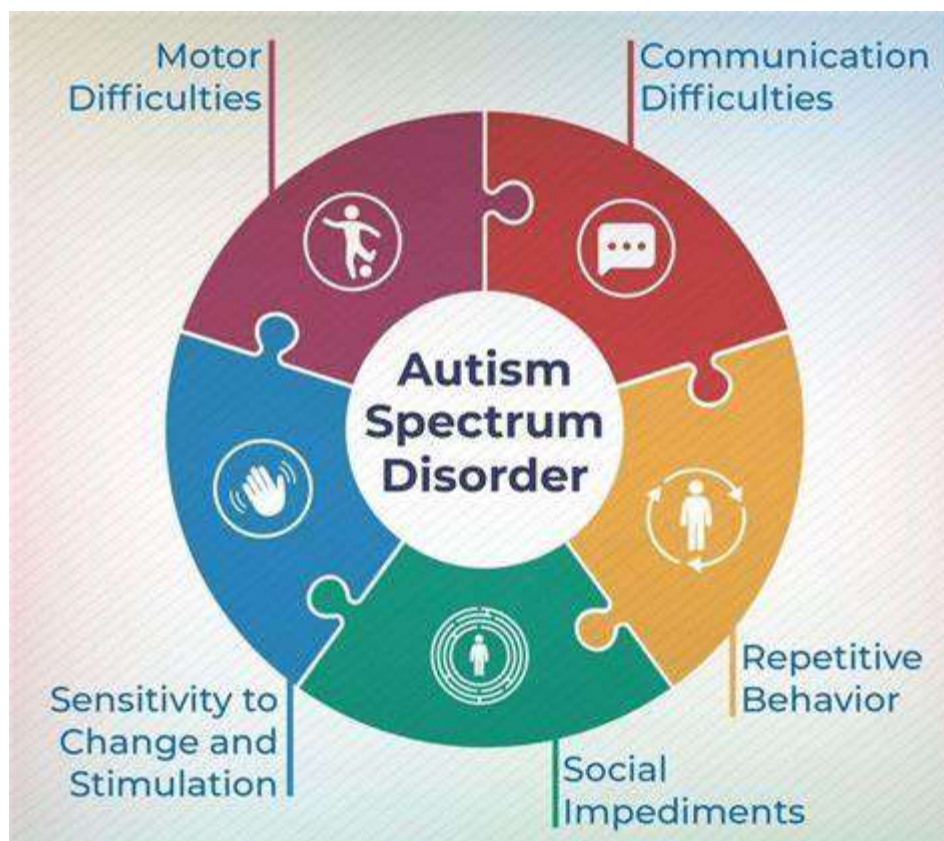


Figure 6 Core Characteristics of Autism Spectrum Disorder (Pinterest 2024)

Figure 6 presents a visual summary of the core characteristics commonly associated with Autism Spectrum Disorder. Organized in a circular format, the graphic highlights six key areas of difficulty: motor difficulties, communication challenges, repetitive behaviors, social impediments, sensitivity to change and sensory stimulation, and communication difficulties. Each segment points to a specific aspect of ASD, illustrating the range of behaviors and challenges that individuals on the spectrum may experience. This diagram underscores the multidimensional nature of ASD, showing that it affects various aspects of development and interaction, which can manifest differently in each person. This holistic view of ASD characteristics aids in understanding the diverse needs of individuals with ASD and emphasizes the importance of tailored support and interventions in these areas.

One of the most significant advantages of digital phenotyping is its scalability, making it a valuable tool for public health programs that aim to reach large populations, including underserved communities. Public health initiatives can leverage digital phenotyping to enhance screening efforts, improve the early detection of ASD, and monitor the effectiveness of interventions over time (Insel, 2017). However, the adoption of digital phenotyping also raises important concerns regarding data privacy, ethical use, and the need for robust data governance frameworks to ensure that sensitive health data is protected (Mohr et al., 2020).

Despite these challenges, digital phenotyping holds considerable promise for revolutionizing healthcare, particularly in neurodevelopmental disorders like ASD. As technology continues to evolve, the integration of artificial intelligence and machine learning with digital phenotyping data may further enhance the ability to predict and respond to health outcomes in real-time, leading to more targeted and effective interventions for children with ASD.

Table 2 highlights the transformative role of digital phenotyping in healthcare, particularly for behavioral and neurodevelopmental disorders like Autism Spectrum Disorder (ASD). Digital phenotyping leverages real-time data collection through devices such as smartphones and wearables, offering a continuous and objective view of an

individual’s behavior. Unlike traditional clinical assessments, which are often limited to periodic observations and patient-reported outcomes, digital phenotyping enables comprehensive tracking of fluctuating behaviors in natural settings, providing richer insights into conditions like ASD. This real-time monitoring allows for early detection of subtle behavioral changes, supporting timely and personalized intervention. Additionally, digital phenotyping’s scalability makes it valuable for public health initiatives aiming to reach underserved populations, though it raises significant data privacy and ethical considerations. Future advancements integrating AI and machine learning promise to enhance predictive capabilities, allowing for more tailored interventions and proactive care in healthcare.

Table 2 Emergence and Impact of Digital Phenotyping in Healthcare for Neurodevelopmental Disorders

Aspect	Description	Traditional Approach	Advantage of Digital Phenotyping	Challenges
Definition	Continuous data collection of human behavior via digital devices, providing real-time behavioral and social insights	Clinical observations, genetic testing, patient-reported outcomes	Provides continuous, objective behavioral data	Data privacy and ethical considerations
Application in Behavioral Health	Used to monitor real-time behaviors, especially in neurodevelopmental disorders like ASD	Periodic clinical visits, caregiver reports	Offers a holistic view of behavior across various contexts	Requires robust data governance and secure data handling
Real-Time Monitoring	Tracks fluctuations in social behavior, language use, and motor activity over time and in natural settings	Infrequent, snapshot-based clinical assessments	Captures subtle changes, enabling timely and personalized care	Potentially high volume and complexity of data management
Impact on ASD Care	Complements traditional assessments with continuous data on social interactions in real-world settings	Standardized in-clinic assessments	Enhances understanding of child’s behavior in daily environments	May need adaptation for diverse socio-economic backgrounds
Scalability	Suitable for large-scale public health initiatives, reaching broad populations	Limited scalability of traditional clinical methods	Can improve early detection and intervention for underserved areas	Access limitations for low-tech populations
Future Potential	AI and machine learning integration may enhance predictive capabilities and enable targeted interventions	Dependent on clinician interpretation	Predicts health outcomes and tailors interventions in real-time	Ethical use and potential for over-reliance on technology

1.5. Objective of the Review: Exploring the Role of Digital Phenotyping in Public Programs for ASD

The primary objective of this review is to examine the integration of digital phenotyping in monitoring social behavior in children with Autism Spectrum Disorder (ASD), particularly within the context of public health programs. Traditional methods of behavioral assessment in ASD, while beneficial, often fall short of capturing the full scope of social behaviors that vary across different environments and times. This review seeks to explore how digital phenotyping, which leverages data from smartphones, wearables, and other digital devices, can provide continuous and objective measurements of social interactions in real-world settings.

In addition, this review will analyze the potential benefits of incorporating digital phenotyping into large-scale public health programs aimed at improving early detection and intervention for children with ASD. It will explore how public health initiatives can utilize digital tools to enhance monitoring capabilities, making it possible to track progress and adjust interventions more effectively. This review will also consider the challenges and limitations, such as privacy

concerns and the need for data governance, that must be addressed to fully realize the potential of digital phenotyping in public ASD programs.

The review aims to provide insights into the current state of digital phenotyping technologies, their applications in ASD care, and the implications for public health policy and practice. By doing so, it seeks to contribute to the development of more efficient, scalable, and personalized approaches to monitoring and treating social behavior in children with ASD, ultimately improving their quality of life and long-term outcomes.

1.6. Structure of the Paper

This paper is organized into five key sections, each focusing on a different aspect of the role of digital phenotyping in monitoring social behavior in children with Autism Spectrum Disorder (ASD) within public programs.

Section 1: Introduction provides an overview of Autism Spectrum Disorder (ASD), the importance of early identification and intervention, the challenges in monitoring social behavior in children with ASD, and the emergence of digital phenotyping in healthcare. It also outlines the objectives of the review and highlights the significance of digital phenotyping in public health programs.

Section 2: Remote Monitoring Technologies for Children with Autism discusses the evolution of monitoring techniques in ASD care, with a particular emphasis on remote monitoring technologies. It explores the specific digital tools and technologies used to track social behaviors in children with ASD, their advantages, limitations, and how they can be integrated into existing healthcare systems.

Section 3: Digital Phenotyping and Its Applications in Autism delves into the concept of digital phenotyping, outlining how it works, its application in ASD care, and its potential for improving the assessment of social behaviors. This section also reviews current tools and platforms in digital phenotyping and presents case studies of its use in ASD intervention programs.

Section 4: Public Programs and Policy Implications focuses on the adoption of digital phenotyping in public health programs targeting children with ASD. It examines policy frameworks, the potential benefits of integrating digital phenotyping into large-scale initiatives, and the challenges of data privacy, security, and accessibility in public health.

Section 5: Future Directions and Conclusion explores emerging trends in digital phenotyping, including the integration of artificial intelligence and machine learning. This section speculates on the future of digital phenotyping in ASD care, discussing the potential for scalability and its impact on diagnosis, treatment, and public health strategies.

The paper concludes by summarizing key insights, identifying opportunities for further research, and providing recommendations for enhancing the use of digital phenotyping in ASD care within public programs.

2. Traditional approaches and emerging technologies

2.1. Overview of Traditional Monitoring Methods in ASD

Traditional methods of monitoring social behavior in children with Autism Spectrum Disorder (ASD) have predominantly relied on clinical observations, standardized assessments, and caregiver reports. These approaches have long been the cornerstone of ASD diagnosis and intervention, providing valuable insights into a child's developmental trajectory. Standardized diagnostic tools, such as the Autism Diagnostic Observation Schedule (ADOS) and the Autism Diagnostic Interview-Revised (ADI-R), have been widely used to assess social, communicative, and behavioral patterns in children with ASD (Lord et al., 2012). These assessments typically involve structured or semi-structured interactions with trained clinicians, who observe the child's responses to social stimuli to identify core features of ASD, such as impaired eye contact, lack of reciprocal communication, and repetitive behaviors.

Caregiver-reported questionnaires, such as the Social Responsiveness Scale (SRS) and the Childhood Autism Rating Scale (CARS), are also integral to traditional monitoring (Schopler et al., 2010). These tools rely on parents' or guardians' observations of their child's behaviors in everyday settings, providing a comprehensive view of the child's social interactions over time. Although these reports offer valuable context that might not be captured during brief clinical visits, they are subject to the biases and interpretation of the caregiver, which can limit objectivity (Constantino & Gruber, 2012).

While these traditional methods have been instrumental in diagnosing ASD, they face several limitations, particularly in monitoring social behavior over time and across different settings. First, assessments like ADOS and ADI-R are typically administered at specific intervals, often months or even years apart, limiting their ability to capture the dynamic nature of ASD symptoms, which can vary depending on environmental factors (Lord et al., 2020). Additionally, in-clinic evaluations can create artificial environments that may not reflect the child's natural behavior in everyday social contexts, leading to potential discrepancies between observed behaviors in clinical settings versus home or school environments (Grzadzinski et al., 2016).

Another challenge is that traditional monitoring methods can be resource-intensive, requiring trained professionals, specialized equipment, and substantial time for administration and interpretation. These demands create barriers to frequent and ongoing monitoring, particularly in underserved populations or rural areas where access to specialized care may be limited (Daniels & Mandell, 2014). As a result, many children with ASD do not receive the continuous and comprehensive monitoring needed to assess their progress and adjust interventions accordingly.

Figure 7 illustrates the traditional methods of monitoring social behavior in children with Autism Spectrum Disorder (ASD). It starts with two main approaches: clinical observations and caregiver reports. Clinical observations involve direct interaction and assessment by professionals to identify core ASD characteristics, while caregiver reports provide ongoing insights from parents or guardians based on everyday behaviors. Despite their value, these traditional methods face challenges such as infrequent assessments, artificial clinical settings that may not reflect natural behaviors, and high resource demands, including specialized training and time. Due to these limitations, there is growing interest in remote monitoring technologies, which offer continuous, context-sensitive data, enabling a more comprehensive and accessible way to monitor ASD over time.

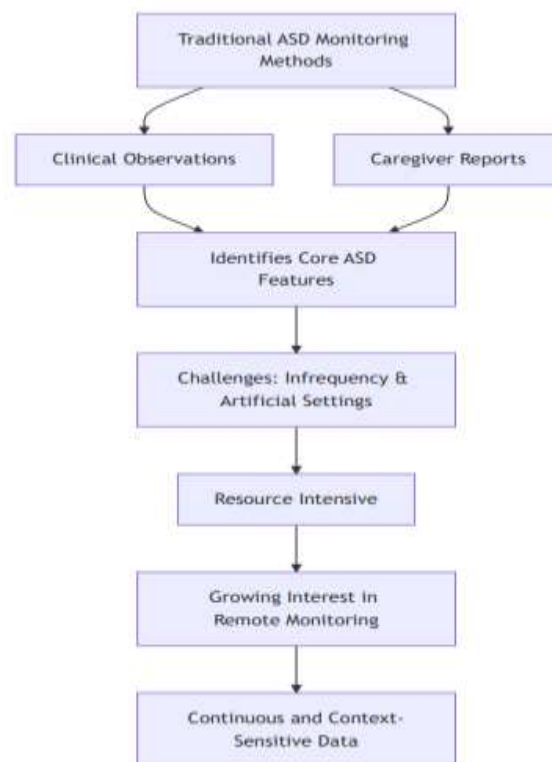


Figure 7 Core Components of Traditional Autism Spectrum Monitoring Methods

Given these limitations, there has been a growing interest in developing new methods for monitoring social behavior that are less invasive, more scalable, and capable of capturing real-time data across a variety of settings. Remote monitoring technologies, including digital phenotyping, have emerged as promising alternatives that can address the gaps in traditional methods by providing continuous, objective, and context-sensitive assessments of social behavior in children with ASD.

The table provides an overview of traditional methods used to monitor social behavior in children with Autism Spectrum Disorder (ASD), including clinical observations, standardized assessments, and caregiver reports. While tools like the Autism Diagnostic Observation Schedule (ADOS) and the Social Responsiveness Scale (SRS) offer structured insights into core ASD behaviors, these methods have several limitations. Traditional assessments are often infrequent, conducted in clinical settings that may not reflect real-world behavior, and are resource-intensive, requiring specialized training and time. These constraints limit their effectiveness in capturing the dynamic and context-sensitive nature of ASD. In response, there is growing interest in remote monitoring technologies, such as digital phenotyping, which provide continuous and objective data across a variety of settings, addressing some of the gaps in traditional monitoring approaches.

Table 3 Traditional Monitoring Methods for ASD: Tools, Benefits, and Limitations

Aspect	Description	Examples of Tools	Advantages	Limitations
Clinical Observations	Structured interactions observed by trained clinicians to assess social and communicative behaviors	Autism Diagnostic Observation Schedule (ADOS)	Provides structured assessment of ASD core features	Limited by artificial clinical settings that may not reflect natural behavior
Standardized Assessments	Diagnostic tools to identify social, communicative, and behavioral patterns	Autism Diagnostic Interview-Revised (ADI-R)	Offers validated, structured diagnostic criteria	Typically administered at infrequent intervals, missing behavioral fluctuations over time
Caregiver Reports	Questionnaires completed by caregivers, providing observations of child's behavior in natural settings	Social Responsiveness Scale (SRS), CARS	Captures behaviors across everyday settings	Subject to caregiver biases, potentially impacting objectivity
Infrequent Monitoring	Assessments usually conducted months or years apart, which can miss real-time changes in behavior	ADOS, ADI-R, clinical visits	Provides longitudinal data	Inability to capture dynamic and context-sensitive changes in behavior over short intervals
Resource Intensive	Requires trained professionals, specialized equipment, and considerable time for administration and interpretation	ADOS, ADI-R, SRS, CARS	Ensures high-quality diagnostic evaluation	High costs and resource demands, limiting access in rural and underserved communities
Gaps in Natural Contexts	Clinical settings may not accurately represent child's natural behavior across home, school, and other environments	ADOS, ADI-R, clinic-based observations	Structured clinical insights	Potential discrepancies between observed behaviors in clinic and real-world settings
Emerging Alternatives	New remote monitoring tools provide continuous, objective, and context-sensitive behavioral data across various settings	Digital phenotyping, wearable devices	Enables continuous, real-time monitoring	Emerging technology requires further validation for widespread adoption

2.2. Rise of Remote Monitoring Technologies in Healthcare

Remote monitoring technologies have revolutionized healthcare, offering unprecedented capabilities for continuous, real-time tracking of health metrics and behaviors outside clinical settings. These innovations have emerged as valuable tools in managing chronic diseases, monitoring post-operative recovery, and supporting mental health, particularly in neurodevelopmental disorders such as Autism Spectrum Disorder (ASD). Remote monitoring technologies leverage sensors, mobile applications, and wearable devices to gather data passively, enabling clinicians to gain insights into patients' daily activities and health status without the need for constant in-person visits (Lu et al., 2020).

In the context of ASD, remote monitoring technologies hold great promise for addressing the limitations of traditional observational methods. One of the major advantages is the ability to capture naturalistic behavior in real-world settings, as opposed to the artificial and often restrictive environments of clinics (Schuller et al., 2022). This continuous data collection enables the detection of subtle, context-dependent behavioral patterns that may be missed during sporadic clinical assessments. For example, wearables equipped with sensors can track physiological and movement data, providing insights into a child's physical activity levels, sleep patterns, and even social engagement through proximity and interaction metrics (Goodwin et al., 2018).

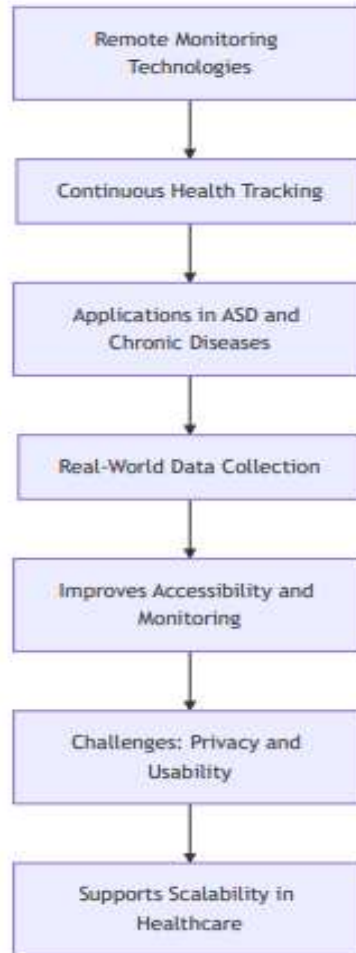


Figure 8 Remote Monitoring in Healthcare

Figure 8 outlines the role of remote monitoring technologies in healthcare. It begins with these technologies enabling continuous health tracking, which is especially useful in managing Autism Spectrum Disorder (ASD) and chronic diseases. Through real-world data collection, remote monitoring captures health metrics and behaviors outside clinical environments, providing a more natural and comprehensive view of patients' conditions. This approach improves accessibility, allowing consistent monitoring without frequent in-person visits, which is particularly beneficial for underserved populations. However, it also introduces challenges related to data privacy and usability. Despite these hurdles, remote monitoring technologies support scalability in healthcare, making them viable tools for large-scale public health initiatives.

Mobile applications are another key component of remote monitoring in ASD care. These apps allow parents and caregivers to record behavioral observations, complete surveys, and track developmental milestones, all of which can be shared with healthcare providers for ongoing evaluation and intervention adjustment (Daniels et al., 2019). Additionally, advances in artificial intelligence (AI) and machine learning algorithms have enabled these systems to analyze large datasets generated by remote monitoring technologies, identifying patterns and predicting outcomes in ways that were previously impossible with manual analysis (Jiang et al., 2020). This data-driven approach provides a

more comprehensive understanding of ASD-related behaviors and offers opportunities for early intervention and personalized treatment.

Remote monitoring technologies also enhance accessibility, particularly for families in rural or underserved areas who may have limited access to specialized care (Boyd et al., 2021). By reducing the need for frequent travel to healthcare facilities, these technologies facilitate regular and consistent monitoring, ensuring that children with ASD can receive timely interventions regardless of geographic barriers. Furthermore, the scalability of these technologies allows for wider implementation in public health programs, making them an essential tool in large-scale efforts to improve the diagnosis and treatment of ASD.

Despite these advantages, there are challenges associated with the use of remote monitoring technologies, including concerns about data privacy, the potential for over-reliance on technology, and the need for user-friendly interfaces that can be seamlessly integrated into daily life (Schuller et al., 2022). Addressing these challenges is critical to ensuring the widespread adoption and effectiveness of remote monitoring technologies in ASD care.

Table 4 Impact and Challenges of Remote Monitoring Technologies in Healthcare for ASD

Aspect	Description	Examples	Advantages	Challenges
Continuous Data Collection	Enables real-time tracking of health metrics and behaviors outside of clinical settings	Wearables, mobile apps, sensors	Provides comprehensive, naturalistic data on daily health behaviors	Concerns about data privacy and management
Application in ASD	Captures real-world behavior, addressing limitations of clinic-based observations	Wearables for tracking movement, sleep	Detects context-dependent behavioral patterns	User-friendliness and integration into daily routines
Parental and Caregiver Input	Mobile apps allow caregivers to record observations and track milestones	Mobile apps for behavioral tracking	Facilitates regular feedback for ongoing evaluation	Potential bias in caregiver-reported data
AI and Machine Learning	Advanced algorithms analyze data to identify patterns and predict health outcomes	Machine learning algorithms, AI analytics	Provides personalized insights and early intervention opportunities	Complexity and need for robust analysis models
Accessibility and Scalability	Enhances access to care for rural and underserved populations	Remote monitoring for public health	Reduces travel needs, enables timely interventions	Variability in access to necessary technology
Public Health Integration	Supports large-scale health initiatives, improving diagnosis and treatment	Remote monitoring in public health programs	Scalable for broad implementation in underserved areas	Scalability may require substantial initial infrastructure
Challenges to Adoption	Issues with data security, reliance on technology, and usability	Privacy protocols, user-centered design	Critical for ensuring effectiveness and public trust	Addressing privacy, usability, and over-reliance concerns

Table 4 summarizes the role of remote monitoring technologies in healthcare, focusing on their application in Autism Spectrum Disorder (ASD) care. It highlights the advantages of continuous, real-time data collection through tools like wearables, mobile apps, and sensors, which allow for more naturalistic and comprehensive monitoring of behaviors outside clinical settings. By enabling caregiver input and leveraging AI for data analysis, these technologies provide personalized insights and facilitate timely intervention, particularly benefiting families in rural or underserved areas. However, challenges such as data privacy, user-friendliness, and over-reliance on technology present barriers that must be addressed to ensure widespread adoption and effectiveness in ASD management.

2.3. Key Technologies Used in Remote Monitoring for ASD

Remote monitoring technologies have become essential tools in managing Autism Spectrum Disorder (ASD), providing innovative ways to track behavior, detect patterns, and offer real-time interventions. These technologies, which include wearable devices, smartphones, and the Internet of Things (IoT), allow for continuous monitoring of physiological, behavioral, and environmental data, enabling healthcare professionals and caregivers to gather insights into a child's day-to-day activities (Goodwin et al., 2018). By leveraging these technologies, remote monitoring offers a more comprehensive and objective assessment of ASD-related behaviors that are difficult to capture through traditional clinical methods.

Wearable devices are one of the most widely used tools in remote ASD monitoring. These devices, often equipped with sensors that measure movement, heart rate, and other physiological indicators, can help track repetitive behaviors, physical activity, and stress levels in children with ASD (Rai et al., 2019). For instance, accelerometers within wearable devices can detect stereotypical motor movements, which are a common feature of ASD. This data is valuable for both clinicians and caregivers, as it provides objective evidence of behavioral changes that may occur in response to environmental triggers or stress (Pereira et al., 2020). Additionally, wearables can monitor sleep patterns, an area where many children with ASD experience challenges, offering critical data for evaluating sleep-related interventions (Mazurek et al., 2019).

Figure 9 illustrates the main functions of each technology in remote ASD monitoring. Wearable devices focus on tracking physiological and behavioral metrics, smartphone apps gather behavioral and communication data, and IoT connects sensors to capture environmental factors impacting behavior.

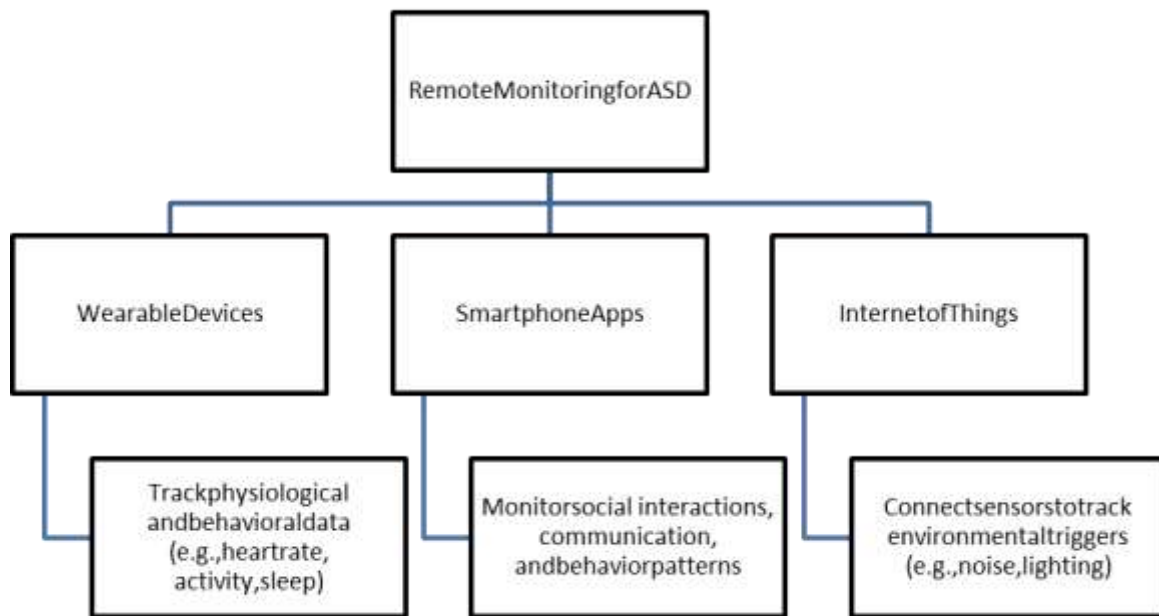


Figure 9 Core Technologies in Remote ASD Monitoring

Smartphone applications play a crucial role in remote ASD monitoring by enabling the collection of behavioral data through passive and active methods. These apps can track various metrics, such as the frequency of social interactions, language use, and communication patterns, using sensors already embedded in modern smartphones (Jiang et al., 2020). Many apps also allow parents and caregivers to input observations and assessments of the child's behavior, providing a more holistic view of the child's interactions in everyday settings (Daniels et al., 2019). Some apps even incorporate AI and machine learning algorithms to analyze behavioral data and offer personalized recommendations for interventions, making them powerful tools for real-time monitoring and decision support (Torous et al., 2018).

The Internet of Things (IoT) further enhances the capabilities of remote monitoring technologies by connecting various devices and sensors to create a network of data points that provide a richer, more contextualized understanding of the child's behavior (Zhang et al., 2020). IoT-enabled devices, such as smart home sensors, can monitor environmental factors that may influence a child's behavior, such as noise levels, lighting, or the presence of others. This data can help

identify potential triggers for stress or anxiety in children with ASD, allowing for more targeted interventions (Gaggi et al., 2019). IoT technologies also enable the integration of data from multiple sources, providing a more comprehensive picture of the child's overall health and well-being.

Artificial intelligence (AI) and machine learning have become integral components of many remote monitoring systems for ASD. These technologies can analyze large datasets generated by wearables, smartphones, and IoT devices to identify patterns in behavior that might be difficult for humans to discern (Gordon et al., 2021). AI algorithms can track changes over time, providing insights into the effectiveness of interventions and predicting future behaviors. For instance, machine learning models can analyze speech patterns to detect early signs of language development issues, a common challenge in children with ASD (Jiang et al., 2020).

Virtual reality (VR) and augmented reality (AR) technologies are also being explored for remote monitoring and intervention in ASD care. These technologies create simulated environments where children with ASD can practice social interactions in a controlled and safe setting (Lorenzo et al., 2016). VR and AR can be used to monitor how children respond to various social situations, providing valuable data that can inform future interventions. The immersive nature of these technologies allows for the creation of highly individualized therapy sessions tailored to the specific needs of each child.

The integration of wearable devices, smartphone applications, IoT technologies, AI, and VR/AR into remote monitoring systems offers a multifaceted approach to understanding and managing ASD. These technologies provide real-time, objective data that enhances traditional assessment methods and opens new possibilities for personalized, continuous care in ASD management.

Table 4 Key Technologies in Remote Monitoring for ASD: Applications and Benefits

Technology	Description	Examples of Data Collected	Applications in ASD	Benefits
Wearable Devices	Devices equipped with sensors to monitor physiological and behavioral data	Movement, heart rate, stress levels, sleep	Tracks repetitive behaviors, stress response, sleep patterns	Provides objective, continuous physiological and behavioral data
Smartphone Applications	Apps that collect behavioral data through passive and active input from caregivers and embedded sensors	Social interactions, language use, caregiver input	Monitors social interactions, communication, and daily behavior	Real-time monitoring, caregiver input, AI-driven intervention
Internet of Things (IoT)	Network of connected devices that monitor environmental factors impacting behavior	Noise, lighting, proximity of others	Identifies environmental stressors and triggers	Provides contextual understanding of behavioral influences
Artificial Intelligence (AI) and Machine Learning	Analyzes large datasets to identify behavioral patterns and predict outcomes	Speech patterns, activity changes over time	Tracks intervention effectiveness, predicts behavioral changes	Enables data-driven, personalized intervention recommendations
Virtual Reality (VR) and Augmented Reality (AR)	Simulated environments for practicing social interactions	Child's responses in virtual social scenarios	Creates safe, controlled settings for social skill development	Individualized therapy, adaptable to specific social situations

Table 4 presents the main remote monitoring technologies used in managing Autism Spectrum Disorder (ASD), detailing their functions, the types of data they collect, specific applications, and the benefits they bring to ASD care. Wearable devices, smartphone applications, IoT networks, AI, and VR/AR are highlighted as essential tools for real-time, objective, and contextual tracking of behavioral and environmental data. Each technology contributes uniquely to understanding and supporting ASD, offering continuous monitoring, personalized insights, and an enhanced ability to detect and respond to behavioral patterns outside traditional clinical settings.

2.4. Advantages of Remote Monitoring in ASD Care

Remote monitoring technologies have introduced several advantages in the care and management of Autism Spectrum Disorder (ASD), enhancing the ability to observe, assess, and intervene in real time. One of the key benefits is the continuous, real-time data collection provided by these technologies. Unlike traditional methods, which rely on periodic clinical assessments or subjective caregiver reports, remote monitoring technologies—such as wearables, smartphones, and other digital tools—allow for the seamless collection of data over extended periods. This provides a more comprehensive view of the child's behaviors, capturing patterns and fluctuations that might not be evident during infrequent clinical visits (Goodwin et al., 2018). Continuous monitoring can reveal insights into the child's everyday experiences, helping clinicians make more informed decisions about interventions.

Additionally, remote monitoring facilitates naturalistic observation, which allows for the monitoring of behaviors in real-world environments rather than the artificial settings of clinical or laboratory assessments (Schuller et al., 2022). Children with ASD may exhibit different behaviors in the comfort of their homes, schools, or playgrounds than they would in a clinical setting where the presence of unfamiliar people and environments may affect their behavior. Remote monitoring tools overcome this limitation by capturing naturalistic data, thus providing a more accurate reflection of the child's social, communicative, and behavioral challenges (Mazurek et al., 2019). This naturalistic data is essential for understanding the child's typical responses to various stimuli, interactions, and environments.

Personalization of care is another significant advantage of remote monitoring in ASD. By collecting detailed behavioral and physiological data, these technologies allow for the customization of interventions tailored to each child's specific needs. For instance, wearable devices that track stress levels, heart rate, and physical activity can inform clinicians when a child is experiencing anxiety or distress, enabling them to adapt therapeutic interventions accordingly (Rai et al., 2019). Personalized data-driven approaches ensure that treatments are more targeted and effective, potentially leading to better long-term outcomes for children with ASD.

Remote monitoring also offers improved accessibility to ASD care, particularly for families in remote or underserved areas who may have limited access to specialized services. Many rural or low-income families struggle to access frequent, in-person evaluations due to logistical and financial constraints (Boyd et al., 2021). Remote monitoring technologies bridge this gap by allowing for consistent data collection and communication with healthcare providers without the need for frequent travel to clinics. This accessibility enhances the continuity of care, enabling timely adjustments to interventions based on the data collected, regardless of the family's geographical location (Gaggi et al., 2019).

Finally, remote monitoring technologies provide longitudinal data, which is crucial for understanding how ASD symptoms evolve over time. This is especially important because ASD is a lifelong condition, and its symptoms and impacts can change as the child develops. Wearable devices and mobile applications that continuously collect data enable clinicians to track long-term trends in behavior, communication, and social interaction (Jiang et al., 2020). This longitudinal data can inform early interventions, monitor the progress of therapeutic interventions, and even predict future outcomes, leading to more proactive and preventive care.

Remote monitoring technologies bring significant advantages to ASD care, including continuous real-time data collection, naturalistic observation, personalized interventions, improved accessibility, and the ability to gather longitudinal data. These benefits highlight the potential of remote monitoring to enhance the quality of care and outcomes for children with ASD, while addressing some of the limitations inherent in traditional methods of diagnosis and intervention.

Table 5 outlines the primary advantages that remote monitoring technologies bring to Autism Spectrum Disorder (ASD) care. By enabling continuous, real-time data collection, these technologies provide a comprehensive view of a child's behaviors across various settings and times, going beyond the limitations of infrequent clinical visits. Remote monitoring supports naturalistic observation, capturing a child's behavior in familiar environments, leading to more accurate assessments. It also allows for personalized interventions based on specific behavioral and physiological data, which can enhance the effectiveness of treatments. Improved accessibility means that families in remote or underserved areas can access consistent care without frequent clinic visits, reducing logistical barriers. Lastly, the ability to collect longitudinal data helps clinicians track ASD symptoms over time, enabling early intervention and proactive care adjustments as the child develops.

Table 5 Key Benefits of Remote Monitoring Technologies in ASD Care

Advantage	Description	Benefits	Advantage	Description
Continuous Real-Time Data	Provides seamless data collection over long periods, capturing behaviors beyond clinical visits	Offers comprehensive insights into daily behaviors, improving intervention decisions	Continuous Real-Time Data	Provides seamless data collection over long periods, capturing behaviors beyond clinical visits
Naturalistic Observation	Monitors behaviors in real-world settings rather than clinical environments	Reflects the child's true social, communicative, and behavioral challenges for accurate assessments	Naturalistic Observation	Monitors behaviors in real-world settings rather than clinical environments
Personalization of Care	Collects detailed physiological and behavioral data for tailored interventions	Enables targeted, data-driven treatments, improving effectiveness of interventions	Personalization of Care	Collects detailed physiological and behavioral data for tailored interventions
Improved Accessibility	Allows families in remote or underserved areas to access consistent care	Bridges care gaps for rural or low-income families, reducing need for frequent in-person clinic visits	Improved Accessibility	Allows families in remote or underserved areas to access consistent care
Longitudinal Data Collection	Tracks ASD symptoms over time, documenting developmental changes	Supports proactive, preventive care by monitoring long-term trends and enabling early intervention adjustments	Longitudinal Data Collection	Tracks ASD symptoms over time, documenting developmental changes

2.5. Limitations and Ethical Considerations in Remote Monitoring of Children with ASD

While remote monitoring technologies offer promising advancements in the management of Autism Spectrum Disorder (ASD), there are significant limitations and ethical concerns that must be carefully addressed. One of the primary limitations is data accuracy and reliability. Remote monitoring systems, such as wearable devices and smartphone applications, rely on sensor data to track behaviors and physiological responses. However, factors like device malfunction, signal interference, or improper usage by the child or caregiver can result in inaccurate or incomplete data (Goodwin et al., 2018). This limitation is particularly critical in ASD care, where precise and consistent monitoring is required to ensure that interventions are based on reliable information.

Another challenge is accessibility and equity. While remote monitoring technologies have the potential to improve accessibility, not all families have the resources or technological literacy to fully benefit from these systems (Creswell et al., 2020). The cost of devices, lack of internet access, and varying levels of comfort with technology can create disparities in who can take advantage of these innovations. Families from low-income or rural backgrounds may find it difficult to implement and maintain these technologies, potentially exacerbating existing healthcare inequalities (Boyd et al., 2021). Additionally, some children with ASD may have sensory sensitivities or motor coordination difficulties that prevent them from wearing or using certain devices, further limiting their participation in remote monitoring systems (Rai et al., 2019).

Data privacy and security are significant ethical concerns in the use of remote monitoring technologies for children with ASD. The continuous collection of sensitive personal data, such as behavioral patterns, location, and physiological metrics, raises questions about how this data is stored, shared, and protected (Millett et al., 2020). Ensuring robust cybersecurity measures and clear data governance policies is essential to prevent unauthorized access or misuse of the data. Parents and caregivers must also be fully informed about how their child's data will be used, and there should be transparent consent processes that allow them to opt in or out of specific data-sharing practices (Schuller et al., 2022).

Additionally, over-reliance on technology poses an ethical concern. While remote monitoring technologies provide valuable insights, they should not replace human judgment or reduce face-to-face interactions with healthcare

professionals. There is a risk that the convenience of remote monitoring could lead to a decreased emphasis on in-person evaluations, which are critical for developing nuanced understandings of each child’s unique needs and challenges (Jiang et al., 2020). Balancing the use of technology with human-centered care is essential to avoid depersonalization and ensure that the child’s well-being remains at the forefront.

Finally, there are concerns about data interpretation and clinical application. The vast amount of data generated by remote monitoring technologies can be overwhelming for both caregivers and clinicians, particularly if they lack the training or tools to interpret the data effectively (Gaggi et al., 2019). Without proper frameworks for analyzing and applying this data, there is a risk of misinterpretation or information overload, which could lead to inappropriate interventions or delays in care. Developing user-friendly interfaces and providing adequate training for both professionals and caregivers are crucial steps in mitigating this limitation.

While remote monitoring technologies hold great potential for enhancing ASD care, it is important to address the limitations related to data accuracy, accessibility, privacy, over-reliance on technology, and data interpretation. By tackling these challenges, remote monitoring can be effectively integrated into comprehensive ASD care plans that prioritize ethical considerations and ensure equitable access for all children.

Table 6 Limitations and Ethical Considerations in Remote Monitoring for ASD Care

Aspect	Description	Challenges	Impact	Considerations
Data Accuracy & Reliability	Sensor data may be affected by device malfunctions, interference, or improper usage	Potential for inaccurate or incomplete data	Risk of basing interventions on unreliable information	Need for quality control and backup monitoring protocols
Accessibility & Equity	Not all families have resources, internet access, or tech literacy for effective use	Cost barriers and technological disparities among families	May exacerbate existing healthcare inequalities	Subsidies and support for underserved families
Privacy & Security	Continuous collection of sensitive data raises concerns over storage, sharing, and protection	Risk of unauthorized data access or misuse	Compromises on family and child’s data security	Implement robust cybersecurity and transparent consent processes
Over-Reliance on Technology	Risk of reducing face-to-face interactions and over-dependence on digital tools	Could decrease emphasis on in-person evaluations	Potential loss of nuanced, personalized care	Balance technology with in-person assessments
Data Interpretation	Large data volumes may overwhelm caregivers and clinicians without proper training	Risk of misinterpretation and potential for inappropriate interventions	Information overload may delay or misguide care	Develop user-friendly interfaces and provide training

Table 6 outlines significant limitations and ethical considerations associated with remote monitoring technologies for Autism Spectrum Disorder (ASD) care. Key concerns include data accuracy, where device malfunctions or improper usage can lead to unreliable data, and accessibility, as not all families have the resources or tech literacy to use these tools effectively, potentially widening health disparities. Privacy and security are paramount due to the sensitive nature of continuous data collection, necessitating strong protections and transparent data policies. There is also a risk of over-reliance on technology, which may reduce valuable face-to-face interactions with clinicians. Finally, interpreting vast amounts of collected data can overwhelm caregivers and clinicians, risking misinterpretation without adequate training and user-friendly tools. Addressing these considerations is crucial to ensure ethical, equitable, and effective use of remote monitoring in ASD care.

3. Digital phenotyping

3.1. Definition and Concept of Digital Phenotyping

Digital phenotyping refers to the moment-by-moment quantification of individual behavior and interactions through data collected from personal digital devices, such as smartphones and wearable sensors. This approach allows for the continuous and passive collection of data that can provide insights into a person's mental and physical health in real-world settings (Jain et al., 2015). By leveraging the ubiquitous nature of digital devices, digital phenotyping offers a novel way to monitor human behavior, moving beyond traditional clinical assessments that are often limited by their episodic and subjective nature (Insel, 2017). This method has gained traction in healthcare because of its potential to track symptoms and behaviors that may be difficult to observe in clinical environments, especially for conditions like Autism Spectrum Disorder (ASD), where behaviors fluctuate depending on context.

In the context of ASD, digital phenotyping focuses on capturing social, communicative, and repetitive behaviors through sensor data, which can include movement patterns, speech, facial expressions, and even environmental factors that may affect the individual's behavior (Jiang et al., 2020). This data, when combined with machine learning algorithms, can help detect subtle changes in behavior that may indicate shifts in the individual's condition, enabling more timely interventions. For example, a child's engagement in social interactions can be tracked through smartphone apps that monitor speech patterns and proximity to others, providing valuable information on how the child navigates social environments (Saeb et al., 2015).

One of the primary benefits of digital phenotyping is its ability to provide continuous and objective data. Traditional phenotyping relies heavily on self-reports and clinical observations, which are subject to bias and often reflect only a snapshot of the individual's condition at a specific moment in time. In contrast, digital phenotyping collects data passively over extended periods, offering a more holistic and detailed understanding of behaviors and symptoms in naturalistic settings (Mohr et al., 2020). This is particularly valuable in ASD care, where behaviors may vary significantly depending on the child's environment or emotional state. By providing real-time data, digital phenotyping allows for a more comprehensive and dynamic assessment of the child's development.

Moreover, digital phenotyping can facilitate personalized care. As data is continuously collected, it can be used to tailor interventions to the individual's specific needs, adjusting treatments in real time based on observed behavioral changes. For instance, if a child's stress levels increase in certain environments, this information can inform adjustments to their daily routine or therapeutic interventions (Onnela & Rauch, 2016). Personalized care is critical in ASD management, as the disorder manifests differently in each individual, requiring flexible and adaptive approaches.

However, the use of digital phenotyping also raises important ethical concerns, particularly related to privacy and data security. The continuous collection of personal data, including location, speech, and social interactions, presents risks if not properly managed (Millett et al., 2020). Ensuring that sensitive information is protected, and that there are clear guidelines regarding data ownership and consent, is essential for the ethical implementation of digital phenotyping technologies.

Digital phenotyping offers a powerful tool for understanding and managing ASD by providing continuous, objective data that can inform personalized care. However, its successful integration into healthcare requires careful consideration of privacy and ethical issues to ensure that the benefits of this technology are realized without compromising the rights and well-being of individuals.

Table 7 provides an overview of digital phenotyping, a method of continuously collecting behavioral data through digital devices to support Autism Spectrum Disorder (ASD) care. By using smartphones, wearables, and environmental sensors, digital phenotyping captures real-time data on social, communicative, and repetitive behaviors, offering an objective and dynamic assessment of a child's condition beyond traditional clinical visits. This continuous data collection enables personalized care, allowing clinicians to adjust interventions based on observed behavioral patterns. However, implementing digital phenotyping in ASD care requires addressing critical ethical concerns, particularly regarding data privacy, security, and clear guidelines on data ownership and consent. This approach holds significant promise for enhancing ASD management by providing reliable, context-sensitive insights while maintaining ethical safeguards.

Table 7 Overview of Digital Phenotyping for ASD: Applications, Benefits, and Ethical Considerations

Aspect	Description	Applications in ASD	Benefits	Ethical Considerations
Definition	Continuous, passive data collection of behavior via digital devices	Tracks social, communicative, and repetitive behaviors	Offers objective, real-world behavior tracking	Requires strong data privacy and security measures
Data Sources	Utilizes smartphones, wearables, and environmental sensors for data collection	Monitors movement, speech patterns, facial expressions, environmental factors	Captures subtle behavioral changes in naturalistic settings	Risk of sensitive data exposure if improperly managed
Real-Time Monitoring	Provides continuous insights beyond episodic clinical assessments	Tracks fluctuations in behaviors, enabling timely interventions	Provides a comprehensive, dynamic view of ASD symptoms	Needs clear data ownership and consent guidelines
Personalized Care	Adapts interventions based on ongoing data about individual behavior	Tailors care to each child's specific needs	Allows flexible, adaptive treatment approaches	Balancing personalized care with ethical data use
Objective Data Collection	Moves beyond subjective self-reports and snapshot assessments	Improves accuracy in assessing ASD-related behaviors	Reduces bias, offering more reliable assessments	Potential for over-reliance on technology without human context

3.2. Use of Behavioral Data to Track Social Interactions

Digital phenotyping leverages behavioral data to provide a deeper understanding of social interactions, particularly in individuals with Autism Spectrum Disorder (ASD). Social interaction is a core challenge for individuals with ASD, manifesting as difficulties in understanding and engaging in reciprocal communication, interpreting non-verbal cues, and forming relationships. Tracking these behaviors in real time through digital tools offers valuable insights that traditional observation methods may miss, particularly in naturalistic settings where social interactions occur (Jiang et al., 2020).

Wearable devices and smartphone applications are at the forefront of collecting behavioral data relevant to social interactions. These technologies can capture data related to proximity, movement, speech patterns, and even facial expressions. For example, proximity sensors in wearables can measure how often and for how long individuals with ASD engage in close contact with others, providing an objective measure of their social engagement. Similarly, speech analysis tools in smartphone apps can track conversational patterns, including the frequency, duration, and complexity of spoken interactions, offering insights into language use and social reciprocity (Pereira et al., 2020).

One significant advantage of digital phenotyping is its ability to continuously monitor social behavior in real-world settings. Traditional clinical assessments often take place in structured environments that may not reflect the individual's typical behavior in everyday situations. By using digital devices to track behavior in natural settings—such as the home, school, or community—digital phenotyping offers a more accurate and comprehensive view of how individuals with ASD interact socially (Goodwin et al., 2018). This data can help identify patterns, such as avoidance of social situations or increased stress in particular environments, which may not be evident during clinical evaluations.

Machine learning algorithms play a critical role in analyzing the vast amounts of behavioral data collected through digital phenotyping. These algorithms can detect subtle patterns in social interactions that may be indicative of ASD-related challenges, such as repetitive speech, avoidance of eye contact, or atypical responses to social stimuli (Torous et al., 2018). By identifying these patterns, clinicians can better understand the social behaviors of individuals with ASD

and tailor interventions to address specific needs. For instance, if a child consistently avoids eye contact in certain social situations, targeted interventions can be designed to gradually increase comfort in those contexts.

Behavioral data from digital phenotyping also enables early detection of social impairments, which is crucial for timely intervention in ASD. Early identification of social deficits can significantly improve outcomes, as interventions implemented during critical developmental periods are more likely to result in long-term improvements in social and communicative abilities (Daniels et al., 2019). By continuously tracking social behaviors, digital phenotyping can alert caregivers and clinicians to potential issues before they become more pronounced, facilitating earlier intervention and potentially reducing the severity of ASD symptoms.

Despite the promise of using behavioral data to track social interactions, ethical considerations must be addressed. The continuous collection of sensitive behavioral data, such as proximity and speech, raises concerns about privacy and data security. Ensuring that individuals' data is securely stored and that informed consent is obtained from families is essential for the ethical implementation of digital phenotyping in ASD care (Millett et al., 2020). Moreover, data governance frameworks must be established to define how behavioral data is shared and used, ensuring that individuals' rights and autonomy are protected.

The use of behavioral data to track social interactions through digital phenotyping provides a powerful tool for understanding and managing ASD. By capturing real-time, objective data in naturalistic settings, digital phenotyping offers insights into social behavior that traditional assessments may overlook. The integration of machine learning further enhances the ability to detect patterns and personalize interventions, making digital phenotyping a critical tool for improving outcomes in ASD care.

Table 8 Tracking Social Interactions in ASD through Behavioral Data: Applications, Benefits, and Ethical Considerations

Aspect	Description	Data Collected	Benefits	Ethical Considerations
Purpose	Tracks social behaviors in individuals with ASD to understand interaction patterns	Proximity, movement, speech, facial expressions	Provides real-time insights into social engagement	Privacy concerns over continuous data collection
Key Technologies	Wearables and smartphone applications for real-time behavior monitoring	Proximity sensors, speech analysis tools	Captures naturalistic data outside clinical environments	Requires secure data storage and informed consent
Naturalistic Monitoring	Observes social behavior in everyday settings such as home, school, and community	Data on typical behaviors in natural settings	Provides a comprehensive view of social interactions	Need for data governance on sharing and usage
Machine Learning Analysis	Detects subtle behavioral patterns through analysis of large data volumes	Repetitive speech, eye contact, social responses	Helps tailor specific interventions based on observed patterns	Risk of misinterpretation without skilled data analysis
Early Detection	Enables identification of social impairments for timely intervention	Continuous monitoring flags potential issues	Facilitates early intervention, improving social outcomes	Balancing data utility with ethical data handling

Table 8 summarizes how digital phenotyping leverages behavioral data to monitor social interactions in individuals with Autism Spectrum Disorder (ASD). Using tools like wearables and smartphone applications, this approach collects real-time data on behaviors such as proximity, movement, speech patterns, and facial expressions, providing insights into social engagement in naturalistic settings like home and school. Machine learning algorithms analyze these data points, helping to identify specific patterns or challenges, such as repetitive speech or avoidance of eye contact, which can inform personalized interventions. Additionally, continuous tracking enables early detection of social impairments, supporting timely interventions that may improve long-term social outcomes. Ethical considerations, including data

privacy, informed consent, and data governance, are essential to protect individual rights while maximizing the benefits of behavioral data in ASD care.

3.3. Integration of Digital Phenotyping in Autism Care

Digital phenotyping has become a transformative tool in the management of Autism Spectrum Disorder (ASD), providing real-time, objective insights into a child's behavior and allowing for more personalized and continuous care. Its integration into autism care builds on the ability to collect, analyze, and apply data from wearable devices, smartphones, and other digital tools to monitor behavioral patterns, social interactions, and environmental factors that influence a child's development (Jain et al., 2015). This data-driven approach is reshaping traditional methods of assessment and intervention in ASD, enhancing the effectiveness of care.

One of the primary benefits of integrating digital phenotyping into autism care is the ability to capture continuous and passive data on the behaviors and interactions of individuals with ASD. Traditional assessments, such as clinical observations and caregiver reports, often provide only snapshots of behavior in artificial settings, which may not reflect the child's typical interactions (Goodwin et al., 2018). Digital phenotyping overcomes this limitation by monitoring behaviors in real-world environments, such as home, school, or social settings, where the child is most comfortable. This continuous data allows for a deeper understanding of how a child with ASD responds to various stimuli and social interactions throughout the day (Jiang et al., 2020).

In addition, digital phenotyping enhances the ability to personalize interventions. Each individual with ASD presents a unique combination of challenges, making it difficult to apply a one-size-fits-all approach to treatment. By analyzing patterns in the data collected from digital devices, clinicians can identify specific triggers for behaviors, stress levels, or social avoidance and adjust interventions accordingly. For instance, wearable devices that track physiological markers like heart rate and stress levels can help clinicians understand how children with ASD respond to different environments, leading to interventions that are better suited to their individual needs (Saeb et al., 2015). These personalized interventions can be continually adjusted as new data is collected, ensuring that care remains responsive to the child's evolving needs.

Furthermore, digital phenotyping has the potential to improve early detection and diagnosis of ASD, especially in underserved or rural populations. Early identification of ASD is crucial for implementing timely interventions that can significantly improve long-term outcomes (Daniels et al., 2019). Digital phenotyping offers an accessible and scalable method for continuous monitoring, even in areas where specialized ASD care is limited. Remote monitoring through smartphones and wearables can alert caregivers and clinicians to early signs of developmental delays or social impairments, enabling early intervention and reducing the severity of ASD symptoms over time (Schuller et al., 2022).

However, while digital phenotyping holds great promise in enhancing autism care, integration into healthcare systems faces several challenges. One of the key challenges is the standardization and validation of digital phenotyping tools. To be effective in clinical settings, digital phenotyping platforms must be validated through rigorous testing to ensure that they provide reliable and accurate data (Onnela & Rauch, 2016). This process involves ensuring that the data collected by various devices can be consistently analyzed and interpreted across different individuals and environments. Without proper validation, there is a risk of misinterpreting data, which could lead to inappropriate interventions.

Another challenge is the ethical use of data in digital phenotyping. The continuous collection of sensitive information, such as location, social interactions, and physiological responses, raises concerns about data privacy and security (Millett et al., 2020). Clear guidelines on data ownership, consent, and usage are necessary to protect the rights of individuals and families. Establishing secure data storage and governance protocols is essential to build trust in the use of digital phenotyping in ASD care.

The integration of digital phenotyping into autism care offers significant benefits, including continuous data collection, personalized interventions, and improved early detection. However, to fully realize its potential, efforts must be made to validate these tools, address ethical concerns, and ensure that they are seamlessly integrated into existing healthcare frameworks. When implemented effectively, digital phenotyping can revolutionize ASD care by providing real-time, actionable insights that enhance the quality of life for individuals with autism and their families.

Table 9 summarizes how digital phenotyping leverages behavioral data to monitor social interactions in individuals with Autism Spectrum Disorder (ASD). Using tools like wearables and smartphone applications, this approach collects real-time data on behaviors such as proximity, movement, speech patterns, and facial expressions, providing insights into social engagement in naturalistic settings like home and school. Machine learning algorithms analyze these data

points, helping to identify specific patterns or challenges, such as repetitive speech or avoidance of eye contact, which can inform personalized interventions. Additionally, continuous tracking enables early detection of social impairments, supporting timely interventions that may improve long-term social outcomes. Ethical considerations, including data privacy, informed consent, and data governance, are essential to protect individual rights while maximizing the benefits of behavioral data in ASD care.

Table 9 Tracking Social Interactions in ASD through Behavioral Data: Applications, Benefits, and Ethical Considerations

Aspect	Description	Data Collected	Benefits	Ethical Considerations
Purpose	Tracks social behaviors in individuals with ASD to understand interaction patterns	Proximity, movement, speech, facial expressions	Provides real-time insights into social engagement	Privacy concerns over continuous data collection
Key Technologies	Wearables and smartphone applications for real-time behavior monitoring	Proximity sensors, speech analysis tools	Captures naturalistic data outside clinical environments	Requires secure data storage and informed consent
Naturalistic Monitoring	Observes social behavior in everyday settings such as home, school, and community	Data on typical behaviors in natural settings	Provides a comprehensive view of social interactions	Need for data governance on sharing and usage
Machine Learning Analysis	Detects subtle behavioral patterns through analysis of large data volumes	Repetitive speech, eye contact, social responses	Helps tailor specific interventions based on observed patterns	Risk of misinterpretation without skilled data analysis
Early Detection	Enables identification of social impairments for timely intervention	Continuous monitoring flags potential issues	Facilitates early intervention, improving social outcomes	Balancing data utility with ethical data handling

3.4. Current Tools and Platforms for Digital Phenotyping in ASD

The development and application of digital phenotyping tools and platforms have significantly enhanced the capacity to monitor and assess Autism Spectrum Disorder (ASD). These technologies leverage a combination of wearables, smartphones, and cloud-based systems to track behaviors and physiological data, offering clinicians and caregivers insights into the day-to-day experiences of individuals with ASD. The continuous data collected through these platforms allows for real-time monitoring and tailored interventions, improving the management and understanding of ASD (Jain et al., 2015).

Wearable devices are among the most widely used tools in digital phenotyping for ASD. These devices, such as smartwatches or accelerometers, collect data on physiological metrics, including heart rate, physical activity, and stress levels (Pereira et al., 2020). For example, wearable sensors can detect repetitive movements or physical agitation—key indicators in individuals with ASD that may signal distress or discomfort. These devices provide real-time data that can be shared with clinicians or caregivers, allowing them to track how environmental factors influence behavior and intervene when necessary (Goodwin et al., 2018). Additionally, the data from wearables can help clinicians understand how children with ASD react to social situations or stimuli, facilitating the development of more personalized care plans.

Smartphone applications are another crucial tool in the digital phenotyping landscape. These apps can passively collect behavioral data, such as speech patterns, social interactions, and mobility, through the phone's sensors (Jiang et al., 2020). For example, certain apps use voice recognition to analyze speech for signs of social impairment, providing valuable data on how frequently and effectively the child communicates with others. Some apps also allow caregivers to input observations regarding the child's behavior, which can be combined with sensor data to provide a more comprehensive understanding of the individual's condition. Furthermore, many smartphone-based platforms integrate

with wearable devices to provide a holistic view of both physiological and behavioral data, facilitating better analysis and interventions (Torous et al., 2018).

Cloud-based platforms play an essential role in managing the vast amount of data collected from wearables and smartphone apps. These platforms store and process data in real time, allowing clinicians to access comprehensive reports on a child’s behavior over days, weeks, or months (Schuller et al., 2022). Cloud platforms also use machine learning algorithms to analyze the data and detect patterns that might indicate changes in the child’s condition. For instance, if the platform identifies a consistent increase in repetitive behaviors or stress markers, it can alert clinicians or caregivers to potential issues that require intervention. The ability to store and process large datasets remotely enhances the scalability of digital phenotyping, making it feasible to monitor large populations of individuals with ASD over extended periods.

In addition to wearables, smartphones, and cloud platforms, advanced AI-driven platforms are emerging as powerful tools in digital phenotyping. These platforms leverage artificial intelligence (AI) to analyze complex datasets and provide predictive insights about ASD-related behaviors (Saeb et al., 2015). AI algorithms can detect subtle changes in patterns that may not be immediately apparent to human observers, such as changes in speech patterns or sleep disturbances. These insights enable clinicians to adjust interventions proactively, potentially preventing behavioral escalations before they occur. Moreover, AI-driven platforms can facilitate early diagnosis of ASD by identifying markers of social impairment in children as young as two or three years old, helping ensure that interventions are implemented as early as possible (Daniels et al., 2019).

Despite the significant advances in digital phenotyping tools for ASD, there remain challenges related to data privacy and security. Given the sensitive nature of the data collected—such as location, social interactions, and physiological metrics—strong data governance frameworks are essential to protect individuals’ privacy and ensure compliance with regulatory standards (Millett et al., 2020). Platforms must implement robust encryption and data protection measures to safeguard the information collected and ensure that individuals’ rights are respected.

Current tools and platforms for digital phenotyping in ASD—ranging from wearable devices and smartphone apps to cloud-based systems and AI-driven platforms—provide invaluable insights into the day-to-day behaviors of individuals with ASD. These technologies offer a more dynamic and personalized approach to ASD management, improving the ability of clinicians and caregivers to monitor, assess, and intervene in real-time. However, addressing data privacy concerns remains a critical challenge to ensure the ethical use of these tools.

Table 10 Tools and Platforms for Digital Phenotyping in ASD: Functions, Applications, and Key Considerations

Tool/Platform	Description	Data Collected	Key Applications	Considerations
Wearable Devices	Devices like smartwatches and accelerometers to monitor physiological and movement data	Heart rate, physical activity, repetitive movements	Tracks stress levels, agitation, social responses	Ensures real-time data; can aid in personalized interventions
Smartphone Applications	Apps using phone sensors and caregiver inputs to passively collect behavioral data	Speech patterns, social interactions, mobility	Analyzes communication and social engagement	Integrates with wearables; requires caregiver involvement
Cloud-Based Platforms	Systems to store, process, and analyze wearable and app data	Aggregated behavioral and physiological data over time	Provides long-term behavioral trends and pattern analysis	Requires data governance and secure data storage
AI-Driven Platforms	Platforms using AI to detect subtle behavior patterns and provide predictive insights	Complex datasets on speech, behavior, and sleep patterns	Enables early diagnosis, proactive intervention	Essential for early detection; privacy and ethical use crucial

Table 10 provides an overview of the current tools and platforms used in digital phenotyping for Autism Spectrum Disorder (ASD), which include wearable devices, smartphone applications, cloud-based platforms, and AI-driven

systems. Wearables such as smartwatches collect physiological data like heart rate and movement, helping monitor stress and repetitive behaviors in real time. Smartphone apps gather behavioral data on speech and social interactions, often integrating with wearables to create a holistic view of the individual's experiences. Cloud-based platforms facilitate long-term data storage and trend analysis, while AI-driven platforms analyze complex data patterns to provide predictive insights and enable early interventions. Each tool plays a unique role in enhancing ASD care, but robust data privacy and security measures are essential to ensure ethical and safe use.

3.5. Case Studies and Pilot Programs Utilizing Digital Phenotyping for Children with ASD

The application of digital phenotyping in Autism Spectrum Disorder (ASD) has gained momentum through various case studies and pilot programs, which demonstrate its effectiveness in monitoring behavioral patterns, facilitating early diagnosis, and providing personalized interventions. These programs highlight the real-world potential of digital phenotyping to improve the quality of care for children with ASD by utilizing wearable devices, smartphones, and machine learning algorithms to track and analyze key behavioral markers (Jiang et al., 2020).

One notable case study is the use of wearable devices to monitor repetitive behaviors in children with ASD. In a pilot study conducted by Goodwin et al. (2018), children were equipped with wearable sensors that tracked movements throughout the day. The study demonstrated that wearable accelerometers could accurately detect stereotypical motor movements, such as hand flapping and body rocking, which are common in children with ASD. By providing continuous monitoring in natural settings, the wearables allowed researchers and clinicians to gain a deeper understanding of how repetitive behaviors fluctuate based on environmental factors, such as stress or sensory overload. The insights gained from this study were used to tailor interventions that specifically targeted the reduction of these behaviors in high-stress situations.

Another case study, the DigiSibs program, utilized smartphone applications to monitor social interactions among children with ASD and their siblings. The program, piloted by Daniels et al. (2019), employed smartphone sensors to capture proximity and voice data, which provided insights into how often and how long the children engaged in social interactions. The study found that children with ASD tended to have shorter and less frequent interactions with their siblings, particularly in social environments. The real-time data collected through the smartphone app enabled caregivers and clinicians to develop social skill-building activities tailored to each child's specific needs, enhancing their ability to engage meaningfully with their peers and family members.

In another pilot program, Torus et al. (2018) explored the integration of artificial intelligence (AI) and machine learning in digital phenotyping for ASD. This study utilized smartphone applications to collect data on speech patterns, facial expressions, and emotional responses from children with ASD. Machine learning algorithms were employed to analyze this data and detect early signs of social and communicative impairments. The program was particularly effective in identifying subtle changes in speech intonation and facial expressions, which are often difficult for human observers to detect. The findings helped clinicians make earlier diagnoses and implement personalized interventions that addressed each child's unique communication challenges. The use of AI in this study highlights the potential for digital phenotyping to go beyond mere observation and actively assist in diagnostic decision-making.

A successful case study focused on sleep pattern monitoring in children with ASD was conducted by Mazurek et al. (2019). This study utilized wearable sleep trackers to monitor the sleep behaviors of children with ASD, who are known to experience high rates of sleep disturbances. The data collected showed significant variability in sleep patterns, with some children experiencing frequent awakenings, while others had difficulty falling asleep. By monitoring these patterns over time, the study was able to correlate sleep disturbances with daytime behaviors such as irritability and hyperactivity. The insights gained from the study were used to adjust bedtime routines and create individualized sleep interventions, improving the overall well-being of the children involved.

Lastly, the Child Mind Institute piloted a digital phenotyping program aimed at improving early detection of ASD in underserved populations. The program used smartphone-based behavioral assessments to track developmental milestones in children who lacked access to specialized care. By analyzing data related to speech development, motor skills, and social engagement, the program was able to flag children at risk for ASD and recommend further evaluation. The program's success in identifying at-risk children in remote and low-income communities demonstrates the scalability of digital phenotyping as a tool for public health initiatives, ensuring that early diagnosis and intervention are accessible to all (Schuller et al., 2022).

These case studies and pilot programs highlight the significant potential of digital phenotyping to revolutionize the care of children with ASD. By continuously tracking behavior and physiological responses in real-world settings, these

programs offer a more accurate and comprehensive understanding of ASD, leading to earlier diagnoses and more personalized interventions. Furthermore, the scalability of digital phenotyping makes it an ideal solution for public health programs, ensuring that children in underserved communities can benefit from early detection and timely care.

Table 11 summarizes several case studies and pilot programs that leverage digital phenotyping to monitor and improve care for children with Autism Spectrum Disorder (ASD). The studies highlight the use of wearable sensors, smartphone applications, and AI-driven platforms to track key behavioral markers such as repetitive movements, social interactions, speech patterns, and sleep behaviors. These technologies provide valuable insights into how children with ASD respond to different environments and social settings, allowing clinicians and caregivers to develop personalized interventions and improve early diagnosis accuracy. Additionally, these programs show the scalability of digital phenotyping for reaching underserved communities, where smartphone-based assessments facilitate early ASD detection. Together, these studies demonstrate the potential of digital phenotyping to transform ASD care through continuous, real-world monitoring and tailored intervention strategies.

Table 11 Case Studies and Pilot Programs: Digital Phenotyping Applications in ASD Care"

Program/Study	Technology Used	Behavioral Markers Tracked	Key Findings	Impact on ASD Care
Wearable Device Study	Wearable sensors (accelerometers)	Repetitive behaviors (e.g., hand flapping, body rocking)	Detected fluctuations in repetitive behaviors influenced by environmental factors	Enabled tailored interventions for behavior management
DigiSibs Program	Smartphone applications	Social interactions (proximity, voice data)	Identified reduced and shorter sibling interactions in social settings	Developed personalized social skill-building activities
AI and Machine Learning Pilot	Smartphone apps with AI/ML algorithms	Speech patterns, facial expressions, emotional responses	Detected subtle changes in speech intonation and expressions, aiding early diagnosis	Supported early and personalized communication interventions
Sleep Pattern Monitoring	Wearable sleep trackers	Sleep behaviors (e.g., awakenings, difficulty falling asleep)	Linked sleep disturbances with daytime behaviors like irritability and hyperactivity	Improved sleep interventions and overall well-being
Child Mind Institute Program	Smartphone-based behavioral assessments	Developmental milestones (speech, motor skills, social engagement)	Flagged at-risk children in underserved areas for further evaluation	Expanded access to early ASD detection in remote communities

4. Public health programs supporting autism spectrum disorder care

4.1. Public Health Programs Supporting ASD Care

Public health programs play a crucial role in supporting Autism Spectrum Disorder (ASD) care by facilitating early diagnosis, intervention, and ongoing support for children and families affected by the condition. As the prevalence of ASD continues to rise, with current estimates suggesting that 1 in 54 children is diagnosed with the disorder (Maenner et al., 2020), public health systems have had to adapt to ensure that accessible and equitable services are available to all. These programs focus on early identification, promoting awareness, expanding access to care, and leveraging technology to improve outcomes.

One of the key objectives of public health programs in ASD care is early diagnosis and screening. Early identification of ASD is essential for optimizing outcomes, as early intervention can significantly improve cognitive, social, and communication skills in children with ASD (Dawson et al., 2020). Programs such as the U.S. Centers for Disease Control

and Prevention's (CDC) Learn the Signs. Act Early. campaign have been instrumental in promoting awareness about the early signs of ASD and encouraging parents and healthcare providers to engage in early developmental screenings (Zwaigenbaum et al., 2015). These efforts are complemented by initiatives like the American Academy of Pediatrics' (AAP) recommendation for routine ASD screenings at 18 and 24 months, ensuring that developmental delays are detected as early as possible.

In addition to early diagnosis, expanding access to care is a primary goal of public health programs addressing ASD. Many children, especially those from low-income or rural areas, face barriers to accessing specialized ASD services. To address this, public health initiatives have sought to increase the availability of services by providing funding for ASD-related healthcare, including behavioral therapies, speech therapy, and occupational therapy (Boyd et al., 2021). Medicaid programs, for example, have played a vital role in ensuring that children from underserved communities have access to the necessary services. Moreover, the Autism CARES Act, reauthorized in 2019, provides federal funding for research, training, and intervention programs to support children with ASD and their families (Daniels et al., 2019).

Public health programs are also leveraging technology to support ASD care, particularly through telehealth and remote monitoring initiatives. Telehealth has emerged as an effective means of providing ASD services, especially during the COVID-19 pandemic, when in-person services were limited (Schuller et al., 2022). Telehealth platforms allow clinicians to provide virtual therapy sessions, conduct assessments, and offer caregiver training, ensuring continuity of care regardless of geographical barriers. In addition, public health programs are increasingly integrating digital phenotyping tools to enhance the early detection and monitoring of ASD-related behaviors (Jiang et al., 2020). These tools enable continuous data collection through wearables and smartphone applications, providing real-time insights into the child's behavior and facilitating more personalized interventions.

Another important aspect of public health programs in ASD care is caregiver support. Parents and caregivers of children with ASD often face significant emotional and financial challenges. Public health programs aim to provide resources and training to help caregivers navigate the complexities of ASD care. For example, the Autism Navigator program, developed by Florida State University, offers an online resource platform that provides evidence-based information and practical strategies for caregivers (Daniels et al., 2019). This support is critical for ensuring that caregivers are equipped to manage the day-to-day challenges of caring for a child with ASD and can advocate effectively for their child's needs.

Lastly, public awareness campaigns are vital for reducing the stigma associated with ASD and promoting inclusivity in schools, workplaces, and communities. Public health programs often work in partnership with advocacy organizations, such as Autism Speaks, to disseminate information about ASD, encourage acceptance, and support individuals with autism in all aspects of life. These campaigns are crucial for fostering a more inclusive society, where individuals with ASD can thrive and access the services they need without facing discrimination or barriers to participation.

Public health programs play a vital role in providing comprehensive support for Autism Spectrum Disorder (ASD) care by focusing on early diagnosis, expanding service access, leveraging technology, supporting caregivers, and raising awareness. Early and accurate diagnosis is essential, as it enables timely interventions during critical developmental stages. By expanding access to specialized services, these programs work to ensure that children from diverse backgrounds receive equitable, high-quality support. Leveraging advanced technologies such as telehealth and digital screening tools also improves access to diagnostic and therapeutic services, making care more efficient and widely available. Additionally, public health initiatives offer resources and guidance to caregivers, empowering families to navigate the challenges of ASD care effectively. Through awareness campaigns, these programs help reduce stigma and foster a more inclusive environment for individuals with autism. Altogether, these efforts aim to improve developmental outcomes, enhance the quality of life for children with ASD, and promote a supportive, neurodiverse community.

Table 12 outlines essential public health programs that support Autism Spectrum Disorder (ASD) care through a range of initiatives, from early diagnosis and increased service access to leveraging technology and promoting inclusivity. Programs focused on early diagnosis encourage developmental screenings, helping identify ASD symptoms promptly to improve developmental outcomes through early intervention. Expanded access initiatives, supported by Medicaid and federal acts like the Autism CARES Act, ensure that specialized services reach underserved communities. Telehealth and digital tools have enhanced continuity of care, particularly in remote areas. Support for caregivers provides families with resources and training, easing the day-to-day challenges of ASD management. Public awareness campaigns, often in partnership with organizations like Autism Speaks, foster greater societal acceptance, reducing stigma and promoting inclusivity. Together, these public health efforts provide a comprehensive approach to improving the quality of life for individuals with ASD and their families.

Table 12 Key Public Health Initiatives Supporting Autism Spectrum Disorder (ASD) Care

Program Focus	Description	Examples	Impact on ASD Care	Challenges Addressed
Early Diagnosis and Screening	Promotes awareness and developmental screenings for early ASD identification	CDC's "Learn the Signs. Act Early." campaign, AAP screening guidelines	Optimizes outcomes through early intervention	Detects developmental delays early
Expanding Access to Care	Increases availability of specialized ASD services, especially for underserved communities	Medicaid funding, Autism CARES Act	Provides access to behavioral therapies, speech, and occupational therapy	Reduces care barriers for low-income and rural families
Leveraging Technology	Uses telehealth and digital phenotyping for remote assessments and therapy	Telehealth platforms, wearable devices	Ensures continuity of care and personalized interventions remotely	Overcomes geographic and logistical barriers
Caregiver Support	Offers resources and training for parents and caregivers managing ASD	Autism Navigator program by Florida State University	Equips caregivers with practical strategies and support networks	Eases emotional and financial strain on families
Public Awareness and Advocacy	Promotes ASD inclusivity and reduces stigma through information campaigns	Autism Speaks partnerships, community awareness campaigns	Fosters acceptance and inclusivity in schools, workplaces, communities	Reduces social stigma and discrimination

4.2. Adoption of Digital Phenotyping in Public Programs for Children with Autism

The adoption of digital phenotyping in public programs for children with Autism Spectrum Disorder (ASD) represents a significant advancement in how public health systems monitor, diagnose, and provide care for this population. Digital phenotyping, which involves the continuous and passive collection of behavioral and physiological data through smartphones, wearables, and other digital devices, offers a more comprehensive view of an individual's behaviors and environmental interactions than traditional assessments (Jain et al., 2015). Its integration into public health programs can enhance early detection, personalize interventions, and improve outcomes for children with ASD.

One of the primary ways digital phenotyping is being integrated into public programs is through remote monitoring technologies, which allow for the collection of real-time data on children's social interactions, repetitive behaviors, and stress responses. This is especially valuable in public health settings where access to frequent, in-person assessments may be limited due to geographic or resource constraints (Schuller et al., 2022). For example, wearable devices used in conjunction with smartphone applications can track a child's movement patterns and interactions with others, offering valuable insights into their social engagement and behavioral challenges (Goodwin et al., 2018). Public health programs are increasingly adopting these tools to enhance their ability to monitor ASD-related behaviors in real-world settings, ensuring that children receive the support they need without frequent clinic visits.

Early intervention programs are another key area where digital phenotyping is being integrated into public health initiatives. Early identification of ASD is crucial for initiating timely interventions, and digital phenotyping tools can detect early signs of developmental delays more accurately than traditional methods (Daniels et al., 2019). Public health programs are now exploring the use of digital phenotyping as part of their routine developmental screening processes. For instance, smartphone-based assessments that track speech patterns, facial expressions, and movement can be used to identify children who may be at risk for ASD. These tools allow for continuous monitoring in natural environments, providing a clearer picture of the child's developmental trajectory and enabling earlier diagnosis and intervention (Jiang et al., 2020).

The scalability of digital phenotyping also makes it an ideal solution for population-wide monitoring in public health programs. Traditional diagnostic methods for ASD are time-consuming and resource-intensive, often requiring

specialized clinicians and equipment (Boyd et al., 2021). Digital phenotyping, on the other hand, can be scaled to large populations through mobile platforms, allowing public health systems to monitor thousands of children simultaneously. This capability is particularly important in underserved communities where access to specialized ASD care is limited. By implementing digital phenotyping tools, public health programs can expand their reach, ensuring that all children, regardless of location or socioeconomic status, have access to early diagnosis and appropriate care.

Additionally, personalized care facilitated by digital phenotyping is revolutionizing public health interventions for children with ASD. The data collected through digital devices can be used to tailor interventions to each child's unique needs. For example, if a child shows heightened stress levels during specific social interactions, clinicians can adjust their care plan to address these challenges, providing more targeted support (Rai et al., 2019). Public health programs that incorporate digital phenotyping can move away from one-size-fits-all approaches to ASD care and instead offer individualized treatment plans that respond to the specific behaviors and needs of each child.

Despite its potential, there are challenges associated with the adoption of digital phenotyping in public programs, particularly regarding privacy and data security. The continuous collection of personal data, such as location, speech, and physiological responses, raises concerns about how this data is stored, shared, and protected (Millett et al., 2020). Public health programs must establish robust data governance frameworks to ensure that children's sensitive information is safeguarded and that families have control over how their data is used. Addressing these concerns is critical for gaining public trust and ensuring the ethical implementation of digital phenotyping in ASD care.

In conclusion, the adoption of digital phenotyping in public health programs offers numerous benefits for the care of children with ASD, including enhanced monitoring, early diagnosis, scalable interventions, and personalized care. However, to fully realize the potential of these tools, public health systems must address the challenges related to data privacy and ensure that digital phenotyping is implemented ethically and equitably across all communities.

Table 13 Integration of Digital Phenotyping in Public Health Programs for ASD Care"

Aspect	Description	Applications in Public Programs	Benefits	Challenges
Remote Monitoring	Continuous tracking of behaviors like social interaction and stress responses via wearable devices	Used to monitor ASD behaviors without frequent clinic visits	Provides real-time insights into natural settings	Access limitations in resource-constrained areas
Early Intervention	Detects early signs of developmental delays to initiate timely interventions	Integrated into routine developmental screenings	Supports early diagnosis and intervention	Requires validation to ensure reliable early indicators
Scalability	Population-wide monitoring through mobile platforms for ASD-related behaviors	Expands monitoring to underserved and large populations	Ensures broad access to early ASD care	Training and infrastructure needed for large-scale deployment
Personalized Care	Data-driven approach to tailor interventions based on individual needs	Tailors care plans to specific behaviors and stress markers	Moves away from generic care to individualized treatment	Privacy concerns with continuous personal data collection
Data Privacy & Security	Establishing frameworks for safeguarding sensitive data on behaviors, location, and physiological markers	Robust data governance needed to protect child data privacy	Builds public trust and ethical handling of personal information	Ensures control over data use and protection for families

Table 13 summarizes how digital phenotyping is being adopted in public health programs to improve Autism Spectrum Disorder (ASD) care, highlighting key aspects such as remote monitoring, early intervention, scalability, personalized care, and data privacy. By using wearable devices and mobile platforms, public programs can continuously monitor behaviors related to social interaction, stress, and repetitive movements, allowing clinicians to assess ASD behaviors in real-world settings. This enables early identification of developmental delays, more individualized care plans, and

broader outreach to underserved communities. However, the ethical handling of sensitive behavioral data requires robust data privacy and security frameworks to protect children's information. Addressing these privacy concerns and ensuring equitable access are essential for the successful and ethical implementation of digital phenotyping in ASD public health programs.

4.3. Funding and Resources for Digital Health Initiatives in ASD Monitoring

The successful implementation of digital phenotyping and other digital health initiatives in Autism Spectrum Disorder (ASD) care relies heavily on adequate funding and resource allocation. Governments, public health agencies, and private organizations must collaborate to ensure that these technologies are accessible, affordable, and scalable for widespread use. The financial investment in digital health tools for ASD monitoring not only enhances early diagnosis and intervention but also reduces long-term healthcare costs by providing more efficient and effective management of ASD symptoms (Jain et al., 2015).

One key source of funding for digital health initiatives in ASD monitoring is government programs. In the United States, the Autism CARES Act, reauthorized in 2019, allocates substantial federal funding to support research, education, and early intervention programs for individuals with ASD (Daniels et al., 2019). A significant portion of these funds is directed toward advancing technologies that facilitate early diagnosis and monitoring, including digital phenotyping tools. This funding is crucial for expanding the reach of these innovations, particularly in underserved communities where access to specialized care may be limited. By supporting digital health tools, public health agencies can ensure that children with ASD, regardless of their geographic location or socioeconomic status, receive timely and appropriate care.

Private sector investment is another critical factor in the development and deployment of digital health initiatives for ASD monitoring. Technology companies, healthcare organizations, and venture capital firms have increasingly recognized the potential of digital phenotyping to transform ASD care. Companies specializing in wearable technology, artificial intelligence (AI), and digital health platforms have developed partnerships with academic institutions and healthcare providers to create tools specifically designed for ASD monitoring (Schuller et al., 2022). For example, wearable device manufacturers are investing in research to refine sensors that track physiological markers such as heart rate, sleep patterns, and movement, which are critical for understanding the behavior of children with ASD (Goodwin et al., 2018). These collaborations between private industry and healthcare providers help accelerate the development of innovative solutions and bring them to market more quickly.

Non-profit organizations and foundations also play a pivotal role in funding digital health initiatives. Organizations such as Autism Speaks and the Simons Foundation have long supported research and technological advancements in ASD care. These foundations provide grants to academic researchers, technology developers, and public health programs working on digital phenotyping and related tools. For example, Autism Speaks has funded numerous projects aimed at improving early detection and personalized intervention through digital monitoring technologies (Zwaigenbaum et al., 2015). The funding from these non-profit organizations not only promotes innovation but also helps ensure that new technologies are accessible to families and caregivers who may not otherwise afford them.

Academic institutions are another essential resource in the development of digital health tools for ASD. Universities and research centers often receive grants from government agencies, non-profit organizations, and private companies to conduct studies on the efficacy of digital phenotyping in ASD care. These institutions contribute by testing and validating digital tools in real-world settings, ensuring that the technology is clinically effective and practical for widespread use (Jiang et al., 2020). Academic research is particularly important for advancing AI and machine learning algorithms used in digital phenotyping, which rely on large datasets and rigorous analysis to provide accurate predictions and assessments.

Despite the growing investment in digital health initiatives for ASD, challenges remain in sustaining long-term funding and ensuring equitable distribution of resources. Many rural and low-income communities continue to face barriers in accessing digital health tools due to a lack of infrastructure, such as broadband internet, and limited financial resources for purchasing devices (Boyd et al., 2021). Public and private sectors must continue to work together to address these disparities by providing subsidies, expanding internet access, and developing low-cost solutions for ASD monitoring.

Funding and resources for digital health initiatives in ASD monitoring come from a combination of government programs, private sector investment, non-profit organizations, and academic institutions. These funding streams are essential for developing and deploying innovative tools that enhance early diagnosis, personalized intervention, and

long-term management of ASD. However, sustained funding and efforts to ensure equitable access remain critical for the successful integration of digital health initiatives into public health programs.

Table 14 highlights the primary funding sources and resource allocation strategies supporting digital health initiatives in Autism Spectrum Disorder (ASD) care. Government programs like the Autism CARES Act provide foundational funding for research and early intervention, while private sector investments from technology companies and healthcare organizations accelerate the development and accessibility of digital tools such as wearable devices and AI-driven platforms. Non-profit organizations, including Autism Speaks, contribute through grants that make ASD monitoring technologies more affordable. Academic institutions play a vital role by conducting research to validate and enhance these tools, ensuring clinical effectiveness. Despite these efforts, achieving equitable access remains a challenge, especially in rural and low-income communities. Addressing these disparities through subsidies and infrastructure support is essential for the sustainable integration of digital health tools in ASD care.

Table 14 Funding and Resources for Digital Health Initiatives in ASD Care

Funding Source	Role in Digital Health for ASD	Examples	Impact	Challenges
Government Programs	Provides federal funding for ASD research, education, and early intervention	Autism CARES Act in the U.S.	Expands access to digital health tools, especially in underserved areas	Requires sustained investment and resource distribution
Private Sector Investment	Technology companies and healthcare firms fund tool development and innovation	Partnerships with wearable tech and AI firms	Accelerates digital tool development and market deployment	Profit-driven models may limit accessibility
Non-Profit Organizations	Funds grants for ASD-related research and technology development	Autism Speaks, Simons Foundation	Promotes innovation and makes technology more affordable	Limited funding for widespread adoption
Academic Institutions	Conducts studies to validate and improve digital tools for ASD care	University-led digital phenotyping research	Ensures clinical efficacy and practicality of new technologies	Requires continuous funding and support for large-scale research
Equitable Access Initiatives	Efforts to reduce barriers in underserved communities	Subsidies, broadband expansion programs	Aims to make digital health accessible to rural and low-income families	Infrastructure and cost barriers in certain regions

4.4. Challenges and Ethical Considerations in Implementing Digital Phenotyping in Public Programs

The implementation of digital phenotyping in public programs for Autism Spectrum Disorder (ASD) holds significant promise but also presents several challenges and ethical considerations that must be addressed to ensure equitable and ethical use. These challenges include issues related to privacy, data security, informed consent, the potential for data misuse, and disparities in access to technology.

One of the foremost concerns in implementing digital phenotyping for ASD monitoring is data privacy and security. Digital phenotyping involves the continuous collection of highly sensitive data, including physiological, behavioral, and location-based information (Jain et al., 2015). The data gathered from wearables, smartphones, and other digital tools can provide deep insights into an individual's daily life, which, if improperly handled, could lead to privacy violations. Public health programs must establish robust data governance frameworks to ensure that the data is stored securely, that only authorized personnel have access to it, and that clear protocols are in place for data sharing (Millett et al., 2020). Encryption and other security measures are essential to protect this sensitive information from cyberattacks or unauthorized access, especially when dealing with vulnerable populations like children with ASD.

Informed consent is another critical ethical concern. Given the complex nature of digital phenotyping and the types of data collected, it is essential that caregivers and families fully understand how their child's data will be used, who will have access to it, and what protections are in place to safeguard their privacy (Gaggi et al., 2019). Obtaining informed

consent in the context of continuous data collection presents challenges because it requires ongoing consent and transparency, especially when data is being collected passively through devices that children may not always be aware of, such as wearable sensors or smartphone apps (Daniels et al., 2019). Public health programs need to ensure that families are adequately informed about the scope of the data collection and that they have the ability to opt in or out at any stage.

A significant challenge lies in the potential for data misuse or over-reliance on technology. Digital phenotyping generates large volumes of data that can be used to make decisions about diagnosis and intervention. However, there is a risk that clinicians or public health officials might place too much reliance on these digital tools, potentially overlooking the importance of in-person assessments and clinical expertise (Onnela & Rauch, 2016). While digital phenotyping offers valuable insights, it should complement rather than replace traditional methods of diagnosis and treatment. Over-reliance on technology can also lead to situations where the data is misinterpreted, especially when analyzed without the proper context. There is also the risk of data being used beyond its intended purpose, such as for commercial or research purposes without the explicit consent of the families involved.

Another concern is the digital divide, which could exacerbate disparities in access to ASD care. Many rural or low-income families may not have access to the necessary technology, such as smartphones, wearables, or reliable internet, to benefit from digital phenotyping tools (Boyd et al., 2021). Public health programs must ensure that these technologies are accessible to all children with ASD, regardless of their socioeconomic status. This might involve providing financial assistance, subsidizing devices, or offering alternative solutions for families without access to the latest technologies. Failure to address these disparities could result in unequal access to care and exacerbate existing health inequalities.

Bias in data collection and analysis is another ethical challenge in implementing digital phenotyping. The algorithms used to analyze the data collected through digital phenotyping tools are only as good as the data they are trained on. If the data used to train these algorithms does not represent diverse populations—such as children from different racial, ethnic, or socioeconomic backgrounds—it could lead to biased outcomes that disproportionately affect certain groups (Schuller et al., 2022). For example, digital tools that are not trained to account for cultural differences in communication or behavior could misinterpret certain behaviors as signs of ASD when they may not be, or vice versa. Ensuring that algorithms are trained on diverse datasets and are regularly updated to reflect the latest research is critical for avoiding bias and ensuring that digital phenotyping is equitable.

Table 15 Challenges and Ethical Considerations in Implementing Digital Phenotyping for Public ASD Programs

Concern	Description	Implications	Required Solutions
Data Privacy & Security	Continuous collection of sensitive behavioral and location-based data	Risk of privacy violations and unauthorized access	Strong data governance, encryption, and controlled access
Informed Consent	Ensuring families understand and agree to the scope and use of data collected	Difficulty in maintaining ongoing, informed consent	Transparent consent processes, opt-in/out options
Potential for Data Misuse	Risk of data being used beyond its intended purpose, such as for commercial gains	Data may be repurposed without explicit family consent	Clear usage guidelines and restrictions on data use
Over-Reliance on Technology	Risk of overlooking in-person assessments and clinical expertise	Could lead to misinterpretation or reduced clinical judgment	Combine digital phenotyping with traditional assessments
Digital Divide	Limited access to necessary technology for low-income or rural families	Could widen disparities in ASD care	Financial aid, device subsidies, alternative solutions
Bias in Data & Algorithms	Algorithms may not account for diverse backgrounds, risking biased interpretations	Potential for skewed outcomes affecting underrepresented groups	Use diverse datasets, regular algorithm updates

Table 15 summarizes the main challenges and ethical considerations in using digital phenotyping within public ASD programs, covering critical issues such as privacy, consent, data misuse, accessibility, and potential biases. Addressing

these concerns through robust data protections, transparent processes, balanced use of technology, and efforts to reduce disparities will help ensure that digital phenotyping is both effective and ethically implemented in ASD care.

While digital phenotyping offers tremendous potential for enhancing public programs aimed at monitoring and managing ASD, several challenges and ethical considerations must be addressed. Public health programs need to implement strong data privacy and security measures, ensure informed consent, avoid over-reliance on technology, bridge the digital divide, and address bias in data collection and analysis. By proactively addressing these challenges, digital phenotyping can be implemented in a way that is both effective and ethical, providing valuable support to children with ASD and their families.

4.5. Future Directions for Digital Phenotyping in Public Health Programs

As the application of digital phenotyping continues to grow, its future in public health programs for Autism Spectrum Disorder (ASD) looks promising. With advancements in technology, artificial intelligence (AI), and machine learning, the scope and accuracy of digital phenotyping are expected to improve, offering more personalized and scalable care for individuals with ASD. However, the path forward must address challenges related to accessibility, ethical considerations, and data security while maximizing the potential of these technologies to revolutionize ASD care.

Integration with artificial intelligence and machine learning will likely be one of the most significant future directions for digital phenotyping. AI algorithms can analyze the large datasets generated by digital phenotyping tools, detecting patterns and providing predictive insights that are crucial for early diagnosis and intervention (Schuller et al., 2022). For instance, AI can help identify subtle changes in behavior that may indicate the onset of new symptoms or the progression of ASD, allowing for real-time adjustments in treatment. Machine learning models can also enhance the ability of digital phenotyping to predict future behavioral patterns, thus enabling more proactive interventions tailored to each child's specific needs (Jain et al., 2015). These advancements will allow public health programs to move from reactive to predictive care, improving outcomes and reducing the burden on healthcare systems.

Another key area for future development is scalability and accessibility. Digital phenotyping has the potential to democratize ASD care by making remote monitoring tools more accessible to underserved populations. In rural areas or low-income communities, where access to specialized ASD services is often limited, digital tools can provide continuous monitoring and assessment without the need for frequent in-person visits (Boyd et al., 2021). Public health programs can leverage digital phenotyping platforms to monitor large populations of children, ensuring that even those in the most remote areas receive timely diagnoses and interventions. Furthermore, the development of low-cost devices and mobile applications will be critical in expanding the reach of these technologies. Ensuring that these tools are affordable and easy to use will be essential for achieving equitable access to digital health resources (Millett et al., 2020).

Improved interoperability and data sharing between different digital phenotyping platforms and healthcare systems will be another important step forward. Currently, many digital tools operate within closed systems, making it difficult for healthcare providers to integrate data from multiple sources. In the future, creating open standards for data sharing and ensuring that digital phenotyping tools can communicate with electronic health records (EHRs) will be crucial for streamlining care and improving coordination between clinicians, caregivers, and public health agencies (Onnela & Rauch, 2016). Interoperability will allow for a more comprehensive view of each child's condition, as data from wearable devices, smartphone apps, and clinical assessments can be integrated into a unified care plan.

Ethical frameworks and data governance will continue to be a central focus as digital phenotyping becomes more widespread. As the technology advances, so too will the concerns about privacy, data ownership, and the potential for misuse of sensitive information (Millett et al., 2020). Public health programs must establish robust ethical guidelines that prioritize the protection of individuals' data while allowing for its use in improving care. Informed consent processes need to be transparent and dynamic, giving families control over how their data is used and allowing them to opt in or out of specific data-sharing agreements. Additionally, data governance frameworks must ensure that the data collected through digital phenotyping is used solely for the intended purpose of improving health outcomes and not for commercial exploitation.

Lastly, training and education for both clinicians and caregivers will be essential for the successful integration of digital phenotyping into public health programs. As these technologies become more complex, it is important to ensure that healthcare providers are trained to interpret and act on the data generated by digital phenotyping tools (Rai et al., 2019). Similarly, caregivers must be provided with the necessary education to understand how these tools work and how to incorporate them into their daily routines. Public health programs will need to invest in ongoing education initiatives to ensure that all stakeholders are equipped to make the best use of these emerging technologies.

The future of digital phenotyping in public health programs for ASD care is bright, with significant potential to improve early diagnosis, personalize interventions, and expand access to care. By advancing AI integration, enhancing scalability, ensuring interoperability, addressing ethical concerns, and investing in education, public health programs can maximize the benefits of digital phenotyping while safeguarding the well-being and privacy of individuals with ASD.

5. Key insights and future directions for digital phenotyping in asd care

5.1. Summary of Key Findings

This review highlights the significant role that digital phenotyping can play in the remote monitoring of social behaviors in children with Autism Spectrum Disorder (ASD). Through the continuous collection of behavioral and physiological data using digital tools such as wearables, smartphones, and machine learning algorithms, digital phenotyping offers real-time, personalized insights into the daily lives of individuals with ASD (Jain et al., 2015). These technologies have demonstrated their capacity to overcome the limitations of traditional assessment methods by capturing data in naturalistic settings, thus providing a more holistic view of an individual's social interactions and behavior.

One of the key findings of this review is the potential for digital phenotyping to enhance early diagnosis and personalized interventions. By enabling continuous monitoring, digital phenotyping allows clinicians to detect subtle behavioral changes that may signal the onset or progression of ASD, facilitating earlier and more accurate diagnoses (Jiang et al., 2020). Additionally, the integration of artificial intelligence into digital phenotyping platforms enhances the ability to tailor interventions based on each child's unique behavioral patterns, making treatment more effective and responsive to the individual's evolving needs.

Another critical finding is the scalability and accessibility of digital phenotyping in public health programs. By leveraging mobile and cloud-based technologies, digital phenotyping can be scaled to large populations, providing continuous monitoring for children in underserved or rural areas where access to specialized ASD care may be limited (Boyd et al., 2021). Public health programs can use these tools to reach broader populations, ensuring that early interventions are accessible to all children with ASD, regardless of geographic or socioeconomic barriers.

Digital phenotyping offers significant promise in transforming ASD care by providing real-time, personalized, and scalable monitoring. However, as this technology continues to evolve, public health programs must address challenges related to data privacy, equity in access, and ethical concerns to ensure that its benefits are realized in an inclusive and responsible manner.

5.2. Implications for Future Research and Policy

The integration of digital phenotyping in Autism Spectrum Disorder (ASD) care presents numerous opportunities for advancing both research and public health policy. One of the primary implications for future research is the need to further explore the long-term efficacy of digital phenotyping tools in improving outcomes for children with ASD. While current studies have shown promising results in early diagnosis and personalized intervention, more longitudinal research is required to understand how these technologies can support individuals with ASD across different stages of development and over extended periods (Jain et al., 2015). Future research should focus on assessing the impact of continuous monitoring on long-term social, behavioral, and cognitive outcomes, as well as evaluating the scalability of these tools in large, diverse populations.

Additionally, there is a growing need for multidisciplinary collaboration in the research and development of digital phenotyping technologies. The integration of data science, artificial intelligence, psychology, and healthcare is critical to improving the accuracy and functionality of these tools. Researchers must work together to develop machine learning algorithms that can interpret complex behavioral data while ensuring that these systems are trained on diverse datasets to avoid biases in diagnosis and treatment (Jiang et al., 2020). Collaborations between academic institutions, technology companies, and healthcare providers will be essential in refining digital phenotyping platforms to provide accurate, reliable, and inclusive care for individuals with ASD.

From a policy perspective, regulatory frameworks must evolve to address the ethical challenges posed by the widespread adoption of digital phenotyping in public health programs. Policymakers must develop clear guidelines on data privacy, consent, and security to protect the sensitive information collected by these tools. As digital phenotyping relies on continuous, passive data collection, there are significant concerns about how this data is stored, shared, and used (Millett et al., 2020). Future policy should emphasize transparency, ensuring that families are fully informed about how their data will be used and giving them control over consent and data sharing. Additionally, policies must focus on

ensuring equitable access to digital health technologies, particularly in underserved or rural communities where access to ASD care is often limited.

Future research should focus on long-term studies to assess the impact of digital phenotyping on ASD care, while multidisciplinary collaboration is key to advancing these technologies. Policy efforts should address the ethical implications of data collection and prioritize equitable access to ensure that the benefits of digital phenotyping reach all individuals with ASD.

5.3. Recommendations for Public Health Programs and Stakeholders

Based on the key findings and implications of this review, several recommendations can be made to enhance the integration and effectiveness of digital phenotyping in public health programs for Autism Spectrum Disorder (ASD). These recommendations aim to address current challenges, optimize the use of digital tools, and ensure that these technologies are implemented ethically and equitably to improve care for children with ASD.

5.3.1. Increase funding and investment in digital health infrastructure.

To support the widespread adoption of digital phenotyping in public health programs, there must be sufficient investment in digital health infrastructure. Public health agencies, governments, and private sector stakeholders should collaborate to allocate funding toward the development, deployment, and maintenance of digital health tools for ASD care (Schuller et al., 2022). This includes ensuring that the necessary infrastructure, such as broadband internet and access to affordable devices, is available in underserved and rural communities. Increased funding will help close the gap between technological advancement and accessibility, ensuring that all families can benefit from these innovations.

5.3.2. Develop clear data privacy and security frameworks.

One of the most pressing issues in the use of digital phenotyping is data privacy and security. Public health programs and stakeholders must prioritize the development of robust frameworks that safeguard the sensitive data collected through digital phenotyping tools (Millett et al., 2020). These frameworks should include guidelines on data storage, access, and sharing, with particular emphasis on obtaining informed consent from families. Public health programs must ensure that families have full control over their data and are informed about how it will be used. Transparency and trust are critical for the successful integration of digital phenotyping into ASD care.

5.3.3. Promote training and education for clinicians and caregivers.

To maximize the effectiveness of digital phenotyping tools, both clinicians and caregivers need to be properly trained in their use. Public health programs should offer educational resources and training to healthcare professionals on how to interpret and act on the data generated by digital phenotyping devices (Onnela & Rauch, 2016). Similarly, caregivers should receive guidance on how to integrate these tools into their daily routines, enabling them to monitor their child's progress and make informed decisions about care. By investing in education, public health programs can ensure that stakeholders are fully equipped to utilize these technologies effectively.

5.3.4. Encourage multidisciplinary collaboration in the development of digital phenotyping tools.

The development of digital phenotyping tools for ASD care requires collaboration between diverse fields, including healthcare, data science, psychology, and technology. Public health programs should encourage partnerships between academic researchers, private technology companies, and healthcare providers to create more accurate and effective tools (Jain et al., 2015). By fostering collaboration across these disciplines, digital phenotyping platforms can be refined to better serve the needs of individuals with ASD and ensure that the tools are scientifically validated and clinically effective.

5.3.5. Focus on equity and inclusivity in the deployment of digital tools.

Ensuring equitable access to digital phenotyping tools must be a priority for public health programs. Many families, especially those in low-income or rural areas, face barriers to accessing the necessary technology for digital phenotyping (Boyd et al., 2021). Public health programs should provide subsidies, financial assistance, and support programs to help these families gain access to the tools they need. Additionally, digital tools should be designed to be inclusive, taking into account cultural, linguistic, and socioeconomic differences to ensure that all populations can benefit from their use.

The successful integration of digital phenotyping in ASD care will depend on increased funding, robust data privacy frameworks, comprehensive training, multidisciplinary collaboration, and a commitment to equity. By addressing these

areas, public health programs and stakeholders can ensure that digital phenotyping technologies are implemented effectively and ethically, leading to improved outcomes for children with ASD.

5.4. Ethical Considerations in Scaling Digital Phenotyping for Public Health

As digital phenotyping becomes more widely integrated into public health programs for Autism Spectrum Disorder (ASD), ensuring that ethical considerations are at the forefront of implementation is essential. Scaling the use of digital phenotyping raises several ethical concerns, particularly regarding privacy, informed consent, and equity. Addressing these issues is critical for safeguarding the rights and well-being of individuals and families who rely on these technologies for ASD care.

One of the most prominent ethical concerns is data privacy. Digital phenotyping involves the collection of vast amounts of sensitive data, including behavioral, physiological, and location-based information. Given the continuous nature of data collection, individuals' privacy could be compromised if proper data protection measures are not in place (Millett et al., 2020). Public health programs must implement robust data governance frameworks that ensure the secure storage and handling of this data. Encryption and anonymization of data should be standard practices, with access strictly controlled to protect against breaches. Furthermore, clear policies must be established regarding how data is shared and used, both within healthcare systems and beyond. Safeguarding data privacy is essential to building trust between families and public health agencies, ensuring that individuals feel confident using these tools.

Informed consent is another ethical consideration that becomes increasingly complex as digital phenotyping scales. Since these tools collect data passively and continuously, it can be difficult for individuals to fully understand the scope of data being collected and how it will be used. Ensuring that families and individuals are fully informed about data collection processes is paramount (Gaggi et al., 2019). Informed consent should be an ongoing process, with opportunities for individuals to opt in or out of data collection as they see fit. Public health programs must provide clear and accessible information about the purposes of data collection, who will have access to the data, and how long the data will be stored. This transparency will help ensure that individuals have control over their personal information and can make informed decisions about their participation.

Another significant ethical issue is equity and access. While digital phenotyping holds great promise for improving ASD care, it is essential to ensure that all populations have equal access to these technologies (Boyd et al., 2021). Many rural or low-income communities lack the infrastructure, such as reliable internet or access to digital devices, necessary to benefit from digital health tools. Public health programs must prioritize making digital phenotyping tools affordable and accessible to underserved populations, either through subsidies, the provision of devices, or the expansion of digital infrastructure. Without a concerted effort to bridge the digital divide, there is a risk that digital phenotyping could exacerbate existing health disparities, leaving some communities behind in terms of access to early diagnosis and personalized care.

The ethical scaling of digital phenotyping for ASD care requires careful attention to data privacy, informed consent, and equitable access. Public health programs must take proactive measures to ensure that individuals' rights are protected and that the benefits of digital phenotyping are accessible to all. By addressing these ethical considerations, digital phenotyping can be successfully integrated into public health systems while maintaining the trust and well-being of individuals and families.

6. Conclusion

The integration of digital phenotyping into public health programs for Autism Spectrum Disorder (ASD) marks a significant advancement in the ability to monitor, assess, and intervene in the care of children with ASD. This technology offers substantial benefits, including real-time monitoring, early detection, personalized interventions, and scalable solutions that can reach underserved populations. By leveraging tools such as wearable devices, smartphones, and AI-driven platforms, public health systems have the potential to transform the way ASD is managed, ensuring more timely and effective care for children across diverse settings.

However, as digital phenotyping becomes more widespread, it is crucial to address the ethical challenges that accompany its use. Ensuring the privacy and security of sensitive data, obtaining ongoing informed consent, and guaranteeing equitable access to these technologies are paramount to their successful implementation. Public health programs must focus on building trust with individuals and families by safeguarding data and being transparent about how it is used. Furthermore, efforts to bridge the digital divide and ensure that all communities have access to these tools will be essential to prevent disparities in ASD care.

As digital phenotyping continues to evolve, future research and policy efforts should focus on refining these technologies, addressing their limitations, and ensuring that they are used ethically and inclusively. With careful consideration of these factors, digital phenotyping can play a transformative role in ASD care, providing new opportunities for early diagnosis, tailored interventions, and improved quality of life for children with ASD and their families.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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