Analyzing Social Communication Deficits in Autism Using Wearable Sensors and Real-Time Affective Computing Systems

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Abstract: Social communication deficits are a hallmark characteristic of Autism Spectrum Disorder (ASD), often manifesting as challenges in interpreting and expressing emotions, maintaining eye contact, and engaging in reciprocal interactions. Traditional diagnostic and intervention methods, while valuable, can be limited by observer bias and lack of continuous monitoring. This review explores the emerging role of wearable sensors and real-time affective computing systems in assessing and addressing these deficits. By leveraging physiological signals (e.g., heart rate variability, skin conductance, and movement patterns) and behavioral data (e.g., gaze tracking, facial expressions, and speech prosody), wearable devices offer objective, non-intrusive insights into the emotional and communicative states of individuals with ASD. Affective computing systems, powered by machine learning and signal processing techniques, enable real-time analysis and adaptive feedback, potentially enhancing social skills training and personalized intervention. The paper examines current technologies, evaluation metrics, and case studies, while also addressing challenges such as data privacy, model generalizability, and user compliance. Finally, the review highlights future directions for integrating these technologies into clinical practice and educational environments to support early diagnosis, continuous monitoring, and intervention personalization in ASD care.

Keywords: *Autism Spectrum Disorder (ASD); Social Communication Deficits; Wearable Sensor Technology; Affective Computing; Real-Time Emotion Recognition.*

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I. INTRODUCTION

A. Overview of Autism Spectrum Disorder (ASD) and Its Impact on Social Communication

Autism Spectrum Disorder (ASD) is a complex neurodevelopmental condition characterized by persistent deficits in social communication and interaction, alongside restricted, repetitive patterns of behavior, interests, or activities (American Psychiatric Association, 2013). These social communication challenges are central to the diagnosis and significantly impact the daily functioning of individuals with ASD. Social communication encompasses the ability to use verbal and nonverbal behaviors appropriately in social contexts, including skills such as eye contact, facial expressions, gestures, and understanding and using language pragmatically. Individuals with ASD often exhibit difficulties in these areas, leading to challenges in initiating and maintaining conversations, interpreting social cues, and developing peer relationships. These impairments can result in social isolation and hinder the development of essential life skills. Research indicates that deficits in prosody—the rhythm, stress, and intonation of speech—are particularly pronounced in individuals with ASD. Such prosodic challenges can affect the ability to convey and interpret emotions, sarcasm, or questions, further complicating social interactions (Costescu et al., 2022). Moreover, these difficulties are not solely attributable to language deficits but are also linked to broader issues in cognitive flexibility and executive functioning, which are common in ASD populations. Early intervention has been shown to be critical in improving social communication outcomes for children with ASD. A meta-analysis by Fuller and Kaiser (2020) demonstrated that early, targeted interventions could lead to significant improvements in social communication skills. The study emphasized that interventions focusing on joint attention and responsive communication strategies are particularly effective when implemented at a young age.

Understanding the nature of social communication deficits in ASD is essential for developing effective assessment tools and intervention strategies. By recognizing the specific challenges faced by individuals with ASD in social communication, practitioners can tailor interventions to address these areas, thereby enhancing social integration and quality of life.

B. Limitations of Traditional Diagnostic and Intervention Approaches

Traditional diagnostic and intervention approaches for ASD have been instrumental in identifying and supporting individuals on the spectrum. However, these methods present several limitations that can impede timely diagnosis and effective intervention.

One significant limitation is the reliance on behavioral observations and caregiver reports, which can be subjective and influenced by various factors, including cultural perceptions and the observer's experience. This subjectivity can lead to inconsistencies in diagnosis, particularly in individuals who do not exhibit overt or stereotypical behaviors associated with ASD. Furthermore, the diagnostic process often requires multiple assessments over extended periods, delaying the initiation of crucial early interventions (Lord et al., 2022). Early intervention is critical in improving outcomes for children with ASD, yet traditional approaches may not adequately address the diverse needs of this population. Standardized intervention programs may lack the flexibility to tailor strategies to individual strengths and challenges, potentially limiting their effectiveness. Additionally, access to specialized services can be constrained by geographic, socioeconomic, and systemic barriers, leaving many families without the necessary support (Zwaigenbaum et al., 2015). Moreover, traditional interventions often focus on mitigating deficits rather than enhancing strengths, which can affect the self-esteem and motivation of individuals with ASD. This deficit-based approach may overlook the unique abilities and potential contributions of those on the spectrum, underscoring the need for more holistic and person-centered methodologies.

In summary, while traditional diagnostic and intervention methods have provided a foundation for understanding and supporting individuals with ASD, their limitations highlight the necessity for more nuanced, flexible, and inclusive approaches that consider the heterogeneity of the autism spectrum.

C. Rationale for Integrating Wearable Sensors and Affective Computing

The integration of wearable sensors and affective computing technologies presents a transformative approach to addressing the social communication deficits characteristic of Autism ASD. Traditional assessment and intervention methods often rely on subjective observations and retrospective reporting, which can be limited by observer bias and the inability to capture real-time emotional and physiological states. Wearable sensors offer the capability to continuously monitor physiological signals such as heart rate variability, skin conductance, and movement patterns, providing objective data that reflect the user's emotional and arousal states (Keshav et al., 2017). Affective computing systems enhance this by employing algorithms that interpret these physiological signals to infer emotional states, enabling real-time feedback and adaptive interventions. This real-time analysis is particularly beneficial for individuals with ASD, who may have difficulty recognizing and responding to social cues. By providing immediate, context-aware feedback, these systems can assist users in navigating social interactions more effectively (El Kaliouby et al., 2006). Moreover, the data collected through these technologies can inform personalized intervention strategies, allowing for adjustments based on the individual's unique physiological and behavioral responses. This personalization is crucial given the heterogeneity of ASD presentations. Additionally, the unobtrusive nature of wearable devices facilitates their use in naturalistic settings, promoting generalization of skills across environments.

In summary, the convergence of wearable sensor technology and affective computing offers a promising avenue for enhancing the assessment and intervention of social communication deficits in ASD. By providing objective, real-time data and personalized feedback, these technologies have the potential to augment traditional methods and improve outcomes for individuals with ASD.

D. Scope and Objectives of the Review

The integration of wearable sensors and affective computing technologies offers a promising avenue for addressing the social communication deficits characteristic of ASD. This review aims to systematically examine the current landscape of these technologies, focusing on their application in assessing and intervening in the social communication challenges faced by individuals with ASD. The scope of this review encompasses a comprehensive analysis of existing wearable devices and affective computing systems designed to monitor and interpret physiological and behavioral signals relevant to social communication. By evaluating the capabilities of these technologies in real-time emotion recognition and feedback, the review seeks to understand their effectiveness in enhancing social interactions for individuals with ASD.

Key objectives include: (1) identifying the types of physiological and behavioral data captured by wearable sensors pertinent to social communication; (2) assessing the methodologies employed by affective computing systems to process and interpret these data; (3) evaluating the efficacy of these technologies in real-world settings, including clinical, educational, and home environments; and (4) discussing the challenges and ethical considerations associated with their implementation, such as data privacy, user compliance, and model generalizability.

By synthesizing current research and technological advancements, this review aims to provide insights into the potential of wearable sensors and affective computing systems to serve as complementary tools in the assessment and intervention of social communication deficits in ASD. The findings are intended to inform future research directions and the development of personalized, adaptive interventions that can be seamlessly integrated into existing care frameworks.

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E. Organization of the Paper

This review is structured to provide a comprehensive examination of the integration of wearable sensors and real-time affective computing systems in addressing social communication deficits in individuals with ASD. Following the introduction, Section 2 presents a detailed exploration of the types and functionalities of wearable sensors used in autism research, including the physiological and behavioral metrics they capture. Section 3 discusses affective computing technologies, focusing on emotion recognition algorithms, machine learning models, and their applicability to interpreting affective states in ASD populations. Section 4 synthesizes empirical findings from current studies that have implemented these technologies in both clinical and naturalistic settings. Section 5 evaluates the challenges, limitations, and ethical concerns related to the use of these systems, including privacy, data security, and accessibility. Section 6 proposes future directions and opportunities for enhancing the design, scalability, and integration of these tools in personalized autism care. The paper concludes in Section 7 with a summary of key insights and recommendations for stakeholders in research, healthcare, and technology development. Throughout the paper, emphasis is placed on aligning technological innovation with user-centered design and clinical efficacy to ensure that emerging tools meet the nuanced needs of individuals with ASD.

II. UNDERSTANDING SOCIAL COMMUNICATION DEFICITS IN ASD

A. Definition and Clinical Presentation of Social Communication Challenges

Social communication challenges are a core feature of ASD, encompassing persistent difficulties in the use of verbal and nonverbal communication for social purposes. These challenges manifest in various ways, including deficits in social-emotional reciprocity, nonverbal communicative behaviors, and the ability to develop and maintain relationships as presented in table 1. Individuals with ASD may struggle with initiating or sustaining conversations, understanding and using gestures, facial expressions, and eye contact, as well as adapting communication styles to different social contexts. Clinically, these deficits are evident in early childhood and can vary in severity. Children with ASD often exhibit limited joint attention—the shared focus of two individuals on an object—which is crucial for language development and social learning (Mundy & Neal, 2001). Additionally, they may have difficulty understanding the perspectives of others, leading to challenges in interpreting social cues and responding appropriately in social interactions. These impairments can result in social isolation and hinder the development of peer relationships. Language development in individuals with ASD is also affected, with some exhibiting delayed speech or atypical language patterns. Even those with fluent speech may have pragmatic language impairments, such as difficulties with conversational turn-taking, topic maintenance, and understanding idiomatic expressions (Tager-Flusberg, 2006). These language deficits further compound social communication challenges, making it difficult for individuals with ASD to navigate complex social environments. Understanding the multifaceted nature of social communication deficits in ASD is essential for developing targeted interventions (Ogbuonyalu, et al., 2025). By recognizing the specific areas of difficulty, clinicians and educators can implement strategies that address these challenges, thereby improving social functioning and quality of life for individuals with ASD.

B. Relevance of Early Detection and Continuous Monitoring

Early detection and continuous monitoring are pivotal in addressing social communication deficits in individuals with ASD. Identifying ASD at an early stage allows for timely intervention, which can significantly improve developmental trajectories. Pierce et al. (2021) emphasize the importance of initiating screening as early as 12 months, highlighting that early identification facilitates access to specialized services and supports that can mitigate the severity of social communication challenges. Continuous monitoring complements early detection by providing ongoing assessment of an individual's developmental progress. Messinger et al. (2015) discuss the variability in developmental outcomes among high-risk children, underscoring the necessity for sustained observation to tailor interventions effectively. Through regular monitoring, clinicians can adjust therapeutic approaches in response to the evolving needs of the individual, thereby enhancing the efficacy of interventions. The integration of wearable sensors and affective computing technologies offers a promising avenue for facilitating early detection and continuous monitoring. These tools can capture real-time data on physiological and behavioral indicators associated with social communication, enabling the identification of atypical patterns that may signify the onset of ASD-related challenges. By leveraging such technologies, practitioners can implement proactive strategies that address deficits before they become deeply entrenched, ultimately improving social communication outcomes for individuals with ASD.

Table 1 Summary of Social Communication Challenges in ASD

Aspect	Description	Clinical Indicators	Implications
Definition	Persistent difficulties in verbal and nonverbal communication for social purposes in individuals with ASD.	Problems with conversation initiation, facial expressions, gestures, and eye contact.	Leads to miscommunication and difficulty adapting to varied social contexts.
Clinical Presentation	Evident from early childhood and varies in severity. Includes social-emotional reciprocity and nonverbal	Limited joint attention, poor use of gestures, and lack of understanding others' perspectives.	Results in poor peer relationships, social isolation, and reduced social learning.

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	communicative behavior deficits.		
Language Impairments	Delayed or atypical language patterns, including pragmatic language difficulties even in fluent speakers.	Issues with conversational turn-taking, topic maintenance, and understanding figurative language.	Worsens communication and restricts engagement in complex social environments.
Need for Intervention	A detailed understanding of social communication deficits is crucial for tailored intervention strategies.	Informs clinicians and educators on specific targets like joint attention or pragmatic language.	Enhances social functioning, supports relationship building, and improves quality of life for individuals.

C. Neurophysiological and Behavioral Markers Associated with Social Impairments

Social impairments in ASD are underpinned by distinct neurophysiological and behavioral markers that disrupt typical social functioning. Neuroimaging studies have revealed that individuals with ASD exhibit atypical activation and connectivity within the "social brain" network, which includes regions such as the medial prefrontal cortex (mPFC), superior temporal sulcus (STS), and temporoparietal junction (TPJ) as shown in figure 1. These areas are crucial for processing social information, including understanding others' intentions and emotions. Gotts et al. (2012) demonstrated that disruptions in these circuits correlate with the severity of social deficits in ASD, suggesting that these neural anomalies contribute to the challenges in social communication and interaction observed in affected individuals. In addition to central nervous system alterations, peripheral sensory processing abnormalities have been implicated in ASD-related social impairments. Orefice et al. (2016) provided evidence that dysfunction in peripheral mechanosensory neurons leads to tactile hypersensitivity in mouse models of ASD. This heightened sensitivity can result in discomfort during social touch, potentially contributing to social withdrawal and difficulties in forming interpersonal connections (Anyibama, et al., 2025). The study highlights the significance of peripheral sensory neurons in modulating social behaviors, indicating that both central and peripheral nervous system dysfunctions play roles in the social challenges characteristic of ASD. Behaviorally, individuals with ASD often display reduced eye contact, limited use of gestures, and difficulties in interpreting social cues. These observable behaviors are manifestations of the underlying neurophysiological disruptions. (Ogbuonyalu, et al., 2024). By identifying and understanding these markers, researchers and clinicians can develop targeted interventions aimed at mitigating social impairments in ASD. The integration of neuroimaging and behavioral assessments holds promise for enhancing diagnostic accuracy and tailoring individualized treatment strategies.

Fig 1 Picture of Child with ASD Displaying Sensory Sensitivity and Social Withdrawal During a Therapy Session, Reflecting Core Social Communication Challenges (Harkin, & Efron, 2022)

Figure 1 shows a young boy, likely with ASD, displaying a common behavioral marker associated with social impairments—covering his ears and avoiding eye contact—while sitting in a therapeutic or educational setting with an adult. This behavior may reflect heightened tactile or auditory sensitivity, often linked to dysfunction in peripheral mechanosensory neurons. Such sensory processing abnormalities contribute to social withdrawal and discomfort during interpersonal interactions. The woman, possibly a therapist or educator, is engaging the child with colorful learning tools, aiming to facilitate social communication, though the child's avoidance behavior suggests difficulty processing the social and sensory stimuli present. Neurophysiologically, this behavior aligns with atypical activation within the "social brain" network—particularly in the medial prefrontal cortex, superior temporal sulcus, and temporoparietal junction—which affects the child's ability to interpret social cues and respond appropriately. The scene reflects the critical need for personalized interventions that account for both neurophysiological and behavioral markers to support social engagement and communication development in individuals with ASD.

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III. OVERVIEW OF WEARABLE SENSORS FOR ASD

A. Types of Wearable Devices (e.g., Smartwatches, Biosensors, Eye-Tracking Glasses)

Wearable technology has emerged as a transformative tool in the assessment and intervention of social communication deficits in individuals with ASD. Among the various devices, smartwatches, biosensors, and eye-tracking glasses have garnered significant attention for their potential to monitor and enhance social interactions as represented in figure 2. Smartwatches equipped with biosensors can track physiological parameters such as heart rate variability and skin conductance, providing real-time data on an individual's emotional and stress responses. These metrics are invaluable in understanding the autonomic nervous system's role in social engagement and can aid in tailoring interventions to the individual's needs (Liu et al., 2017). Biosensors, often integrated into wearable devices, offer continuous monitoring of physiological signals, enabling the detection of subtle changes associated with social anxiety or discomfort. This continuous data stream allows for the timely identification of stressors in social environments, facilitating prompt intervention strategies to mitigate adverse reactions (Keshav et al., 2018).

Eye-tracking glasses represent another innovative approach, capturing gaze patterns and eye movement data to assess attention and engagement during social interactions. By analyzing these patterns, researchers and clinicians can identify atypical visual attention behaviors characteristic of ASD, such as reduced eye contact or focus on non-social stimuli. This information is critical in developing targeted therapies aimed at improving social attention and communication skills (Liu et al., 2017). The integration of these wearable devices into therapeutic settings offers a personalized approach to intervention, allowing for real-time feedback and adjustments based on the individual's physiological and behavioral responses (Abiodun, et al., 2023). As technology continues to advance, the refinement and accessibility of these tools hold promise for enhancing the quality of life for individuals with ASD through improved social communication and interaction.

Figure 2 showcases four distinct types of wearable technologies frequently utilized in autism research and intervention to monitor and enhance social communication. In panel A, a young child wears an EEG-based biosensor cap designed to record neural activity and assess real-time brain responses associated with social stimuli—an essential tool for understanding atypical neural processing in ASD. Panel B shows a participant equipped with multisensory biosensors and headphones, likely capturing physiological signals such as heart rate variability and skin conductance—key indicators of autonomic nervous system activity during social engagement or stress, as described in 3.1. Panel C features a smartwatch capable of continuously monitoring physiological data such as heart rhythm, which aids in detecting emotional states like anxiety or arousal during social interactions. Panel D displays children using virtual reality (VR) headsets, potentially integrated with eye-tracking systems that capture gaze patterns and visual attention metrics—critical for identifying reduced eye contact and atypical focus, hallmark traits in ASD. These wearable systems provide continuous, real-time data that inform personalized, adaptive interventions aimed at improving emotional regulation and social communication in individuals with ASD.

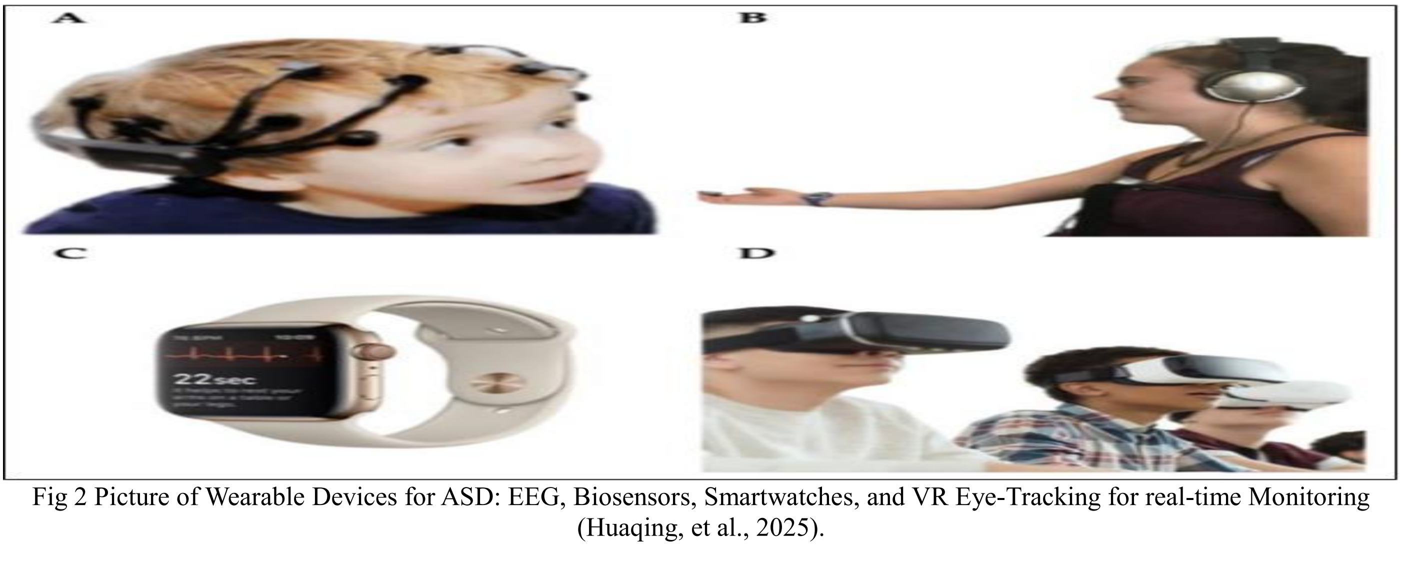

Fig 2 Picture of Wearable Devices for ASD: EEG, Biosensors, Smartwatches, and VR Eye-Tracking for real-time Monitoring (Huaqing, et al., 2025).

B. Physiological and Behavioral Signals Captured (e.g., Heart Rate, GSR, Movement)

Wearable devices designed for individuals with ASD capture a range of physiological and behavioral signals that provide insights into emotional and physical states. These signals are crucial for understanding the individual's responses to various stimuli and can inform personalized interventions. Heart rate (HR) is a fundamental physiological parameter monitored by many wearable devices. Variations in HR can indicate changes in emotional arousal or stress levels. For instance, elevated HR may signify anxiety or agitation, common in individuals with ASD during social interactions or sensory overload situations. Continuous HR monitoring allows for the detection of these physiological changes in real-time, enabling timely interventions (Amiri et al., 2017). Galvanic Skin Response (GSR), also known as

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Electrodermal Activity (EDA), measures the skin's conductance, which varies with moisture levels due to sweating. This metric is sensitive to emotional arousal, providing insights into the individual's stress or excitement levels. In ASD, atypical GSR responses have been observed, such as heightened reactivity to stimuli, which can inform the development of coping strategies (Keshav et al., 2018).

Movement data, captured through accelerometers, offer information on physical activity levels and motor coordination. In individuals with ASD, movement patterns can reflect behavioral states; for example, repetitive movements or lack of movement may indicate distress or disengagement. Analyzing these patterns aids in understanding behavioral responses and tailoring interventions accordingly (Amiri et al., 2017). Collectively, these physiological and behavioral signals provide a comprehensive view of an individual's responses to their environment. By integrating data from various sensors, wearable devices can offer a holistic understanding of the individual's emotional and physical states, facilitating more effective and personalized interventions for those with ASD.

C. Advantages and Limitations of Wearable Technologies in Autism Research

Wearable technologies have revolutionized autism research by providing real-time, objective data that enhances understanding and intervention strategies for individuals with ASD. These devices offer continuous monitoring of physiological and behavioral signals, facilitating a more nuanced comprehension of the individual's experiences and responses in various settings. One significant advantage is the ability to capture data in naturalistic environments, such as homes or schools, where traditional clinical assessments may not accurately reflect the individual's typical behavior. This ecological validity ensures that the data collected is representative of real-world conditions, leading to more applicable and effective interventions (Fioriello et al., 2020) as presented in table 2. Additionally, wearable devices can detect subtle physiological changes, such as increased heart rate or skin conductance, which may precede behavioral outbursts or meltdowns. This early detection allows for timely interventions that can prevent escalation and improve outcomes (Fioriello et al., 2020).

However, there are limitations to consider. The accuracy of data collected by wearable devices can be influenced by factors such as sensor placement, device calibration, and individual differences in physiology. These variables can introduce noise into the data, potentially affecting the reliability of the insights gained. Furthermore, the continuous nature of data collection can lead to information overload, making it challenging for researchers and clinicians to identify meaningful patterns without advanced analytical tools (Fioriello et al., 2020).

In summary, while wearable technologies offer valuable insights into the lives of individuals with ASD, their effectiveness is contingent upon careful design, implementation, and data analysis. Addressing these challenges is crucial to fully harness the potential of wearable devices in autism research.

Table 2 Summary of Advantages and Limitations of Wearable Technologies in Autism

Aspect	Description	Advantages	Limitations
Data Collection	Wearables provide real-time, objective data on physiological and behavioral signals in naturalistic environments.	High ecological validity; captures behavior in real-world settings like home or school.	Sensor placement and calibration issues may reduce accuracy; individual physiological differences can introduce noise.
Behavioral Insight	Devices detect subtle changes (e.g., heart rate, skin conductance) that may precede emotional or behavioral outbursts.	Enables early detection of distress; facilitates timely interventions before escalation.	Subtle physiological signals require precise interpretation; variability among users can limit generalizability.
Data Utility	Continuous monitoring supports in-depth understanding of the user's experiences and responses across contexts.	Enhances individualized intervention strategies based on comprehensive data sets.	Continuous data can cause information overload; advanced analytical tools are needed to extract meaningful insights.
Implementation	Effectiveness of wearable use depends on thoughtful application in design, data handling, and research protocols.	Potential to personalize care and improve quality of life for individuals with ASD.	Misuse or poor implementation may limit effectiveness and reduce trust in the technology.

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IV. REAL-TIME AFFECTIVE COMPUTING SYSTEMS

A. Definition and Principles of Affective Computing

Affective computing is an interdisciplinary field that focuses on developing systems and devices capable of recognizing, interpreting, and simulating human emotions. It integrates principles from computer science, psychology, and cognitive science to enable machines to process and respond to human affective states in ways that are contextually appropriate and sensitive to individual differences (Afzal et al., 2023) as represented in figure 3. The foundational principle of affective computing is the recognition and interpretation of emotional cues from users. This involves capturing data through various modalities, including facial expressions, speech patterns, body language, and physiological signals such as heart rate and galvanic skin response (Azonuche, et al., 2025). Advanced algorithms and machine learning techniques are then employed to analyze this data, allowing systems to identify emotional states with a degree of accuracy comparable to human perception (Afzal et al., 2023).

Another core principle is the simulation of emotions by machines. This aspect aims to enhance human-computer interactions by enabling systems to exhibit emotional responses that are congruent with the user's emotional state, thereby fostering more natural and empathetic interactions. For instance, virtual assistants or robots might adjust their tone of voice or facial expressions to convey empathy or understanding, improving user engagement and satisfaction (Afzal et al., 2023).

Furthermore, affective computing emphasizes the importance of context and individual variability in emotional expression. Recognizing that emotions are influenced by cultural, social, and personal factors, affective computing systems are designed to adapt their responses accordingly, ensuring that interactions are respectful and appropriate across diverse user populations (Afzal et al., 2023).

In summary, affective computing seeks to bridge the gap between human emotional experiences and machine understanding, aiming to create systems that are not only intelligent but also emotionally aware and responsive.

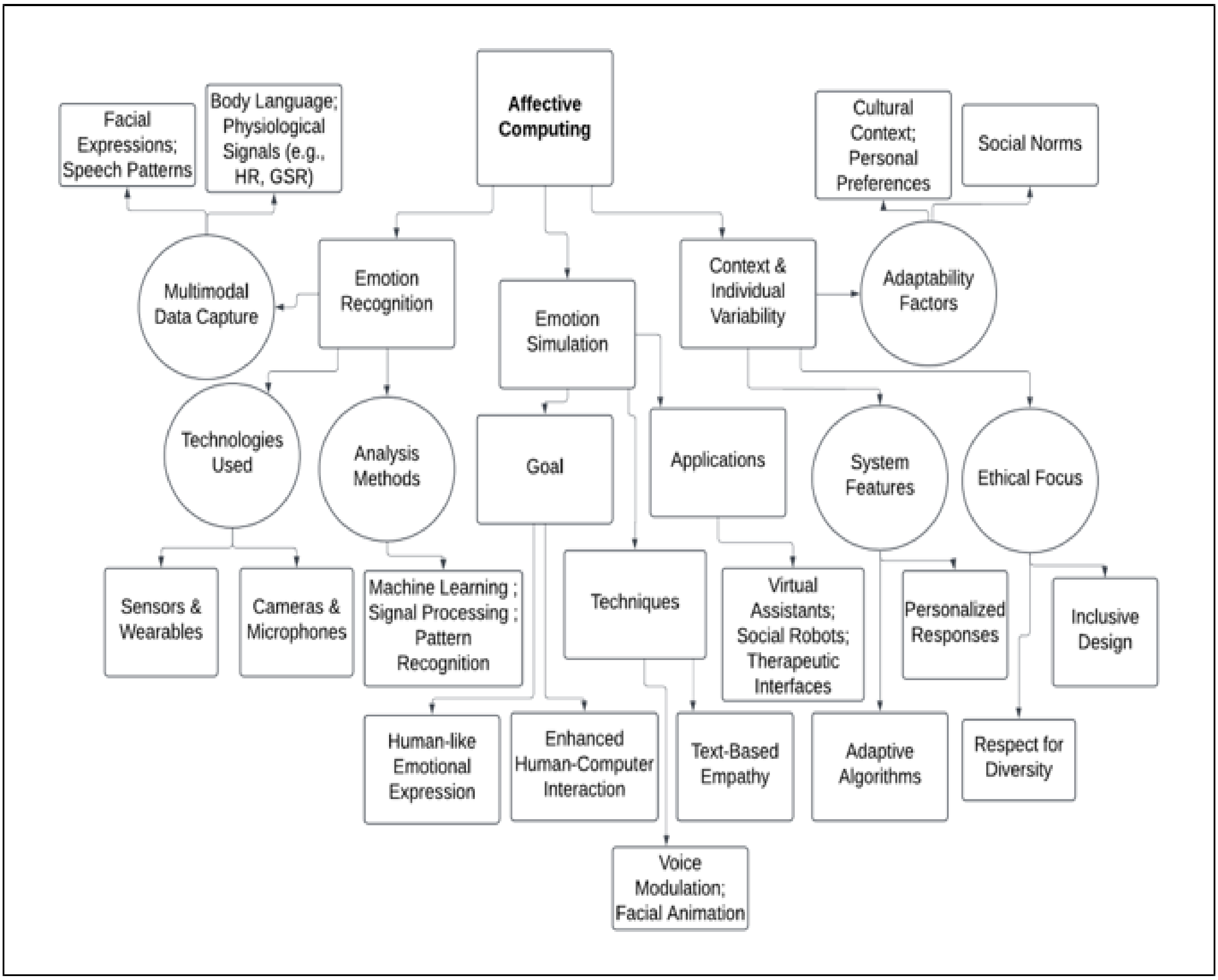

Fig 3 Diagram Illustrating the Core Principles of Affective Computing Including Emotion Recognition Simulation and Adaptive Context-aware Personalization

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Figure 3 summarizes the core components and principles of affective computing through three interconnected branches: Emotion Recognition, Emotion Simulation, and Context & Individual Variability. The Emotion Recognition branch illustrates how affective computing systems capture and analyze emotional data through multiple modalities such as facial expressions, speech patterns, body language, and physiological signals like heart rate and galvanic skin response. These inputs are processed using advanced machine learning and pattern recognition algorithms to accurately detect the user's emotional state. The Emotion Simulation branch highlights the system's ability to generate appropriate emotional responses using techniques such as voice modulation, animated facial expressions, and text-based empathy. These responses enhance user interaction by making machines appear more human-like and emotionally responsive, particularly useful in applications like social robots and virtual assistants. Lastly, the Context & Individual Variability branch addresses how affective computing systems account for differences in cultural backgrounds, social norms, and individual preferences. By incorporating adaptive algorithms and personalized response mechanisms, these systems ensure that emotional interactions are respectful, inclusive, and contextually appropriate. Together, the diagram illustrates how affective computing bridges human emotion and machine intelligence to foster empathetic, user-centered technology.

B. Algorithms and Techniques for Emotion Recognition (e.g., Machine Learning, Signal Processing)

Emotion recognition has evolved significantly with advancements in machine learning and signal processing techniques, enabling more accurate and real-time detection of human emotions. These methodologies are pivotal in affective computing, facilitating the development of systems that can understand and respond to human emotions effectively. Machine learning algorithms, particularly supervised learning models, have been extensively utilized for emotion classification tasks. Models such as Support Vector Machines (SVM), Decision Trees, and Neural Networks are trained on labeled datasets to distinguish between various emotional states based on extracted features from physiological signals. For instance, a study by Liu et al. (2023) demonstrated the efficacy of a hybrid approach combining Convolutional Neural Networks (CNNs) and Long Short-Term Memory (LSTM) networks for emotion recognition, achieving high accuracy rates across multiple emotional categories. Signal processing techniques play a crucial role in preprocessing and feature extraction from raw data. Methods such as Discrete Wavelet Transform (DWT) and Fast Fourier Transform (FFT) are employed to decompose signals into various frequency components, facilitating the identification of patterns associated with different emotional states (Azonuche, & Enyejo, 2025). Additionally, feature selection techniques like Principal Component Analysis (PCA) are applied to reduce dimensionality and enhance the performance of classification models. In a study by Bazgir et al. (2019), PCA was used to extract relevant features from EEG signals, leading to improved classification accuracy for emotion recognition tasks.

The integration of machine learning algorithms with advanced signal processing techniques has significantly enhanced the accuracy and reliability of emotion recognition systems. These advancements are instrumental in developing applications that require nuanced understanding of human emotions, such as in healthcare, human-computer interaction, and personalized learning environments.

C. Examples of Real-Time Feedback and Adaptive Systems for ASD Users

Real-time feedback and adaptive systems play a crucial role in supporting individuals with ASD, particularly in enhancing their social communication skills. These systems utilize technologies such as wearable devices, emotion recognition algorithms, and machine learning to provide immediate responses to user behavior and emotions as presented in table 3. One notable example is the use of wearable sensors that monitor physiological signals, including heart rate and skin conductance, to detect stress or anxiety levels in real-time. For instance, wearable devices like smartwatches and biosensors are employed to give immediate feedback when users experience heightened emotional states, prompting them to engage in calming exercises or other coping mechanisms (Gao, et al., 2024). Additionally, adaptive systems have been developed to provide dynamic and personalized interventions. These systems use real-time data to adjust the feedback based on the user's emotional and behavioral responses. In a study by (Talaat, F. M. 2023)., an adaptive system was designed to provide visual or auditory feedback to ASD users during social interactions. The system analyzed facial expressions and body language to assess emotional states and tailored its feedback accordingly. This real-time adjustment facilitated improvements in social communication and emotional regulation over time. Such systems have proven particularly effective in helping individuals with ASD to better navigate social scenarios by offering timely assistance and guidance (Azonuche, & Enyejo, 2024). These technologies not only aid in managing emotional responses but also empower users by promoting independent self-regulation. The integration of real-time feedback with adaptive systems provides significant advancements in autism research, particularly in personalized care and intervention (Kasyanov et al., 2020; D'Cruz et al., 2022).

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Table 3 Summary of Real-Time Feedback and Adaptive Systems for ASD Users

Aspect	Description	Examples	Impact on ASD Users
Technology Utilized	Real-time systems integrate wearable sensors, emotion recognition, and machine learning for immediate behavioral and emotional feedback.	Smartwatches and biosensors detect heart rate and skin conductance; emotion recognition via facial/body language analysis.	Promotes emotional awareness, provides calming cues, and supports independent coping strategies.
Feedback Mechanism	Systems provide visual or auditory feedback tailored to emotional and behavioral states detected in real-time.	Adaptive systems deliver cues like deep breathing prompts or visual guidance during stressful social interactions.	Enhances emotional regulation and facilitates real-time social learning.
Personalization	Feedback is adjusted dynamically based on continuous input from user behavior and emotion analysis.	Machine learning algorithms modify intervention strategies in real time to suit user-specific responses.	Increases intervention relevance and efficacy, promoting long-term social skill improvement.
Research Significance	Demonstrates potential for individualized, technology-driven care in autism therapy and research.	Integration of real-time feedback and adaptive systems in clinical studies.	Empowers users through personalized support, advancing autism care and promoting independence in navigating social environments.

V. APPLICATIONS AND CASE STUDIES

A. Review of Studies Utilizing Wearables and Affective Computing in ASD Populations

Wearable devices and affective computing technologies have been increasingly employed to support individuals with ASD, offering valuable insights into the emotional and physiological states of these individuals. A significant body of research has demonstrated how these technologies can be utilized to assess and enhance emotional regulation, communication skills, and behavioral responses in ASD populations. For instance, a study by Karakaya et al. (2021) explored the use of wearable sensors, such as smartwatches and biosensors, to monitor physiological signals like heart rate variability, skin conductance, and body temperature in children with ASD. These devices provided real-time feedback to both the users and their caregivers, enabling immediate intervention strategies to help manage emotional distress and sensory overload, which are commonly experienced by individuals with ASD.

Furthermore, affective computing, which involves the use of algorithms to analyze emotional responses through facial expressions, voice tones, and physiological data, has been integrated into ASD interventions. In a study by Eissa et al. (2022), emotion recognition systems were incorporated into wearable devices, allowing real-time emotional assessments during social interactions. These systems enabled adaptive feedback based on the emotional cues detected, helping individuals with ASD to adjust their behavior and responses in social settings (Azonuche, & Enyejo, 2024). Such applications have shown promise in enhancing social skills, reducing anxiety, and promoting more positive interactions with peers and caregivers. These studies highlight the potential of wearable and affective computing technologies to provide personalized, real-time interventions, promoting emotional regulation and social engagement among individuals with ASD (Karakaya et al., 2021; Eissa et al., 2022).

B. Use Cases in Clinical, Educational, and Home Environments

Wearable devices and affective computing technologies have shown promise in various environments, offering tailored interventions for individuals with ASD across clinical, educational, and home settings. In clinical environments, wearable devices are often utilized to track physiological and emotional responses during therapeutic sessions as shown in figure 4. For example, a study by Ghai et al. (2021) demonstrated that wearable biosensors could monitor heart rate and skin conductance levels, providing clinicians with real-time data on emotional states. This information allowed clinicians to modify interventions based on the child's immediate needs, improving the effectiveness of therapeutic strategies and helping children with ASD manage anxiety and stress during therapy. In educational settings, wearable technologies are increasingly used to assist with social learning and behavior management. According to Dijk et al. (2022), wearable devices integrated with affective computing algorithms can track students' emotional states and provide timely feedback during classroom activities. This real-time emotional monitoring aids teachers in understanding when students with ASD are becoming overwhelmed or disengaged, enabling them to adjust lesson plans or provide additional support to maintain attention and emotional regulation. At home, wearable technologies can serve as a tool for parents and caregivers to monitor and support children with ASD. The use of wearable sensors that provide data on emotional and behavioral responses helps parents recognize patterns in their child's emotional responses and implement strategies to manage sensory overload or emotional outbursts (Karakaya et al., 2021). In

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addition, these devices can provide ongoing support in non-clinical settings, fostering an environment conducive to positive social interaction and emotional growth (Azonuche, & Enyejo, 2024).

These use cases highlight the versatility of wearable devices in supporting individuals with ASD, with applications in clinical, educational, and home environments offering enhanced emotional regulation, social skills development, and personalized care (Ghai et al., 2021; Dijk et al., 2022).

Figure 4 showcases a series of interventions and sessions involving wearable technology in educational and therapeutic contexts, aimed at supporting individuals with ASD. In Panel A, the participant displays gaze avoidance, a common behavioral marker in ASD, before the session begins. This sets the stage for the use of wearable technology to assess emotional and physiological responses. Panel B shows the participant independently putting on a headset, which could be a part of an intervention involving virtual reality or affective computing, aimed at fostering emotional regulation or social skills. Panel C depicts the intervention session in progress, with the participant engaged in focused attention and eye contact with the instructor. The use of wearable devices such as biosensors or emotion recognition systems can help monitor the participant's heart rate or skin conductance in real-time, offering immediate insights into their emotional state, allowing the therapist to adjust strategies as needed. In Panel D, the teacher is conversing one-on-one with the participant, a setup in which wearable devices integrated with affective computing technologies can provide feedback on the child’s emotional state, helping the teacher maintain engagement and emotional regulation. Panel E highlights a session in a regular educational setting, illustrating the seamless integration of wearable technologies in a full-inclusion classroom. These devices monitor emotional responses, aiding teachers in recognizing when a student may need additional support. Panel F shows a wider classroom perspective, where the full class remains undisturbed, emphasizing the non-intrusive nature of wearable technologies in everyday educational environments. These technologies are pivotal in supporting ASD individuals by tracking emotional and behavioral responses, aiding emotional regulation, and providing timely interventions in clinical, educational, and home settings.

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Fig 4 Picture of Ntervention Sessions using Wearable Technology in a Classroom Setting, Supporting Emotional Regulation and Social Engagement for Individuals with ASD (Sahin et al., 2018).

C. Effectiveness in Improving Social Interaction and Emotional Awareness

Wearable devices and affective computing technologies have demonstrated effectiveness in improving social interaction and emotional awareness in individuals with ASD. These technologies offer real-time feedback that aids in emotional regulation, thus enhancing social communication skills as presented in table 4. According to a study by O'Connor et al. (2020), wearable biosensors equipped with emotion recognition algorithms significantly improve the ability of individuals with ASD to identify and respond to emotional cues in social interactions. The devices track physiological responses such as heart rate and skin conductance, providing feedback that helps users become more aware of their emotional states (Imoh, & Idoko, 2023). This increased self-awareness allows individuals to better regulate their emotions, which is crucial in social settings. In addition to emotional regulation, wearable devices also facilitate improved social interaction. For example, the integration of affective computing in wearable devices can support individuals with ASD in recognizing social cues such as facial expressions or body language. A study by Qiu et al. (2021) found that a wearable device that used affective computing techniques to analyze facial expressions improved social engagement in children with ASD. By receiving real-time prompts and suggestions on how to respond to social stimuli, children were able to navigate social situations with greater ease, leading to improved peer interactions and reduced social anxiety. Furthermore, these technologies support the development of emotional awareness by providing individuals with immediate feedback during social interactions. This feedback helps users recognize subtle emotional cues, fostering a better understanding of the emotions of others. By enhancing emotional awareness and promoting positive social engagement, wearable devices are proving to be a valuable tool in addressing the social challenges faced by individuals with ASD (O'Connor et al., 2020; Qiu et al., 2021).

Table 4 Summary of Effectiveness of Wearable Devices and Affective Computing in ASD

Aspect	Description	Examples/Studies	Impact on ASD Users
Emotional Regulation	Real-time feedback from biosensors helps individuals with ASD monitor and regulate emotional responses.	Devices track heart rate and skin conductance to enhance self-awareness.	Improves emotional control, reducing likelihood of social withdrawal or behavioral outbursts.
Recognition of Social Cues	Affective computing allows wearable devices to analyze facial expressions and body language to support interpretation of emotional and social signals.	Affective computing in wearables boosted children's ability to recognize and respond to facial expressions.	Facilitates understanding of social interactions, encouraging improved peer engagement and reduced social anxiety.
Real-Time Guidance	Devices provide immediate prompts or suggestions during social interactions to assist decision-making and behavioral responses.	Real-time cues guide users on how to react appropriately in dynamic social settings (O'Connor et al., 2020).	Increases confidence and accuracy in navigating social scenarios.
Emotional Awareness	Continuous biofeedback helps individuals recognize and interpret their own and others' emotional states during interaction.	Feedback loops reinforce emotional learning and empathy.	Enhances emotional intelligence, supporting long-term improvements in communication and social connectedness.

VI. CHALLENGES AND ETHICAL CONSIDERATIONS

A. Data Accuracy, Model Generalization, and Technical Limitations

Wearable devices and affective computing technologies offer promising avenues for supporting individuals with ASD, yet several challenges persist regarding data accuracy, model generalization, and technical limitations. Ensuring the reliability and validity of data captured by wearable sensors is crucial for effective intervention (Imoh, et al., 2024). Factors such as sensor calibration, environmental influences, and individual variability can introduce noise into the collected data, potentially compromising the accuracy of physiological and behavioral measurements (Picard, 2010). Model generalization remains a significant hurdle in applying

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affective computing to diverse ASD populations. Machine learning models trained on specific datasets may not perform optimally when applied to individuals with varying characteristics, including differences in age, cognitive abilities, and sensory processing profiles. This lack of generalizability can limit the effectiveness of interventions and necessitate the development of more robust models that can adapt to individual differences (Picard, 2010). Technical limitations also impede the widespread adoption of wearable technologies in ASD research and practice. Issues such as limited battery life, discomfort during prolonged use, and the need for continuous monitoring can affect user compliance and data quality. Moreover, integrating these technologies into existing therapeutic frameworks requires substantial infrastructure and training, posing additional barriers to implementation (Picard, 2010). Addressing these challenges requires interdisciplinary collaboration to enhance the design, calibration, and application of wearable devices and affective computing systems. Advancements in sensor technology, personalized machine learning algorithms, and user-centered design are essential to overcome these limitations and fully realize the potential of these tools in supporting individuals with ASD.

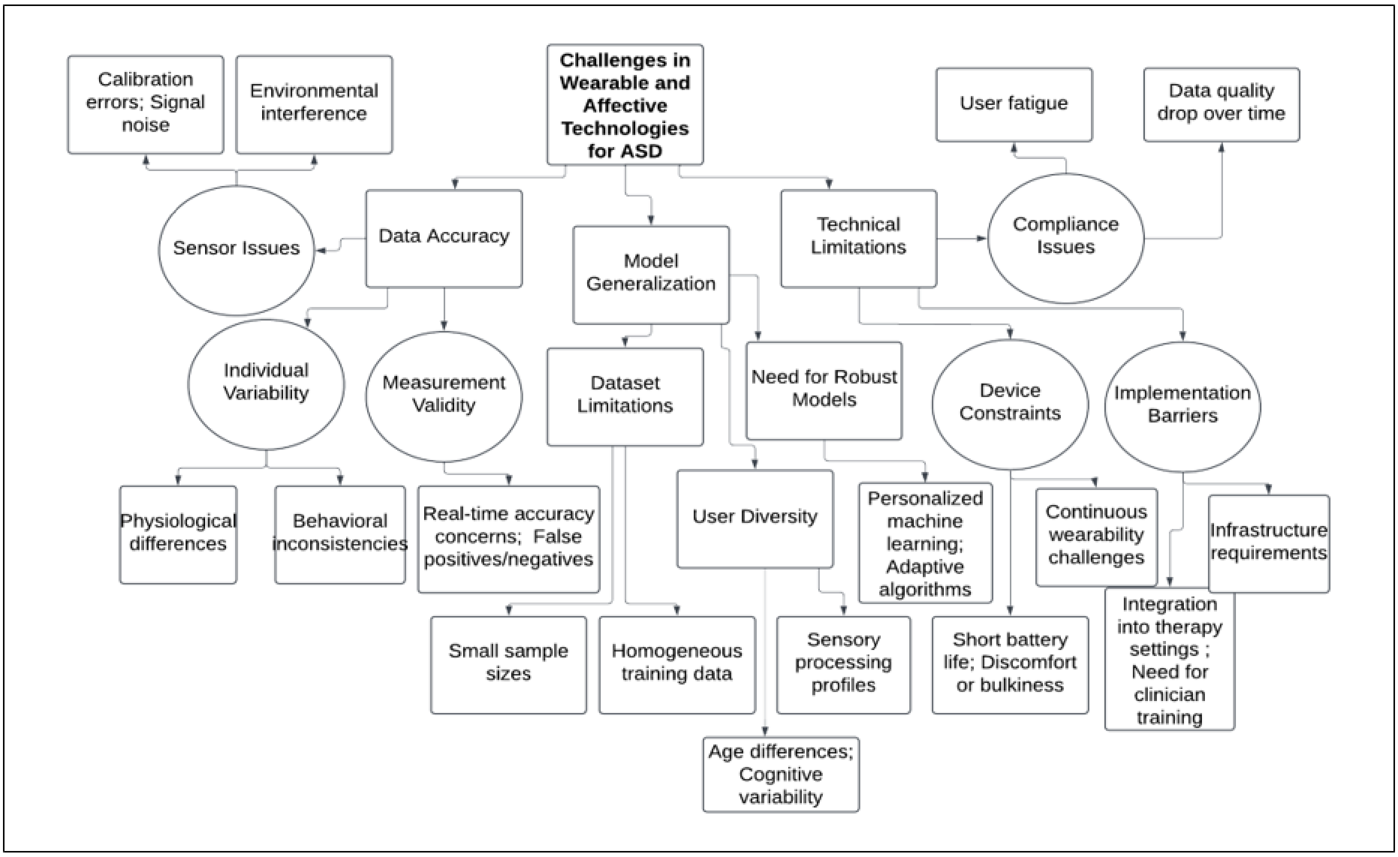

Fig 5 Diagram Illustration of Key Challenges in Deploying Wearable and affective Technologies for ASD Including data Accuracy model Generalization and Technical Limitations

Figure 5 illustrates the key challenges associated with implementing wearable devices and affective computing technologies for individuals with ASD, organized into three main branches: Data Accuracy, Model Generalization, and Technical Limitations. The Data Accuracy branch highlights issues related to sensor calibration errors, environmental interference, and individual physiological variability that can introduce noise and reduce the reliability of real-time emotional and behavioral data. The Model Generalization branch addresses the difficulty of applying machine learning models across diverse ASD populations, noting that models trained on small or homogeneous datasets often fail to generalize to users with differing ages, cognitive profiles, or sensory sensitivities, thus necessitating more personalized and adaptive algorithms. The Technical Limitations branch focuses on practical constraints such as limited battery life, device discomfort, and the challenge of integrating these tools into clinical or educational settings, which often require additional infrastructure and professional training. Collectively, the diagram underscores that overcoming these challenges will require interdisciplinary efforts in improving sensor design, developing robust and inclusive algorithms, and prioritizing user-centered solutions to enhance the effectiveness and accessibility of affective technologies in ASD interventions.

B. Privacy, Consent, and Ethical Issues in Monitoring Neurodiverse Individuals

As wearable devices and affective computing technologies are increasingly employed to monitor and support neurodiverse individuals, such as those with ASD, privacy, consent, and ethical concerns have come to the forefront. These technologies gather sensitive data, including emotional, physiological, and behavioral information, which raises significant privacy issues. Ensuring the protection of personal data is paramount, especially as these systems often

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collect continuous, real-time data, making the risk of unauthorized access or misuse high (Pottie & Ingersoll, 2008) as presented in table 5. The challenge lies not only in securing this data but also in safeguarding it throughout the entire data lifecycle, from collection to storage and transmission. As such, robust encryption techniques and strict data governance policies must be implemented to ensure privacy and prevent data breaches (Binns et al., 2018). In addition to privacy, obtaining informed consent is a critical ethical concern when deploying wearable technologies with neurodiverse individuals. For individuals with ASD, the ability to understand and provide informed consent may be limited, particularly in children or those with severe cognitive impairments (Binns et al., 2018). This necessitates the involvement of guardians or caregivers in the consent process, raising questions about the autonomy of neurodiverse individuals and their right to control their own data. Ethical guidelines must be developed to ensure that individuals with ASD are not subjected to unnecessary or harmful monitoring and that their participation is voluntary and well-understood (Pottie & Ingersoll, 2008). Furthermore, the ethical implications of using affective computing for behavior modification must be carefully considered. There is potential for these technologies to influence or even manipulate emotions and behavior, raising concerns about the long-term effects on the individuals being monitored (Binns et al., 2018). These concerns highlight the importance of creating ethical frameworks that prioritize the well-being and autonomy of neurodiverse individuals while leveraging the benefits of these advanced technologies.

Table 5 Summary of Privacy, Consent, and Ethical Considerations in ASD Monitoring Technologies

Aspect	Description	Challenges	Recommended Actions
Privacy of Data	Wearables collect sensitive emotional, physiological, and behavioral data continuously, increasing the risk of misuse or unauthorized access.	High vulnerability to data breaches throughout collection, transmission, and storage (Pottie & Ingersoll, 2008).	Apply robust encryption, secure storage, and comprehensive data governance frameworks (Binns et al., 2018).
Informed Consent	Many individuals with ASD may lack the capacity to fully understand consent procedures, especially children or those with cognitive impairments.	Raises issues about autonomy and reliance on guardians for consent (Binns et al., 2018).	Involve caregivers while ensuring participants understand the process; create accessible and ethical consent models.
Ethical Monitoring	Continuous affective monitoring may unintentionally manipulate or alter emotional and behavioral responses.	Risk of behavior modification without adequate ethical consideration (Binns et al., 2018).	Develop ethical guidelines to avoid coercion or harm; ensure interventions prioritize well-being and personal agency.
Autonomy and Rights	Ensuring the rights of neurodiverse individuals to control their data and participation in monitoring technologies.	Balancing protection and autonomy in vulnerable populations (Pottie & Ingersoll, 2008).	Create ethical frameworks emphasizing voluntary participation, individual dignity, and long-term impacts of technological interventions.

C. User Engagement and Long-Term Compliance with Wearable Systems

User engagement and long-term compliance are critical factors for the success of wearable systems in supporting neurodiverse individuals, particularly those with ASD. Ensuring that individuals consistently use and engage with wearable systems over an extended period is vital for the collection of meaningful data and the efficacy of these technologies in promoting behavioral changes (Imoh, & Idoko, 2022). However, maintaining user engagement poses significant challenges due to issues such as discomfort, anxiety, and the complexity of the devices (Fitzgerald et al., 2017). Wearable systems must therefore be designed to be user-friendly, comfortable, and tailored to the specific needs of individuals with ASD to minimize resistance and enhance long-term adherence (Petry et al., 2018). Moreover, motivating users to continuously engage with wearable systems requires strategies that address both intrinsic and extrinsic factors. Personalized feedback, gamification, and real-time rewards are common approaches to maintain interest and encourage sustained usage (Petry et al., 2018). For neurodiverse individuals, incorporating feedback that aligns with their preferences and emotional responses is essential in fostering a positive experience with the technology. Additionally, caregiver involvement is often crucial in promoting long-term compliance, as they play an

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instrumental role in facilitating the consistent use of wearable systems (Fitzgerald et al., 2017). However, sustaining compliance over time remains a challenge due to the novelty effect, where initial excitement may wane, leading to decreased adherence (Petry et al., 2018). To address this, ongoing updates, refinements, and features that align with evolving needs are necessary to ensure continued engagement and optimal utilization of wearable systems for ASD populations.

VII. FUTURE DIRECTIONS AND CONCLUSION

A. Emerging Trends in Multimodal Sensor Fusion and AI Integration

The integration of multimodal sensor fusion and artificial intelligence (AI) represents a significant evolution in the development of wearable systems for neurodiverse populations, particularly individuals with ASD. Recent advancements in sensor technology and AI algorithms have made it possible to collect and analyze data from various sensors simultaneously, enhancing the overall accuracy and effectiveness of wearable devices. Multimodal sensor fusion involves the combination of data from multiple sources, such as physiological sensors, motion trackers, and environmental sensors, to provide a comprehensive understanding of the user's behavior, emotional state, and interactions with their surroundings. This fusion of data allows for more precise and context-aware interventions, improving the personalization and responsiveness of wearable systems. AI plays a crucial role in processing and interpreting the complex data generated by multimodal sensors. Machine learning algorithms, particularly deep learning techniques, enable the identification of patterns and correlations within large datasets, facilitating the detection of subtle changes in behavior or emotional states that may not be immediately apparent. Furthermore, AI models can adapt and improve over time, enhancing their predictive accuracy and providing real-time feedback based on the user's specific needs. This adaptability is particularly valuable for individuals with ASD, as their responses to stimuli and interventions may vary significantly over time. One of the most promising trends in this field is the integration of AI with real-time feedback systems, allowing for dynamic adjustments based on sensor data. For instance, wearable devices can now provide immediate sensory feedback to users when they exhibit signs of stress or anxiety, helping them to self-regulate in real-time. The convergence of AI with multimodal sensor fusion is revolutionizing the way that wearable systems can support neurodiverse individuals, enabling a more tailored, efficient, and effective approach to managing behavioral and emotional challenges. This integrated approach also offers new possibilities for long-term engagement, as users benefit from personalized, data-driven insights that evolve in response to their needs.

B. Potential for Personalized and Predictive Interventions

The potential for personalized and predictive interventions in wearable systems for neurodiverse individuals, particularly those with ASD, is rapidly advancing through the integration of AI and multimodal sensor fusion. Personalized interventions refer to strategies tailored to the unique behavioral and emotional needs of each individual, whereas predictive interventions involve anticipating future behavioral or emotional states based on collected data. By leveraging continuous, real-time monitoring of various physiological and environmental factors, wearable systems can offer personalized support that adapts to the changing needs of the user. AI-driven algorithms enable the system to analyze large volumes of data from different sensors, such as heart rate monitors, motion detectors, and facial expression recognition tools. This data can then be processed to recognize patterns in the user's behavior or emotional responses. Predictive models can identify trends and provide early warnings for potential issues, such as heightened anxiety or sensory overload, allowing the system to proactively adjust interventions before the individual experiences distress. For instance, a wearable system might predict when an individual is likely to become overwhelmed by environmental stimuli and preemptively provide calming feedback, such as auditory or tactile cues, designed to prevent escalation.

Furthermore, the integration of personalized feedback mechanisms, tailored to an individual's preferences and sensitivities, ensures that the intervention is not only effective but also acceptable to the user. These personalized interventions could be linked to specific emotional triggers, enabling the system to respond dynamically to the unique sensory and emotional landscape of each user. This form of individualized support is particularly important for individuals with ASD, whose reactions to external stimuli can vary greatly. The predictive capabilities of wearable systems, enhanced by continuous learning and adaptation, offer a new frontier in the development of personalized, real-time interventions that improve the quality of life for neurodiverse individuals.

C. Summary of Key Insights and Recommendations for Future Research and Practice

The integration of wearable systems, multimodal sensor fusion, and AI technologies offers substantial potential for improving the lives of neurodiverse individuals, particularly those with ASD. This review highlights key insights into the effectiveness, challenges, and future directions of using these technologies in various environments, including clinical, educational, and home settings. One of the most significant findings is the capacity of wearable devices to provide real-time monitoring and adaptive interventions, which can address immediate behavioral and emotional needs of users, thereby enhancing social interaction and emotional awareness.

However, despite the promising applications, there remain substantial technical challenges, particularly related to data accuracy, model generalization, and the integration of diverse sensor inputs. The accuracy of sensor data is critical for ensuring the reliability of interventions, and further research is needed to refine sensor fusion techniques to improve the robustness of data collection in complex environments. Additionally, there are concerns surrounding privacy, consent, and ethical issues, as continuous monitoring of neurodiverse individuals raises important questions about data ownership, confidentiality, and the potential for misuse. Looking to the future, research should focus on enhancing the personalization and predictive capabilities of these systems. Future work could explore more sophisticated AI models capable of predicting individual behavioral patterns with greater accuracy. Moreover, long-term user engagement remains a challenge, and developing systems that are both effective and engaging over time will be crucial for sustained adoption and impact. Further investigations into user experience, such as the acceptability and comfort of wearable devices, are essential for ensuring that these technologies meet the diverse needs of neurodiverse individuals.

Finally, interdisciplinary collaboration between researchers, clinicians, educators, and technology developers will be essential for translating these innovations into practical, real-world solutions. Future studies should focus on longitudinal investigations to understand the long-term effects of wearable systems on ASD users and assess their impact on daily life.

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