Computers and Electronics in Medicine
Cutting-Edge Scientific Solutions

e-ISSN: 3023-8609
RESEARCH ARTICLE
Vol.3 / No.2 / 2026 / pp.122-137
https://doi.org/10.69882/adba.cem.2026073

A Virtual Pet for Detecting and Mitigating Autism Spectrum Disorder Stress

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ABSTRACT Individuals with Autism Spectrum Disorder (ASD) frequently experience elevated stress and are at higher risk for mood disorders such as anxiety and depression. Sensory over-responsivity, social challenges, and difficulties with emotional recognition and regulation contribute to such heightened stress. This study presents a proof-of-concept system that detects and mitigates stress through interactions with a virtual pet. Designed for young adults with high-functioning autism, and potentially useful for people beyond that group, the system monitors simulated heart rate, skin resistance, body temperature, and environmental sound and light levels. Upon detection of stress or potential triggers, the system alerts the user and offers stress-reduction activities via a virtual pet companion, including guided breathing exercises and interactive engagement. Through combining real-time stress detection with interactive interventions on a single platform, the system aims to help autistic individuals recognize and manage stress more effectively.

KEYWORDS
Autism spectrum
Stress detection
Stress mitigation
Virtual pet
Prototype app

INTRODUCTION

Individuals with Autism Spectrum Disorder (ASD) often experience higher levels of stress and mood disorders, such as depression and anxiety, than their neurotypical counterparts (Etyemez *et al.* 2020; Hollocks *et al.* 2018; Kirsch *et al.* 2020; McQuaid *et al.* 2022; Underwood *et al.* 2022). Research suggests that sensory over-responsivity, social challenges, and difficulties with emotional regulation contribute to such heightened stress levels (Amos *et al.* 2018; Carpenter *et al.* 2018; Morie *et al.* 2019; Preece *et al.* 2022; van Hulle *et al.* 2019; Vasa *et al.* 2020; Yuan *et al.* 2022). Additionally, alexithymia and impaired interoception, common traits among autistic individuals, can hinder the recognition of stress, preventing timely intervention (Bonete *et al.* 2023; Kinnaird *et al.* 2019; Morie *et al.* 2019; Preece *et al.* 2022; Yuan *et al.* 2022). Even when stress is detected, many autistic individuals struggle to identify effective coping strategies, allowing the stress to accumulate further (?Kapp *et al.* 2019; Marsden *et al.* 2024; McQuaid *et al.* 2022).

These challenges highlight the need for tools that support autistic individuals in recognizing and regulating stress and overstimulation. This research proposes a proof-of-concept system that detects and mitigates the stress through interactions with a virtual pet. Designed for young adults with high-functioning autism, and potentially of use by others on the spectrum, the system leverages evidence-based stress detection and mitigation strategies. Stress and overstimulation can be monitored using biometric and environmental information gathered by sensors integrated into smartphones or wearable devices (Cano *et al.* 2024; Khullar *et al.* 2019; Tomczak *et al.* 2020). Although this study does not utilize physical hardware, it simulates a system capable of tracking heart rate, skin conductance responses, body temperature, and environmental sound and light levels. Biometric readings enable accurate stress detection, and environmental monitoring identifies triggers of overstimulation, allowing the users to address stress before it escalates.

Upon detecting stress or risk factors, the proposed system, i.e., the app, alerts the user through a virtual pet designed to provide a calming presence, and offers interactive stress-reduction strategies. Existing intervention recommendations for autistic individuals often include mindfulness techniques, engagement with special interests, and social or animal-assisted support (Dachez and Ndobo 2017; Kapp *et al.* 2019; O'Haire *et al.* 2015; Verkooijen *et al.* 2025; Wijker *et al.* 2019). The proposed system integrates all these components, offering deep-breathing sessions, interactions with a virtual pet, and guided message writing to a friend/peer.

Autism Spectrum Disorder (ASD) is a developmental disorder characterized by (A) deficits in social communication and interaction, and (B) restricted, repetitive patterns of behavior or interests (American Psychiatric Association 2013). An estimated 1 in 31 children and 1 in 45 adults are living with ASD (Dietz *et al.* 2020; Shaw 2025). Autism is viewed as a spectrum, separated by functional and intellectual abilities. High-functioning autism is defined as autism that occurs in individuals who have an intelligence quotient (IQ) of above 70 and usually have a higher self-awareness

Manuscript received: 9 June 2026,
Revised: 11 July 2026,
Accepted: 11 July 2026.

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of their social difficulties. Low-functioning autism, conversely, is described as those who have an IQ of lower than 70 and low awareness of their social capacities. High-functioning autistic people may require less support than the low-functioning group and may be able to function on their own. Low-functioning autistic individuals may require a caretaker, even into adulthood (Solek *et al.* 2026).

Research efforts on self-perceived stress indicate that adult participants with autism experienced higher stress levels and a poorer ability to cope with the stress, compared to their neurotypical counterparts (Bishop-Fitzpatrick *et al.* 2016; McQuaid *et al.* 2022). A 2022 systematic review on stress levels in autism remarks on the need for stress management. It concluded that both children and adults with autism showed significantly higher emotional stress levels compared to the control groups, as reported by themselves or their parents (van der Linden *et al.* 2022). Various studies suggest that mood disorders are more common in people with autism than in neurotypical people (Etyemez *et al.* 2020; Hollocks *et al.* 2018; Kirsch *et al.* 2020; Underwood *et al.* 2022). ASD has also been associated with poor emotional regulation (Mazefsky and White 2014). These findings underscore the necessity of understanding the factors contributing to stress in individuals with ASD and exploring effective mitigations and interventions to enhance emotional regulation and well-being.

Sensory Over-Responsivity

One manifestation of the B diagnostic criteria restricted, repetitive patterns of behavior or interests is an unusual relationship with sensory inputs. This is typically categorized as hyper- or hypo-reactivity to sensory inputs or an interest in seeking out sensory experiences in the environment (American Psychiatric Association 2013). An autistic individual with hyper- or hypo-reactivity to sensory inputs has, respectively, very high or very low sensitivity to stimuli compared to neurotypical individuals. Between the two responses, hyper-reactivity (also called sensory over-responsivity) is more commonly reported in autistic adults (MacLennan *et al.* 2021). Autistic individuals who contend with sensory over-responsivity may have heightened sensitivity to sensory input of all types. Common sensory stimuli to which autistic individuals with hyper-reactivity are sensitive include loud sounds, bright lights, bright colors, certain textures, crowds, and smells (MacLennan *et al.* 2021; Advanced Autism Services 2025).

Effects of Sensory Over-Responsivity: Sensory over-responsivity has been associated with elevated levels of stress and has been linked to comorbid conditions such as anxiety and obsessive-compulsive disorder, particularly among autistic children (Amos *et al.* 2018; Carpenter *et al.* 2018; Green and Ben-Sasson 2010; van Hulle *et al.* 2019; Vasa *et al.* 2020; Yuan *et al.* 2022). Research has also identified broader functional impacts. For example, sensory over-responsivity has been associated with sleep disturbances in autistic children (Mazurek and Petroski 2015). Additionally, heightened sensory reactivity may contribute to negative physical symptoms such as migraines (Sullivan *et al.* 2013).

Individuals with hyper-reactivity to sensory input may be more likely to experience sensory overstimulation, often referred to as sensory overload. Sensory overload can significantly impact daily functioning. A Swedish study examining sensory overload in healthcare settings revealed that autistic adults experienced increased stress due to sensory stimuli, which negatively affected their ability to communicate with healthcare providers (Strömberg *et al.* 2021). Similarly, autistic adults in Australia identified sensory overload as a common trigger for the onset of autistic burnout. Described impacts of burnout included increased repetitive behavior, difficulties with emotional processing, reduced functional capacity, social withdrawal, and suicidal ideation (Higgins *et al.* 2021). Together, these findings indicate that sensory over-responsivity can have extensive psychological, physical, and functional negative effects on autistic children and adults.

Environmental Stressors: Although sensory over-responsivity can occur with any sensory input, research suggests that auditory input and lights are the two most common culprits among autistic adults (Strömberg *et al.* 2021). Exact stimuli thresholds vary by the individual, but research by Danesh *et al.* (2021) suggests an average overstimulating sound level for people with hyperacusis. Hyperacusis, a disorder characterized by decreased sound tolerance that can make some sounds unbearable or painful, is common among people with autism. The typical uncomfortable loudness level (ULL) for the average person is around 100 decibels (dB); however, for patients with hyperacusis, the level is between 60 and 85 dB (Danesh *et al.* 2021).

Many sources suggest that bright lights are a common stimulus; however, few offer a threshold for what constitutes "bright". Research on autistic individuals' responses to hospital environments indicates that participants are bothered by hospital lighting (DeGuzman *et al.* 2024; Strömberg *et al.* 2021). Results from DeGuzman *et al.* (2024) reveal that the most frequently recommended mechanism to improve sensory experiences for autistic people in the emergency department (also known as the emergency room) is dimmable lights. Hospital lighting guidelines encourage emergency rooms to have an illumination of 300–500 lux (Li 2025), suggesting that this lux range for indoor light is comparable to the range that the autistic participants perceived as too harsh in the studies. Another study about automated assessment of light sensitivity in autistic children defined high brightness as greater than 100 lux. The study categorized the children as hypo- or hyper-reactive to light based on further assessment using this threshold (Reddy *et al.* 2024).

Environmental Stressor Detection: Many smartphones are already equipped with ambient light sensors that automatically adjust screen brightness in response to ambient light (Dutta 2019). Ambient light refers to the level of natural or artificial illumination in an environment, e.g., from the sun or indoor lighting, and is typically measured in lux (Wikipedia 2026). As excessive light can contribute to sensory overload in autistic individuals, these sensors provide a practical way to monitor potentially overstimulating lighting conditions with a standard smartphone. Similarly, smartphones are equipped with microphones that can detect elevated sound levels. Monitoring environmental noise in this manner enables the identification of auditory conditions that may contribute to sensory overload.

Current research suggests that tactile stimuli can be approximated using accelerometer data, which is readily available on most smartphones (Dutta 2019; Khullar *et al.* 2019). Similarly, unpleasant odors can be detected using gas sensors (Khullar *et al.* 2019). To the best of our knowledge, there are currently no widely available sensors capable of detecting taste.

Stressor Management: Yuan *et al.* (2022) suggest interventions for sensory over-responsivity that is based on existing literature. They identify four core types of interventions aimed at reducing sensory sensitivity: regular physical activity, such as horseback riding; Ayres Sensory Integration Therapy (ASIT), which incorporates structured sensory activities into play for autistic children; Mindfulness-Based Training (MBT), in which individuals are taught to focus attention on the present moment; and Cognitive Behavioral Therapy (CBT), a form of talk therapy that helps individuals identify relationships between thoughts, feelings, and behaviors (Yuan *et al.* 2022).

While the previous recommendations require long-term commitment, DeGuzman *et al.* (2024) propose quicker, short-term solutions for managing sensory overload. Through survey responses, autistic adults and caregivers of autistic children recommend various strategies to reduce sensory overstimulation in healthcare settings. For auditory issues, respondents recommend that hospitals provide private, quieter waiting rooms, or offer hearing protection, such as headphones or earplugs. In order to address visual concerns, they suggest using dimmable lights, choosing neutral colors, decluttering rooms, creating more private waiting areas to limit the number of people present, or adding curtains to block visual distractions. Other suggestions include calming visual elements, such as fish tanks. To manage smells, it is recommended to let fresh air into the room, incorporate plants, and use products with neutral scents. When dealing with tactile issues, suggestions include providing soft blankets or other tactile distractions, such as fidget toys (DeGuzman *et al.* 2024). These recommendations originate from surveys focused on healthcare environments but can also be applied to everyday situations. For instance, if someone is experiencing auditory overstimulation, they might choose to move to a quieter room or use hearing protection.

Stress and Emotional Regulation

APA dictionary defines stress as "the physiological or psychological response to internal or external stressors" (American Psychological Association 2018). Stress is typically divided into two categories: acute and chronic. The difference between these two lies in the periods in which stress occurs. Acute stress is a short-term condition, whereas chronic stress is long-term, lasting for weeks or months (MedlinePlus 2022). Acute stress, if unmanaged, can turn into chronic stress.

Stress can affect memory and cognition (understanding and acquiring knowledge). In some cases, it can lead to behavioral, cognitive, and mood disorders. Stress can also cause distress in many different physical systems in the body, including the immune, cardiovascular, gastrointestinal, and endocrine systems (Yaribeygi *et al.* 2017). Because of the various negative effects of stress, early recognition of stress is important for enabling timely coping strategies and effective stress management. However, autistic groups struggle with recognizing emotions and physiological sensations, indicating a need for assistance in detecting stress.

Alexithymia and Interoception: As stated previously, mood disorders are more common in people with autism. A number of studies have established a relationship among mood disorders, sensory over-responsivity, and alexithymia (Kinnaird *et al.* 2019; Morie *et al.* 2019; Preece *et al.* 2022; Yuan *et al.* 2022). Alexithymia, defined as difficulty in recognizing or describing emotions, is common among autistic people. Likewise, many autistic people struggle with impaired interoception, which means difficulties in recognizing physiological sensations (Bonete *et al.* 2023). With alexithymia and impaired interoception, efficiently and effectively recognizing stress may be difficult for many autistic individuals. Difficulties with recognizing emotions and physiological sensations demonstrate a need for an outside mechanism to aid in continuous stress detection for individuals with autism.

Stress Detection Methods: One method to measure stress is to measure cortisol or dehydroepiandrosterone sulfate (DHEA-S) levels in saliva, hormonal biomarkers present during acute and chronic stress, respectively. However, it is noted that these biomarkers are not suitable for the instantaneous, continuous detection of stress in autism. Continuous stress monitoring requires a portable, non-invasive device to measure it, limiting the stress markers measured in bodily fluids. The study instead recommends heart rate variability (HRV) as a measure of stress in autism, likely measured using a watch (Hufnagel *et al.* 2017).

Cano *et al.* (2024) examine existing wearable real-time stress monitors for people with ASD. They emphasize the need for stress detection using multiple types of data, such as physiological, behavioral, and contextual data, due to the atypical ways that people with autism express stress. They conclude that the most used physiological signals for stress in relevant research are cardiac activity, electrodermal activity, and skin temperature. In some cases, accelerometers were also used. However, they note that wearable stress detection methods may have limitations for autistic people. As individuals with autism can perform sudden repetitive movements, it may disrupt signal accuracy (Cano *et al.* 2024). Discussion of stress-detection wearables is included in a later section.

Social Deficits

Primary diagnostic criteria for ASD highlight the prevalence of social deficits. Social communication impairments are manifested through deficits in social-emotional reciprocity, nonverbal communication, and the development, maintenance, and understanding of relationships (American Psychiatric Association 2013). Such impairments can significantly impact daily functioning and are associated with elevated stress levels in autistic individuals (Bishop-Fitzpatrick *et al.* 2014).

Interpersonal Conflict: Interpersonal relations and social inclusion are key components of overall quality of life (Schalock 2004). Effective communication, particularly in navigating conflict, is therefore essential. However, autistic individuals may experience challenges in identifying and describing their emotions, often due to alexithymia, which can strain interpersonal relationships. For example, sensory overload may result in emotional outbursts or social withdrawal. These responses can be misinterpreted by others, leading to hurt feelings or conflict. Misunderstandings are further compounded by differences in nonverbal communication. Autistic individuals may display atypical facial expressions of emotion, which are often less accurately recognized by neurotypical individuals (Brewer *et al.* 2015).

In addition to differences in outward expression, difficulties in recognizing and articulating an individual's own emotional state can limit the ability to repair misunderstandings. The frequency of such misunderstandings has been shown to be negatively associated with relational satisfaction (Edwards *et al.* 2020).

Autonomy, Advocacy, and Decision-Making: Autistic individuals may also experience challenges in communicating their needs to others, which can further hinder access to support. When needs are not clearly expressed, peers or caregivers may be unaware that assistance is required, even if they are willing to provide support.

Self-advocacy, defined as an individual's ability to understand and communicate their needs, preferences, and rights, is a critical skill within the autism community. It has been shown to be positively associated with academic and employment success, as well as the development and maintenance of relationships (Martino *et al.* 2025). However, differences in social communication and difficulties with emotional awareness may limit both the development and use of self-advocacy skills.

Closely related to self-advocacy is the concept of self-determination, which encompasses autonomy and competence. Higher levels of self-determination have been associated with improved quality of life across social, educational, and employment domains (Martino *et al.* 2025). Despite its importance, autonomy in decision-making may be more difficult for autistic individuals than for their neurotypical peers, contributing to increased stress and anxiety. These challenges may stem from difficulties in understanding relevant information, becoming overwhelmed by excessive or irrelevant information or stimuli, or the fear of negative judgments from others. There are recommended strategies to improve the decision-making process, including allocating additional time for processing, minimizing irrelevant stimuli, and providing encouragement and reassurance.

Collectively, these findings highlight the importance of supporting the development of self-advocacy, self-determination, and decision-making skills in autistic individuals, as these factors play a critical role in both functional outcomes and stress reduction.

I-Statements: I-statements, or I-messages, are a communication strategy commonly recommended in therapeutic and conflict-resolution contexts. These statements emphasize expressing one's own feelings and experiences while avoiding accusatory or blaming language toward others. Typically, an I-statement includes a description of the speaker's emotional response, the situation that prompted it, and a desired outcome or change in behavior. Informally, these components are often framed as "I feel", "because/when", and "I need" (Montemurro 2011; Muhyatun 2022; Rogers *et al.* 2018).

Although research on the use of I-statements in the autism community is limited, the structured and predictable nature of this communication strategy may be beneficial for individuals with ASD in both interpersonal conflict and self-advocacy contexts. This potential benefit may relate to a preference for structure and consistency, as well as to characteristics such as restricted and repetitive patterns of behavior described in the DSM-5 diagnostic criteria (American Psychiatric Association 2013).

Inflexible Routines

The DSM-5 diagnostic criteria for autism include a requirement of insistence on sameness or inflexible adherence to routines. Examples given for this criterion include extreme distress in response to small changes and difficulty with transitions (American Psychiatric Association 2013). Situations such as a change in location due to travel or taking an unfamiliar route to work may provoke stress in autistic individuals.

Stress Interventions and Coping Mechanisms

Compared to neurotypical people, autistic adults reported a reduced ability to cope with stress (McQuaid *et al.* 2022). Additionally, people with ASD are suggested to have weak emotional regulation (Mazefsky and White 2014). Upon build-up of stress, autistic individuals can engage in self-harming behavior to cope (Kapp *et al.* 2019; Marsden *et al.* 2024).

Such findings suggest a need for assistance in identifying effective interventions and coping mechanisms for stress. Interviews with adults with high-functioning autism have revealed various preferred coping strategies, including special interests, militancy, seeking support from friends and animals, normalization, and humor (Dachez and Ndobo 2017). Other sources suggest coping mechanisms such as mindfulness practices and technology-based interventions (Agius *et al.* 2023; Hatfield *et al.* 2022; Simione *et al.* 2024).

Stimming and Special Interests: Under the "restricted, repetitive patterns of behavior, interests, or activities" B diagnostic criteria in the DSM-5, one manifestation of this criterion is defined as "highly restricted, fixated interests that are abnormal in intensity or focus" (American Psychiatric Association 2013). Special interests are a manifestation of this subcategory and can include an intense fascination with any hobby or interest, usually in a repetitive nature, e.g., math, lining up stuffed animals, memorizing facts about planes, organizing books alphabetically, or collecting and smelling candles. It is reported that over 75% of autistic individuals have a special interest (Klin *et al.* 2007; Turner-Brown *et al.* 2011).

A different interview-style study with autistic adults supports the idea of special interests providing a stress-relieving effect, as seen in the Dachez and Ndobo (2017) interviews. Special interests were described as having a calming, soothing effect and were especially useful in moments of burnout or depression. However, some acknowledged that the intensity of their special interests could sometimes distract from important responsibilities or cause embarrassment due to social stigma and ableism (Long 2024). Another survey-led study supports the existence of a trade-off between special interests, their intensity, and well-being. While many autistic adults express general positive satisfaction and well-being in association with special interests, a very high intensity of engagement with special interests was associated with decreased well-being. Common special interests identified in the study included autism, computers and gaming, music, science, religion, politics, and animals (Grove *et al.* 2018).

Self-stimulatory behaviors, or stimming, are likewise soothing, repetitive behaviors for self-regulation. In one study, autistic adults recognized stimming as a behavior that can occur during stressful situations. Stimming was viewed as a useful mechanism for calming overwhelming emotions, and participants agreed that stims should be restricted only when injurious. However, social stigma again restricts self-regulatory behavior, causing embarrassment for the individual engaging in it (Kapp *et al.* 2019). These findings suggest that while special interests and stimming should be considered coping strategies, they should be monitored for harmful actions or repercussions. For special interests, this means monitoring for high intensity to prevent a decrease in productivity or well-being. Stimming should also be monitored for self-injurious behavior.

Technology-Based Interventions: Technology-based interventions have emerged as a prominent approach for stress reduction in individuals with autism. Computers and gaming are recognized as particularly common special interests, suggesting that technology-based interventions may provide additional stress-reduction benefits, as mentioned previously (Grove *et al.* 2018).

A growing body of literature demonstrates the effectiveness of such approaches, reporting reduced stress levels as well as improvements in social and communication skills through the use of video games, mobile health applications, educational software, virtual pet systems, and robotic companions (Finke *et al.* 2018; Hoeberichts *et al.* 2025; Malinverni *et al.* 2017; Scarcella *et al.* 2023). More in-depth discussion on related stress-relief applications and robotic interventions is provided in a later section.

Interaction with Pets: Autistic individuals seeking support from pets may also reduce stress, as indicated in the Dachez and Ndobo (2017) study. Dog-assisted therapy was shown to reduce stress and improve social awareness and communication in high-functioning adults with ASD (Wijker *et al.* 2019). Autistic children, as well, showed decreased social stress and anxiety (through decreased skin conductance) when playing with peers in the presence of animals (O'Haire *et al.* 2015). As animals are a common special interest, interaction with animals may also reap the same benefits as coping mechanisms through special interests, as mentioned in prior sections.

The benefits of interacting with animals can also be gained through simulation. Although limited, existing research examines the links between artificial/virtual pets, autism, and/or stress relief. A study on the response of adults with ASD to virtual reality pet therapy yielded promising results, with participants forming connections with virtual pets (Karunakaran *et al.* 2025). Altschuler (2008) notes the appeal of virtual pets as an easy, safe, inexpensive, and fun therapy method for autistic children, stating the best way to evaluate this method is a randomized, controlled trial. Molasm *et al.* (2024) describe some of the positive impacts that virtual pets can have on children with ASD, including improved social skills, reduced stress and anxiety, and enhanced empathy. Interaction with a robotic seal was shown to improve social communication in children with high-functioning autism (Veronesi *et al.* 2023). Such studies support the idea that pets provide stress relief, although research on virtual pets remains limited and warrants further exploration.

Interaction with Peers: Many coping strategies identified in Dachez and Ndobo (2017) study involve interacting with other people, namely support from friends, normalization, militancy, and humor. Normalization, as defined by the study, is the idea of "normalizing" behavior by imitating neurotypical peers to conceal atypical behavior. This is commonly referred to as masking. However, this may not be a healthy coping mechanism, as several studies have shown that masking is associated with more stress, mental health issues, and lower self-esteem (Evans *et al.* 2023). Therefore, normalization should not be considered an effective stress-relief mechanism. Support from peers for people with autism, on the other hand, does appear to have positive effects on stress, mental health, self-esteem, and well-being (Verkooijen *et al.* 2025). Humor, likewise, can improve general well-being (Manfredi *et al.* 2026). Militancy (actively supporting and advocating) for autism, in the context of Dachez and Ndobo (2017), most specifically refers to political activism, which may not have many benefits for immediate stress relief. Nevertheless, the principles of advocacy can be applied to stress relief, as discussed in earlier sections. This can connect to seeking support from others, as it may require individuals to understand and voice their needs. Considering these findings, it is important to encourage seeking support from and positive interaction with peers, while discouraging the utilization of social masking.

Mindfulness: Mindfulness-based stress reduction (MBSR) is a frequently used approach for regulating stress responses. It typically incorporates practices such as meditation, controlled breathing techniques, and yoga. This approach has been shown to be effective in reducing stress among individuals with autism (Agius *et al.* 2023; Hatfield *et al.* 2022; Simione *et al.* 2024). One example of a breathing technique used in mindfulness practice is box breathing. This technique follows a structured 4-4-4-4 pattern: inhaling for 4 counts, holding the breath for 4 counts, exhaling for 4 counts, and holding again for 4 counts before repeating the cycle (Myerholtz 2023).

RELATED WORK

Applications

General Stress-Relief Apps: A number of stress management applications are available to the general population, including Breathe2Relax, Calm, Happy Minds (also called Humin), Headspace, Lief, Welltory, and Wysa. These apps primarily emphasize mindfulness-based coping strategies, such as guided breathing exercises and meditation. Many also incorporate therapeutic approaches, most commonly cognitive behavioral therapy (CBT).

In addition to structured mindfulness sessions, these apps often include supplementary features such as calming soundscapes or music, narrated stories, AI-guided chat interactions, psychoeducational articles, and guided physical exercises (such as yoga). Prior studies demonstrate their effectiveness. For example, a large-scale study of Headspace users reported significant reductions in perceived stress (Callahan *et al.* 2024), while Calm has shown positive outcomes across multiple age groups (Huberty *et al.* 2019; Laird *et al.* 2022). Similarly, Breathe2Relax has been shown to reduce heart rate and perceived stress in individuals with post-traumatic stress disorder (Skopp *et al.* 2024). Li *et al.* (2025) describe the effectiveness of such apps for autistic individuals in reducing stress and anxiety symptoms, based on a randomized controlled trial using the Happy Minds app.

However, these applications present several limitations relative to the goals of this research. Most notably, they do not incorporate real-time sensor data, preventing detection of physiological stress signals or environmental triggers. Instead, they rely on user-initiated engagement, requiring individuals to recognize when they are stressed and select an appropriate intervention. This reliance may present challenges for autistic individuals, who may experience difficulty with interoception and rapid stress recognition.

Additionally, the wide range of features offered by these apps may contribute to cognitive overload, particularly during periods of heightened stress. Many applications also rely heavily on auditory components, which may exacerbate sensory sensitivities or be impractical in public settings. Additional descriptions of the apps and their functionality are available on their respective websites (Breathe2Relax 2026; Headspace 2026; Humin 2026; Lief 2026; Welltory 2026; Wysa 2026).

Virtual Pet Apps: A smaller subset of stress-relief applications incorporates virtual pet interactions, including Wysa and Finch. In Wysa, the user interacts with an AI chatbot represented as a bird; however, engagement is primarily text-based and lacks deeper interactive elements. Finch gamifies self-care by allowing users to nurture a virtual pet through completing daily goals and activities (Finch 2026). Molasm *et al.* (2024) propose a prototype application specifically for children with ASD. Their implementation features an interactive virtual pet in augmented reality, aimed at improving the children's social skills and emotional regulation.

While these applications provide virtual pet companionship to a degree, they remain limited in their ability to respond dynamically to stress. None of the apps incorporate real-time stress detection or environmental sensing; instead, they rely on user input to initiate interactions. As a result, they are better suited for general self-care and habit-building rather than immediate stress mitigation during sensory overload.

Sensor-Integrated Apps: Some stress-management applications have begun integrating wearable sensor data. For example, Calm has introduced functionality that connects with Fitbit devices to track stress-related metrics and support mood logging (Calm 2026). Similarly, apps such as Welltory and Lief rely on wearable devices to monitor physiological indicators, such as heart rate variability (HRV). While Welltory provides recommendations to help users reduce stress, such as breathing practices, meditation, and exercise, its primary focus is simply on monitoring stress. Lief, when paired specifically with the Lief Smart Patch, provides stress relief through guided breathing via biofeedback, once stress is detected.

Autism-Specific Apps: Although less prevalent and supported by a smaller body of research, several stress-relief applications have been developed specifically for autistic individuals. Examples include Molehill Mountain and Stress Autism Mate. Molehill Mountain is designed around cognitive behavioral therapy (CBT) principles and incorporates mood tracking to help users manage anxiety. A recent study found that the use of the app led to reductions in self-reported anxiety and stress among autistic users (Oakley *et al.* 2025).

Stress Autism Mate (SAM) focuses on structured self-reporting through daily questionnaires, enabling users to monitor stress levels, reflect on experiences, and identify patterns over time. The app also enables users to define personalized coping strategies, while offering general stress-management suggestions (van Asselt and Roke 2025). Research has shown that SAM can improve users' ability to recognize stress and enhance the effectiveness of their coping strategies (Hoeberichts *et al.* 2025).

Despite their targeted design and demonstrated benefits, these applications primarily rely on self-reported data and lack real-time detection of physiological or environmental stress. As a result, they depend on the users to recognize and report stress, which may present challenges for individuals with difficulties in interoception or emotional awareness. Additionally, these applications may present engagement challenges, as they lack interactive features, such as virtual pet companions, which may otherwise enhance user engagement and sustained use.

Research Gap: Across these categories, existing applications address individual aspects of stress management, such as mindfulness or physiological monitoring. However, no current solution integrates real-time biometric sensing, environmental stress detection, and interactive virtual pet support into a unified system tailored for autistic individuals. This gap motivates the system proposed in this research. Table 1 summarizes related apps and their features.

Wearables

Several studies have examined wearable methods for stress detection and monitoring, using biometric data. As previously mentioned, Cano *et al.* (2024) conducted a literature review of wearable stress-monitoring solutions for people with autism. The most common physiological signals used in wearables to detect stress were cardiac activity, skin conductance responses, and skin temperature. Although many devices were identified, they note that the Empatica E4 is the only wearable device that is reported to be clinically validated in children with ASD. This device is equipped with electrodermal, photoplethysmography (PPG), accelerometer, and skin temperature sensors; however, the Empatica E4 model has since been discontinued (Empatica 2026).

Tomczak *et al.* (2020) developed and evaluated a wearable stress sensor for individuals with autism. Their model monitors changes in skin resistance, heart rate, and body temperature to detect stress events and classify different stress levels. The system was tested on a small group of autistic participants, predominantly male, aged 5 to 24, demonstrating that the device accurately detected and classified stress events.

Several commercial stress detection devices also exist, including the Lief Smart Patch and wearable devices such as the Fitbit, Google Pixel Watch, Apple Watch, and Samsung Galaxy Watch. Most of these devices estimate stress using cardiac activity (Lief 2026; Lui *et al.* 2022; Samsung 2026). However, the Google Pixel Watch additionally measures skin conductance and skin temperature to monitor stress levels (Google 2026a). Likewise, the Fitbit device uses electrodermal activity and heart rate (Google 2026b).

The Assistive Companion for Hypersensitive Individuals is a hardware system designed to be a companion for autistic children. The system monitors the environment to detect overstimulating conditions and communicates its findings to caregivers via a graphical user interface. It provides calming interventions through specified audio and video clips. This system uses sensors to emulate four of the five human senses, utilizing microphones to measure sound loudness, cameras to assess light intensity, accelerometers to detect textile movement, and a gas sensor to monitor air quality (Khullar *et al.* 2019).

Robotics

In Japan, robotic companions such as PARO have gained popularity. PARO, a robotic seal covered with artificial fur, employs artificial intelligence and sensors to respond to user interaction. Owners of such companions can form real emotional bonds with these robotic pets, which provide a sense of connection and may reduce stress (Chang *et al.* 2013; Burton 2013). Studies examining interactions between PARO and autistic children have reported positive effects on communication skills (Veronesi *et al.* 2023). Perusquía-Hernández *et al.* (2019) propose a wearable robotic system designed to monitor and mirror the user's stress level, aiming to promote self-compassion. The system encourages the users to engage in self-supportive behaviors by interacting with and caring for the robotic companion (Perusquía-Hernández *et al.* 2019).

RESEARCH METHODOLOGY

Research Hypothesis

This study investigates whether stress-onset detection and intervention, based on biometric data and environmental cues, and delivered through an interactive virtual pet, can help individuals with autism mitigate stress episodes. In order to explore this question, a proof-of-concept system is developed to detect stress in autistic users and connect them with a virtual pet designed to encourage engagement in stress-reduction activities.

The proposed system is titled Mist, a name selected to reflect its intended calming function. "Mist" is an anagram of "stim," a term commonly used in the neurodivergent community to refer to self-stimulatory behaviors that individuals often use for self-regulation. These behaviors are also reflected in the diagnostic criteria for autism spectrum disorder under the category of "restricted, repetitive patterns of behavior, interests, or activities" (American Psychiatric Association 2013; Kapp *et al.* 2019).

Requirements

A system aimed at integrating continuous stress detection for autistic users with calming interventions through a virtual pet must include several features and functions, as outlined in the following sections.

Table 1 Stress-Relief App Features

App	Primary Functionality	Biometric Sensing	Environmental Sensing	Virtual Pet Interaction
Breathe2Relax	Guided Breathing	None	None	None
Calm	CBT, Breathing, Meditation	Fitbit integration	None	None
Happy Minds	Mindfulness, Meditation	None	None	None
Headspace	CBT, Breathing, Meditation	None	None	None
Wysa	CBT, Breathing, Meditation	None	None	Limited
Finch	Goal setting	None	None	Substantial
Lief Guided	Breathing	Lief Smart Patch	None	None
Welltory	Stress Analysis	Various (Apple Watch, Samsung Watch, Google Pixel Watch)	None	None
Molehill Mountain	CBT, Mood Tracking	None	None	None
Stress Autism Mate	Mood Tracking	None	None	None

Stress Detection: The system must estimate the user's stress levels at regular intervals. Rationale: Due to impaired interoception and alexithymia, the autistic user may have difficulty recognizing when they are stressed (Bonete *et al.* 2023; Kinnaird *et al.* 2019; Morie *et al.* 2019; Preece *et al.* 2022). Regular stress estimation is required to enable earlier intervention and to determine when to recommend calming strategies.

Stressor Identification: The system must process environmental information at regular intervals to identify the specific stimuli that may contribute to stress responses.

Rationale: Sensory over-responsivity, common in people with autism (American Psychiatric Association 2013), easily leads to stress due to overstimulation. Detecting environmental triggers allows the system to (1) inform the user of potential sources of overstimulation, (2) recommend environmental modifications when possible, and (3) provide warnings when the user enters environments associated with elevated stress, to proactively prevent overstimulation.

User Notification: The system must provide the user with feedback through indirect mechanisms in cases when elevated stress levels or stress-inducing stimuli are detected. Rationale: People with autism may struggle with interoception (Bonete *et al.* 2023). Notifying the user of potential stress may help them improve their interoception by increasing awareness of their bodily cues. Feedback must be provided indirectly to avoid inducing anxiety through incorrect or overly explicit labeling (Perusquía-Hernández *et al.* 2019).

Stress Mitigation: The system must provide guided activities or recommendations to help the user mitigate stress when elevated stress levels or stress-inducing stimuli are detected. Rationale: Higher perceived stress levels and poor coping ability in autistic adults and sub-par decision-making abilities indicate a need for assistance in identifying healthy coping mechanisms (Hirvikoski and Blomqvist 2014). Providing guided activities or simple suggestions enables the system to support stress reduction in a structured manner.

Stress Prevention: The system must recommend strategies to help prevent stress from overstimulation when stress-inducing stimuli are detected. Rationale: After the user is advised of potential overstimulation by detecting stress-inducing environmental stimuli, they may not know how to halt the further progression of stress triggered by those stimuli due to reduced coping abilities (?McQuaid *et al.* 2022). Therefore, to aid successful stress prevention, the system must provide strategies to support it.

Virtual Pet Interaction: The system must deliver stress detection, mitigation, and prevention via interactions with a virtual pet. Rationale: The presence of a virtual pet companion provides a calming and engaging presence, which can further reduce stress (Altschuler 2008; Dachez and Ndobo 2017; Karunakaran *et al.* 2025; Molasm *et al.* 2024; Veronesi *et al.* 2023).

User Personalization: The system must adapt stress-detection thresholds and intervention strategies to the individual user's responses and preferences. Rationale: Individual users have different physiological responses and their own preferred coping mechanisms. Static thresholds and uniform intervention strategies may not effectively account for individual preferences. Therefore, the system must provide personalization to tailor stress detection and mitigation to individual users.

Portable: The system must be portable. Rationale: The system must be portable to remain in the user's space to support continuous biometric and environmental monitoring for immediate stress detection and mitigation.

Non-Invasive: The system must be non-invasive, requiring no intrusive sensors or equipment that may cause discomfort or disrupt daily use. Rationale: Due to sensory over-responsivity in autistic individuals (American Psychiatric Association 2013) and the need for practicality in social and everyday contexts, the system must minimize physical, emotional, and sensory disturbance and discomfort.

System Design

Stress Detection and Stressor Identification: Research studies have shown that stress can be measured from a user's biometric data. In these studies, the most used biometrics to determine whether a stress response had occurred in people with ASD were heart rate, skin conductance responses, and body temperature (Cano *et al.* 2024). Skin conductance responses can include electrodermal activity (EDA) and skin resistance, which measure changes in the skin's electrical properties caused by sweat gland activity. These two are inversely related. These biometrics can be measured in real-time using wearable devices; the most common device is a wristband (Cano *et al.* 2024). This is an ideal design because wrist-worn wearable devices are minimally invasive and portable, making them suitable for continuous stress-level estimation as required by the proposed Mist system.

Tomczak *et al.* (2020) introduce a system to monitor stress in autistic users. The system is a wristband that measures heart rate, skin resistance, and body temperature to detect stress events. The study's promising results demonstrate the feasibility of detecting stress events in autistic participants using these physiological signals and a wearable device. Since that research effort closely aligns with the proposed system's desired stress-detection approach, Mist adopts a similar methodology. Following Tomczak *et al.* (2020), stress events are determined by changes in heart rate, skin resistance, and body temperature. The system keeps track of the following for each biometric: the user's current measurement, the user's reference value, the threshold for a stressful condition, the duration that a measurement must remain elevated before it is considered normal again, and a list of measurements within the last specific, predetermined timeframe.

A stress event can occur in three ways (Tomczak *et al.* 2020): an increase in heart rate followed by a decrease in skin resistance; an increase in heart rate followed by a decrease in body temperature; and a decrease in skin resistance followed by a decrease in body temperature. An increase or decrease is considered significant when it passes a predetermined threshold. Each event must also occur within a specific, predetermined interval. The number of stress events present determines the user's stress level (Tomczak *et al.* 2020). The stress detection system in this project follows this methodology. The app holds four stress levels: 0 for no stress, 1 for low stress, 2 for medium stress, and 3 for high stress. Stress levels are categorized by the number of stress events present: 1 event maps to level 1, 2 events map to level 2, and so on.

The biometric reference values are set upon startup, which are based on actual, realistic values reported in the literature. The heart rate reference value is initially set to 71.5 beats per minute (bpm). This value is based on the mean heart rate measurement of an adult ASD group (Villar *et al.* 2023). The body temperature reference value is set to 36.26 degrees Celsius. This value reflects the average body temperature from two surveys of adult participants with ASD (Hidaka *et al.* 2023). Skin resistance varies substantially from person to person. Dry skin typically has a resistance of 1,000–100,000 ohms (Reddy and Reddy 2013). There is little research to indicate that the average skin resistance in an individual with ASD differs noticeably from that of a neurotypical individual. Therefore, the skin resistance reference value is initially set to 50,500 ohms, the average from the Reddy and Reddy source.

To account for each user's biometric differences and anticipated fluctuations, reference values are recalculated and stored during each program run, as needed. User reference data are preserved in a file when the program closes. This file is referenced upon each subsequent program startup and loads the saved reference data back to the program's biometric reference variables. Following Tomczak *et al.* (2020), biometric reference value recalibration is performed when the average biometric measurement deviates from the reference value by a prescribed threshold over a specified period of time. The new reference value is then set to the average of the values within the specified timeframe.

Biometric deviation thresholds and timeframes in the Mist system also follow the guidelines in Tomczak *et al.* (2020). As established by the study's stress detection methodology, the thresholds for heart rate, skin resistance, and body temperature are set as follows: heart rate as 5% of the reference value; skin resistance as 10% of the reference value; and body temperature as 0.1 degrees Celsius. These thresholds determine what deviation in measurements is notable. If the heart rate exceeds the stated threshold, or if the body temperature or skin resistance falls below the stated thresholds, it qualifies as a stress condition for the respective biometric, and it then enables evaluation of the presence of the described stress events. As stated previously, if any of the biometric measurements deviate by the respective thresholds in either direction for a prolonged period (30 seconds for heart rate and 60 seconds for body temperature and skin resistance), the program recalculates the reference value to reflect the average of the values within the specified timeframe, which is set to 10 seconds.

The 10-second timeframe (Δt) additionally defines the time period during which the stress events must occur, except for the third event, a decrease in skin resistance followed by a decrease in body temperature, which must occur within $2\Delta t$. At the end of each timeframe, the program checks for stress events. Table 2 summarizes the values of the stress detection parameters. Data collection and system operation are limited by the technology used. As stated previously, the device used should ideally be minimally invasive and portable. The cost to the user should also be a factor. Users should not be expected to purchase an expensive niche device to use the system. Therefore, the ideal devices for the system should be a wristband (for biometric data collection) and a mobile phone (for user interaction and environmental data collection), since many people already have these.

Environmental data collection is restricted by device specifications. Due to storage, memory, and ability limitations, phone sensors may have issues with keeping track of many different stressors and keeping track of niche stressors, such as clothing textures and smells. To account for these limitations, environmental data collection is limited to the two most common stressors, namely, sound and light (Strömberg *et al.* 2021). These sensory inputs can be measured using the microphone and ambient light sensors already available on most smartphones.

Environmental data are continuously monitored by the system. Thresholds for each environmental variable are set to determine whether the current level qualifies as a stressor that may contribute to overstimulation. If a variable is above the specified threshold, it increases the "risk level". The risk level, similar to the stress level, is a derived value that showcases how many stressors currently exist in the environment. With two environmental variables, the highest risk level is 2, and the lowest is 0. As shown in Table 2, the sound stress threshold is set to 77.5 decibels, reflecting the average of the range of overstimulating sound levels for people with hyperacusis (Danesh *et al.* 2021). This value also accounts for crowded rooms, another known stressor for autistic individuals, which is estimated to be around 80 dB (MacLennan *et al.* 2021; White 2026).

Table 2 Stress Detection Parameter Values

Name	Value Ranges	Value	Unit	Source
Heart Rate Initial Reference Value	60.7–82.3	71.5	bpm	Villar et al., 2023
Heart Rate Deviation Threshold	—	5%	—	Tomczak et al., 2020
Heart Rate Reference Recalibration Duration	—	30	sec	Tomczak et al., 2020
Body Temperature Initial Reference Value	35.92–36.58	36.26	℃	Hidaka et al., 2023
Body Temperature Deviation Threshold	—	0.1	°C	Tomczak et al., 2020
Body Temperature Reference Recalibration Duration	—	60	sec	Tomczak et al., 2020
Skin Resistance Initial Reference Value	1,000–100,000	50,500	Ω	Reddy and Reddy, 2013
Skin Resistance Deviation Threshold	—	10%	—	Tomczak et al., 2020
Skin Resistance Reference Recalibration Duration	—	60	sec	Tomczak et al., 2020
Sampling Interval (Δt)	—	10	sec	Tomczak et al., 2020
Sound Threshold	60–85	77.5	dB	Danesh et al., 2021
Light Threshold	100–500	300	lux	Various

User Notification: Once stress is detected, the system communicates the user's stress level through both text and visual cues centered on the virtual pet. Prior research suggests that incorrectly labeling a user's emotional state can reduce trust in the system (Perusquía-Hernández *et al.* 2019). To mitigate this, the application externalizes stress by attributing it to the virtual pet rather than the user. The interface displays text indicating the pet's stress level, accompanied by an image of the pet expressing that emotion. While the system does not explicitly label the user's feelings, this indirect approach encourages users to reflect on their own emotional state without imposing potentially inaccurate interpretations.

The virtual pet used in the design is based on a ferret. Each stress expression image is loosely based on a ferret's physical fear indicators. These indicators include a raised tail, puffed hair, and an arched back (Fisher 2006). Figure 1 shows the four different expressions during each estimated stress level. Stress level 0 shows the ferret in a neutral stance. Stress level 1 shows the ferret with a more arched back and a slightly raised tail. Stress level 2 shows the ferret in a position similar to 1, and with slightly puffed hair. Finally, stress level 3 shows the ferret with extremely puffed hair, a higher raised tail, and an extreme arch in its back. Stress levels 2 and 3 also show objects above the ferrets to help the user differentiate between states.

The user is notified of excessive sound or light via a text-based indicator. Once excess sound or light is detected, the appropriate phrase will be displayed on the screen, stating that the pet has noticed it. This phrase can occur with or without stress events. With stress events, observing excessive sensory input will help the user determine what may be causing the stress. Without stress events, it can help prevent overstimulation by alerting the user to potential stressors.

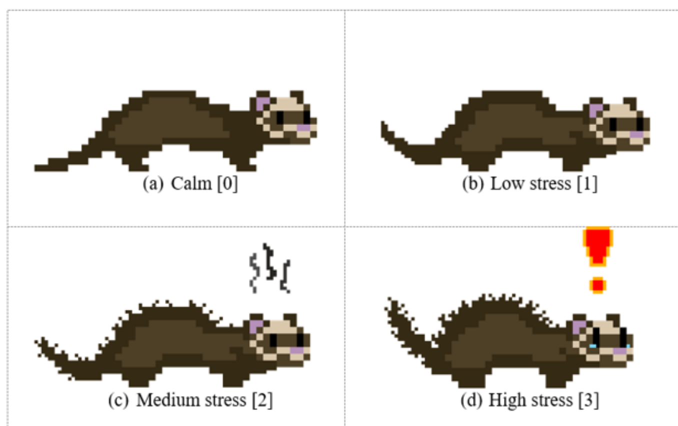

Figure 1 Ferret Stress Level Expressions

Stress Mitigation: A primary mechanism for stress reduction in the developed prototype is the virtual pet, which functions as an emotional proxy. This design allows users to engage in self-regulation through caregiving behaviors, rather than direct introspection. The virtual pet remains present throughout the application, including during periods without detected stress, to encourage ongoing user engagement and emotional connection. By mirroring the user's emotional state, the pet prompts users to respond with care, indirectly supporting their self-regulation. In this way, self-care is reframed as an interactive and game-like experience. This approach integrates two established stress-reduction strategies of virtual pet interaction and game-based engagement (Finke *et al.* 2018; Karunakaran *et al.* 2025; Malinverni *et al.* 2017; Scarcella *et al.* 2023; Veronesi *et al.* 2023).

Once stress or an environmental stimulus is detected, the system provides the user with various stress-mitigation techniques. This is provided as activities the user can participate in, prompted by the virtual pet's dialogue. The prototype includes a number of stress-relief activities, as described in this section.

Play with the Virtual Pet: This activity allows the user to directly interact with their virtual pet. Video games have been reported to reduce stress in autistic individuals (Finke *et al.* 2018; Malinverni *et al.* 2017; Mazurek *et al.* 2015; Scarcella *et al.* 2023), and additional research suggests that interaction with virtual pets can further promote stress reduction and emotional comfort (Karunakaran *et al.* 2025; Veronesi *et al.* 2023). The current design enables the user to engage in simple, soothing interactions, such as petting the animal and providing it with treats, fostering a sense of companionship and engagement.

Deep Breathing: This activity initiates a guided deep breathing session accompanied by visual representations of the virtual pet. Guided breathing is a mindfulness-based technique that has been demonstrated to reduce stress in autistic individuals (Agius *et al.* 2023; Hatfield *et al.* 2022; Simione *et al.* 2024). The interface presents both text-based prompts, including a timer and breathing instructions, and synchronized animations of the pet inhaling and exhaling. Users are encouraged to follow the pet's breathing pattern. The implemented technique is box breathing, a structured, repetitive method that follows a 4-4-4-4 pattern: inhaling for 4 seconds, holding for 4 seconds, exhaling for 4 seconds, and holding again for 4 seconds.

Contact a Friend: This activity guides the user in composing a message to share with a trusted friend or family member. It is designed to support self-advocacy by helping users clearly communicate their needs during periods of stress. Facilitating this type of communication can strengthen interpersonal relationships by improving mutual understanding and reducing the likelihood of frustration caused by misinterpretation (Edwards *et al.* 2020; Martino *et al.* 2025).

Additionally, this activity supports the development of emotional awareness and expression, enabling users to more effectively identify and articulate their feelings. This is particularly important for autistic individuals, who may experience difficulty expressing internal states or communicating needs in socially appropriate ways (American Psychiatric Association 2013; Kinnaird *et al.* 2019; Morie *et al.* 2019; Preece *et al.* 2022; Yuan *et al.* 2022).

The activity incorporates a structured communication format based on I-statements, a commonly recommended strategy in therapeutic and clinical settings. This approach encourages users to express their feelings, identify the cause, and communicate their needs clearly and non-confrontationally (Montemurro 2011; Muhyatun 2022; Rogers *et al.* 2018). When stress leads to social withdrawal or reduced communication, peers may misinterpret these behaviors, potentially resulting in strained relationships (Edwards *et al.* 2020). By proactively communicating their experiences, the users can provide context for their behavior and, when appropriate, allow others to offer support in reducing stress.

Real-World Activity Recommendations: These activities cannot be performed in the app; rather, they are recommendations for calming activities that the user can do on their own in the real world. The activity recommendations included in the prototype at startup are exercising, using a fidget toy, finding a safe space, and listening to calming music. These recommendations are medically recommended activities for stress-relief (DeGuzman *et al.* 2024; Yuan *et al.* 2022). The system also allows the user to suggest their own activities, which the program stores in the user data files and includes them as new activity recommendations during subsequent system runs. This encourages users to recognize and develop coping mechanisms that work for them, especially since they may have special interests that reduce stress (Long 2024).

Stress Prevention: Upon detecting an environmental stressor, the system includes functionality to view the stressor and recommend ways to reduce its effects on the user. If the user is not currently stressed, following the recommendations to mitigate the stressor could prevent future overstimulation. If the user is currently stressed, following recommendations to address the stressor could help reduce stress.

Implementation

The Mist system is designed to integrate with smartphones and existing wrist-wearable sensors, such as the Fitbit or Empatica E4, to collect biometric and environmental data. The current prototype is designed and developed as a proof-of-concept prototype and does not interface with physical sensors. Instead, the system is implemented as a desktop web application using the Windows Presentation Foundation (WPF) framework with .NET. The system's program logic is written in C#, while the user interface is designed in XAML. User data are stored in XML files, allowing the application to maintain and manipulate reference values and activity recommendations. Biometric and environmental measurements are currently manually input or simulated, serving as placeholders until sensor integration is implemented in future versions.

SYSTEM RESULTS

Primary Graphical User Interface

The app's main screen focuses on stress detection and user notifications. It is divided into four parts: the virtual pet image; text and actions; current biometric, environmental, and stress data; and controls for adjusting biometric and environmental values. An example of the full-window display at startup is shown in Figure 2. The virtual pet's image reflects the user's calculated stress level, which is constantly monitored. The text displayed additionally describes how the virtual pet feels, reflecting the user's potential state. The four messages displayed are "Mist feels calm." (stress level 0), "Mist feels slightly stressed." (stress level 1), "Mist feels stressed." (stress level 2), and "Mist feels very stressed." (stress level 4). Depending on which environmental triggers have surpassed their respective stress thresholds, the text will also include a message indicating such; for example, after the text describing the emotion (calm, stressed, etc.), the textbox will also state "Mist noticed it is very loud" or "Mist noticed it is very bright" or a combination of both. This text display is shown in Figure 3. Also displayed in Figure are buttons that prompt the user to begin stress mitigation techniques. These buttons do not appear until the stress level is above 0.

The "Tell Mist it's okay" button allows the user to dismiss the prompts. This prevents the system from warning the user about their potential stress for a default of two minutes. Interacting with "Manage Mist's triggers" and "Give Mist attention" leads the user to stress-mitigation and prevention techniques. The controls, located at the bottom of the screen, enable user adjustments of the biometric and environmental variable data. Each of the three biometrics has two buttons: one to increase the value and one to decrease it.

Figure 2 Main Window of app at Startup

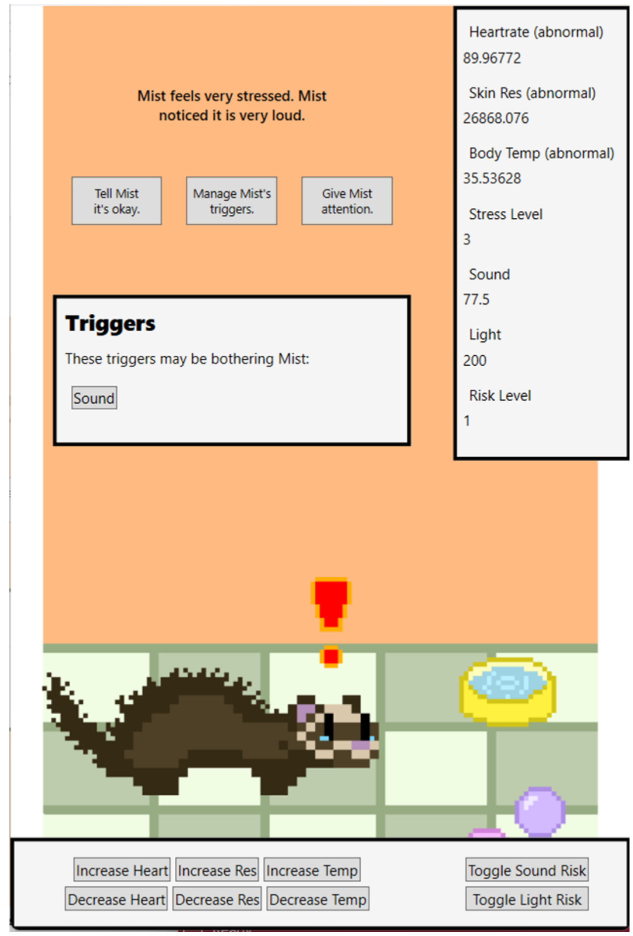

Figure 3 Manage Triggers Popup

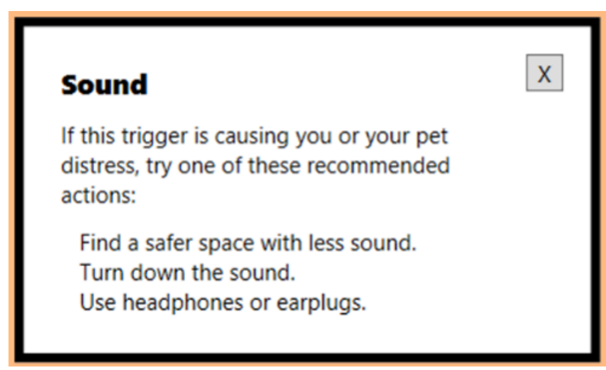

Figure 4 Sound Trigger Mitigations Popup

Each environmental trigger has a single button; clicking it toggles the trigger's value to a stressful level if it is currently in the normal range, or back to the normal range if it is currently at a stressful level. Changes in the values can be seen on the right-hand side of the screen, where the variable values are displayed. Values are shown for heart rate (bpm), body temperature (°C), skin resistance (Ω), sound (dB), and light (lux). There are also regions for risk and stress levels, which are derived values. The stress level indicates how many stress events are present. The risk level indicates how many environmental triggers have surpassed the stress value threshold.

In addition to detecting physiological stress, the system monitors environmental stimuli that may contribute to user discomfort. There are two environmental triggers programmed into the app: elevated light and elevated sound. Upon detecting high levels of light or sound, the detection text and buttons will reappear. Stimulant detection does not alter the pet's image, but the text above indicates that the pet notices the change and warns the user. This prompt indicates that the sound and/or light levels have exceeded the threshold for causing stress. This is in addition to stress prompts that may already be present if the Stress Level is above 0.

Interacting with the "Manage Mist's triggers" button displays the environmental stimuli that exceed the acceptable thresholds. The pop-up box lists the triggers as buttons. Clicking each trigger launches a pop-up that provides information about the specific stimulant. The example for sound is displayed in Figure 4.

The pop-up for each trigger is divided into three parts: the name, the prompt, and a list of recommended actions. The name informs the user what trigger they are reading about ("Sound" or "Light"). The prompt is the same for all triggers and states: "If this trigger is causing you or your pet distress, try one of these recommended actions". This explains to the user that this trigger in the environment could cause overstimulation. Finally, the list of actions lets the user know what they can possibly do to make the trigger more manageable. For Sound, this list includes the following: "Find a safer space with less sound," "Turn down the sound," and "Use headphones or earplugs." For Light, the list includes the following: "Find a safer space with softer light," and "Turn down the light."

Stress Mitigation Activities

Clicking the "Give Mist attention" prompt reveals a pop-up with a list of activities and activity recommendations for the user to select from (Figure 5). These options, intended to mitigate stress, include playing with the pet, deep breathing, creating a message, and other activities for the user to do outside the app.

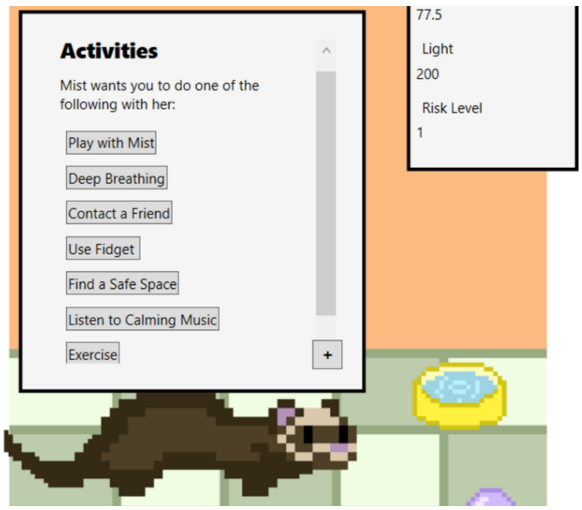

Figure 5 Activity Recommendations

Play with Mist: The play feature opens a new window for the user to interact directly with their virtual pet. There are currently two options for playing with the pet. The first option is "petting," where the user can click and drag their mouse along the pet's body, and the pet will respond with a corresponding animation. The second option is to feed treats to the pet. There is a bundle of treats on screen that the user can click and drag to the pet's mouth, and the pet consumes the treat. Options to quit or repeat the activity appear after all the treats have been fed to the pet. Repeating the activity will refill the treats. The user can still pet the animal.

Deep Breathing: The deep breathing activity opens a separate window that guides the user to take deep breaths (Figure 6). In the app, this is guided by text prompts that describe which step the user is on and how much time they have left in that step, along with corresponding images of the pet performing the actions in tandem with the user. System shows the instruction box during the exercise, including the instruction and the remaining time, and displays the instruction box at the end of the exercise with options to quit or repeat the activity. These options appear after four iterations of the box breathing activity.

Create a Message: The personalization mechanism allows the user to generate personal messages. The "Create a message" option opens a new window that guides the user in composing a message to send to their friends following the I-statement guidelines. It has four text boxes, each preceded by a prompt, and a final text box that combines the results of the four prompt text boxes. Because all five text boxes do not fit onto one screen, the window includes a scrollbar to allow the user to view the text boxes not currently shown. An exit button is located at the bottom of the scrollable window, allowing the user to quit the activity.

The first text box is the greeting box, which lets the user choose whom to address. It includes options such as "mom", "dad", "brother", "sister", "friend", etc. Upon clicking one of the prompts,

Figure 6 Deep Breathing Window

the textbox will autofill with "Dear [option],". The second textbox is the "I feel" statement. It allows the user to choose what emotion they may be feeling. It includes options such as "sad" and "overwhelmed". Upon clicking one of the prompts, the textbox will autofill with "I feel [option]".

The third textbox is the "because of" statement. It enables the user to choose the reason for their feelings if they know it. The options include "too many people around", "too much sound", and "I don't know". Upon clicking one of the prompts, the textbox will autofill with "because of [option]". The fourth textbox is the "I need" statement. It allows the user to self-advocate for what, if anything, they need from their friend. The prompts include options such as "to go home" and "space". Upon clicking one of the prompts, the textbox will autofill with "I need [option]".

The final textbox is an amalgamation of all the previous textbox contents, creating a fully formed message to send or say to their friend. Each textbox gives the user the option to edit it any way that they want, as the prompts are meant to be guidelines, not restrictions. Figure 7 shows the "I need" statement text box and the final message generated using the example prompts. Although the "I need" statement textbox did not have a prompt for "and rest", as shown in the figure, the user was able to type it in themselves.

Figure 7 The Final Message

Activity Recommendations: After the three previous options, the activities list includes a few more. Clicking these does not open a new window with a fully programmed activity; instead, it displays a pop-up with simple text. The system shows a pop-up that appears when clicking the "Exercise" option in the activity recommendations. These activities are recommendations for the user to do outside the app, such as exercising and listening to music. The user can also add their own activity recommendations by clicking the "+" button in the activity recommendations list. The new activity will be included in subsequent stress- or stressor-detection instances. New recommendations are stored in files that are loaded at runtime on subsequent program runs (Figure 8). For instance, there is a progression of adding "Reading" as a new activity to the recommendations list. If the user no longer wants the recommendation, they can remove it from the list using the "Delete" button at the bottom right of the pop-up. The "X" in the top-right corner will close the pop-up.

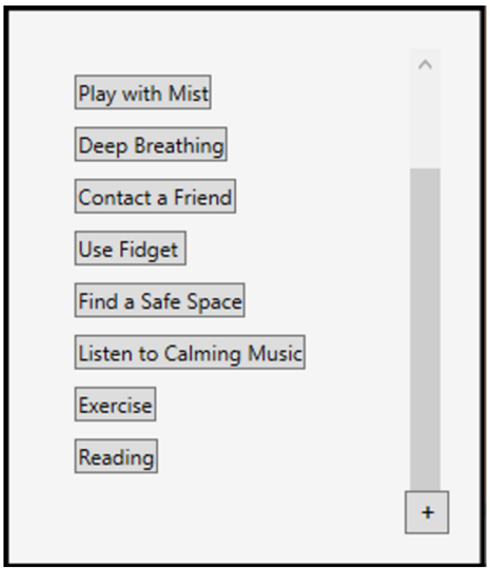

Figure 8 New Activity Recommendations

CONCLUSION

Current research on autism and the challenges in stress recognition and coping highlight the need for systems that can detect stress onset and provide effective interventions. This work examined whether stress-onset detection and mitigation via a stress-responsive virtual pet could reduce the magnitude of stress episodes in autistic individuals. A prototype app was developed that integrates a virtual pet with biometric and environmental data to detect, notify, and mitigate stress at its onset, in alignment with medically recommended intervention strategies and stress detection. To our knowledge, this work is among the first systems to combine stress detection and mitigation for autistic users through a virtual pet interface. The novelty is in the development of requirements, design, and implementation of the virtual pet interface for not only detecting stress, but also mitigating the stress.

This study focused on development of the requirements, design, and implementation of a system prototype to illustrate the conceptual design. The next step, beyond the scope of this paper is to conduct human subject experiments. The primary limitation of this study is the lack of a real-world evaluation with autistic participants. The most appropriate evaluation would involve real-time sensor data and user feedback collected through user studies. Human subject experiments will involve institutional approval, ethical considerations, user safety, data privacy, computational cost of the system, real-time performance, and its feasibility on mobile devices. The effectiveness and efficiency of the system can only be analyzed through future human subject experiments. Another limitation of this prototype is the limited range of stress and stressor detection. As noted by Cano et al. (2024), stress in autistic individuals is more reliably identified using multimodal approaches than relying solely on physiological measures. Although the app currently accounts for environmental risk factors, additional stress-detection methods should be explored for integration. For example, computer vision techniques could be used to monitor facial expressions and body movements for indicators of stress, such as changes in affect or repetitive behaviors.

In addition to detecting stress itself, expanding stressor identification is also important. One potential approach is to monitor disruptions to the user's routine, such as by incorporating GPS data to detect significant location changes. Future research into lightweight, resource-efficient methods for identifying less accessible stressors, such as olfactory or tactile stimuli, may also be worth exploring. Additionally, the current prototype's lighting threshold is based on indoor lighting levels; expansion to account for outdoor lighting may be beneficial. Subsequent development will focus on translating the web application prototype into a mobile app that connects to both the phone's sensors and existing models of a wearable wrist biometric monitor. Future work must include conducting extensive testing of the app and sensors with human subjects, requiring proper Institutional Review Board (IRB) approvals. Additional enhancements include expanding stress mitigation strategies (e.g., guided meditation, isometric exercises, and cognitive behavioral techniques), increasing the complexity of virtual pet interactions, and enabling optional notifications to caregivers or trusted contacts. Further improvements may incorporate personalization and machine learning to adapt stress- and risk-detection thresholds and intervention strategies for individual users. An additional direction for future work is developing a robotic embodiment of the virtual pet to enhance user engagement and emotional connection. Overall, this work provides a foundation for interactive, medically-based, technology-driven approaches to supporting stress management in autistic individuals.

Conflicts of interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

Availability of data and material

Not applicable.

Ethical standard

The authors have no financial or non-financial interests to disclose.

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How to cite this article: Hull, B.E., and Agah, A. A Virtual Pet for Detecting and Mitigating Autism Spectrum Disorder Stress. *Computers and Electronics in Medicine*, 3(2), 122-137, 2026.