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Review Article

Enhancing Proprioception and Regulating Cognitive Load in Neurodiverse Populations through Biometric Monitoring with Wearable Technologies

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Abstract

This paper considers the realm of wearable technologies and their prospective applications for individuals with neurodivergent conditions, specifically Autism Spectrum Disorders (ASDs). The study undertakes a multifaceted analysis that encompasses biomarker sensing technologies, AI-driven biofeedback mechanisms, and haptic devices, focusing on their implications for enhancing proprioception and social interaction among neurodivergent populations. While wearables offer a range of opportunities for societal advancement, a discernable gap remains: a scarcity of consumer-oriented applications tailored to the unique physiological and psychological needs of these individuals. Key takeaways underscore the emergent promise of tailored auditory stimuli in workplace dynamics and the efficacy of haptic feedback in sensory substitution. The investigation concludes with an urgent call for multidisciplinary research aimed at the development of specific consumer applications, rigorous empirical validation, and an ethical framework encompassing data privacy and user consent. As the pervasiveness of technology in daily life continues to expand, the article posits that there is an imperative for future research to shift from generalized solutions to individualized applications, thereby ensuring that the spectrum of wearable technology truly accommodates the full scope of human neurodiversity.

Keywords: Neurodiversity; Autism; ADHD; Wearable technology; Wearables; Biochemical markers; Ethical considerations

Introduction

Advancements in wearable technology have ushered in an era of real-time on-body monitoring and computation of various facets of human physiology [1]. The academic community has developed an extensive array of sensors designed to monitor both the internal physiological states-such as Electroencephalograms (EEG), Electrooculograms (EOG), Electromyograms (EMG), skin conductivity, and heart rate-and the external behaviors and conditions-like movement, geographic location, and social interactions [2,3]. These data can subsequently be processed to offer instantaneous feedback to the user through an assortment of actuators, ranging from audio and visual cues to olfactory, electrical, and haptic stimulations. Consequently, wearable devices evolve into closed-loop systems capable of enhancing human capabilities [4].

Furthermore, innovations in radio and wireless sensing technologies have enabled researchers to extend the boundaries of physiological monitoring to include scenarios that obviate the need for direct bodily contact with sensors [5]. Such advancements are rendered feasible through the synergistic amalgamation of high-resolution wireless sensing technology and sophisticated machine learning algorithms [6]. Researchers have already showcased the potential of wireless sensing in monitoring a spectrum of variables including, but not limited to, body movement, respiratory cycles, heart rates, emotional states, and sleep patterns [7,8]. However, research in the domain of wearable technology has largely focused on monitoring physiological markers, such as heart rate, respiration, and electrodermal activity [9].

Contemporary devices have demonstrated capabilities in collecting data via sensors that measure electrical activity, particularly through Electroencephalograms (EEG) [10]. However, a significant lacuna exists: these wearables are not yet proficient in continuously monitoring biochemical markers that underpin these physiological signals. Additionally, only recently has there been a concerted effort to use such devices to assist in identifying and treating states of stress or anxiety in the body. Current biosensors offer limited scope in that they are typically one-time use, non-continuous, and rigid in their selection of biomarkers to monitor [11]. Proposed solutions include the so-called "wearable lab on body" to fill this gap by offering a platform for active, continuous monitoring of human biomarkers, argue [12]. Such platforms incorporate both digital sensors, such as Inertial Measurement Units (IMUs) for activity recognition, and an automated system for non-intrusive sampling of biomarkers from biological fluids such as saliva.

The utilization of wearable technology for supporting mental health already has garnered attention [13-15]. However, monitoring individuals with neurodiverse conditions presents a compelling avenue for exploration, building on this research into use cases for lowering heart rates and addressing anxiety disorders from a distance [16]. Neurodivergent individuals often exhibit a range of physiological and biochemical markers that diverge from neurotypical patterns, thereby necessitating specialized approaches for effective health management [17]. Wearable technologies offer the prospect of tailored, data-driven strategies, facilitated through continuous monitoring that transcends the limitations of periodic clinical assessments [18]. With an estimated 15-20% of the global population considered to be neurodivergent, the business case for broader commercial investment in research and development is demonstrable [19]. The concept of neurodiversity encapsulates a broad range of cognitive functions and behavioral attributes, including but not limited to social communication capacities, emotional recognition and expression, attentional levels, and various other mental faculties [20]. Initial scholarly investigations into neurodiversity were largely predicated on the medical model, which primarily focuses on prevention and curative strategies for the impairments frequently correlated with these diverse conditions. These discourses evolved within a context characterized by a normative educational and social history, which often framed neurodiverse traits as deficits [21,22]. For instance, the construct of dyslexia became prominent with the increasing societal emphasis on literacy [23], while attentional challenges such as ADHD gained visibility following societal shifts towards more sedentary lifestyles in the wake of industrialization [24].

Moreover, the advent of more complex social communication structures and controlled sensory environments, such as those found in contemporary workspaces, has led to greater recognition of neurodivergence and Autism Spectrum Disorder (ASD) [25]. Etymologically, the term "disorder" finds its origin in the unknown and is employed particularly when symptoms of dysfunction lack a definitive diagnosis [26]. Concomitantly, the usage of the term "disability" inherently carries an assumption that diagnosed individuals manifest below-average neurological or physical capabilities. For example, recent studies indicate that approximately 50% of individuals diagnosed with ASD also present with at least four co-occurring conditions, including learning difficulties and language disorders. Furthermore, 75% of those diagnosed with autism exhibit traits associated with ADHD, one of the most prevalent neurological challenges affecting aspects such as working memory, impulsivity, and stress management [27].

The intriguing interplay between proprioception and workplace dynamics represents an untapped avenue for research [28]. Proprioception, or kinesthesia, denotes the inherent cognitive ability to perceive one's own bodily movements and spatial orientation [29]. Individuals diagnosed with autism spectrum disorders frequently exhibit challenges in this particular sphere, often encountering difficulties in recognizing bodily signals, such as fatigue or hunger [30]. The advent of Artificial Intelligence (AI) in biofeedback mechanisms for emotion recognition posits a compelling opportunity for workplace adaptation. Specifically, the innovative coupling of AI-driven biofeedback systems with auditory stimuli, such as tailored musical soundtracks, may offer a transformative approach to facilitate self-awareness and modulate energy expenditure in professional settings [31].

Given these complexities, the development of wearables for the neurodiverse population warrants nuanced considerations to address their specific needs. Critical to the discussion of use with neurodivergent individuals are considerations of disclosure, thus the ethical responsibility attached to the deployment of such technologies is key [32]. According to a recent report, the Americans with Disabilities Act (ADA) encompasses not only physical disabilities but also 'invisible' ones, affecting approximately 16% of U.S. workers [33]. Despite this legal inclusion, a concerning 47% of workers with invisible disabilities have refrained from disclosing their condition to managers or colleagues. The reluctance to disclose stems from multiple concerns: 34% fear behavioral scrutiny, 31% worry about perceived incompetency in fulfilling work responsibilities, and 30% are concerned about negative gossip [33]. Therefore, issues of data privacy, informed consent, and the potential for stigmatization must be carefully weighed against the prospective benefits [34]. As [35] contends, privacy is contextual integrity; it is the appropriate flow of personally identifiable information in context. The assertion accentuates the need for contextualizing the use of wearables, ensuring that data gathering respects the informational boundaries of individuals while serving the intended healthcare goals [36].

Moreover, the efficacy of new wearable solutions in capturing accurate and actionable data for neurodiverse individuals remains an empirical question. Skeptics may argue that technological monitoring cannot substitute for the nuanced understanding offered by trained medical professionals [37]. However, as [38] observes, technology will make it feasible to place healthcare in the hands of the consumers, permitting a far more decentralized system. This perspective, echoed by [39] suggests that wearables, when effectively designed and ethically deployed, can indeed offer valuable complementary data that healthcare professionals can utilize to improve treatment outcomes.

Given the potential benefits for the neurodivergent community, this paper will post a compelling need to redirect the development and application of commercial wearable technologies to cater to this ever-growing population. While contemporary devices like the Apple iWatch, Fitbit and Med-Watch have made significant strides in encouraging neurotypical individuals to engage in healthier behaviors—such as walking and focused breathing—these devices often overlook the distinct challenges faced by neurodivergent individuals, particularly in areas such as self-regulation and proprioception [40]. Emerging technologies that extend beyond the monitoring of traditional physiological markers hold substantial promise for these underserved communities. The paper aims to delineate the potential for using biometric data, captured through advanced wearable devices, to regulate cognitive load, enhance proprioception, and facilitate better mental state monitoring among neurodivergent individuals. To negotiate the complexities surrounding these technologies—be they ethical, technical, or interdisciplinary in nature-a collaborative and nuanced approach becomes imperative. Therefore, this article embarks on a multifaceted exploration that marries engineering innovations with bioethical prudence, aiming to contribute meaningfully to the healthcare management toolkit for neurodivergent populations.

Literature Review

Wearable Devices to Promote Physical Health

The advent of wearable technology in healthcare has brought about a transformational shift in the methods available for health monitoring. These devices, designed to be worn on various parts of the body such as the wrist, facilitate the continuous collection of health-related data [41]. Their popularity has witnessed a more than threefold increase over the past four years, mirroring a growing consumer interest in personal health and well-being [42]. Indeed, wearables like FitBits and smartwatches have seamlessly integrated into the mainstream healthcare industry, a phenomenon corroborated by the burgeoning market value for smart wearable health devices, which surged from $13.8 billion in 2020 to an expected $37.4 billion by 2028 [43].

The range of wearable technology applications in healthcare is diverse. Continuous Glucose Monitoring (CGM) sensors, for example, offer real-time tracking of blood sugar levels for diabetes patients [44]. Electrocardiogram (ECG) sensors focus on the electrical activity of the heart, providing vital data on any irregularities in heart rhythm [45]. Further, electronic skin patches monitor essential physiological markers such as heart rate, respiratory rate, and body temperature [46]. Hydration and sweat sensors offer another layer of data collection by monitoring hydration levels and sweat composition, thereby benefiting both athletes and individuals with specific medical conditions [25]. Photoplethysmography (PPG) sensors, which measure blood flow, can monitor heart rate and blood oxygen levels [47]. The utility of wearable technology even extends to prenatal and postnatal care, where devices can monitor fetal heart rate, contractions, and other vital signs [48].

Within the broader healthcare framework, wearable technology serves not merely as an adjunct but as a potentially powerful tool for preventative healthcare. Devices can be programmed to facilitate goal-setting and tracking of health-related decisions, thereby aiding in the prevention of diseases before the onset of overt symptoms [49]. Furthermore, a review of literature demonstrates the many opportunities and challenges for both healthcare providers and patients. For instance, [50] postulates that wearable technologies could potentially alleviate the workload of healthcare professionals and optimize hospital spaces for more critical or responsive care. The premise underscores the importance of wearables as instruments that could bring about efficiencies in healthcare delivery systems.

The realm of smart textiles-based body sensor networks offers an intriguing avenue for wearable technology. As [51] note, the development of these sensor networks poses considerable technical challenges. However, these challenges also serve as gateways to innovation, potentially advancing sensor and sensor network design for enhanced accuracy and reliability. The discourse surrounding wearable technology's capabilities extends beyond merely physical health parameters. [52] delves into systems that are capable of collecting both physical and psychological health data, hinting at the multidimensional capabilities of wearable technologies in healthcare.

In addition to preventative measures, [53] also argues that wearable systems can significantly influence the outcome of clinical interventions. These systems are particularly valuable in assessing their impact on patient mobility, independence, and overall quality of life—variables often considered secondary but intrinsically important in medical rehabilitation. A parallel line of research focuses on the Internet of Things (IoT) enabled health monitoring systems. [54] observe that most existing wearables rely on smartphones for data processing, visualization, and transmission, thus questioning the independence of such devices but also highlighting their symbiotic relationship with other smart technologies.

The persuasion capability of wearable technology should not be underestimated. [55] argue that wearables have the potential to motivate physical activity by enhancing health awareness and enabling change through real-time feedback. The advent of artificial intelligence and flexible electronics, as [56] point out, is likely to pave the way for wearables that can generate real-time medical data, thereby enriching the existing IoT ecosystem. While the commercial viability of these devices remains a subject of scrutiny, [57] note that wearable systems for monitoring various health conditions are now being patented, signaling a trend toward mainstream adoption.

Flexibility and user interaction in health-monitoring devices have also been explored extensively. [58] focus on the critical role those flexible electronic devices play in personal healthcare systems. Moreover, a systematic review by [59] predicts that wearable medical devices are likely to dominate the future mobile medical market. Such a prediction illuminates the trajectory of wearable technology, highlighting its potential role as an integral component in future healthcare landscapes.

Having discussed the broader dimensions of the impact of wearable technology on healthcare systems, it becomes pertinent to shift from a macro-level focus for implementations to micro-level intricacies. While the macro perspective offers a panoramic view of how wearable technologies could redefine healthcare paradigms—from professional workload to patient rehabilitation—the micro-level explores the intimate relationship between individual users and their wearable devices. This transition necessitates a more nuanced examination of how wearable technologies interact with specific physiological and psychological variables, including but not limited to, biofeedback, neurodiversity, and even individual health idiosyncrasies.

Biological Biomarker Technology

In transitioning from the realm of digital sensing of macro-level physiological states, [12] point out that there is an increasing emphasis on the role of biochemical markers—molecules indicative of a range of biological phenomena encompassing behavior, disease manifestations, infection, or exposure to environmental variables. These markers comprise a gamut of organic and inorganic compounds emanating from metabolic activities within the human organism. Within the medical discipline, these molecular-level markers offer invaluable prognostic or predictive insights, thereby serving as instrumental tools for the advent of personalized medicine [60].

The biological fluid of saliva in particular has recently garnered attention as a promising medium for the sensing of such biomarkers and diagnostics [61-63]. Saliva, a clear and mildly acidic complex solution, is produced at a rate of approximately 0.75 to 1.5 liters per day in the human body, originating from the major salivary glands. In a manner functionally analogous to blood serum, saliva contains a variety of biomarkers, including but not limited to hormones, enzymes, antibodies, antimicrobial substances, and growth factors. These biochemical entities find their way into saliva, often translocating from the blood by permeating through intercellular spaces. Consequently, a majority of the key compounds typically present in blood can also be detected in saliva. Therefore, saliva stands as a functional correlate to blood serum, capably mirroring various physiological states of the human organism, be they emotional, hormonal, nutritional, or metabolic [64].

The development of biomarker sensor technology has transitioned from invasive to increasingly non-invasive methods. Economical biosensor platforms have facilitated the identification of biomarkers within biological fluids, accomplished through the deployment of chemically-coated receptors on flexible substrates, such as paper strips or microfluidic channels [65]. Upon collection of biological fluid—whether through spitting or swabbing samples of saliva, sweat, urine, or blood—individuals can place the sample onto these platforms. The chemical receptors on the sensor engage in binding reactions with biomarker molecules, signaling the presence of the biomarker via various means, including chromatic alterations, fluorescence, or electrochemical signals [66].

Among the prevalent techniques for biomarker detection, colorimetric reactions occupy a significant role, particularly within paper-based sensors. Noteworthy developments in this realm include Dermal Abyss, a smart tattoo augmented with colorimetric and fluorescent biosensors that undergo chromatic shifts in response to changes in interstitial fluid [67]. Additionally, as [68] have noted, capillary flow mechanisms have been employed in the detection of salivary biomarkers. Advancements in microfluidics have led to the creation of devices like Ampli—a modular, real-time diagnostic platform comprising paper-based blocks that can be arranged in diverse configurations to facilitate instantaneous, personalized biochemical testing [69].

Wearable Devices to Promote Psychological Health

The domain of wearable technology has not restricted itself solely to the realm of physiological monitoring and enhancement; indeed, a burgeoning body of literature indicates a significant promise in the domain of psychological health. One salient thematic element emerging from the corpus of research is the emphasis on the perceived acceptability and effectiveness of wearable devices in mental health contexts [70]. High levels of user satisfaction, particularly among those with serious mental illnesses, substantiate the broader claim that wearables can serve as effective tools for psychological monitoring [71]. Another thematic avenue explores the intricacies of user interface and design, especially concerning the psychological comfort of the user. Studies such as those conducted by [72] indicate that location preferences for wearables, like the wrist, significantly affect user psychology and therefore the efficacy of these devices. This theme dovetails with the need for patient-centered design considerations, a factor identified as crucial in ensuring the broader acceptability of wearable technology among geriatric populations [73].

A significant discussion in the literature pertains to the quantifiable impact of wearable devices on health behaviors. Devices have been shown to foster increased physical activity, contributing to a more robust psychological state [70,74]. However, cautionary notes are sounded, emphasizing that wearable devices should be viewed as facilitators rather than drivers of health behavior change [75]. The stress of limitations and the need for more precise measurements serve as another noteworthy theme. For instance, [9] note that commonly used metrics such as average heart rate may not be as accurate as more nuanced markers like heart rate variability or electrodermal activity in detecting stress or anxiety. This facet underscores the essential need for technological refinement to ensure that psychological parameters are monitored with utmost precision.

Lastly, a glimpse into the future suggests the integration of wearable devices in advanced psychological practices, including neuro-rehabilitation and stress management (Balconi, Crivelli, Fronda, & Venturella, 2018). Thus, the cumulative evidence supports the assertion that wearables possess transformative potential in mental health contexts. Transitioning from general psychological well-being to more specialized psychological conditions, the literature also presents preliminary but encouraging results concerning the role of wearable devices in neurodivergent populations. These wearables offer the tantalizing possibility of individualized support structures for neurodiverse individuals, thereby marking a significant step towards more inclusive and personalized healthcare paradigms.

Recommendations

The forthcoming section delineates a set of recommendations, formulated through a critical synthesis of the existing body of literature, with a particular focus on the intersectionality of proprioception, invisible disabilities, and workplace dynamics. The corpus of academic scholarship has hitherto provided comprehensive examinations of both traditional and state-of-the-art technologies in biomarker sensing and wearable devices for physical and mental well-being. [28] assert that the interrelationship between proprioception and workplace dynamics is a relatively untapped domain for empirical investigation. According to [29], proprioception, also known as kinesthesia, encompasses the cognitive faculties responsible for sensing bodily movement and spatial orientation—a facet often compromised in individuals with autism spectrum disorders [30].

The introduction of AI into the realm of biofeedback and emotion recognition provides a potential avenue for modifying workplace environments to accommodate these individuals more effectively. [31] delineate how AI-driven biofeedback systems, when synergistically coupled with auditory stimuli such as specially designed musical soundtracks, hold the promise to dramatically enhance individual self-awareness and regulate energy levels in workplace settings. Hence, the ensuing recommendations seek to elucidate specific, actionable strategies aimed at utilizing AI technologies to foster an environment that is not only more inclusive but also conducive to the well-being of all employees, including those with invisible disabilities.

Wearable Devices to Promote Proprioception in Neurodivergent Individuals

The realm of wearable devices offers unprecedented opportunities for fostering proprioception in neurodivergent individuals, particularly those with congenital absence of proprioception due to genetic conditions like PIEZO2 Loss of Function (LOF). A compelling study by [76] outlines the development of a wearable haptic device designed to facilitate proprioceptive feedback through haptic stimuli. The prototype focuses on the elbow joint and utilizes deep pressure applied to the forearm as a form of sensory substitution. In doing so, the device aims to address the absence of pharmacological treatments or assistive technologies explicitly tailored for individuals grappling with PIEZO2-LOF. The preliminary research posits that future endeavors should concentrate on evaluating the device's impact on proprioceptive acuity and movement ability in both healthy and PIEZO2-LOF populations, while also exploring the potential of soft robotics and multi-joint sensory substitution.

Further expansion into the application of wearable technology for individuals diagnosed with ASD has been explored by [77]. The authors present a ground-breaking, robot-based approach using artificial intelligence. Their wearable robot adopts a first-person perspective, addressing the limitation of traditional robotics, which often fail to capture the third-view cognitive capabilities. The system utilizes reinforcement learning to adapt to interactive environments, thereby enhancing the wearer’s social interaction skills. The wearable robot seeks to meet the dynamic and highly individualized requirements of children with autism, thereby filling a critical gap in existing AI-based treatment paradigms.

Extending the discussion to the so-called “high-functioning” end of the autism spectrum, [78] delve into the efficacy of wearable and mobile systems for emotional self-regulation. Their experimental approach utilizes Taimun-Watch, a smartwatch system previously tested with individuals in the low-functioning range of the autism spectrum. Although a small sample size, the findings suggest that individuals with Level 1 Autism can, with a more protracted customization process, utilize the technology to recover from stress episodes effectively. The caveat here is that the sharper, more complex cognitive abilities and perceptions of individuals with HFA make the customization of effective self-regulation strategies a more time-consuming endeavor.

Simultaneously, [79] provide a panoramic view of wearable assistive technologies for autism, mapping out both the opportunities and challenges inherent in this evolving field. Their review elucidates several key areas of interest and difficulty—social interaction and communication, stereotypical behavior, and sensory processing and attention. Each of these domains presents its own unique set of challenges for autistic individuals, from difficulties in attending and responding to social cues to sensory processing impairment. Significantly, the authors point to the considerable variance in autistic individuals' sensory and communicative challenges, positing additional complexities in designing Wearable Assistive Technologies (WAT) that can adaptively cater to such a diverse user base.

Within the framework of sound therapy, an interesting avenue emerges for the integration of auditory stimuli with wearable technology [80]. The utilization of specific sound frequencies, calibrated to the individual’s heart rate, aims to engage the parasympathetic nervous system, thereby fostering a state of relaxation and homeostasis. Products such as EVOKE from Widex, a smart hearing aid, have already been designed to provide adaptive auditory experiences. By monitoring environmental sounds, these devices can enhance the listener's ability to focus on specific auditory stimuli, such as conversations, while simultaneously mitigating background noise [81]. Such interventions pave the way for targeted sound therapies that could prove particularly efficacious for individuals with heightened sensitivities, such as those on the autism spectrum. The advent of haptic feedback in wearable technology extends the multisensory potential of these devices. For instance, the Nadi X smart yoga pants from WearableX offer real-time proprioceptive feedback through embedded sensors and vibrations, which aim to improve body alignment during yoga exercises [82]. Even more ambitious are Google’s plans for interactive garments with multiple haptic feedback points, providing a comprehensive, multisensory experience [83,84].

Thus, the rapidly expanding domain of wearable technology offers a plethora of applications geared toward enhancing sensory perception and emotional self-regulation. Given the unique sensory and emotional needs of neurodivergent individuals, such as those with autism, these technological advancements offer promising pathways for targeted, personalized interventions. Sound therapy, haptic feedback, and the burgeoning field of "smart" garments all contribute to a more inclusive and adaptive landscape, one in which wearable technology evolves beyond a one-size-fits-all model to cater to the diverse needs of a neurodiverse population.

Conclusion

The corpus of this scholarly investigation has sought to elucidate the emerging nexus between wearable technology and sensory perception, with particular emphasis on neurodivergent populations such as individuals with autism spectrum disorders. In a world increasingly dominated by technology, the ascendancy of wearable devices offers unprecedented opportunities for improving the quality of life of neurodivergent individuals. However, an in-depth analysis reveals a lacuna: a dearth of consumer applications specifically tailored to the unique physiological and psychological needs of these populations.

Key takeaways underscore the technological advances in biomarker sensing, the transformative potential of AI-driven biofeedback systems in workplace settings, and the burgeoning field of haptic technology. Technologies such as smart hearing aids, smart garments with embedded sensors, and smartwatches have shown promise in facilitating adaptive behavior and enhancing sensory perception. Yet, their current form seldom caters to the unique sensory sensitivities and social communication difficulties often encountered within neurodivergent communities.

As technology continues to permeate various facets of human life, a critical need arises for multidisciplinary research that explicitly addresses the sensory and emotional challenges specific to neurodivergent individuals. The intriguing interplay between proprioception and workplace dynamics, especially as modulated by auditory stimuli, holds considerable promise for further inquiry. Future research endeavors must be guided by three primary imperatives: 1) development of more consumer applications with specific focus on neurodivergent populations; 2) rigorous empirical assessment to ensure the efficacy and adaptability of these technologies; and 3) engagement with ethical considerations, such as data privacy and user consent, which are often overlooked yet crucial components of technology deployment.

While research in this domain is still in its nascent stages, the potential for significant societal impact cannot be overstated.

A paradigm shift is needed from generalized to individualized solutions, especially as consumer demands evolve in tandem with technological advancements. Thus, as the tapestry of this dynamic field continues to unfold, the onus falls upon researchers, technologists, and policy-makers alike to ensure that the spectrum of wearable technology applications embraces the full spectrum of human neurodiversity.

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