ARTICLE

Gamified Mobile Health Strategies for Promoting Physical Activity in Autistic Adults

Daehyoung Lee[1], Georgia C. Frey[2], and Patrick C. Shih[3]

[1]Department of Health Behavior and Nutrition Sciences, University of Delaware, Newark, DE; [2]Department of Kinesiology, Indiana University, Bloomington, IN; and [3]Department of Informatics, Indiana University, Bloomington, IN

LEE, D., G.C. FREY, and P.C. SHIH. Gamified mobile health strategies for promoting physical activity in autistic adults. *Exerc. Sport Sci. Rev.*, Vol. 53, No. 2, pp. 68–76, 2025. *Physical inactivity and sedentarism among autistic adults are a growing public health concern. By integrating behavior change theories and emphasizing unique preferences for visuospatial learning and gaming technology, we hypothesize that gamified mobile health (mHealth) applications can be effective at increasing free-living physical activity and reducing sedentary behavior in autistic adults.* **Key Words:** physical activity, sedentary behavior, autism, gamification, mobile health

KEY POINTS

- Autistic adults are at elevated risk of chronic physical and mental health conditions, and insufficient physical activity and prolonged sitting may worsen their already compromised health status.
- Leveraging a natural affinity for gaming technology and a preference for predictable interactive environments, gamification and behavior change techniques-guided mHealth interventions show promise in increasing physical activity and reducing sedentary behavior in autistic adults.
- To effectively promote physical activity in autistic adults, we introduce the ICE principles — Individualized, Characteristic-oriented, and Evidence-based strategies — as practical, tailored guidelines to address their unique social and behavioral characteristics.
- A recent proof-of-concept study demonstrated the potential of a gamified mHealth application, PuzzleWalk, to increase moderate-to-vigorous physical activity and reduce sedentary time among autistic adults in real-world settings.

INTRODUCTION

Autism spectrum disorder (ASD) is a lifelong neurodevelopmental condition characterized by social interaction and communication difficulties and repetitive and restricted behavioral patterns and interests (1). The prevalence of ASD in the United States has increased approximately 317% in the past 24 years from 1:150 children in 2000 to the current prevalence of 1:36 children (2). Among adults, over 5.4 million Americans, or 2.2% of the population, live with ASD (3). The male-to-female ratio is approximately 4:1 in both pediatric (2) and adult populations (3). The increased incidence of ASD has led to increased awareness of and attention to health disparities in this population, particularly among autistic adults (4).

Autistic adults typically exhibit poorer health outcomes compared to neurotypical individuals (5). Examining a sample of over 1,500 autistic adults in the United States, Croen *et al.* (6) called attention to a myriad of physical and mental health conditions in this population, including but not limited to obesity, hyperlipidemia, type 2 diabetes, depression, and anxiety, among other conditions. A retrospective medical chart review also reported a high prevalence of overweight and obesity among autistic adults (7). It is projected that these health disparities will continue to grow (8), placing autistic adults into a new minority group who are at elevated risk of chronic physical and mental health conditions across the lifespan (6,9). The onset of such health concerns typically initiates in childhood and likely persists into adulthood (10,11). The chronic diseases in autistic people likely are linked to unhealthy lifestyles, such as physical inactivity and excessive sedentary behavior (SB), similar to what is frequently observed in neurotypical populations (12,13). Physical activity (PA) has been recognized as a mediator for addressing social, behavioral, and mental health issues in autistic individuals, serving as an alternative or complementary treatment to pharmaceutical and psychological approaches, but there is a paucity of research in this area (14,15).

Health-enhancing mHealth, particularly leveraging gamification techniques, has shown promise in motivating changes in PA and SB in autistic adults and deserves further investigation given the well-documented predilection for gaming technology use in these individuals (15,16). Autistic adults exhibit a higher preference for technology use and gaming compared to non-

Address for correspondence: Daehyoung Lee, Ph.D., Department of Health Behavior and Nutrition Sciences, College of Health Sciences, University of Delaware, 26 North College Avenue, CSB 013, Newark, DE 19716 (E-mail: dhlee@udel.edu).
Accepted for publication: December 4, 2024.
Editor: Marni D. Boppart, Sc.D.

0091-6331/5302/68–76
Exercise and Sport Sciences Reviews
DOI: 10.1249/JES.0000000000000353

autistic adults (16,17), highlighting the need for more strength- and preference-based approaches in behavior change interventions. We hypothesize that gamified mHealth tailored to distinct characteristics and strengths of autistic individuals can be an effective strategy to increase PA and reduce SB in autistic adults in real-world environments. Understanding preventive health behaviors and validating innovative research approaches in mHealth are crucial for helping this population avoid developing chronic diseases associated with physical inactivity and sedentarism (18).

MIXED RESULTS ON PA AND SB LEVELS IN AUTISTIC INDIVIDUALS

Limited data exist on PA and SB as components of preventive health in autistic adults (19). Most research has focused on children and adolescents, with outcomes suggesting that youth with ASD exhibit either lower PA levels (20) or comparable PA participation to their neurotypical peers (21). Of particular note was the age-related decline in moderate-to-vigorous PA (MVPA) (22). Jones *et al.* (23) systematically analyzed 35 studies on PA, SB, and their correlates in children with ASD and reported a consistent inverse association between age and PA, highlighting a declining trend of overall PA levels with age in this population. Although it is unclear how PA and SB levels change in adulthood, autistic adults often perceive and experience barriers to PA participation, such as lack of intrinsic motivation for exercise and transportation support, perceiving exercise as boring (24), poor self-efficacy, and negative social comparison and past experience (25). Beyond individual and environmental barriers, factors like unique sensory sensitivities and fewer social and recreational opportunities can make it difficult for autistic adults to engage in PA and can lead to increased SB (26). In an earlier study relying on parental proxy reports, autistic adults engaged in MVPA only once a week while spending an average of 13 $h{\cdot}d^{-1}$ in SB (27). Two recent studies employing accelerometer-based objective measurements revealed that autistic adults may exhibit both adequate levels of PA and excessive SB by accumulating the recommended 150 min of MVPA per week and also spending 9 to 16 $h{\cdot}d^{-1}$ sitting (28,29). It remains uncertain whether these individuals modify or sustain their behavioral patterns amid expectations of independent healthy behaviors in adulthood.

Sedentary behavior is viewed as an independent health risk factor because physically active people can still face serious health consequences from sitting or reclining for too long (30). Past studies have established a correlation between prolonged sedentary time and an elevated risk of developing a range of chronic physical and mental health problems in neurotypical adults, including cardiovascular disease, obesity, depression, and anxiety (31,32). Dhanasekara *et al.* (33) also observed the increased risk of cardiometabolic diseases, including diabetes, dyslipidemia, and heart disease, among autistic individuals as compared to neurotypical individuals. Although etiological factors such as medications and maternal obesity contribute to cardiometabolic diseases in autistic individuals, lifestyle factors, including SB, may play a crucial role in moderating this association (33). Excessive and uninterrupted SB may be one of the factors causing a high incidence of lifestyle-related chronic diseases in autistic adults (6). The *2018 PA Guidelines for Americans* (34) and *Healthy People 2030* highlight the role of regular PA participation and reducing SB in overall health. American adults, including autistic adults, tend to become more sedentary with age, with 50% of the adult population spending more than 9.5 h sedentary each day (35). Physical activity guidelines and SB recommendations for the general population also apply to autistic adults, but the limited existing data suggest that these individuals may not be meeting these guidelines/recommendations (36).

Despite ongoing efforts, sample and methodological heterogeneity make it difficult to synthesize the previous findings on PA and SB in autistic adults. The literature consistently emphasizes the inherent diversity within ASD, spanning behavioral, cognitive, psychosocial, and neurobiological dimensions (37). Although common autistic traits exist as diagnostic criteria, levels of functional abilities and health outcomes vary significantly among autistic individuals. Moreover, co-occurring clinical conditions such as gastrointestinal issues, epilepsy, and intellectual disability (ID) often exist, further illustrating the diverse nature of this *spectrum* disorder (6). Studies comparing autistic adults with and without ID reveal that individuals identified as higher functioning showing greater autonomy and decision-making capabilities often exhibit poorer health profiles than those with co-occurring ID (38,39). Research suggests that autistic adults without ID are significantly more likely to experience lifestyle-related chronic diseases such as obesity, hypertension, diabetes, and substance use disorders (38), as well as mental health problems including depression and anxiety (39). Therefore, it is critical to identify and provide more prevention-focused strategies promoting physically active lifestyles for autistic adults who experience a broad range of symptoms and levels of functional independence.

Methodological heterogeneity in measurement instruments presents another challenge in research on PA and SB in autistic adults. The use of research-grade accelerometry for assessing free-living PA and sedentary time is favored for its high reliability and accuracy as compared to retrospective self-reports (40). However, accelerometer-based approaches present elevated participant burden and costs, posing difficulties for application in large population-based studies (41). In addition, sensory over-responsivity across various sensory domains (*e.g.*, vision, tactile) is common in autistic adults (42), and, thus, wearing an unfamiliar accelerometer for an extended period can cause sensory overreaction and negatively affect the adherence rate in this population (43). Sensory over-responsivity in autistic individuals is associated with heightened tactile sensitivity, which can make wearing devices like accelerometers uncomfortable or distressing (42). The continuous physical sensation caused by the accelerometer may induce avoidance behaviors or noncompliance, significantly hindering their ability to wear the device consistently. Self-report methodologies offer a more cost-effective, less burdensome, and accessible option for estimating PA and sedentary time (44). However, the concordance between objective and subjective instruments has not been consistently robust, with a tendency to overestimate MVPA and underestimate sedentary time via self-reports (45). This measurement bias raises concerns about the reliability of self-reports as a trustworthy measure (44). Lee *et al.* (29) assessed the degree of agreement between accelerometry-derived and self-reported PA and sedentary time in autistic adults without ID using ActiGraph GT3X+ waist-worn accelerometers (Pensacola, FL) and the International Physical Activity

Questionnaire — Short Form (IPAQ-SF) (46). The results reiterated previous findings in neurotypical samples, as autistic adults significantly overreported MVPA and underreported sedentary time via the IPAQ-SF compared to ActiGraph accelerometry (29).

PA INTERVENTIONS FOR AUTISTIC ADULTS

Most PA interventions for autistic adults have used structured exercise protocols, such as supervised aerobic sessions, gym-based resistance or sports training, and leisure activities (47). Few studies have attempted to increase free-living PA using everyday activities like walking. Lalonde *et al.* (48) employed a reinforcement-based and goal setting–oriented intervention to promote daily walking steps in five young autistic adults who were enrolled in a special education program. All participants increased their step counts to levels sufficient for health benefits, surpassing the 10,000 steps per day threshold (48). Although these findings are promising, the highly controlled nature of the intervention and the small sample of participants with ID restrict the generalizability of the results. Existing PA interventions in autistic adults often lack methodological rigor within study designs due to restricted age ranges, use of small and less representative samples, reliance on subjective or proxy measures, and absence of effect size calculations (47). Additionally, the lack of everyday PA interventions presents a significant gap in effective strategies to promote lifestyle modifications for increasing daily PA in autistic individuals (23). There is a need for more comprehensive PA intervention studies that focus on incorporating free-living PA for sustainable health benefits. These studies should include larger and more diverse samples, encompassing individuals with and without co-occurring ID (14).

Despite limited research on free-living intervention studies, PA and exercise have exhibited moderate efficacy as motor and social interventions for children and adults with ASD (49,50). A meta-analysis revealed that exercise enhances motor skills and social competency among autistic individuals (49). Individualized PA programs yielded greater improvements in both domains than group interventions (49), which may be explained by the social deficits commonly observed in this population (51). However, small sample sizes precluded definitive and conclusive outcomes from the reported results (49,50). A recent systematic review analyzed 22 experimental studies that explored the impact of PA and exercise interventions in young autistic adults (n = 763). Findings provided moderate-to-strong evidence for positive improvements in motor outcomes, physical fitness, and psychological function following a range of movement interventions (47). Despite promising functional outcomes, there is an insufficient body of evidence to validate sustained change in PA levels as a result of exercise interventions in autistic adults (47).

There also exists empirical support for the beneficial effects of acute exercise on mental health in autistic individuals. Hillier *et al.* (52) observed a reduction in both salivary cortisol levels and self-reported anxiety following a weekly session of low-intensity exercise in autistic youth and adults. Although sustained effects were not observed throughout the 8-wk intervention, the findings propose that light PA or low-intensity exercise may benefit mental health in this demographic (52). The literature demonstrates that PA and exercise may act as a preventive medicine for both physical and mental health in autistic adults (47,52). Nevertheless, evidence gaps remain in the autism behavioral health literature, particularly regarding how the behavioral and neurodevelopmental variability in ASD should be considered when developing interventions. Further, there appear to be no interventions specifically addressing SB in this population. Innovative and accessible interventions that are tailored to a) the functional level of those with ASD, b) individual characteristics or symptoms, and c) evidence-based health promotion strategies are necessary to mitigate health disparities in autistic adults (18,47,53).

Engagement in health-enhancing PA and reducing SB among autistic adults may be best facilitated by mHealth applications (apps). It is well-documented that autistic individuals' inclination toward technology stems from the predictability of human-technology interactions and their preference for visuospatial learning, thereby reducing social burdens associated with in-person, face-to-face interactions (54). Limited research has reported that autistic adults spend an average of over 4 $h \cdot d^{-1}$ using mobile devices to engage in activities, such as social media use, Internet browsing, and gaming (55). The widespread adoption of mobile technology within autism studies focuses on expanding learning opportunities and improving social skills, emotional regulation, and occupational functioning for independent living (54). Efforts also have been made to address physical fitness among children with ASD through mobile app-based video modeling, showing potential for increasing energy expenditure and heart rate (56). However, these beneficial outcomes were restricted to children with ASD who needed extensive support and supervision to effectively carry out the exercise program (56). It is imperative to develop and validate preventive health interventions that align with the autonomous health behavior choices of self-determined, free-living autistic adults. Although mHealth-based interventions can offer autistic adults enhanced personalization and motivation for behavior change (57), addressing practical issues, such as the lack of guidelines for intervention delivery and validation protocols, relatively short-term user adherence, and disparities in access to technology devices, remains crucial for the sustainable delivery of mHealth interventions for autistic adults (58). Health behavior researchers and service providers should recognize that individuals from lower socioeconomic backgrounds may face additional barriers to accessing necessary technology devices and Internet services, which can potentially limit the reach and impact of mHealth or digital interventions among autistic adults (58).

Although mHealth apps have proliferated in commercial markets, their designs rarely incorporate the distinct characteristics of autistic adults, such as preference for sameness, avoidance of uncertainty, and adherence to routines (1). Moreover, autistic adults often have low self-efficacy and intrinsic motivation for voluntary health behavior changes (51). As such, traditional self-monitoring mHealth apps are less likely to induce positive changes in PA and SB among autistic adults. When developing mHealth systems for behavior changes in autistic individuals, it is essential to employ user-centered design principles, ensuring all design decisions and functional features are tailored to the distinct needs and behavioral characteristics of the target audience in real-world environments (59). To empower autistic adults through positive PA and SB changes, we propose a framework that integrates "ICE" principles into a mHealth intervention design focusing on Individualized, Characteristic-oriented, and Evidence-based behavior change strategies (Fig. 1). Individualized: In real-world settings, interventions should be adaptable to each participant's specific needs, interests, and preferences. Personalizing PA goals, feedback, and reminders could enhance self-efficacy and motivation and help overcome environmental barriers. Characteristic-oriented: mHealth-based PA interventions also should account for the social and behavioral characteristics of autistic individuals, such as sensory sensitivities and challenges with traditional social interactions and routine disruptions. Designing and delivering strength-focused behavior change strategies (*e.g.*, online social engagement, visuospatial learning) could improve the acceptability of novel interventions in this population. Evidence-based: To establish and validate the long-term effectiveness of mHealth interventions, they should be grounded in PA behavior change theories and evidence-based guidelines (*e.g.*, ≥150 min of MVPA per week and ≤8 h of sedentary time per day).

GAMIFICATION AND BEHAVIOR CHANGE TECHNIQUES-GUIDED MHEALTH INTERVENTION DESIGN FOR PA PROMOTION

Gamification is "the use of game design elements in non-game contexts" (60). In the realm of mHealth apps, gamified approaches incorporate game-like features such as point systems, problem-solving mechanisms, and leaderboards to initiate targeted behavior changes (61). Gamified behavior change interventions reflect a rapid technological advancement for promoting health behaviors in accessible and cost-effective ways (62). Beyond providing users with a sense of enjoyment, gamification also can enhance feelings of autonomy, competence, and relatedness, aligning with the psychological principles of Self-Determination Theory (SDT). The application of SDT in gamification is emerging and can offer valuable insights into various aspects of gamification design and research, particularly by supporting a continuum of motivation that can facilitate the adoption and sustained use of app (63,64). Schmidt-Kraepelin *et al.* (65) identified eight archetypes of the prevalent gamification approaches in commercial mHealth apps, highlighting the diversified strategies for health promotion, such as competition and collaboration, goal setting, and positive and negative reinforcement. Moreover, incentivizing behavioral changes has represented a promising tactic for tackling physical inactivity and prolonged SB across diverse populations, particularly among individuals with poor motivation for PA participation (66).

Gamified incentivization of behavior change (*e.g.*, financial and social incentives based on step counts) demonstrated great potential to elevate extrinsic motivation and increase PA among inactive (67) and obese adults (68). Patel *et al.* (68) conducted a 36-wk randomized controlled trial to assess the impact of three types of social gamification strategies (*i.e.*, competition, support, and collaboration) on increasing daily steps among neurotypical overweight and obese adults (n = 602). Participants were equipped with wearable devices and randomly assigned to one of three gamification interventions or a control group. All three gamified approaches effectively increased step counts during the 24-wk intervention period, with the competition arm demonstrating the most pronounced effect (68). Although the level of PA decreased across all groups during the follow-up period, this study highlighted the potential of gamification, particularly in initiating PA behavior changes through competitive gamification elements among overweight and obese adults. Francis *et al.* (69) conceptualized and validated the effectiveness of a Fitbit-incorporated gamified app "MapTrek" on increasing PA in neurotypical adults at elevated risk of type 2 diabetes in a large-scale randomized controlled trial (n = 388). The MapTrek group engaged in weekly virtual races during the 6-month intervention where participants competed with others achieving a similar number of steps. The study estimated a 97% probability that the use of MapTrek could result in over 1,000 additional steps per day, significantly

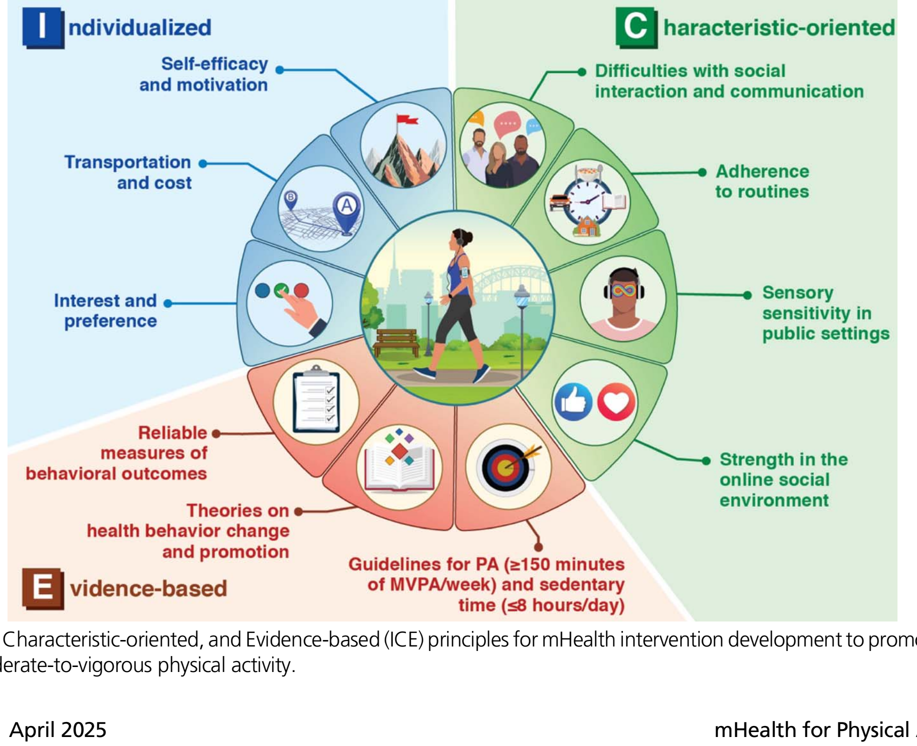

Figure 1. Individualized, Characteristic-oriented, and Evidence-based (ICE) principles for mHealth intervention development to promote physical activity (PA) in autistic adults. MVPA, moderate-to-vigorous physical activity.

increasing the voluntary engagement in walking activities (69). It is expected that gamification in mHealth will continue to attract considerable attention from healthcare disciplines as an effective strategy for screening, monitoring, and managing behavioral health with particular focus on PA and mental health (70). However, the acceptability and adoptability of gamified mHealth remains an open subject in the autism community. Also, gamification strategies in general e-health, including mHealth, tend to induce relatively short-term participant adherence, emphasizing the need for robust empirical evidence and more integrated solutions grounded in health behavior change and promotion theories that lead to long-term adherence (70).

Although gamification is gaining notable attention in mHealth apps, there is criticism regarding its long-term effectiveness on PA and SB changes, particularly due to the lack of scientific validation or integration of behavior change theories in the design and developmental foundation of mHealth apps (71). Behavior Change Techniques (BCTs) represent a theoretically grounded approach aimed at modifying psychological determinants of behavior, such as self-efficacy and attitude (72). The accessibility of mobile technologies has provided a viable and cost-effective avenue for the delivery of diverse BCTs within real-world settings. Major app stores (*e.g.*, App Store and Google Play) offer over 325,000 apps dedicated to promoting health and PA (73). Despite the potential of mHealth apps to increase PA engagement, the majority of these apps lack a foundation in BCTs or other behavior change theories, and only a few have undergone rigorous scientific evaluation (74). Nearly 170 leading apps designed for monitoring or promoting PA were systematically reviewed (75), and the findings revealed that incorporation of BCTs in the top-ranked apps was not widespread. The absence of systematic evaluation raised uncertainty regarding the effectiveness of mHealth apps on inducing long-term PA behavior change. Thus, it is unclear whether positive health outcomes (*e.g.*, increased daily steps or decreased sedentary time) are attributable to robust intrinsic motivation or other contributing factors (75). Nonetheless, mHealth apps that integrate BCTs, specifically emphasizing goal setting, reward systems, and self-monitoring of performance, offer potential for initiating PA and SB changes in real-world environments (76). Prioritizing evidence-based and customized BCTs is especially critical when developing and implementing PA and SB interventions for autistic individuals given their diminished social motivation and constrained repertoires of behavioral patterns or interests (77).

PUZZLEWALK: GAMIFIED MHEALTH FOR PA PROMOTION IN AUTISM

"PuzzleWalk," a gamified PA-enhancing mobile app designed for autistic adults, underwent a participatory, user-centered iterative development process (55,78). This collaborative development process incorporated a literature review on ASD, needs analysis, prototype design, usability testing, and field deployment, which adhered to the modified IDEAS framework (*i.e.*, Integrate, Design, Assess, and Share) (79). Preliminary user feedback was gathered through surveys and individual interviews with key stakeholders, including autistic adults, parents, autism-focused therapists, and experts in PA and autism research. The feedback led to significant refinements, such as simplifying the prototype interfaces and incorporating interactive gamification features. These features included "travel around the world" storylines, three different difficulty levels for puzzle games, and leaderboards based on step counts and puzzle points, which ensured the app met the specific preferences and interests of autistic users (55,78). The PuzzleWalk design leveraged several BCTs, including a visualized, comprehensive user guide, self-monitoring of target performance (*i.e.*, increasing daily steps), contingent rewards, and goal setting (72). The development of the PuzzleWalk app also was grounded in SDT, addressing three core psychological needs — autonomy, competence, and relatedness — as critical elements for motivation and engagement in gamified contexts (80). To enhance autonomy, the app allows users to customize their experience by selecting preferred puzzle games and activity types, setting individualized step goals, and monitoring their progress at daily, weekly, and monthly intervals. Competence is supported through structured, visual step-by-step guides for new users (*e.g.*, functional features of icons, concept of step-game playtime conversion), alongside consistent positive reinforcement for PA engagement (*e.g.*, motivational messages aimed at encouraging users to increase their step counts). Finally, a gamified leaderboard enables interactive competition with other autistic users, cultivating a sense of relatedness and community among users (78,81).

PuzzleWalk utilizes a visual cognitive task, specifically "spot the difference" puzzle games featuring over 600 famous global city images (78,81). The choice of this format was based on findings from the preliminary needs and preference analysis conducted in collaboration with autism community stakeholders, including autistic adults. The simplicity and straightforwardness of the "spot the difference" puzzle games allow autistic users to easily understand the game's objective and quickly capture their interest without demanding intricate cognitive processing (78,81). Furthermore, visually attractive game designs were intended to leverage the distinct strengths of visuospatial learning in autistic individuals. The notable aspect of PuzzleWalk lies in its incorporation of a conversion algorithm that translates the user's accumulated step counts into game playtime (*e.g.*, 1 step count is equivalent to 1 s of game playtime), serving as a motivational strategy for PA engagement (78,81). The steps taken by the user are directly converted into time for gameplay, which incentivizes regular PA participation. This gamified token economy strategy is a key element that differentiates PuzzleWalk from other conventional PA-promoting apps in commercial markets (15). Lastly, PuzzleWalk employs a gamified leaderboard system that offers tangible rewards, such as gift cards, to top scorers based on their puzzle scores and accumulated steps (15,78). The implementation of the gamified leaderboard aligns with the BCT of providing tangible rewards contingent on quantifiable changes directed toward accomplishing the target behavior (Fig. 2).

Our feasibility randomized controlled trial compared the effectiveness of PuzzleWalk with that of the commercial activity-tracking app Google Fit in increasing daily PA and reducing sedentary time and anxiety in autistic adults without ID. Over a 5-wk intervention period, 24 autistic adults (M_{age} 29.5 ± 9.7; 63% females) were randomly assigned to either app and wore a research-grade triaxial accelerometer during waking hours (15). All measures were collected at baseline

Figure 2. Functional interfaces of a gamified, physical activity–promoting app PuzzleWalk [Adapted from (78,81). Copyright © 2020 The Authors. CC BY-NC 4.0 & CC BY 4.0.]

and during the 5-wk intervention and compared between the two groups and time points using repeated-measures ANCOVA and spearman rank correlation analyses. The use of PuzzleWalk moderately increased MVPA and reduced sedentary time in autistic adults without ID, and this was comparable to the use of Google Fit (15). Although the level of user engagement (*e.g.*, app usage time) was high among PuzzleWalk users compared to Google Fit users throughout the intervention period ($F_{2,38} = 5.07$; $P = 0.01$; partial $\eta^2 = 0.21$), the positive changes in MVPA did not persist until the end of the intervention period (15) (Fig. 3). Interestingly, the perceived anxiety of participants was inversely associated with the reduced sedentary time and increased light PA, as well as total activity and step counts immediately following the intervention (all $P < 0.05$) (15). It was suggested that these unexpected results might be attributed to the disruption of routinized behavioral patterns, which led to unintended short-term negative effects on perceived mental health (82). We acknowledge that, although the PuzzleWalk mHealth intervention shows promise, there are potential limitations regarding scalability and long-term user adherence. Scaling

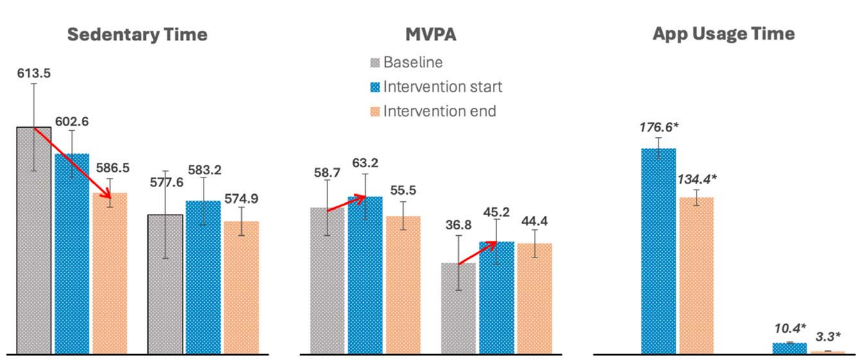

Figure 3. Between- and within-group comparisons of sedentary time, moderate-to-vigorous physical activity (MVPA), and app usage time (min·d^{-1}; $n = 12$ for each arm. Behavioral outcomes were measured at baseline (week 1), intervention start (week 4), and end (week 8). [Adapted from (15). Copyright © 2022 The Authors. CC-BY.]

the intervention to diverse autism populations, including those with co-occurring ID, may require further adaptations to address varying needs and ensure technological accessibility. There is a critical need for longitudinal research to evaluate the sustained effectiveness of gamified, behavior change theory–guided mHealth systems in improving both physical and mental health in autistic adults with varying levels of support needs. Future research also should examine the dose–response relation between PA, SB, and mental health profiles in this population segment.

CONCLUSIONS

The unique social and behavioral characteristics of ASD present persistent challenges that often limit autistic adults' ability to regularly engage in PA and reduce SB, which has negative consequences on overall health. Emerging evidence points to the unmet need for effective behavior change strategies to address health disparities among autistic adults. Gamification and BCT-guided mHealth interventions including PuzzleWalk demonstrate promise in increasing PA and reducing SB in this population. In particular, the design strategies implemented in PuzzleWalk resulted in greater user engagement compared to a widely used commerci app. However, further longitudinal research is needed to evaluate its potential to support sustainable health outcomes.

Building on previous findings, the authors propose the ICE principles (*i.e.*, Individualized, Characteristic-oriented, and Evidence-based strategies) as practical guidelines for designing mHealth PA interventions. This highlights the importance of a user-centered, participatory research methodology tailored to the diverse health profiles of autistic adults. Health practitioners should consider incorporating gamification elements into PA interventions to increase voluntary and sustainable PA engagement within this population. Additionally, funding for research on digital interventions that address the specific needs and preferences of autistic individuals is crucial for developing effective public health interventions. This review underscores the urgency for more innovative and accessible interventions to promote healthy and active lifestyles in autistic individuals with a wide range of functional abilities and symptoms. Future research should prioritize randomized controlled trials and longitudinal studies with larger and more diverse samples to validate the effectiveness of gamified mHealth strategies for autistic individuals in real-world settings. Examining the sustained cause-effect relationships between various gamification elements and the behavioral and mental health outcomes of autistic individuals will be critical for establishing robust empirical evidence supporting this novel approach.

Acknowledgments

The PuzzleWalk development and research were funded in part by the Indiana University Office of the Vice President for Research, the American College of Sports Medicine Foundation, and the Autism Intervention Research Network on Physical Health.
The authors declare that they have no conflicts of interest.

References

1. American Psychiatric Association. *Diagnostic and Statistical Manual of Mental Disorders*. 5th Edition. Washington (DC): American Psychiatric Publishing; 2013.
2. Maenner MJ, Warren Z, Williams AR, et al. Prevalence and characteristics of autism spectrum disorder among children aged 8 years — Autism and Developmental Disabilities Monitoring Network, 11 sites, United States, 2020. *MMWR Surveill. Summ.* 2023; 72(SS-2):1–14.
3. Dietz PM, Rose CE, McArthur D, Maenner M. National and state estimates of adults with autism spectrum disorder. *J. Autism Dev. Disord.* 2020; 50:4258–66.
4. Fombonne E, Green Snyder L, Daniels A, Feliciano P, Chung W. Psychiatric and medical profiles of autistic adults in the SPARK cohort. *J. Autism Dev. Disord.* 2020; 50(10):3679–98.
5. Weiss JA, Isaacs B, Diepstra H, et al. Health concerns and health service utilization in a population cohort of young adults with autism spectrum disorder. *J. Autism Dev. Disord.* 2018; 48(1):36–44.
6. Croen LA, Zerbo O, Qian Y, et al. The health status of adults on the autism spectrum. *Autism.* 2015; 19(7):814–23.
7. Thom RP, Palumbo ML, Keary CJ, Hooker JM, McDougle CJ, Ravichandran CT. Prevalence and factors associated with overweight, obesity, and hypertension in a large clinical sample of adults with autism spectrum disorder. *Sci. Rep.* 2022; 12(1):9737.
8. Tyler CV, Schramm SC, Karafa M, Tang AS, Jain AK. Chronic disease risks in young adults with autism spectrum disorder: forewarned is forearmed. *Am. J. Intellect. Dev. Disabil.* 2011; 116(5):371–80.
9. Mandell DS. Adults with autism — a new minority. *J. Gen. Intern. Med.* 2013; 28(6):751–2.
10. Vasa RA, Keefer A, Reaven J, South M, White SW. Priorities for advancing research on youth with autism spectrum disorder and co-occurring anxiety. *J. Autism Dev. Disord.* 2018; 48(3):925–34.
11. Karpur A, Lello A, Frazier T, Dixon PJ, Shih AJ. Health disparities among children with autism spectrum disorders: analysis of the National Survey of Children's Health 2016. *J. Autism Dev. Disord.* 2019; 49:1652–64.
12. Anderson E, Durstine JL. Physical activity, exercise, and chronic diseases: a brief review. *Sport Med. Heal Sci.* 2019; 1(1):3–10.
13. Dempsey PC, Matthews CE, Dashti SG, et al. Sedentary behavior and chronic disease: mechanisms and future directions. *J. Phys. Act. Health.* 2020; 17(1):52–61.
14. Hallett R. Physical activity for autistic adults: recommendations for a shift in approach. *Autism Adulthood.* 2019; 1(3):173–81.
15. Lee D, Frey GC, Cothran DJ, Harezlak J, Shih PC. Effects of a gamified, behavior change technique–based mobile app on increasing physical activity and reducing anxiety in adults with autism spectrum disorder: feasibility randomized controlled trial. *JMIR Form Res.* 2022; 6(7):e35701.
16. Hassrick EM, Holmes LG, Sosnowy C, Walton J, Carley K. Benefits and risks: a systematic review of information and communication technology use by autistic people. *Autism Adulthood.* 2021; 3(1):72–84.
17. Engelhardt CR, Mazurek MO, Hilgard J. Pathological game use in adults with and without autism spectrum disorder. *PeerJ.* 2017; 5:e3393.
18. Lee D. Knowledge gaps in mobile health research for promoting physical activity in adults with autism spectrum disorder. *Front. Psychol.* 2021; 12:635105.
19. Thompson C, Brook M, Hick S, Miotti C, Toong R, McVeigh JA. Physical activity, sedentary behaviour and their correlates in adults with autism spectrum disorder: a systematic review. *Rev. J. Autism. Dev. Disord.* 2023; 10(3):546–62.
20. Stanish HI, Curtin C, Must A, Phillips S, Maslin M, Bandini LG. Physical activity levels, frequency, and type among adolescents with and without autism spectrum disorder. *J. Autism Dev. Disord.* 2017; 47(3):785–94.
21. Bandini LG, Gleason J, Curtin C, et al. Comparison of physical activity between children with autism spectrum disorders and typically developing children. *Autism.* 2013; 17(1):44–54.
22. Liang X, Haegele JA, Healy S, et al. Age-related differences in accelerometer-assessed physical activity and sleep parameters among children and adolescents with and without autism spectrum disorder: a meta-analysis. *JAMA Netw. Open.* 2023; 6(10):e2336129.
23. Jones RA, Downing K, Rinehart NJ, et al. Physical activity, sedentary behavior and their correlates in children with autism spectrum disorder: a systematic review. *PLoS One.* 2017; 12(2):1–24.
24. Healy S, Brewer B, Laxton P, et al. Brief report: perceived barriers to physical activity among a national sample of autistic adults. *J. Autism Dev. Disord.* 2022; 52:4583–91.
25. Parsons K, Payne S, Holt N, Wallace J. A qualitative study of physical activity drivers in autistic individuals using COM-B. autistic and non-autistic perspectives. *Res. Autism Spectr. Disord.* 2024; 111:102331.
26. Blagrave AJ, Colombo-Dougovito AM, Healy S. "Just invite us": autistic adults' recommendations for developing more accessible physical activity opportunities. *Autism Adulthood.* 2021; 3(2):179–86.

27. Eaves LC, Ho HH. Young adult outcome of autism spectrum disorders. *J. Autism Dev. Disord.* 2008; 38:739–47.
28. Garcia-Pastor T, Salinero JJ, Theirs CI, Ruiz-Vicente D. Obesity status and physical activity level in children and adults with autism spectrum disorders: a pilot study. *J. Autism Dev. Disord.* 2019; 49:165–72.
29. Lee D, Frey GC, Cothran DJ, Harezlak J, Shih PC. Concordance between accelerometer-measured and self-reported physical activity and sedentary time in adults with autism. *J. Autism Dev. Disord.* 2024; 54(4):1517–26.
30. Dempsey PC, Biddle SJH, Buman MP, et al. New global guidelines on sedentary behaviour and health for adults: broadening the behavioural targets. *Int. J. Behav. Nutr. Phys. Act.* 2020; 17:1–12.
31. Owen N, Healy GN, Matthews CE, Dunstan DW. Too much sitting: the population-health science of sedentary behavior. *Exerc. Sport Sci. Rev.* 2010; 38(3):105–13.
32. Thorp AA, Owen N, Neuhaus M, Dunstan DW. Sedentary behaviors and subsequent health outcomes in adults: a systematic review of longitudinal studies, 1996–2011. *Am. J. Prev. Med.* 2011; 41(2):207–15.
33. Dhanasekara CS, Ancona D, Cortes L, et al. Association between autism spectrum disorders and cardiometabolic diseases: a systematic review and meta-analysis. *JAMA Pediatr.* 2023; 177(3):248–57.
34. Piercy KL, Troiano RP, Ballard RM, et al. The physical activity guidelines for Americans. *JAMA.* 2018; 320(19):2020–8.
35. Matthews CE, Carlson SA, Saint-Maurice PF, et al. Sedentary behavior in United States adults: fall 2019. *Med. Sci. Sports Exerc.* 2021; 53(12):2512–9.
36. Hillier A, Buckingham A, Schena D. Physical activity among adults with autism: participation, attitudes, and barriers. *Percept. Mot. Skills.* 2020; 127(5):874–90.
37. Velikonja T, Fett A-K, Velthorst E. Patterns of nonsocial and social cognitive functioning in adults with autism spectrum disorder: a systematic review and meta-analysis. *JAMA Psychiatry.* 2019; 76(2):135–51.
38. Gilmore D, Harris L, Longo A, Hand BN. Health status of Medicare-enrolled autistic older adults with and without co-occurring intellectual disability: an analysis of inpatient and institutional outpatient medical claims. *Autism.* 2021; 25(1):266–74.
39. Crowley N, O'Connell H, Gervin M. Autistic spectrum disorder without intellectual impairment in adult mental health services–fostering new perspectives and enhancing existing services. *Ir. J. Psychol. Med.* 2022; 39(3): 312–8.
40. Ward DS, Evenson KR, Vaughn A, Rodgers AB, Troiano RP. Accelerometer use in physical activity: best practices and research recommendations. *Med. Sci. Sports Exerc.* 2005; 37(11):S582–8.
41. Troiano RP, Berrigan D, Dodd KW, Masse LC, Tilert T, McDowell M. Physical activity in the United States measured by accelerometer. *Med. Sci. Sports Exerc.* 2008; 40(1):181–8.
42. Tavassoli T, Miller LJ, Schoen SA, Nielsen DM, Baron-Cohen S. Sensory over-responsivity in adults with autism spectrum conditions. *Autism.* 2014; 18(4):428–32.
43. Cascio CJ, Moana-Filho EJ, Guest S, et al. Perceptual and neural response to affective tactile texture stimulation in adults with autism spectrum disorders. *Autism Res.* 2012; 5(4):231–44.
44. Prince SA, Adamo KB, Hamel ME, Hardt J, Gorber SC, Tremblay M. A comparison of direct versus self-report measures for assessing physical activity in adults: a systematic review. *Int. J. Behav. Nutr. Phys. Act.* 2008; 5(1):56.
45. Cerin E, Cain KL, Oyeyemi AL, et al. Correlates of agreement between accelerometry and self-reported physical activity. *Med. Sci. Sports Exerc.* 2016; 48(6):1075–84.
46. Craig CL, Marshall AL, Sjostrom M, et al. International physical activity questionnaire: 12-country reliability and validity. *Med. Sci. Sports Exerc.* 2003; 35(8):1381–95.
47. Shahane V, Kilyk A, Srinivasan SM. Effects of physical activity and exercise-based interventions in young adults with autism spectrum disorder: a systematic review. *Autism.* 2024; 28(2):276–300.
48. Lalonde KB, MacNeill BR, Eversole LW, Ragotzy SP, Poling A. Increasing physical activity in young adults with autism spectrum disorders. *Res. Autism Spectr. Disord.* 2014; 8(12):1679–84.
49. Sowa M, Meulenbroek R. Effects of physical exercise on autism spectrum disorders: a meta-analysis. *Res. Autism Spectr. Disord.* 2012; 6(1):46–57.
50. Li Y, Feng Y, Zhong J, et al. The effects of physical activity interventions in children with autism spectrum disorder: a systematic review and network meta-analysis. Rev. *J. Autism Dev. Disord.* 2023; 1–15.
51. Cooper K, Smith LGE, Russell A. Social identity, self-esteem, and mental health in autism. *Eur. J. Soc. Psychol.* 2017; 47(7):844–54.
52. Hillier A, Murphy D, Ferrara C. A pilot study: short-term reduction in salivary cortisol following low level physical exercise and relaxation among adolescents and young adults on the autism spectrum. *Stress Heal.* 2011; 27(5): 395–402.
53. Colombo-Dougovito AM, Lee J. Social skill outcomes following physical activity–based interventions for individuals on the autism spectrum: a scoping review spanning young childhood through young adulthood. *Adapt. Phys. Activ. Q.* 2020; 38(1):138–69.
54. Kientz JA, Hayes GR, Goodwin MS, Gelsomini M, Abowd GD. *Interactive Technologies and Autism.* 2nd Edition. Cham: Springer International Publishing; 2020.
55. Lee D, Frey G, Cheng A, Shih PC. Puzzle walk: a gamified mobile app to increase physical activity in adults with autism spectrum disorder. In: *10th International Conference on Virtual Worlds and Games for Serious Applications (VS-Games).* New York: IEEE; 2018. p. 1–4.
56. Bittner MD, Rigby BR, Silliman-French L, Nichols DL, Dillon SR. Use of technology to facilitate physical activity in children with autism spectrum disorders: a pilot study. *Physiol. Behav.* 2017; 177:242–6.
57. Dugas M, Gao G, Agarwal R. Unpacking mHealth interventions: a systematic review of behavior change techniques used in randomized controlled trials assessing mHealth effectiveness. *Digit Heal.* 2020; 6:2055207620905411.
58. Nuske HJ, Mandell DS. Digital health should augment (not replace) autism treatment providers. *Autism.* 2021; 25(7):1825–7.
59. Koumpouros Y, Kafazis T. Wearables and mobile technologies in autism spectrum disorder interventions: a systematic literature review. *Res. Autism Spectr. Disord.* 2019; 66:101405.
60. Deterding S, Dixon D, Khaled R, Nacke L. From game design elements to gamefulness: defining gamification. In: *15th Int Acad MindTrek Conf Envisioning Futur Media Environ (MindTrek '11).* New York: Association for Computing Machinery; 2011. p. 9–15.
61. Sailer M, Hense JU, Mayr SK, Mandl H. How gamification motivates: an experimental study of the effects of specific game design elements on psychological need satisfaction. *Comput. Hum. Behav.* 2017; 69:371–80.
62. Edwards EA, Lumsden J, Rivas C, et al. Gamification for health promotion: systematic review of behaviour change techniques in smartphone apps. *BMJ Open.* 2016; 6(10):e012447.
63. Alahäivälä T, Oinas-Kukkonen H. Understanding persuasion contexts in health gamification: a systematic analysis of gamified health behavior change support systems literature. *Int. J. Med. Inform.* 2016; 96:62–70.
64. Gao F. Advancing gamification research and practice with three underexplored ideas in self-determination theory. *TechTrends.* 2024; 68:661–71.
65. Schmidt-Kraepelin M, Toussaint PA, Thiebes S, Hamari J, Sunyaev A. Archetypes of gamification: analysis of mHealth apps. *JMIR Mhealth Uhealth.* 2020; 8(10):e19280.
66. Elliott M, Eck F, Khmelev E, Derlyatka A, Fomenko O. Physical activity behavior change driven by engagement with an incentive-based app: evaluating the impact of Sweatcoin. *JMIR Mhealth Uhealth.* 2019; 7(7):e12445.
67. Mason MR, Ickes MJ, Campbell MS, Bollinger LM. An incentivized, workplace physical activity intervention preferentially increases daily steps in inactive employees. *Am. J. Health Promot.* 2018; 32(3):638–45.
68. Patel MS, Small DS, Harrison JD, et al. Effectiveness of behaviorally designed gamification interventions with social incentives for increasing physical activity among overweight and obese adults across the United States: the STEP UP randomized clinical trial. *JAMA Intern. Med.* 2019; 179(12):1624–32.
69. Francis SL, Simmering JE, Polgreen LA, et al. Gamifying accelerometer use increases physical activity levels of individuals pre-disposed to type II diabetes. *Prev. Med. Rep.* 2021; 23:101426.
70. Sardi L, Idri A, Fernández-Alemán JL. A systematic review of gamification in e-health. *J. Biomed. Inform.* 2017; 71:31–48.
71. Xu L, Shi H, Shen M, et al. The effects of mHealth-based gamification interventions on participation in physical activity: systematic review. *JMIR Mhealth Uhealth.* 2022; 10(2):e27794.
72. Michie S, Richardson M, Johnston M, et al. The behavior change technique taxonomy (v1) of 93 hierarchically clustered techniques: building an international consensus for the reporting of behavior change interventions. *Ann. Behav. Med.* 2013; 46(1):81–95.
73. Qudah B, Luetsch K. The influence of mobile health applications on patient-healthcare provider relationships: a systematic, narrative review. *Patient Educ. Couns.* 2019; 102(6):1080–9.
74. Cowan LT, Van Wagenen SA, Brown BA, et al. Apps of steel: are exercise apps providing consumers with realistic expectations? A content analysis of

exercise apps for presence of behavior change theory. *Health Educ. Behav.* 2013; 40(2):133–9.

75. Conroy DE, Yang CH, Maher JP. Behavior change techniques in top-ranked mobile apps for physical activity. *Am. J. Prev. Med.* 2014; 46(6): 649–52.
76. Direito A, Carraça E, Rawstorn J, Whittaker R, Maddison R. mHealth technologies to influence physical activity and sedentary behaviors: behavior change techniques, systematic review and meta-analysis of randomized controlled trials. *Ann. Behav. Med.* 2017; 51(2):226–39.
77. Chevallier C, Kohls G, Troiani V, Brodkin ES, Schultz RT. The social motivation theory of autism. *Trends Cogn. Sci.* 2012; 16(4):231–9.
78. Kim B, Lee D, Min A, et al. PuzzleWalk: a theory-driven iterative design inquiry of a mobile game for promoting physical activity in adults with autism spectrum disorder. *PLoS One.* 2020; 15(9):e0237966.
79. Mummah SA, Robinson TN, King AC, Gardner CD, Sutton S. IDEAS (integrate, design, assess, and share): a framework and toolkit of strategies for the development of more effective digital interventions to change health behavior. *J. Med. Internet Res.* 2016; 18(12):e317.
80. Ryan RM, Deci EL. *Self-Determination Theory: Basic Psychological Needs in Motivation, Development, and Wellness.* New York: Guilford Publications; 2017.
81. Lee D, Frey GC, Min A, et al. Usability inquiry of a gamified behavior change app for increasing physical activity and reducing sedentary behavior in adults with and without autism spectrum disorder. *Health Informatics J.* 2020; 26(4):2992–3008.
82. Muniandy M, Richdale AL, Lawson LP. Stress and well-being in autistic adults: exploring the moderating role of coping. *Autism Res.* 2023; 16(11): 2220–33.