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ORIGINAL RESEARCH

Identifying Optimal Moments for Delivering Digital Prompts to Reduce Prolonged Sedentary Behavior in Older Adults: An Intensive Longitudinal Study Using Sensor-Triggered Ecological Momentary Assessment

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Background: The optimal moment to deliver digital prompts for reducing sedentary behavior (SB) is when individuals are susceptible to prolonged SB (vulnerability) and open to behavior change (opportunity). This study aims to examine both vulnerability and opportunity. ***Methods:*** A 14-day ecological momentary assessment study was conducted with 105 older adults. Participants wore a Fitbit activity tracker and an ActivPAL accelerometer and used a smartphone-based ecological momentary assessment app. Sensor-triggered questionnaires were delivered via the app after 30 minutes of SB to capture participants' activity, physical, social, and temporal contexts; feelings of pain and fatigue; and willingness to interrupt SB. Descriptive statistics identified states of vulnerability, whereas linear mixed models examined when participants are willing to interrupt prolonged SB, shedding light on states of opportunity. ***Results:*** Ecological momentary assessment data (n = 2580) showed that older adults were most vulnerable to prolonged SB while watching TV (36.3%) and using digital devices (14.7%). Prolonged SB predominantly occurred at home (91.2%), in the evening (46.4%), when feeling fatigue (52.2%), and when experiencing mild pain (21.1%). The willingness to interrupt SB varied by activity, physical and social context, perceived pain, and level of fatigue, but not by time of day. Specifically, participants were more willing to interrupt their SB when engaging in mentally active SB and when indoors, alone, or with close relatives. ***Conclusions:*** Contextual factors significantly influence older adults' vulnerability to prolonged SB and their willingness to interrupt it. This empirical information can guide the design of just-in-time adaptive interventions that deliver strategically timed prompts to reduce prolonged SB in older adults.

Keywords: sitting, just-in-time adaptive intervention, experience sampling, elderly

Key Points

- Older adults are most vulnerable to prolonged sedentary behavior at home, especially while watching TV, in the evening, when fatigued, or experiencing mild pain.
- Willingness to interrupt sedentary behavior is higher during mentally active tasks, indoors, and when alone or with close relatives—key factors for tailoring just-in-time digital prompts.

To respond to the global challenges of population aging, the World Health Organization has introduced the concept of healthy aging.[1] The idea of healthy aging is to focus on extending older adults' health span, instead of focusing on their life span.[1] Evidence suggests that promoting health behaviors is crucial for healthy aging.[2,3] One health behavior that has often been ignored in the past is sedentary behavior (ie, any waking behavior characterized by an energy expenditure of 1.5 metabolic equivalent of tasks or less while in a sitting reclining or lying posture).[4–6] Older adults spend approximately 65% of their awake time in sedentary activities, amounting to approximately 9.3 hours per day.[7,8] Sedentary behavior has been associated with frailty, physical disability, type 2 diabetes, cardiovascular diseases, and all-cause mortality.[9–12] Although there is ongoing debate about the extent to which physical activity can counteract these adverse effects, recent evidence indicates that only relatively high volumes of moderate to vigorous physical activity—approximately 30 to 70 minutes per day—may be sufficient for fully offsetting the associated health risks.[13–15] Consequently, actions are required to impact sedentary behavior—in addition to those aimed at increasing physical activity.

Existing sedentary behavior interventions have mainly focused on reducing total sedentary time.[16] However, increasing evidence indicates that the pattern in which sedentary time is accumulated also influences health outcomes.[12,17] Experimental

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studies report that prolonged uninterrupted sedentary behavior (≥30 min) acutely exacerbates postprandial cardiometabolic risk biomarkers (eg, insulin resistance, impaired glucose tolerance, and increased plasma triglyceride levels) and may decrease vasodilatory function.[18] Laboratory studies have shown that these adverse effects can be negated by interrupting prolonged sedentary behavior with brief bouts of light-intensity physical activity.[18,19] As such, next to reducing total sedentary time, efforts to regularly break up prolonged bouts of sedentary behavior might offer additional benefits. Although these findings stem from controlled laboratory settings, they highlight the importance of regularly interrupting sedentary time in daily life as well. Many daily activities involve prolonge sedentary behavior, making it crucial to find practical ways to encourage people to break up their sedentary time.[20]

One potential strategy is to provide real-time prompts that remind individuals to interrupt prolonged sedentary behavior.[21–25] According to Carey et al,[26] providing prompts (ie, introducing or defining an environmental or social stimulus with the purpose of prompting or cueing the behavior as defined by Michie et al[27]) activates several key mechanisms of action. These include memory, attention, and decision-making processes, as well as behavioral cueing and the utilization of environmental resources. Specifically, prompts can enhance memory and attention by bringing the need to act to the individual's conscious awareness while facilitating decision making by making the desired behavior more salient and easier to implement. Furthermore, prompts can serve as effective behavioral cues, triggering action in moments when individuals may otherwise not consider interrupting their sedentary behavior. Finally, by leveraging environmental resources—such as reminders in the immediate surroundings or social context—prompts can further support behavior change, particularly for contexts in which individuals are most likely to engage in sedentary activities. Results of an exploratory study evaluating the acceptability, usability, and preliminary efficacy of a prompt-based intervention in 28 older adults confirmed that they are open to automatically generated sedentary behavior prompts.[24,25] However, the study also highlighted 2 important limitations. First, delivering prompts at fixed moments (eg, after every 30 min of sedentary behavior) can lead to frustration if the individual is unable or unwilling to change his behavior, potentially resulting in disengagement over time. Second, fixed-timing prompts become predictable, which may result in a diminished impact on behavior.[28]

To address this issue, future prompt-based interventions should optimize and vary the timing of the prompts based on an individual's real-time context. This can be achieved through just-in-time adaptive interventions (JITAIs), a novel and promising class of digital interventions that leverage advances in wearable technology and data science to provide real-time support. JITAIs are designed to intervene during moments when individuals are susceptible to (1) engaging in negative health behavior (*states of vulnerability*) and (2) adopting positive behavior change (*states of opportunity*).[29,30] States of vulnerability and opportunity can arise rapidly—over the span of days, hours, minutes, or even seconds[31–33]—and are often unpredictable, following an irregular pattern.[34] Both vulnerability and opportunity states are shaped by a combination of stable and transient factors. Stable factors are influences that predispose individuals to specific behaviors. These include internal factors (eg, personality traits, genetics) and contextual factors (eg, living environment). In contrast, transient factors are dynamic influences that can prompt a shift from latent (subthreshold) to manifest vulnerability or opportunity states. Transient factors also encompass internal factors (eg, momentary feelings, pain) and contextual factors (eg, immediate physical or social surroundings). Although much research has focused on understanding stable factors, less is known about transient factors. Addressing this gap is crucial as empirical insights into moments of heightened vulnerability and opportunity can help identify key decision points—moments when delivering an intervention may be most effective.[29] Establishing these decision points provides a "warm start" for reinforcement learning algorithms in future JITAIs designed to reduce prolonged sedentary behavior in older adults. This warm start optimizes the intervention's initial performance by reducing the need for extensive trial-and-error learning, ensuring the algorithm begins with evidence-based decision rules. Consequently, fewer but more strategically timed digital prompts will be delivered, minimizing participant burden and reducing the risk of habituation to the intervention.[29,35]

To gather information on transient factors, we conducted a sensor-triggered ecological momentary assessment (EMA) study. Sensor-triggered EMA is a real-time data collection method that activates in response to specific events, allowing for capturing contexts and behaviors in natural environments. It has proven valuable for understanding the physical, social, temporal, and behavioral contexts of sedentary behavior across various occasions within a given individual.[31] The aim of this study is 3-fold: first, to describe transient internal and contextual factors that characterize older adults' vulnerability to prolonged sedentary behavior (*state of* vulnerability); second, to determine transient internal and contextual factors that make older adults' receptive to positive behavior change; and third, to combine empirical evidence on states of vulnerability and receptivity and establish optimal decision points for the timely delivery of digital prompts aimed at reducing prolonged sedentary behavior in older adults.

Methods

Study Design and Participants

A 14-day intensive longitudinal EMA study was conducted between March and October 2024. Participants were recruited through purposive convenience sampling to ensure heterogeneity in sex and age. Recruitment primarily occurred through word-of-mouth in the social network of the involved researchers, advertisements on social media, and contact with community associations for older adults. The inclusion criteria specified Dutch-speaking individuals aged 60 years or older who lived at home. Individuals who were physically unable to walk at least 100 m without assistance, were affected by severe neurological conditions such as dementia or Parkinson's disease, or had significant visual or hearing impairments were excluded. The study has been approved by the Committee for Medical Ethics of the University Hospital of Ghent (B6702023000649), and an adapted Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) checklist for reporting EMA Studies was used to describe the procedures of this EMA study (see Supplementary Material S1 [available online]).[32]

Procedures

During the initial home visit (day 0), participants received detailed study information, gave written informed consent, and completed a baseline questionnaire covering sociodemographic characteristics, health-related factors, sleep patterns, and social isolation variables. Following this, they were provided with a Fitbit activity tracker (Inspire 3, Fitbit), an Android smartphone (Motorola G20, Motorola E40, and Samsung Galaxy A9) equipped with the EMA application HealthReact, and an ActivPAL4 accelerometer (Physical Activity

Technologies). Instructions were given on how to charge the Fitbit and smartphone, along with a brief tutorial on using the smartphone-based EMA app. To help participants become familiar with the EMA questionnaire, a test questionnaire was administered in the presence of the researcher. Participants were advised, during the first home visit, to avoid responding in unsafe situations, such as while driving. The first home visit was followed by a measurement period of 14 consecutive days (days 1–14) during which sensor-triggered EMA questionnaires were delivered to the smartphone. Participants were monitored throughout this period, and follow-up was provided in case of issues (eg, nonwear of Fitbit activity tracker, connection problems) or if very few questionnaires were answered. After these 14 days, a second home visit (day 15) was conducted to collect all devices and materials. During the second home visit, participants completed a second questionnaire assessing capabilities, opportunities, and motivation to interrupt and reduce sedentary behavior.

Measures

Baseline Questionnaire

Participants self-reported demographic information, including age, sex, height, weight, educational level, primary occupation, and marital status using a paper-based questionnaire. To assess their health status, participants completed the Short Form 36 Health Survey, which is widely used to estimate general health across multiple domains, including physical functioning, pain, vitality, social functioning, and mental health.[33] In addition, the Patient-Reported Outcomes Measurement Information System (PROMIS) was employed to measure aspects of social isolation and sleep quality. PROMIS is a reliable and valid tool designed to assess the subjective experience of various health domains, including the psychological and social dimensions of health.[34]

Sensor-Triggered EMA Questionnaires

Participants were instructed to wear the Fitbit activity tracker continuously during the day. The Fitbit activity tracker transmits data to the Fitbit application on the user's smartphone via Bluetooth. This application then synchronizes the data with the Fitbit server—Fitbit's cloud infrastructure—approximately every 16 minutes through an internet connection. The Fitbit server is connected with the EMA application, HealthReact. The data are made accessible through the Fitbit Application Programming Interface. This setup enabled questionnaires to be triggered on the smartphone during or immediately after specific behavioral events.[36] The questionnaires were triggered after 30 consecutive minutes with fewer than 2 steps, as detected by the Fitbit, indicating sedentary time.[37] The 30-minute threshold aligns with common definitions of prolonged sedentary behavior[38] and is based on findings suggesting that breaking up sedentary time every 20 to 30 minutes is realistic[39] and can improve metabolic health.[18,40] This occurred up to 6 times per day, a frequency found to be feasible in prior EMA studies.[41,42] The 6 daily triggers were distributed across 3 time frames: the morning (7 AM–12 PM), the afternoon (1 PM–6 PM), and the evening (6 PM–10 PM). Each time frame allowed for a maximum of 2 triggers with a minimum interval of 90 minutes between them. To ensure participants were already awake when the morning questionnaires were triggered, a "start rule" was applied; it stated that triggers would initiate only after participants had walked a few steps (at least 10 steps within 2 min). The EMA questionnaire comprised 16 items, taking approximately 1 to 2 minutes to complete. EMA questionnaires began by asking whether participants were indeed sitting right before the prompt, to confirm the accuracy of the sensor-triggered event. Following this, closed questions addressed various contexts, such as behavioral ("What sedentary activity were you engaged in?"), physical ("Where were you located at that time?"), and social ("Who was with you at that time?") contexts to better understand the vulnerability of older adults to prolonged sedentary behavior.[43–45] In addition, participants' willingness to modify their ongoing sedentary behavior was assessed using 2 questions. First, they were asked whether they would be open to performing the activity while standing. Second, they were asked whether they would consider briefly interrupting the activity. Both questions were rated on a 5-point Likert scale ranging from "not at all" to "absolutely certain." For the second question, an additional response option ("I am already interrupting the activity") was included to account for participants who were not continuously sedentary at the time of assessment. Although most questions were static, 2 elements involved dynamic branching. First, if participants indicated that they were not sitting or lying down at the time of the prompt, the questionnaire ended immediately. Second, the physical context question was adaptive: participants were first asked whether they were indoors or outdoors. Based on this response, they were presented with a tailored list of location-specific options. No further branching logic or contextual adaptation was applied based on previous responses. The full EMA questionnaire can be found in Supplementary Material S2 (available online). Participants had 15 minutes to complete the questionnaire on the smartphone after receiving the trigger, after which the questionnaire disappeared if not completed.

ActivPAL Accelerometer

The ActivPAL accelerometer, which is considered the gold standard, was used to characterize participants by assessing total sedentary time and prolonged bouts of sedentary behavior.[46] The accelerometer was attached to the midline of the participant's right anterior thigh for the entire study duration, worn continuously both day and night, to assess device-based sedentary time. Data were summarized in 15-second epochs and processed using the ActivPAL CREA algorithm (PAL Technologies). A day was considered valid if participants had at least 10 hours of waking wear time and if <95% of that time was spent in one posture.[47,48] Total sedentary time was calculated as the average daily sedentary time (in hours) on valid days, and prolonged bouts of sedentary behavior were defined as bouts lasting at least 30 minutes without interruption. This threshold aligned with literature defining prolonged bouts of sedentary behavior.[49,50] The usual sedentary bout duration, representing the midpoint of the cumulative distribution of sedentary bouts, indicates the bout duration at which half of all sedentary time is accumulated.[39] This measure also serves as a standardized metric for reporting bout lengths in relation to total sedentary time, enhancing comparability across studies.[51]

Data Processing and Analysis

REDCap (Research Electronic Data Capture, 14.5.42), hosted at Ghent University, was used to collect and manage baseline data,[52,53] and R version 4.4.2 was used to conduct the analyses. Prior to data analysis, data from the baseline questionnaire were merged with the processed ActivPAL data (ie, sedentary behavior) and the EMA data (ie, transient factors and state of opportunity). The percentage of missing EMA data was computed to decide which participants should be excluded. Because a clear cutoff for exclusion is not yet established in the literature,[54] we explored various compliance thresholds ranging from 50% to 80%. Ultimately, a cutoff of 60% compliance was chosen for the analysis based on a balance between maximizing data inclusion and minimizing the risk of bias due to excessive missing data. Descriptive statistics were employed to describe the sample, and chi-square tests, *t* tests, and Wilcoxon rank tests were performed to explore potential differences between the excluded participants and those retained in the data set. As missing mobile EMA data (due to uncompleted questionnaires) are usually not missing completely at random in older adults,[55] multiple imputation with 5 pooled data iterations was executed through the mice package in R. Five imputations were chosen as a standard practice to balance computational efficiency and the precision of the imputed estimates, as research suggests that 5 iterations often provide stable and reliable results in the context of missing data imputation.[56] The original and the imputed data sets were used to first calculate descriptive statistics on the transient internal and contextual factors related to older adults' vulnerability to prolonged sedentary behavior and their state of opportunity toward positive behavior change. Next, linear mixed models were employed on the imputed data to investigate the influence of internal (pain and fatigue) and contextual transient factors (activity, physical, social, and time-related context) on states of opportunity, specifically participants' willingness to (1) interrupt prolonged sedentary bouts, including stopping the activity in which they are engaged and (2) interrupt prolonged sedentary bouts by standing up while continuing the activity. These models accounted for the nested structure of the data, capturing both within- and between-person variability to better understand the dynamics underlying these states of opportunity. To ensure that the assumptions of the linear mixed models were met, normality and homoscedasticity were evaluated through visual inspection of residual and Q-Q plots. Intraclass correlations (ICCs) were first estimated using unconditional models to determine the proportion of variance attributable to between-person versus within-person differences in the outcomes. Subsequently, the predictors were added to the models, and age and educational level were included as confounders to account for their potential impact. The reference category for the categorical predictors was selected based on the context in which participants were most likely to take action to reduce their sedentary behavior. If the most prevalent context was not sufficiently represented, the second most prevalent context was used as the reference category. As a result, a significant difference indicates that, in that specific context, older adults are significantly less likely to be receptive to positive behavior change. In addition, estimated marginal means were computed to better understand how willingness to reduce sedentary behavior varied across different internal and contextual conditions, providing a more nuanced view of the differences between all groups, rather than only relative to the reference group.

Results

Sample Description

A total sample of 107 older adults was recruited; of these, 105 participants completed the 14-day EMA protocol. Of these, 90 met the cutoff of 60% for EMA compliance and were included in the analyses. The average EMA compliance of the included participants was 83.3% (SD = 11.6%), resulting in 2580 completed EMA questionnaires. Participants (n = 90) had a mean age of 70.2 years (SD = 6.4), ranging from 60 to 87 years. Women represented 64.4% of the sample (n = 58). The participants had an average body mass index of 26.0 kg/m^2 (SD = 3.1), with values ranging from 19.1 to 33.8 kg/m^2. On average, sedentary time was 9.3 hours per day (SD = 1.7), with a minimum of 6.2 hours and a maximum of 13.9 hours daily. About half of participants' sedentary time was spent in prolonged bouts (ie, bouts >30 min). More detailed information on sample characteristics is provided in Table 1.

Descriptive Results on Transient Factors Related to States of Vulnerability and Opportunity

The descriptive statistics for states of vulnerability and opportunity are summarized separately for both the original and the imputed data sets in order to present the impact of the imputations (see Table 2). The analysis of the original data set revealed that older adults were vulnerable to prolonged sedentary behavior (ie, ≥30 min) primarily during activities like watching TV (36.3% of observations); using computers, tablets, or smartphones (14.7%); eating/drinking (11.9%); and reading (11.8%). Prolonged sedentary behavior was mostly observed indoors (92.4%), predominantly at home (91.2%), and was often spent with a partner (54.2%) or alone (32.9%). Almost half (46.4%) of all prolonged sedentary bouts occurred in the evening, between 5 and 10 PM. In addition, during more than half (52.2%) of the prolonged sedentary bouts, individuals were at least slightly fatigued, and in 21.1% of the cases, they experienced at least mild pain. Descriptive results for states of opportunity indicate that self-care was the only activity for which older adults showed a willingness to perform while standing (mean = 3.8, SD = 1.1). All other activities received average scores of 2.5 or below, reflecting responses of "not at all" or "probably not." The willingness to briefly interrupt their sedentary behavior was much higher. Except for household tasks, all activities received at least a 3, which indicates that they are at least somewhat willing to interrupt their prolonged sedentary behavior.

Analytical Results on Transient Factors Related to States of Opportunity

The results of the unconditional models showed substantial person-level variance in states of opportunity. Specifically, for standing, the person-level variance was 0.31, with an ICC of .26, indicating that 26% of the variability in standing opportunities was attributed to differences between individuals. For interrupting sedentary behavior, the person-level variance was 0.39, with an ICC of .22, indicating that 22% of the variability in interrupting opportunities was due to between-person differences. The day-level variance was extremely small (essentially 0), meaning that daily fluctuations did not contribute much to the variability in these opportunities. The results of the linear mixed model analyses (see Table 3) revealed that temporal context was not a significant predictor of individuals' willingness to stand or interrupt prolonged sedentary behavior. However, activity type emerged as a key predictor for both outcomes. Compared with talking (reference category), no significant differences were found for listening to music and commuting, indicating a relatively high willingness to switch from sitting to standing to perform these activities. Most other activities were associated with significantly lower willingness, except for self-care, which showed a significantly higher willingness to be performed while standing. For interrupting prolonged sedentary behavior, reading was used as the reference category. No significant differences were found for listening to music, engaging in creative or cognitive tasks, using digital devices, or performing self-care routines, suggesting a relatively high willingness to interrupt these activities. In contrast, older adults were significantly less willing to interrupt

Table 1 Participant Characteristics

Participant characteristics	Total sample (N = 105)	Included (n = 90)	Excluded (n = 15)	P^a
Sociodemographic factors				
Age, y, mean (SD)	70.4 (6.3)	70.2 (6.4)	71.1 (5.5)	.50
Gender, n (%)				.05*
Female	63 (60.0%)	58 (64.4%)	5 (33.3%)	
Male	42 (40.0%)	32 (35.6%)	10 (66.7%)	
Living situation, n (%)				.13
Living alone	16 (15.2%)	13 (14.4%)	3 (20.0%)	
Living with partner	84 (80.0%)	74 (82.2%)	10 (66.7%)	
Other	5 (4.8%)	3 (3.3%)	2 (13.3%)	
Occupational status, n (%)				.69
Retired, volunteer work or flexi job	41 (39.0%)	34 (37.8%)	7 (46.7%)	
Retired, no volunteer work or flexi job	52 (49.5%)	46 (51.1%)	6 (40.0%)	
Not yet retired	12 (11.4%)	10 (11.1%)	2 (13.3%)	
Type of home, n (%)				.10
House	90 (87.4%)	79 (87.8%)	12 (85.7%)	
Studio/apartment	13 (12.6%)	11 (12.2%)	2 (14.3%)	
Neighborhood, n (%)				.06
Countryside	26 (25.0%)	23 (25.6%)	3 (21.4%)	
Village	36 (34.6%)	30 (33.3%)	6 (42.9%)	
City suburb	30 (28.8%)	29 (32.2%)	1 (7.1%)	
City	12 (11.5%)	8 (8.9%)	4 (28.6%)	
Children, n (%)				.62
0	8 (7.6%)	7 (7.7%)	1 (7.1%)	
1–2	65 (61.9%)	53 (58.9%)	12 (85.7%)	
3–4	32 (30.5%)	30 (33.3%)	2 (14.3%)	
Grandchildren, n (%)				.07
0	17 (16.2%)	14 (15.6%)	3 (20.0%)	
1–2	35 (33.3%)	31 (34.4%)	4 (26.7%)	
3–4	28 (26.7%)	26 (28.9%)	2 (13.3%)	
>4	25 (23.8%)	19 (21.1%)	6 (40.0%)	
Educational level, n (%)				.98
Primary education	25 (24.0%)	22 (24.4%)	3 (21.4%)	
Secondary education	23 (22.1%)	19 (21.1%)	4 (28.6%)	
Bachelor's degree	43 (41.3%)	37 (41.1%)	6 (42.9%)	
Master's degree	13 (12.5%)	12 (13.3%)	1 (11.5%)	
Body mass index, kg/m^2, mean (SD)	26.0 (3.3)	26.0 (3.1)	26.3 (4.3)	.78
Smartphone familiarity, n (%)				1.00
Yes	95 (95.0%)	82 (91.1%)	13 (92.9%)	
No	5 (5.0%)	8 (8.9%)	1 (7.1%)	
Sedentary behavior				
Total sedentary time, min/d, mean (SD)	555.4 (101.3)	555.0 (100.5)	558.5 (109.4)	.90
Prolonged bouts, min/d, mean (SD)	288.6 (101.5)	288.9 (102.6)	287.3 (98.3)	.96
Usual bout duration, min/d, mean (SD)	27.54 (12.6)	27.51 (12.63)	27.73 (12.36)	.70
Ecological momentary assessment questionnaires				
Received questionnaires, n, mean (SD)	33.2 (15.7)	34.7 (16.2)	28.7 (14.0)	<.001
Answered questionnaires, n, mean (SD)	26.2 (14.5)	23.9 (7.6)	11.1 (5.1)	<.001
Compliance, %, mean (SD)	77.9 (17.5)	83.3 (11.6)	45.4 (10.3)	<.001

[a]Independent samples *t* test, Wilcoxon rank test, and Pearson chi-squared test.
*$P < .05$ indicates statistical significance.

Table 2 Descriptive Results on States of Vulnerability and Opportunity

	Vulnerability; When do older adults engage in prolonged sedentary behavior?				Opportunity; When is someone receptive to disrupting his/her prolonged sedentary behavior?[a]			
	Original data set (n = 2580)		Imputed data sets (n = 3124)		Original data set (n = 2580)		Imputed data sets (n = 3124)	
	n	%	n	%	Standing, mean (SD)	Interrupting, mean (SD)	Standing, mean (SD)	Interrupting, mean (SD)
Activity								
Watching TV	869	36.3	1125	36.0	2.3 (1.4)	4.0 (1.4)	2.1 (1.0)	4.0 (1.2)
Talking	148	6.2	190	6.1	2.5 (1.1)	3.3 (1.4)	2.5 (1.1)	3.4 (1.3)
Sleeping	134	5.6	188	6.0	1.1 (0.5)	3.2 (1.7)	1.2 (0.7)	3.2 (1.5)
Self-care	21	0.9	27	0.9	3.8 (1.1)	4.1 (1.1)	3.8 (1.1)	3.9 (1.1)
Reading	283	11.8	365	11.7	1.9 (1.0)	4.2 (1.1)	1.9 (1.0)	4.2 (1.1)
Listening to music	18	0.8	24	0.8	2.3 (1.2)	3.9 (1.7)	2.3 (1.1)	3.8 (1.6)
Household chores	63	2.6	83	2.7	1.4 (1.1)	2.3 (1.7)	1.4 (1.1)	2.3 (1.6)
Eating/drinking	285	11.9	374	12.0	1.8 (0.9)	3.5 (1.4)	1.8 (0.9)	3.5 (1.4)
Creative activity	27	1.1	35	1.1	1.6 (1.0)	4.0 (1.1)	1.7 (1.0)	4.1 (1.1)
Computer/tablet/smartphone	351	14.7	457	14.6	2.4 (1.2)	4.0 (1.2)	2.4 (1.2)	4.1 (1.2)
Commuting	23	1.0	29	0.9	2.2 (1.6)	4.0 (1.1)	2.3 (1.5)	4.0 (1.2)
Cognitive activity	56	2.3	77	2.5	1.8 (0.8)	4.1 (1.3)	1.9 (0.8)	4.2 (1.2)
At work	35	1.5	45	1.4	1.9 (1.0)	3.2 (1.9)	1.9 (1.1)	3.2 (1.5)
Others	80	3.3	106	3.4	1.7 (1.3)	3.4 (1.7)	1.6 (1.2)	3.3 (1.7)
Pain								
None	1523	63.5	1953	65.5	2.1 (1.1)	3.8 (1.4)	2.1 (1.1)	3.8 (1.3)
Very mild	371	15.5	484	15.5	1.8 (1.0)	3.7 (1.4)	1.8 (1.0)	3.7 (1.4)
Mild	298	12.4	398	12.7	2.0 (1.2)	4.1 (1.1)	2.0 (1.2)	4.1 (1.2)
Moderate	153	6.4	202	6.5	1.9 (1.0)	3.8 (1.3)	1.9 (1.0)	3.8 (1.3)
Severe	44	1.8	68	2.2	2.0 (0.8)	3.5 (1.3)	2.0 (1.0)	3.5 (1.4)
Very severe	11	0.5	19	0.6	1.7 (0.8)	3.5 (1.3)	1.8 (1.1)	3.4 (1.4)
Fatigue								
Not fatigued at all	1090	47.8	1469	47.0	2.1 (1.2)	3.8 (1.4)	2.1 (1.1)	3.8 (1.3)
Slightly fatigued	789	34.6	1080	34.6	1.9 (1.0)	3.7 (1.3)	1.9 (1.0)	3.7 (1.3)
Neither fatigued nor refreshed	132	5.8	187	6.0	1.8 (1.0)	4.2 (1.2)	1.8 (1.0)	4.2 (1.2)
Fatigued	222	9.7	310	9.9	1.8 (1.0)	3.7 (1.3)	1.9 (1.0)	3.7 (1.3)
Very fatigued	49	2.1	78	2.5	1.6 (0.7)	3.4 (1.4)	1.6 (0.9)	3.3 (1.4)
Physical context								
Inside	2223	92.4	2875	92.0	2.0 (1.0)	3.9 (1.3)	2.0 (1.1)	3.8 (1.3)
At home	2028	91.2	2766	88.6	2.0 (1.1)	3.9 (1.3)	2.0 (1.1)	3.9 (1.3)
At a family/friend's/neighbor's/acquaintance's house	69	3.1	107	3.4	1.9 (1.0)	3.5 (1.5)	1.9 (1.0)	3.4 (1.4)
At work	14	0.6	22	0.7	1.9 (1.1)	3.5 (1.7)	1.9 (1.1)	3.5 (1.6)
Restaurant/café	27	1.3	50	1.6	1.9 (1.1)	2.7 (1.3)	1.5 (1.0)	2.6 (1.3)
In the car or train/tram/bus	26	1.2	85	2.7	1.0 (0.2)	2.5 (1.8)	1.0 (0.6)	2.1 (1.6)
In another public space	30	1.3	48	1.5	2.0 (1.0)	2.9 (1.6)	2.1 (1.1)	2.9 (1.4)
Other	29	1.3	45	1.4	1.5 (0.8)	2.7 (1.3)	2.1 (1.3)	3.0 (1.7)
Outside	184	7.6	249	8.0	1.9 (1.1)	3.1 (1.5)	1.8 (1.1)	3.2 (1.5)
Social context								
Partner	1301	54.2	1682	54.0	2.0 (1.0)	3.8 (1.3)	2.0 (1.0)	3.8 (1.3)
Close relatives	99	4.1	132	4.2	2.0 (0.9)	3.9 (1.2)	2.0 (1.0)	3.8 (1.3)
Nobody	790	32.9	1031	33.0	2.1 (1.2)	4.0 (1.3)	2.1 (1.2)	4.0 (1.3)
Others	212	8.8	278	8.9	2.0 (1.0)	3.1 (1.6)	1.9 (1.1)	3.1 (1.6)
Temporal context								
Morning	659	21.1	659	21.1	2.1 (1.2)	3.8 (1.4)	2.0 (1.2)	3.8 (1.4)

(continued)

Table 2 (continued)

	Vulnerability; When do older adults engage in prolonged sedentary behavior?				Opportunity; When is someone receptive to disrupting his/her prolonged sedentary behavior?[a]			
	Original data set (n = 2580)		Imputed data sets (n = 3124)		Original data set (n = 2580)		Imputed data sets (n = 3124)	
	n	%	n	%	Standing, mean (SD)	Interrupting, mean (SD)	Standing, mean (SD)	Interrupting, mean (SD)
Afternoon	1012	32.4	1012	32.4	2.0 (1.1)	3.7 (1.4)	2.0 (1.1)	3.7 (1.4)
Evening	1448	46.4	1448	46.6	2.0 (1.0)	3.8 (1.2)	2.0 (1.0)	3.8 (1.3)

[a]Five-point Likert scale.

watching TV, talking, sleeping, household activities, eating/drinking, commuting, and work-related activities. Regarding pain, the results suggest that having pain makes older adults less willing to perform their sedentary activities while standing. For interrupting sedentary behavior, there was no clear direction for the effect of pain as participants were more likely to interrupt sedentary bouts when experiencing mild pain compared with no pain, but less likely to do so when experiencing severe pain. In addition, fatigue played a significant role in determining both the willingness to stand and the willingness to interrupt sedentary behavior. Participants were generally unwilling to stand as soon as they experienced mild fatigue, and they were similarly reluctant to break from sitting when they experienced a severe level of fatigue. Environmental and social contexts also influenced the likelihood of disrupting sedentary behavior. Specifically, participants were most inclined to take action when indoors, especially at home. In terms of social context, they were more likely to act when alone or in the company of close relatives.

Optimal Moments for Delivering Digital Prompts to Reduce Prolonged Sedentary Behavior

Figure 1 presents a synthesis of the descriptive findings on states of vulnerability to prolonged sedentary behavior and the analytical results on states of opportunity to disrupt it. Activities that are both commonly performed during prolonged sedentary bouts and that older adults are willing to interrupt include reading and using digital devices. In addition, key physical and social contexts associated with both prolonged sedentary behavior and a greater willingness to take breaks include being at home and being alone.

Discussion

JITAIs are emerging as promising digital health interventions, providing the right support at the most optimal moments. These moments are identified based on individuals' states of vulnerability and opportunity. To minimize extensive trial and error during the launch of a JITAI aimed at disrupting prolonged sedentary behavior, this sensor-triggered EMA study aimed to gain insight into older adults' states of vulnerability and opportunity related to prolonged sedentary behavior.

Regarding states of vulnerability, our results showed that older adults' prolonged sedentary bouts most commonly occurred during activities such as watching TV, using digital devices, reading, and eating or drinking. These bouts predominantly took place at home, either alone or with a partner, and in the evening. Although no prior studies have specifically mapped the activities and physical and social contexts related to older adults' prolonged sedentary bouts, our findings align with those from Leask et al,[57] who conducted a study using camera-based monitoring to describe sedentary bouts of at least 2 minutes in older adults. Their study revealed that most leisure-time sedentary behavior among older adults is spent in front of screens (TV and computer) and that sedentary bouts predominantly occurred at home, often in solitude. Similarly, qualitative research has reported similar findings, noting that most sitting activities among older adults occur in the leisure-time domain and typically take place at home. Watching TV was the most frequently mentioned activity, with time spent ranging from less than an hour to almost the entire day. Other commonly reported sedentary activities included reading, doing puzzles, and using computers or tablets, further supporting our findings.[58,59] Beyond activity type and physical and social contexts, we also investigated the temporal context of prolonged sedentary behavior. Nearly half of the prolonged sedentary behavior bouts occurred in the evening, corroborating previous cross-sectional research highlighting that sedentary behavior peaks during this time of the day.[60,61] Fewer prompts were triggered in the morning as older adults typically engage in less prolonged sedentary behavior during this time, with more activity occurring in the early hours, thus not meeting the 30-minute sedentary threshold for prompting. This finding is in line with the study by Compernolle et al,[60] which also highlighted that sedentary behavior is typically lower in the morning hours among older adults. Finally, vulnerability results suggest a link between fatigue and prolonged sitting. Older adults were more likely to engage in prolonged sedentary behavior when feeling at least slightly fatigued, whereas pain was less frequently associated with prolonged sitting. A possible explanation is that pain may serve as a trigger to break up prolonged sedentary behavior. In particular, previous research has identified back pain as a helpful internal cue for interrupting sitting.[62] In addition to fatigue, recent research suggests that mood, another internal state, may also influence sedentary behavior. Giurgiu et al[63] found that higher momentary valence and energetic arousal predicted less sedentary behavior, whereas calmness was linked to more sedentary time, particularly at home. Although mood was not assessed in our study, these findings highlight the potential value of including mood as a dynamic factor in future JITAIs.

Regarding states of opportunity, we observed that older adults are more inclined to briefly interrupt their sedentary activities rather than perform them while standing. This tendency may be explained by the Theory of Effort Minimization, which suggests that individuals naturally prefer the least effortful option when engaging in activities.[64] In this case, briefly interrupting sitting requires less effort than maintaining a standing posture while performing typically sedentary tasks. In addition, we observed that certain factors

Table 3 Analytical Results on States of Opportunity

Random part	Opportunity: standing		Opportunity: interrupting	
	Unconditional random intercepts model			
	Variance	ICC	Variance	ICC
Person-level variance	0.31	.26	0.39	.22
Day-level variance	<0.01	<.01	<0.01	<.01

Fixed part	Two-level linear mixed model							
	B	EMM	95% CI	*P*	*B*	EMM	95% CI	*P*
Activity (ref: talking [standing] and reading [interrupting])								
Watching TV	**−0.51**	1.94	**−0.67 to −0.35**	**<.001**	**−0.22**	3.97	**−0.79 to −0.07**	**.01**
Talking	ref	2.40	ref	ref	**−0.78**	3.36	**−1.03 to −0.54**	**<.001**
Sleeping	**−1.34**	1.12	**−1.57 to −1.11**	**<.001**	**−1.08**	3.08	**−1.31 to −0.86**	**<.001**
Self-care	**1.29**	3.77	**0.92 to 1.66**	**<.001**	−0.15	4.28	−0.64 to 0.33	.81
Reading	**−0.59**	1.86	**−0.80 to −0.37**	**<.001**	ref	4.22	ref	ref
Listening to music	−0.16	2.27	−0.69 to 0.37	.68	−0.49	3.80	−1.12 to 0.14	.22
Household chores	**−1.09**	1.41	**−1.47 to −0.71**	**<.001**	**−1.94**	2.16	**−2.26 to −1.61**	**<.001**
Eating/drinking	**−0.74**	1.74	**−0.94 to −0.53**	**<.001**	**−0.71**	3.48	**−0.89 to −0.52**	**<.001**
Creative activity	**−0.69**	1.71	**−1.28 to −0.10**	**<.001**	0.07	4.24	−0.56 to 0.70	.95
Computer/tablet/smartphone	**−0.23**	2.23	**−0.42 to −0.03**	**.11**	−0.06	4.07	−0.24 to 0.11	.20
Commuting	−0.15	2.31	−0.51 to 0.21	.66	**−1.14**	3.12	**−1.60 to −0.67**	**<.01**
Cognitive activity	**−0.60**	1.77	**−1.01 to −0.19**	**<.001**	−0.04	4.09	−0.38 to 0.31	.59
At work	**−0.42**	1.99	**−0.76 to −0.09**	**.05**	**−0.79**	3.41	**−1.17 to −0.40**	**.01**
Others	**−0.84**	1.66	**−1.11 to −0.57**	**<.01**	**−0.83**	3.32	**−1.16 to −0.51**	**<.001**
Pain (ref: none)		1.98				3.76		
Very mild	**−0.17**	1.81	**−0.30 to −0.03**	**.02**	−0.02	3.74	−0.23 to 0.19	.83
Mild	−0.11	1.86	−0.25 to 0.03	.12	**0.25**	4.01	**0.06 to 0.45**	**.01**
Moderate	**−0.24**	1.74	**−0.40 to −0.07**	**<.01**	0.14	3.90	−0.07 to 0.36	.19
Severe	**−0.30**	1.67	**−0.57 to −0.04**	**.03**	**−0.46**	3.30	**−0.80 to −0.11**	**.01**
Very severe	−0.55	1.43	−1.15 to 0.05	.09	−0.55	3.21	−1.53 to 0.43	.30
Fatigue (ref: not fatigue at all)		2.05				3.80		
Slightly fatigued	**−0.17**	1.84	**−0.26 to −0.07**	**<.001**	−0.04	3.78	−0.16 to 0.08	.61
Neither fatigued nor refreshed	**−0.21**	1.83	**−0.38 to −0.04**	**.05**	0.27	4.11	**0.03 to 0.51**	**.02**
Fatigued	**−0.26**	1.76	**−0.43 to −0.10**	**<.001**	−0.07	3.71	−0.25 to 0.12	.33
Very fatigued	**−0.68**	1.31	**−1.03 to −0.33**	**<.001**	**−0.66**	3.16	**−1.03 to −0.28**	**.003**
Physical context (ref: inside)		1.93				3.83		
Outside	−0.14	1.80	−0.29 to 0.01	.09	−0.60	3.21	**−0.76 to −0.42**	**<.001**
Physical context (ref: at home)		1.95				3.90		
At a family/friend's/neighbor's/acquaintance's house	**−0.08**	**1.85**	**−0.29 to 0.13**	**.03**	−0.53	3.33	**−0.80 to −0.27**	**<.001**
At work	−0.05	1.96	−0.52 to 0.43	.99	−0.58	3.35	−1.08 to −0.07	.09
Restaurant/café	−0.43	1.70	−0.78 to −0.08	.12	**−1.18**	2.75	**−1.60 to −0.77**	**<.001**
In the car or train/tram/bus	**−1.01**	**1.03**	**−1.32 to −0.69**	**<.001**	**−1.88**	2.00	**−2.18 to −1.57**	**<.001**
In another public space	0.20	2.18	−0.10 to 0.49	.27	**−1.00**	2.86	**−1.41 to −0.59**	**<.01**
Other	−0.02	1.89	−0.37 to 0.33	.68	**−1.00**	2.84	**−1.40 to −0.60**	**<.001**
Social context (ref: nobody)		2.03				3.96		
Partner	**−0.13**	**1.86**	**−0.24 to −0.02**	**<.01**	**−0.20**	3.78	**−0.31 to −0.08**	**.02**
Close relatives	−0.11	1.91	−0.37 to 0.15	.33	−0.21	3.80	−0.46 to 0.05	.25
Others	−0.09	1.93	−0.26 to 0.09	.32	**−0.90**	3.06	**−1.07 to −0.72**	**<.001**
Temporal context (ref: morning)		1.96				3.54		
Afternoon	−0.02	1.98	−0.13 to 0.08	.22	0.01	3.46	−0.11 to 0.13	.23
Evening	−0.04	1.93	−0.14 to 0.06	.61	−0.06	3.57	−0.18 to 0.07	.77

Abbreviations: EMM, estimated marginal means; ICC, intraclass correlation. Note: Statistically significant values are presented in bold.

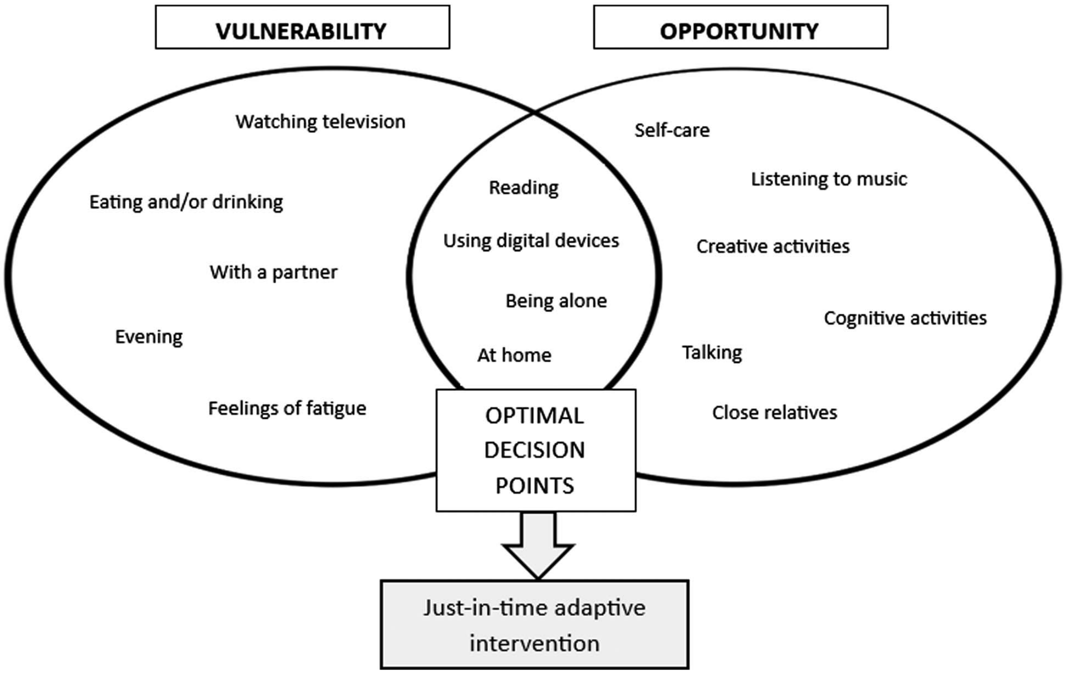

Figure 1 — Optimal decision points for delivering digital prompts to reduce prolonged sedentary behavior.

were not associated with the willingness to interrupt sedentary behavior, such as temporal context and perceived pain. However, other factors—such as activity type, physical and social context, and feelings of fatigue—appeared to be related to the willingness to break up prolonged sitting. Specifically, we found that older adults were most inclined to interrupt their sedentary behavior during activities such as reading, using digital devices, and engaging in cognitive tasks. These activities, previously referred to in research as mentally active sedentary behaviors,[65] require concentration and cognitive effort, which may explain why occasional interruptions are desirable or even necessary. In addition, we found that older adults were more likely to interrupt activities done indoors, particularly those performed at home, possibly because they perceive these interruptions as an opportunity to do meaningful tasks, such as getting something to eat or drink or hanging the laundry.[66] We also observed a preference for interrupting activities done alone or in the presence of close relatives. Social norms may play a significant role here as previous research has shown that opposing social norms can be a major barrier to reducing sedentary behavior.[59,62] For example, in the study of Lansing et al,[62] participants reported finding it difficult to reduce sitting during social activities in which others remained seated. Many expressed feeling uncomfortable or "weird" when deviating from what they perceived as the expected seated behavior.[62] Finally, our results also showed that higher levels of fatigue were associated with a lower likelihood of interrupting prolonged sedentary behavior. This aligns with previous research showing that fatigue is one of the most consistent predictors of reduced physical activity.[67,68]

When combining the results regarding states of vulnerability and opportunity—which is essential for identifying the potentially optimal moment to deliver a digital prompt to interrupt sitting—we arrive at the following conclusions. First, it seems advisable that JITAIs prioritize sending prompts when individuals are engaged in mentally active tasks, such as reading and using digital devices, as these situations were associated with both a higher risk of prolonged sitting and a greater willingness to take action. Second, JITAIs should be designed to deliver prompts in home settings where individuals feel comfortable responding without social pressure. In addition, prompts should avoid moments when older adults are in social situations in which movement may be perceived as inappropriate. Finally, moments of fatigue appeared to be associated with a reduced likelihood of interrupting sedentary behavior. Delivering prompts during such times may place an additional burden on participants and could risk disengagement. These insights provide a critical foundation for establishing a warm start with reinforcement learning-based JITAIs. Rather than relying solely on trial-and-error learning, JITAIs can begin with an evidence-based prompting strategy that aligns with older adults' vulnerability and opportunity states. This minimizes unnecessary or poorly timed prompts and enhances the intervention's effectiveness from the outset. Over time, reinforcement learning algorithms can refine these decision rules based on individual user responses, further optimizing the timing and frequency of prompts. This warm start approach ensures that JITAIs are both effective and minimally intrusive, reducing participant burden and the risk of habituation while maximizing engagement and long-term behavior change. To implement this effectively, JITAIs could leverage sensor-based data and self-reported activity tracking to detect when individuals are engaged in specific sedentary behaviors, their physical and social context, and their feelings of fatigue.[69,70] Initially, these data should be gathered to assess the participant's susceptibility to prolonged sedentary behavior and identify opportunities for delivering digital prompts. Once a baseline profile is established, initial prompts can be deployed. Over time, machine learning algorithms can further optimize the timing of prompts by detecting patterns in individual routines and identifying the most effective windows for behavior change.[71] Moreover, prompts should be context-aware and personalized, adjusting their frequency and messaging based on user preferences and previous responses.[72] Providing simple, actionable suggestions—such as standing up to stretch, walking a few steps, or changing posture—could further enhance compliance and long-term behavior change. However, more research is needed on the FITT (Frequency, Intensity, Time, and Type) principles of sedentary behavior interruptions. Although brief activity breaks are beneficial, current evidence is inconclusive regarding the optimal FITT. Findings vary across studies, and most studies focus on glycemic outcomes, with limited insight into other health effects.[18] The ideal FITT is likely context- and population-dependent rather than one-size-fits-all, highlighting the need for JITAIs that optimize not only the timing but also the content of prompts and examine their effects on health parameters.

Strengths and Limitations

This study provides valuable insights into the factors related to older adults' state of vulnerability and opportunity regarding prolonged sedentary behavior. A key strength of the study is the use of sensor-triggered, event-based EMA, which enabled real-time data collection in naturalistic settings, allowing for a more accurate and dynamic understanding of prolonged sedentary behaviors. The focus on transient factors, such as physical and social contexts, and fatigue is innovative, filling a gap in research on prolonged sedentary behavior in older adults. By examining a diverse sample of 90 older adults over the course of 2 weeks, the study captures a wide range of activities, contexts, and individual experiences, contributing to the richness of data. The use of multiple imputations to handle missing data strengthens the reliability of the findings and minimizes potential bias from incomplete data. Despite these strengths, the study has several limitations. First, activities, contexts, and feelings of pain and fatigue were assessed only when participants were already engaged in prolonged sitting, so we cannot determine whether these factors actually influence prolonged sitting behavior. This limits our ability to draw causal conclusions regarding vulnerability to prolonged sedentary behavior. Second, although EMA offers real-time data collection, it relies on participants' self-reporting, which may introduce response biases, potentially affecting the accuracy of the data. Also, because internal and contextual factors were only measured when participants responded to an EMA prompt, we cannot rule out the possibility that experiences of high fatigue or pain may have decreased the likelihood of responding. As such, the data may be missing not at random, potentially leading to an underestimation of the true impact of these states.[55] Third, data were collected between March and October, and thus seasonal variation—such as temperature, daylight, and weather conditions—existed, which may be particularly important for our descriptive findings[73]; future studies should consider year-round data collection to account for potential seasonal effects. Finally, participants were recruited using convenience sampling, which means that more vulnerable older adults, who may be less comfortable using technology or more likely to be sedentary, may have been excluded, limiting the generalizability of the findings to the broader older adult population. At the same time, the average sedentary time observed in our sample (9.3 h/d) closely aligns with findings from large-scale epidemiological studies,[7,8,17] suggesting comparable behavioral patterns. Moreover, we actively reached out to individuals without smartphones—often considered less technologically literate—by providing devices and support, thereby broadening the sample's diversity.

Conclusion

In conclusion, this study provides important insights into the vulnerability and opportunity states related to prolonged sedentary behavior in older adults by using sensor-triggered, event-based EMA. The results suggest that digital prompts within JITAIs may be more effective during mentally active tasks, in home settings, and when individuals are alone and not fatigued, to maximize their effectiveness in interrupting prolonged sitting. These insights can help inform the development of future JITAIs that incorporate sensor-based and self-reported data and machine learning techniques to provide context-specific, personalized prompts aimed at reducing prolonged sedentary behavior in older adults.

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