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Adjunctive smart ring monitoring during digital cognitive behavioral therapy for insomnia

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Digital cognitive behavioral therapy for insomnia (dCBT-I) has emerged as a treatment for chronic insomnia. Smart rings provide objective, wearable-derived sleep data that may complement subjective sleep diaries, but their role in monitoring treatment response remains unclear. This study evaluated the clinical effectiveness of dCBT-I with smart rings and compared subjective and wearable-derived sleep measures. In this single-arm study, individuals with insomnia completed a dCBT-I program, alongside daily sleep monitoring using a smart ring and sleep diary. Changes in clinical symptoms were analyzed, and sleep parameters were compared across the two tools. Twenty-eight participants completed the study, with significant improvements in insomnia severity (ΔISI = − 6.16, $p = .011$) and anxiety symptoms (ΔGAD-7 = − 2.38, $p = .038$). Adherence to the smart ring was higher than to sleep diaries (52.5 vs. 44.5 days, $p = .002$). Sleep diaries showed significant improvements in sleep parameters, which were not reflected in smart ring data. Systematic differences were observed between data sources. dCBT-I combined with smart rings improved clinical symptoms. However, smart rings did not reflect sleep improvements seen in diaries, limiting their clinical use as a standalone monitoring tool for insomnia management.

Clinical trial registration **Study of Efficacy of Digital Cognitive BehavioralTherapy with Wearable Device for Insomnia. Registered on 24/03/2024, ClinicalTrials.gov (NCT06339853), https://clinicaltrials.gov/study/NCT06339853.**

Keywords Insomnia, Digital cognitive behavioral therapy, CBT-I, Sleep–wake state discrepancy, Smart ring, Wearable devices, Mobile application, mHealth

Abbreviations

CBT-I	Cognitive behavioral therapy for insomnia
DSM-5	Diagnostic and statistical manual of mental disorders, 5th edition
dCBT-I	Digital cognitive behavioral therapy for insomnia
GAD-7	Generalized anxiety disorder-7
IQR	Interquartile range
ISI	Insomnia severity index
MINI	Mini-international neuropsychiatric interview
PHQ-9	Patient health questionnaire-9
SE	Sleep efficiency
SOL	Sleep onset latency
TST	Total sleep time
WASO	Wakefulness after sleep onset

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Insomnia, characterized by the difficulty initiating or maintaining sleep or experiencing non-restorative sleep[1,2], affects 9–30% of the general population[3–6]. Beyond impaired daily functioning, it is associated with adverse health outcomes, including depression, anxiety, cognitive impairment, hypertension, metabolic syndrome, and reduced quality of life, underscoring its significant public health impact[7–12]. Cognitive Behavioral Therapy for Insomnia (CBT-I) is the first-line treatment for chronic insomnia[13–16], demonstrating efficacy in both short- and long-term symptom improvement[17–20]. However, its utilization is limited by accessibility issues, high costs, and a shortage of trained clinicians, leaving many patients without access to evidence-based care[21–26].

To address these challenges, digital cognitive behavioral therapy for insomnia (dCBT-I) has been developed as a scalable alternative, integrating the core components of CBT-I—psychoeducation, sleep–wake structure interventions, and cognitive strategies—into digital platforms[27,28]. Delivered via mobile applications and websites, dCBT-I may offer features such as interactive sleep diaries, tailored feedback, and educational resources, enhancing its accessibility[29,30]. Studies have demonstrated that dCBT-I achieved moderate to strong effectiveness in reducing insomnia severity[27,28] and improving related outcomes, including anxiety, depression, and daytime functioning[31–33]. However, the effectiveness of digital interventions is often hindered by low adherence, which can reduce therapeutic outcomes and limit their potential impact.

The assessment and treatment of insomnia traditionally rely on subjective measures, such as sleep diaries, clinical interviews, and questionnaires[1,15,34,35], which remain the clinical gold standard for diagnosing and monitoring insomnia. These measures also play a vital role in fostering self-reflection and symptom monitoring, but they can be burdensome for patients, leading to incomplete data collection[36]. As consumer wearables become increasingly popular in mental health and sleep care, it is important to understand whether the data they provide offer clinically meaningful insights during evidence-based interventions such as dCBT-I. Wearable devices, such as smart rings and smartwatches, which collect continuous physiological data, including sleep metrics, offer an alternative and are increasingly adopted by individuals with insomnia to monitor their sleep[37–40]. Smart rings, in particular, have gained increasing attention in sleep research due to their compact design, extended battery life, and ability to collect high-resolution data on sleep patterns, heart rate, and body movement[41]. Unlike traditional actigraphy devices, smart rings are lightweight and unobtrusive, making them potentially suitable for long-term monitoring in everyday settings[42]. While validation studies in healthy subjects have shown that smart rings perform comparably to medical-grade actigraphy and polysomnography in estimating key sleep parameters[43,44], their clinical utility in patients with insomnia, especially in the context of CBT-I intervention, has not yet been established.

Adherence poses a challenge in digital interventions, potentially limiting their clinical effectiveness[45]. Consequently, existing research has focused on whether wearables could mitigate this issue by improving user engagement and data completeness[46–48]. However, wearables also raise critical questions regarding their alignment with subjective measures, which remain central to insomnia diagnosis and therapy[13–15]. As insomnia relies on subjective criteria, self-assessment through tools like sleep diaries plays an integral role in the therapeutic process, and the use of wearable devices could potentially diminish this reflective self-evaluation component[49]. Moreover, discrepancies between subjective and sensor-derived measures may occur in insomnia patients, which are critical to recognize as they may affect their perceptions of their symptoms and treatment progress[50].

While a few studies have explored dCBT-I with wearable devices, these have largely focused on clinical outcomes or adherence[49,51] rather than systematically comparing wearable-derived sleep metrics with subjective measures throughout the course of treatment. To our knowledge, this is the first study to investigate smart rings as part of a dCBT-I intervention while systematically analyzing the relationship, divergence, and clinical implications of subjective versus wearable-derived sleep data.

This study aimed to assess the potential utility of smart rings as an adjunct to dCBT-I. Specifically, we sought to (1) assess changes in clinical symptoms (insomnia severity, anxiety, and depressive symptoms); (2) evaluate adherence to sleep monitoring tools; (3) compare changes in sleep parameters recorded by subjective (sleep diary) and objective (smart ring) measures, including the relationship and discrepancies between these data sources.

Methods

Design and setting

This study employed a single-arm, pre-post design to evaluate the use of a smart ring alongside a digital CBT-I intervention. The trial was registered on ClinicalTrials.gov (NCT06339853). Ethical approval was obtained from the Institutional Review Board of Yonsei Severance Hospital (Approval No. 1–2023-0023), and the study adhered to the ethical principles outlined in the Declaration of Helsinki. Written informed consent was obtained from all participants prior to enrollment. The study design, intervention content, and methodological approach were determined before initiation, and no modifications were made during the study. Participation was voluntary, and all participants retained the right to withdraw from the study at any time without specifying a reason.

Participants

Participants were recruited through multiple channels, including clinic bulletin boards, flyers, and word of mouth. The study was conducted at Yonsei Severance Hospital in Seoul, South Korea. Prospective participants received detailed information about the study and underwent an in-person screening process. A board-certified psychiatrist determined eligibility based on a comprehensive review of medical and medication history, alongside assessments using the Mini-International Neuropsychiatric Interview (MINI)[52] and a general health evaluation.

Individuals were eligible for participation if they

- Were between 19 and 65 years of age.

- Met DSM-5 diagnostic criteria for insomnia disorder[1]
- Had significant insomnia symptoms with an Insomnia Severity Index (ISI) Score ≥ 11[34]
- Had sufficient Korean language skills,
- owned a smartphone and could use mobile applications and smart ring independently.
- Provided informed consent and demonstrated an understanding of the study requirements.

Individuals were excluded if they

- Had a coexisting sleep disorder, including obstructive sleep apnea, parasomnia, or restless legs syndrome, as determined by medical history review and screening interview.
- Had a psychiatric diagnosis of schizophrenia spectrum disorder, bipolar disorder, or substance use disorder, as determined by the MINI.
- Exhibited severe depressive symptoms (PHQ-9 score ≥ 20) or significant suicidality (Columbia-Suicide Severity Rating Scale score ≥ 4)[53].
- Reported a history of harmful substance use or dependency, including alcohol and hypnotics.
- Were receiving non-pharmacological treatments for insomnia, such as CBT-I or light therapy.
- Had participated in psychotherapy, such as CBT or psychoanalysis, within the past 3 months.
- Had adjustments in dosing or schedule of hypnotics, sedatives, antidepressants, anxiolytics, anticonvulsants, or antipsychotics within the past 3 months.
- Were pregnant or planning to become pregnant during the study.
- Worked in shift-based roles or jobs where sleep deprivation posed a safety risk.
- Had significant medical conditions, including active or progressive physical illnesses (e.g., congestive heart failure, chronic obstructive pulmonary disease, or acute pain), neurological conditions (e.g., stroke), neurodegenerative diseases (e.g., dementia, multiple sclerosis), or unstable health with a life expectancy of less than six months.
- Had participated in another clinical trial within four weeks prior to screening.

Procedure

The study was conducted between September 2023 and February 2024. Participants who consented to join the study were instructed to download a mobile application delivering dCBT-I and were provided with unique usernames to access the platform. The application encouraged participants to engage in CBT-I sessions, self-monitor their progress, and log in regularly over the eight-week intervention period. In addition to the mobile application, each participant was given a smart ring to capture sleep data continuously. Participants were instructed to wear the smart ring at night and to ensure it was properly synced with the mobile application for data collection. Participants attended two clinic visits: a baseline visit for screening, enrollment, and initial data collection, and a post-intervention visit for final data retrieval.

Mobile application

The mobile application was developed to deliver dCBT-I. A multidisciplinary team comprising experienced clinicians, software developers, product designers, and behavioral scientists collaborated to ensure both clinical relevance and user accessibility. The application, compatible with Android and iOS smartphones, features a modular structure with educational content, self-monitoring tools, goal-setting functionalities, and interactive elements.

The CBT-I modules were delivered sequentially, beginning with psychoeducation to provide foundational knowledge about sleep and insomnia. This was followed by an introduction to stress and relaxation techniques, bedtime restriction to consolidate sleep, and sleep hygiene education to promote healthy sleep practices. Stimulus control addressed behaviors linking the bedroom with wakefulness, while cognitive restructuring targeted dysfunctional beliefs about sleep. The program concluded with relapse prevention strategies to support the long-term management of insomnia. Additionally, relaxation techniques, including mindfulness exercises and progressive muscle relaxation, were available daily for participants to practice throughout the intervention.

Participants were instructed to log their sleep data daily based on their subjective recollection, recording details each morning about the previous night's sleep in the sleep diary. Sleep diary data collection adhered to the Korean clinical guideline for insomnia, ensuring consistency with established practices for assessing subjective sleep parameters[13]. Based on the input analysis, participants were also provided a recommended time in-bed schedule to facilitate efficient bedtime restriction.

Smart ring

Participants were provided with a commercial sleep tracker device, an Oura Ring (Model: Heritage)[54]. The ring was worn on the finger of the nondominant hand, and participants received verbal instructions and a written guideline for its use. The smart ring utilizes multiple sensing modalities to estimate physiological and activity parameters, including accelerometer and gyroscope data, photoplethysmogram signals, and body temperature. These data are used to calculate sleep parameters, as well as metrics such as heart rate variability, respiratory rate, and physical activity. The ring connects to the Oura mobile application via Bluetooth, which is compatible with Android and iOS platforms. Data collected by the ring are automatically transmitted to the app and subsequently stored on a cloud server. Pseudonymized participants' sleep data were extracted from the Oura cloud for analysis in this study. Participants could access their nightly sleep metrics directly through the Oura mobile application, which displayed outputs generated by the device's proprietary algorithms. However, these data were not integrated into the dCBT-I program. Therapeutic components, including sleep scheduling recommendations,

were based exclusively on self-reported diary entries. The study did not monitor or quantify the extent to which participants viewed or engaged with their ring-derived data.

Assessments

At baseline, participants provided sociodemographic data, lifestyle habits, medical history, and medication use. Validated questionnaires were completed every two weeks through the mobile application, including the Insomnia Severity Index (ISI) for insomnia symptoms[34,55], the Patient Health Questionnaire-9 (PHQ-9) for depressive symptoms[56,57], and the Generalized Anxiety Disorder-7 (GAD-7) for anxiety symptoms[58,59]. Daily sleep data, including sleep efficiency (SE), total sleep time (TST), wakefulness after sleep onset (WASO), and sleep onset latency (SOL), were collected from the sleep diary in the mobile application and the smart ring. Adverse events were monitored and recorded throughout the study to ensure participant safety. During the post-intervention visit, participants were also asked about their overall satisfaction with the program using a 5-point Likert scale, ranging from 1 (very dissatisfied) to 5 (very satisfied).

Outcomes

The outcomes evaluated during the eight-week intervention included changes in psychological assessments (ISI, GAD-7, and PHQ-9) and sleep measures (SOL, TST, SE, and WASO), which were recorded daily using the sleep diary and the smart ring. Paired data points were analyzed to compare the two data sources, identifying discrepancies and relationships between subjective (sleep diary) and objective (smart ring) sleep measures. Therapeutic directives within the dCBT-I program were driven by sleep-diary inputs. Ring data were collected in parallel for observational analyses and were not incorporated into intervention content or feedback. Adherence to the sleep diary and the smart ring was evaluated by comparing the number of days with valid data recorded during the 56 days study period. Valid data were defined as a completed sleep diary entry or a successfully recorded sleep session from the smart ring. Additional outcomes included participant satisfaction with the program and the occurrence of adverse events.

Statistical analysis

Descriptive statistics were used to summarize the baseline characteristics of participants. Continuous variables were reported as means and standard deviations (SD) or medians and interquartile ranges (IQR), while categorical variables were presented as frequencies and percentages.

Changes in psychological assessments over time were analyzed using linear mixed-effects models with a random intercept for participants and time as a fixed effect. Adherence to the sleep diary and smart ring was compared using the Wilcoxon signed-rank test, and its impact on ISI improvement (ΔISI) was analyzed using linear regression. Daily sleep measures (SE, TST, WASO, and SOL) recorded by the sleep diary and smart ring were analyzed using separate linear mixed-effects models to assess changes over time for each data source. Interaction terms were incorporated to examine differences in trends between the two data sources over time.

For paired data points where both sleep diary and smart ring measures were available on the same day, paired t-tests were conducted to compare mean differences for each sleep parameter. Bland–Altman analysis[60] was performed to evaluate agreement and systematic biases, calculating mean differences and limits of agreement (mean difference ± 1.96 SD). Spearman correlation analysis assessed relationships between sleep measures from the two sources.

Missing or incomplete daily sleep entries were excluded listwise from the relevant analyses. Only valid data, defined as completed sleep diary entries or successfully recorded smart ring sessions, were included in day-level models and comparisons. No imputation was performed, as the primary focus was on comparing observed subjective and objective data.

All statistical analyses were performed using RStudio (Version 2024.04.2 + 764), using the dplyr package for data preparation, lme4 for mixed-effects modeling, BlandAltmanLeh for agreement analysis, and ggplot2 for visualization[61,62]. All statistical tests were two-tailed, with significance set at $p < 0.05$. No correction for multiple comparisons was applied, as the primary hypotheses were pre-specified. Results were reported with corresponding p values.

Results

Baseline characteristics

Of the 30 participants enrolled, 28 (93.3%) completed the eight-week intervention. One participant withdrew consent voluntarily, and another was excluded due to reported difficulties in meeting the technical requirements for connecting the wearable device. The mean (SD) age was 28.37 (8.97) years, and 53.33% were female. Most participants were non-smokers (86.67%) and moderate alcohol consumers (90%). Baseline scores indicated moderate to severe insomnia with a mean ISI score of 17.23 (3.08), mild depressive symptoms with a mean PHQ-9 score of 9.27 (4.14), and mild anxiety symptoms with a mean GAD-7 score of 5.70 (3.77). Detailed baseline characteristics are summarized in Table 1.

Changes in symptoms, adverse events, and participant satisfaction

Over the eight-week intervention, significant improvements were observed in insomnia severity and anxiety symptoms. The mean ΔISI score decreased by 6.16 points ($t = -2.72$, $p = 0.011$), and the mean ΔGAD-7 score decreased by 2.38 points ($t = -2.18$, $p = 0.038$). Mean ΔPHQ-9 score decreased by 3.95 points, yet this change was not statistically significant ($t = -0.25$, $p = 0.807$) (Fig. 1, Supplementary Table S1).

No adverse events were reported throughout the intervention period. Participant satisfaction with the mobile application was high, with 66.7% of participants expressing satisfaction (60.0% "satisfied" and 6.7%

Characteristic	Values
Age, mean (SD)	28.37 (8.97)
Sex, n (%)	
Women	16 (53.33)
Men	14 (46.67)
Years of Education, mean (SD)	13.2 (1.9)
Smoking Status, n (%)	
Non-Smoker	26 (86.67)
Ex-Smoker	2 (6.67)
Current Smoker	2 (6.67)
Alcohol Consumption, n (%)	
Non-Drinker	1 (3.3)
Moderate Drinker	27 (90.0)
Hazardous Drinker	1 (3.3)
Employment status	
Employed	10 (33.33)
Not currently employed	20 (66.67)
Medication Use, n (%)	
Sedative-hypnotics	1 (3.33)
Other	7 (23.33)
Baseline Scores, mean (SD)	
Insomnia Severity Index (ISI)	17.23 (3.08)
Patient Health Questionnaire-9 (PHQ-9)	9.27 (4.14)
Generalized Anxiety Disorder-7 (GAD-7)	5.70 (3.77)

Table 1. Baseline characteristics of participants (N = 30). Data presented as mean (SD) for continuous variables and n (%) for categorical variables.

"very satisfied"), while 26.7% rated their experience as neutral. Two participants reported dissatisfaction (3.3% "dissatisfied" and 3.3% "very dissatisfied").

Comparison of adherence between smart ring and sleep diary

Adherence, defined as the number of days with valid data recorded during the 56 instructed days, was significantly higher for the smart ring compared to the sleep diary. The median (IQR) adherence for the smart ring was 52.5 (48–55) days, while the sleep diary demonstrated a median adherence of 44.5 (38.2–52) days. Statistical analysis using the Wilcoxon signed-rank test with continuity correction showed a significant difference between the two methods ($p = 0.002$). Regression analysis was performed to evaluate the association between adherence (smart ring or sleep diary) and changes in ISI from baseline to post-intervention. No significant association was found for either the smart ring ($\beta = 0.11$, $p = 0.198$) or the sleep diary ($\beta = 0.18$, $p = 0.107$).

Changes in sleep measures and comparison between data sources

Significant discrepancies were observed between sleep diary and smart ring measurements (see Fig. 2 and Supplementary Table S2). SOL decreased significantly over time in the sleep diary ($\beta = -0.25$ min per day, $p < 0.001$) but not in the smart ring ($\beta = -0.04$ min per day, $p = 0.072$), with a significant interaction effect ($p = 0.028$), such that reductions in SOL were observed in the diary but not in the smart ring. Similarly, TST increased significantly in the sleep diary ($\beta = 0.53$ min per day, $p = 0.004$) but not in the smart ring ($\beta = 0.06$ min per day, $p = 0.763$), with a significant interaction effect ($p < 0.001$), such that increases in TST were captured in the diary but not in the smart ring. For SE, the sleep diary showed a significant improvement over time ($\beta = 0.09\%$ per day, $p < 0.001$), while no significant change was observed in the smart ring ($\beta = 0.02\%$ per day, $p = 0.135$). The interaction term ($p = 0.591$) indicated no significant difference in patterns of change over time between the two sources for SE. For WASO, the sleep diary showed a significant decrease over time ($\beta = -0.13$ min per day, $p = 0.007$), while no significant change was observed in the smart ring ($\beta = -0.07$ min per day, $p = 0.329$). The interaction term ($p = 0.773$) indicated no significant difference in patterns of change over time between the two sources for WASO. These findings highlight systematic differences in how self-reported and wearable-derived methods capture changes in sleep over time within insomnia patients undergoing dCBT-I.

Comparison and correlation of sleep diary and smart ring measurements

Paired data points where both sleep diary and smart ring measures were available for the same user on the same day were used for analysis, with the sleep diary as the reference. Bland–Altman plots revealed systematic differences, with the sleep diary providing higher estimates for SOL, TST, and SE and lower estimates for WASO relative to the smart ring (see Fig. 3): SOL, TST, and SE were all significantly higher in the sleep diary compared to the smart ring (SOL: $t_{993} = 8.06$, $p < 0.001$, mean difference = 11.92 min; TST: $t_{990} = 4.56$, $p < 0.001$, mean

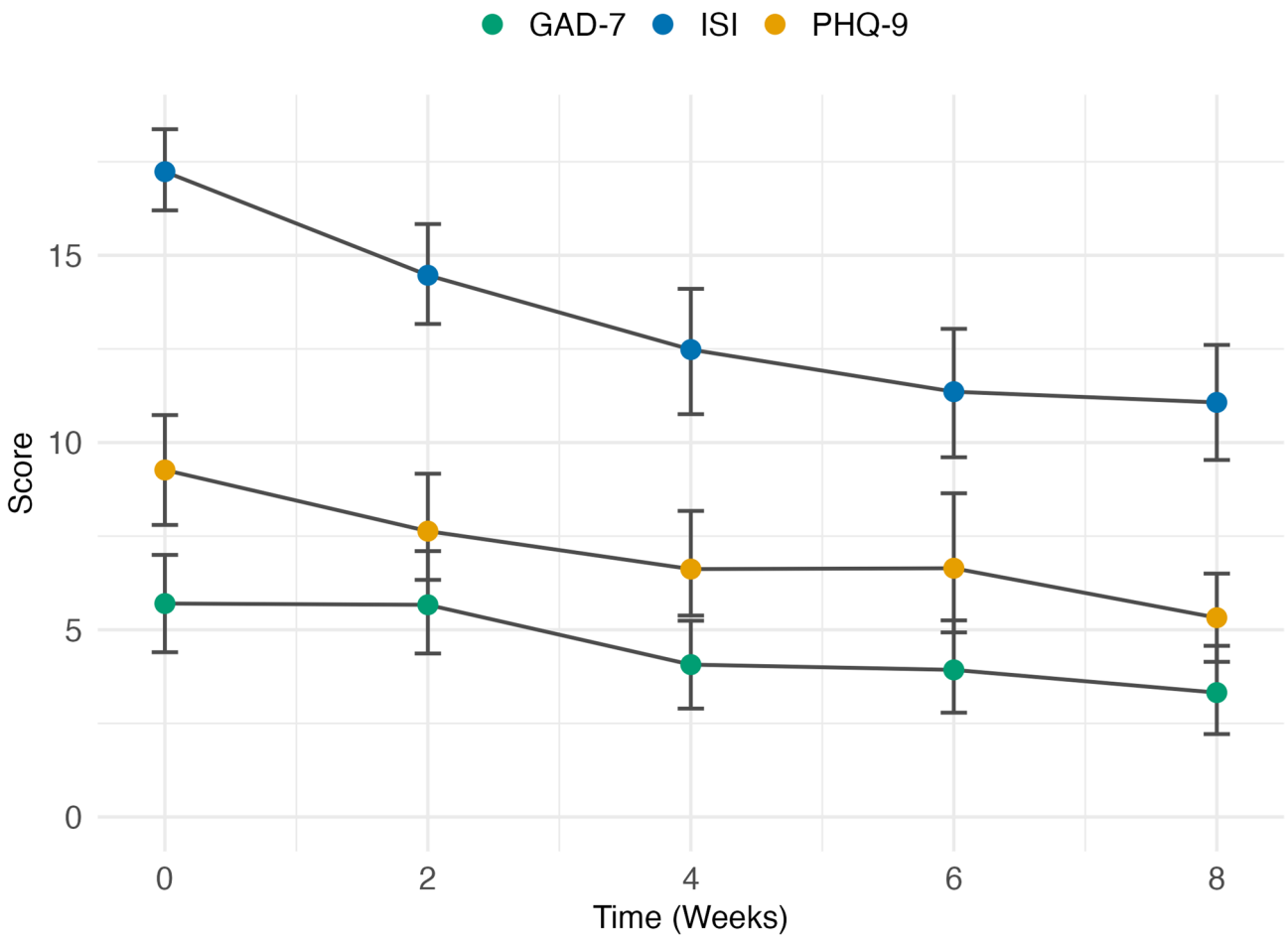

Fig. 1. Observed Trajectories of Insomnia, Anxiety, and Depression Symptoms Over the Study Period. The mean scores with 95% confidence intervals for ISI (blue), GAD-7 (green), and PHQ-9 (yellow).

difference = 16.23 min; SE: $t_{990} = -5.39$, $p < 0.001$, mean difference = 2.50%). In contrast, WASO was significantly shorter in the sleep diary compared to the smart ring ($t_{993} = -22.26$, $p < 0.001$, mean difference = −35.24 min). Detailed numerical results, including mean differences and limits of agreement, are provided in Supplementary Table S3.

Spearman correlation analyses further assessed the relationship between sleep diary and smart ring measures. Among the metrics, TST showed the strongest association, with a moderate correlation (r = 0.441, $p < 0$ 0.001). SOL and WASO exhibited weak correlations (r = 0.079, $p = 0.013$ and r = 0.115, $p < 0.001$, respectively). SE showed no significant correlation (r = 0.055, $p = 0.083$), reflecting the weakest relationship between the two methods.

Discussion

This study evaluated the effectiveness of dCBT-I with smart rings in improving insomnia symptoms and sleep measures. Additionally, we compared subjective sleep measures captured via self-reported sleep diaries with wearable-derived data from smart rings.

Clinical effectiveness and feasibility

The intervention demonstrated significant improvements in insomnia severity and anxiety symptoms following an eight-week dCBT-I intervention, consistent with prior studies highlighting the efficacy of dCBT-I in reducing insomnia severity and associated mood symptoms[28,63,64]. Participant satisfaction was high, with low dropout rates, indicating the feasibility and acceptability of the intervention. Adherence was higher for the smart ring than the sleep diary, suggesting that automated data collection may reduce participant burden. However, adherence to either tool was not associated with changes in severity of insomnia. This lack of association could be due to limited statistical power, given the relatively small sample size, or it may indicate that adherence to monitoring tools does not necessarily translate into clinical improvement, as outcomes may be more influenced by engagement with the therapeutic components of dCBT-I. Previous controlled dCBT-I studies with wrist-worn wearable devices have shown similar improvements in subjective outcomes but did not reveal significant additional benefits of wearables in enhancing therapeutic effectiveness[49,51,65]. While wearables have been associated with higher adherence and behavioral changes in some digital health contexts[46,49,51], the impact of adherence on outcomes may vary across interventions and indications[45]. Although the smart ring did not capture

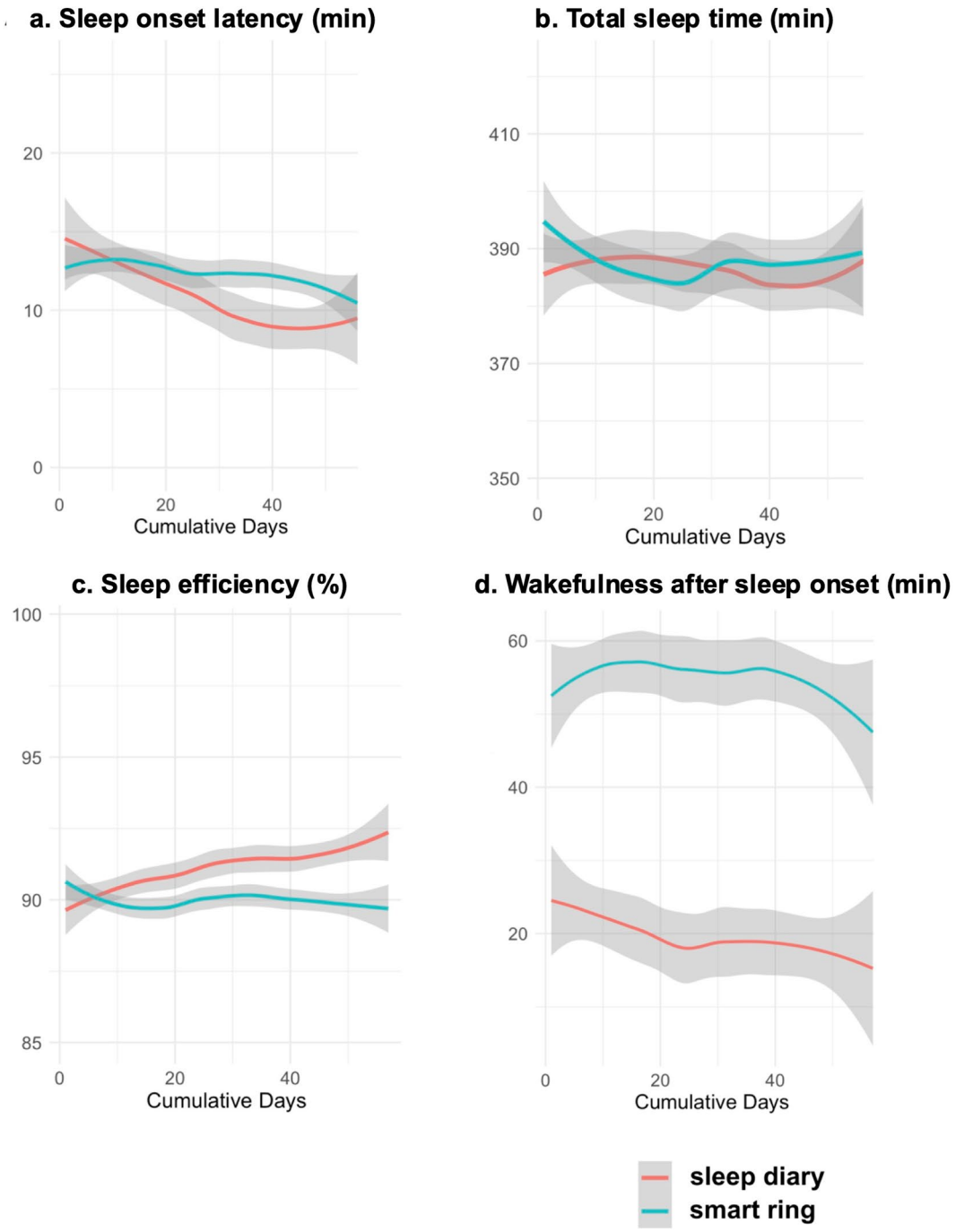

Fig. 2. Sleep measures over time, stratified by data source (sleep diary vs. smart ring). Lines represent mean values, with grey shaded areas indicating 95% confidence intervals. Red lines correspond to sleep diary data, and blue lines represent smart ring data. (**a**) Sleep onset latency (minutes). (**b**) Total sleep time (minutes). (**c**) Sleep efficiency (%). (**d**) Wakefulness after sleep onset (minutes).

changes in insomnia symptoms in this study, its higher adherence indicates potential value for improving data completeness and supporting continuous monitoring. In this sense, wearable-derived data may complement, but not replace, validated self-report tools, particularly in contexts requiring long-term feasibility or passive collection of sleep–wake patterns.

Discrepancies between self-reported and wearable-derived sleep measures

Systematic differences were observed between sleep diary and smart ring measures across all key sleep parameters (SOL, TST, SE, WASO). While sleep diaries captured significant improvements in these measures over the intervention, these changes were not reflected in the smart ring data. Notably, interaction effects for SOL and TST highlighted diverging trajectories between the two data sources. Bland–Altman analysis revealed

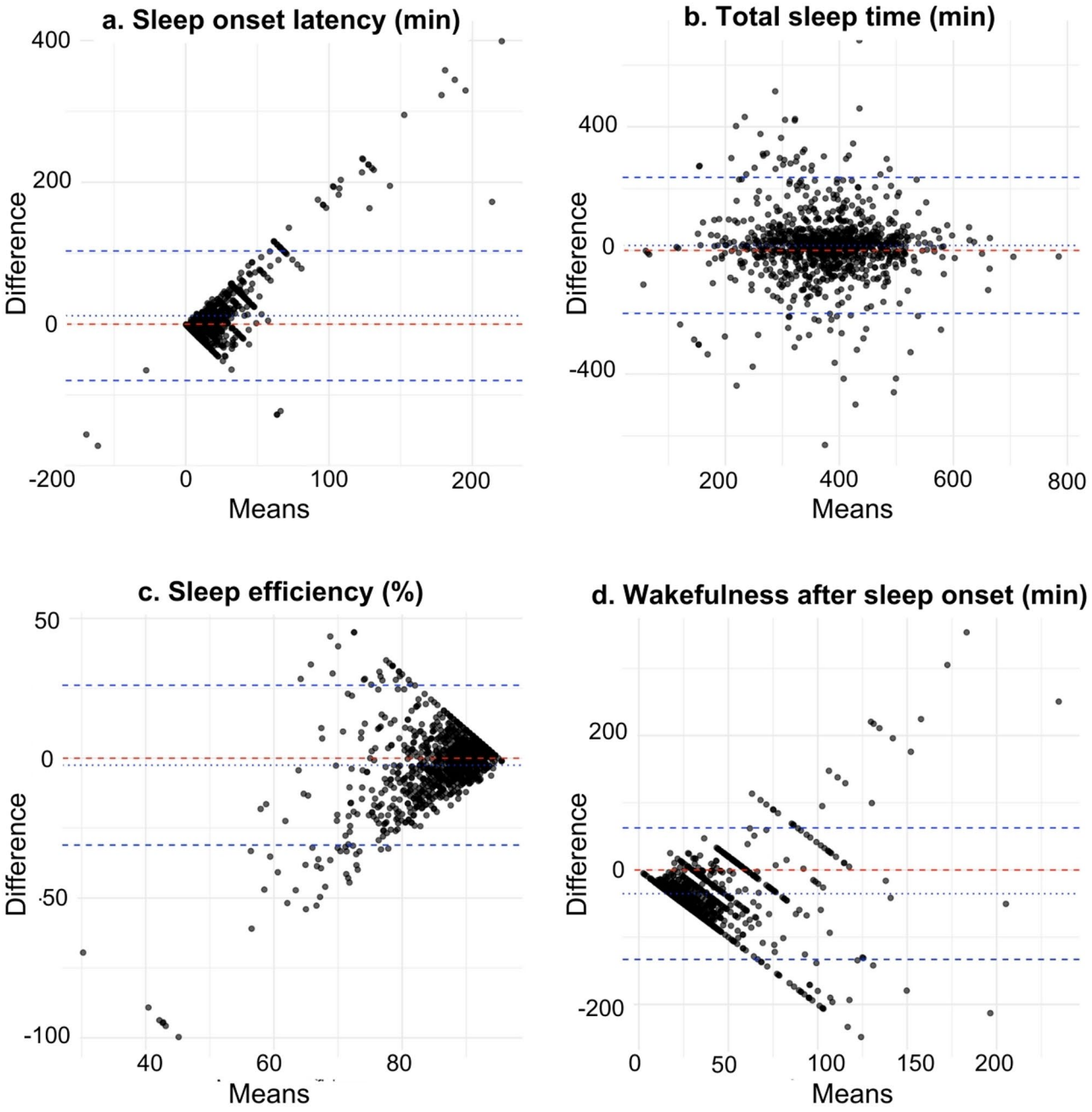

Fig. 3. Bland–Altman Plots Comparing Sleep Diary and Smart Ring Measures. Bland–Altman plots show the agreement between sleep diary and smart ring for (**a**) sleep onset latency (minutes), (**b**) total sleep time (minutes), (**c**) sleep efficiency (%), and (**d**) wakefulness after sleep onset (minutes). The blue dotted line represents the mean difference, and the blue dashed lines represent the limits of agreement (mean difference ± 1.96 SD).

systematic differences, with the sleep diary providing higher estimates for SOL, TST, and SE and lower estimates for WASO compared to the smart ring. Spearman correlations indicated weak to moderate relationships, with TST exhibiting a moderate correlation, while SOL and WASO showed weak correlations, and SE displayed no significant correlation.

The divergence observed between subjective (sleep diary) and objective (smart ring) sleep data may reflect a combination of perceptual processes and technical limitations. First, the observed pattern is consistent with the well-documented phenomenon of sleep–wake state discrepancy, in which subjective sleep reports often diverge from objective measurements[50], particularly in individuals with insomnia[66–68]. The underlying mechanisms are likely multifactorial. Cognitive factors, such as heightened sleep-related worry and selective monitoring, may lead to exaggerated perceptions of sleep deficits[69,70]. Physiological hyperarousal may further distort self-reported assessments, while neurophysiological models suggest that local aspects of wakefulness during sleep and reduced

information integration may contribute to sleep misperception[71–73]. In this sense, changes captured in the sleep diary may reflect meaningful therapeutic gains, such as reduced pre-sleep arousal and improvements in sleep-related cognitions, effects that are central to CBT-I but not detectable by wearable sensors. Second, limitations of the smart ring itself may contribute to the absence of detectable change. Smart rings use proprietary multi-sensor algorithms based on movement, heart rate, and temperature, developed primarily for consumer health applications. However, they have not been clinically evaluated in individuals with insomnia or in the context of behavioral interventions[43,44]. As CBT-I primarily targets subjective experiences, including perceived restfulness and reduced cognitive arousal, objective physiological changes may be limited despite clinical improvement.

Previous research has shown that individuals with insomnia often report higher values for SOL and WASO and lower values of TST and SE relative to objective measures such as actigraphy or polysomnography[74–77]. In our study, sleep diaries provided higher estimates for SOL, TST, and SE and lower estimates for WASO compared to smart ring data. These discrepancies may reflect differences in measurement modalities, sample characteristics, or the influence of CBT-I. A meta-analysis of CBT-I further demonstrated that diary-based outcomes consistently improved for SOL, WASO and SE but not for TST. In contrast, actigraphy outcomes showed only small reductions in SOL, no significant changes in WASO or SE, and moderate reductions in TST in the opposite direction of diary findings. PSG outcomes also showed no consistent improvements[78]. Together, these findings indicate that wearable-derived measures do not parallel subjective improvements after CBT-I, and in some domains may diverge. Further research is needed to evaluate the consistency and clinical relevance of these patterns, particularly when comparing subjective reports with data from newer wearable technologies.

Strengths

This study is, to our knowledge, the first to incorporate a smart ring alongside dCBT-I, providing preliminary insights into its feasibility and utility for insomnia management. Significant improvements in insomnia severity, subjective sleep measures, and anxiety symptoms, coupled with high participant satisfaction and low dropout rates, underscore the intervention's acceptability and clinical potential. In contrast to previous dCBT-I studies that included wearable devices but focused primarily on clinical and adherence outcomes[49,51,65], the present study systematically examined the relationship between wearable-derived and subjective sleep data throughout the intervention period. This approach enabled a direct evaluation of the agreement and discrepancies between data sources, contributing new evidence on their comparative value and implications for digital insomnia management.

Limitations

The study's single-arm design without a control group limits causal inferences regarding the observed improvements. Future controlled trials could compare dCBT-I with and without wearable integration to evaluate the utility of smart rings in reducing insomnia symptoms. The small sample size limits the generalizability of the findings and reduces the power to detect more nuanced effects. The study duration of eight weeks may have been insufficient to evaluate long-term feasibility and therapeutic outcomes, highlighting the need for extended follow-up periods in future research to assess the clinical effectiveness.

An additional limitation relates to participant access to wearable data. While the Oura application provided nightly sleep metrics that participants could view, these data were not tracked or quantified within the study, and their potential influence on diary responses cannot be ruled out. Because app-viewing behavior was not captured, any such influence cannot be quantified in the present dataset. It is possible that seeing wearable-derived outputs may have shaped participants' perceptions or recall of their sleep, thereby affecting diary reports. However, because the dCBT-I program relied exclusively on diary data to generate therapeutic recommendations, the smart ring served only as an observational adjunct. Future studies should systematically evaluate whether access to wearable feedback influences subjective reporting and therapeutic engagement.

The accuracy of smart rings in insomnia populations remains uncertain, as no validation studies have been conducted specifically for these devices in individuals with insomnia. In healthy individuals, smart rings have shown good agreement with polysomnography for TST and SOL but limited specificity for wakefulness[44]. Comparisons with actigraphy revealed biases, such as overestimating TST and underestimating WASO and SE[43]. These limitations underscore the need for dedicated validation studies of smart rings in insomnia populations. Moreover, the smart ring used in this study relies on proprietary algorithms that are not publicly disclosed, which may limit transparency and reproducibility[44]. As algorithm updates may alter data outputs over time, future research should address the implications of using closed-source consumer devices in clinical research[37]. Until such studies are conducted, wearable-derived data should be interpreted cautiously, particularly in the context of sleep–wake state discrepancy[40].

Finally, the reliance on self-reported sleep diaries introduces potential bias. While sleep diaries are essential for capturing subjective experience and guiding CBT-I, they are susceptible to placebo effects and reporting bias. Participants may overreport improvements due to treatment expectations, perceived demand to demonstrate progress, or post-intervention optimism[79]. These factors may contribute to the divergence between subjective and objective sleep measures in this study, particularly in the absence of a control group. Future studies may benefit from including expectancy assessments, blinding procedures, or the use of a sham app as a comparator to mitigate these effects and better contextualize self-reported improvements[80,81].

Future research

While this study collected both self-reported and wearable-derived sleep data, participants did not receive feedback or guidance based on these measures. However, a recent randomized controlled trial demonstrated the potential utility of integrating wearable-derived data into insomnia interventions. In that study, participants who received feedback on wearable-derived sleep measures without undergoing dCBT-I showed improvements

in insomnia severity compared to a control group that received only sleep hygiene education[82]. This finding suggests that leveraging wearable data to address sleep–wake discrepancies could enhance insomnia treatments. Combining such feedback with cognitive-behavioral strategies targeting misperceptions of sleep may help reduce discrepancies and improve clinical outcomes[83,84]. When designing feedback-based interventions, user expectancy should be considered, as beliefs about the credibility or usefulness of wearable data may influence how feedback is received and acted upon[85]. Future studies may explore how best to frame wearable-derived feedback to support adherence, reduce misperceptions, and enhance clinical engagement.

Furthermore, wearable devices, including smart rings, collect a broader range of physiological and behavioral metrics beyond sleep parameters, such as heart rate variability, step counts, and body temperature. These additional data streams may provide valuable insights into the mechanisms underlying insomnia. For instance, heart rate and heart rate variability can reflect autonomic arousal, which is often elevated in individuals with insomnia[86], while step counts may serve as a proxy for physical activity, a known regulator of sleep patterns[87,88]. Future research should investigate the integration of these metrics with sleep measures to develop a more comprehensive and personalized approach to insomnia management.

Conclusion

This study evaluated the use of a smart ring alongside dCBT-I, demonstrating significant improvements in insomnia severity and anxiety symptoms, high participant satisfaction, and low dropout rates. However, systematic discrepancies between subjective (sleep diary) and wearable-derived (smart ring) sleep measures highlight the limitations of relying on wearable data alone to monitor treatment response in insomnia. While smart rings offer benefits such as higher adherence and automated, passive data collection, they cannot replace sleep diaries, which remain essential in dCBT-I for capturing subjective sleep experiences and therapeutic gains. Given the single-arm design and limited sample size, this study does not allow conclusions about the comparative effectiveness of dCBT-I with versus without wearable integration, but it provides preliminary evidence on feasibility and user adherence. Clinicians should interpret smart ring data with caution and use it only as a complementary tool alongside validated self-report measures. Further validation is needed to determine their accuracy and clinical relevance in insomnia care. Combining wearable-derived data with cognitive-behavioral strategies may help address sleep–wake discrepancies and support more personalized insomnia care, but such approaches should be carefully evaluated in future clinical studies.

Data availability

The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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Author contributions

DM conceptualized the study, designed the methodology, performed formal analysis and data visualization, and was the primary contributor to writing the original draft as well as reviewing and editing the manuscript. YL contributed to the study methodology and participated in reviewing and editing the manuscript. AL contributed to the manuscript through review and editing. SL conducted the investigation and assisted with manuscript review and editing. EL provided conceptual oversight, supervised the investigation and project administration, secured funding, and contributed to the manuscript through review and editing. All authors read and approved the final manuscript.

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Declarations

Competing interests
DM was previously employed by WELT Corp. Ltd., the company behind the digital CBT program evaluated in this manuscript. YL is currently employed by WELT Corp. Ltd. The other authors declare no competing interests.

Additional information
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