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Beyond the numbers: expectations and experiences of using wearables for stress management in three older persons with borderline symptoms

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Abstract

Background: Older adults with Borderline Personality Disorder (BPD) struggle with emotion regulation and heightened arousal that disrupts daily functioning. Wearables, such as a finger sensor measuring electrodermal activity, may enhance arousal monitoring and support regulation strategies.
Research questions: What are the expectations and experiences of using a wearable sensor during arousal interventions in three individuals with BPD symptoms?
Methods: In this exploratory qualitative study, three clients participated over 28 days, including a five-day baseline period, using an alternating-treatment ABAB design with feedback and non-feedback phases. Participants wore a sensor, practiced daily relaxation exercises, and completed self-assessment questionnaires before each exercise to measure mood. Arousal levels were measured before, during, and after exercises. Randomization tests analyzed individual changes. Correlations were assessed between subjective (questionnaire) and objective (sensor) stress measures and between stress levels and study days. In-depth interviews before and after participation captured expectations and experiences.
Results: Participants consistently used the sensor despite technical issues such as connectivity and lack of water resistance. All three found it suitable for monitoring emotion regulation challenges but emphasized the need for therapeutic guidance. No significant results were found regarding the effectiveness of the moodmetric® ring.
Conclusion: This exploratory home-setting study shows that wearable technology could benefit older adults with BPD in aiding emotion regulation, especially when therapeutic guidance effectively integrates insights gleaned from the device. Future research should focus on long-term monitoring, ecological momentary interventions, and therapist involvement to optimize the effectiveness of stress management with wearable technology.

Keywords: older adults, borderline personality disorder, electrodermal activity, emotion regulation, single-case experimental design

Introduction

Borderline personality disorder (BPD) is a severe mental disorder characterized by affective instability, impulsivity, and interpersonal difficulties (American Psychiatric Association, 2013). Adults with BPD experience high arousal levels, causing emotional dysregulation and disruptions in daily life. The prevalence of BPD in the general population in the United States is estimated to be 1.6% (The Recovery Village, 2023).

The four most effective psychotherapeutic treatments for adults with BPD are: Dialectical Behavioral Therapy, Schema-Focused Therapy (Videler et al., 2020), Transference-Focused Therapy and Mentalization-Based Therapy (Finch et al., 2019). These treatments focus on emotion regulation and reducing impulsivity. Systems Training for Emotional Predictability and Problem Solving (STEPPS) is a group psychotherapy that has also proven effective for adults with BPD and focuses specifically on emotion regulation skills. Research shows that participants in STEPPS show improvement by no longer meeting the DSM-5 criteria for BPD - by less than five out of nine criteria - and by refraining from self-harm, suicidal behavior or severe anger outbursts for at least 3 months after treatment (González-González et al., 2021).

However, it is important to note that much of this research has primarily focused on younger adults, typically between the ages of 25 and 35 (Hutsebaut et al., 2017). This leaves a significant gap, especially considering that the prevalence of personality disorders among older adults is around 14.5%, with up to 3.2% having BPD (Reynolds et al., 2015). Older adults represent a distinct population due to a variety of biological, social, cultural, and psychological factors that make them increasingly heterogeneous as they age (Kessler et al., 2014). This heterogeneity can result in a combination of somatic, neurocognitive, and psychosocial problems, which may reduce the effectiveness of psychotherapies developed for younger adults (Videler et al., 2018).

Additionally, older adults often face life-stage-specific challenges, such as dealing with loss, retirement, or physical decline, and they may have a more limited coping repertoire to address these issues (Knight & Pachana, 2015). As more studies begin to explore the application of STEPPS in older adults, they increasingly indicate its feasibility, but also emphasize the need for possible modifications to better meet the unique needs of this population (Ekiz et al., 2022). This highlights the importance of further research specifically targeting older adults with BPD to optimize therapeutic interventions.

Currently, standard care for individuals with BPD often relies on self-assessment questionnaires, which may sometimes be less reliable due to potential difficulties with insight, particularly in cases involving externalizing psychiatric disorders like BPD (Halkola et al., 2019). It is therefore recommended that, in addition to subjective measurements, objective measurement devices, such as wearable technology, which measure physiological arousal, be incorporated into the treatment process, as this may prove beneficial in achieving more positive treatment outcomes.

Wearables are defined as electronic devices that are worn on the body and are equipped with sensors that are capable of collecting and processing objective data about the human body. For instance, arousal levels can be quantified objectively and with ease through the use of wearables. This enables real-time monitoring and continuous data collection in everyday life. The utilization of wearable technology has increased markedly in recent years. These devices have become capable of collecting data of increasing quality, which is also relevant to mental health (Debard et al., 2020). Wearables can enhance the reliability of measuring arousal levels, in addition to the subjective experiences. They can measure a range of variables, including electrocardiography (heart activity), blood pressure, electroencephalography (brain activity), and electrodermal activity (EDA). EDA, also known as skin conductance (SC), reflects electrical conductance in the skin, influenced by sweat gland activity during sympathetic nervous system arousal (Raugh et al., 2019). EDA has two components: the slowly changing Skin Conductance Level (tonic) and the rapidly changing Skin Conductance Response (phasic), which reflects reactions to environmental events (Georgiev et al., 2013).

Research has shown that EDA is more sensitive than other methods in detecting changes in autonomic functions of both heightened and reduced physiological and emotional arousal (Critchley, 2002; Lang et al., 1993; Sequeria et al., 2009; D'Hondt et al., 2010; Delannoy et al., 2015; Kosonogov et al., 2017), even when participants are unaware of their stress (Doberenz et al., 2010). Changes in EDA levels are indicative of stress and can be measured objectively using wearables (Boucsein, 2012).

Combining EDA with self-assessments provides a comprehensive understanding of arousal and valence, integrating objective physiological data with subjective self-assessments. This integration of objective physiological data with subjective self-assessments through wearable technology could enhance therapeutic interventions, such as STEPPS, in individuals with BPD, providing more personalized and responsive care.

The application of wearables in healthcare remains a relatively unexplored area of research. Various models have been developed to explain the use of technology, including TAM (Technology Acceptance Model) and UTAUT (Unified Theory of Acceptance and Use of Technology) (Bao and Lee, 2023). Given the aging population and the prevalence of mental disorders such as BPD, it is crucial to investigate how older people experience the use of technology like wearables. Understanding their experiences can lead to more effective implementation and increased use of these technologies, ultimately improving support and the quality of care for this group.

In this mainly qualitative study, we focus on examining the expectations and experiences of older persons regarding wearables during their care as usual relaxation exercise. Based on the literature (Heynsbergh et al., 2018), the following aspects are relevant to study when applying wearables in older persons: usability (user-friendly device), feasibility (practical aspects for implementation), suitability (meets specific needs and preferences), and acceptance (readiness and willingness to use). Only suitability will also be assessed quantitatively, i.e. whether there is a relationship between the objective measures and the subjective experience of stress, and whether the feedback from a wearable actually helps to achieve better outcomes.

The aim of this study is to explore expectations and experiences of using wearables in older people with BPD. Therefore, we hypothesize that participants will experience a greater reduction in stress over time due to the feedback learning effect, which will increase the appropriateness (suitability) and effectiveness of the therapeutic intervention.

Methods

Participants

The study was conducted at a mental health organisation Eindhoven, department Nestor, the Netherlands. Nestor provides in and outpatient treatment services for among others older adults. The Substance Abuse and Mental Health Services Administration Guideline (2019) for psychosocial interventions for Older Adults with Serious Mental Illness, defines older adults as 50 years and older. Mainly because of adults with serious mental illness over age 50 have high rates of medical comorbid conditions and significantly reduced life expectancy.

Inclusion criteria were (a) the participant meets at least three criteria of BPD in terms of DSM-5 (DSM-5; American Psychiatric Association, 2013); (b) treated for arousal at mental health organisation Eindhoven, department Nestor; (c) living at home with spouse or close relation; (d) participants must be able to operate the app (moodmetric®) used for data collection and monitoring; and (e) spouse or close relation is able to upload the data at least once a day. Exclusion criteria were (a) intellectual disability based on observations by a therapist; (b) cognitive disorders due to for example dementia; (c) acute condition (such as psychosis or suicidality); (d) suffering from any serious physical or medical condition— including epilepsy, brain injury, cardiac arrhythmia or other heart disorders—or those using a pacemaker are encouraged to consult with a medical professional before using the wearable; (e) who does not speak the Dutch or English language; (f) a continuous high arousal level without fluctuations on the wearable.

Between February 2023 and June 2024, potential participants were recruited based on predefined criteria. The screening was conducted by the healthcare professional in collaboration with the researcher, and potential candidates were informed about the study's aims, procedures, and the use of the wearable technology. Informed consent was obtained, and participants meeting the inclusion criteria were enrolled.

Study design

The study is exploratory in nature, primarily qualitative, and supplemented with quantitative data, utilizing a single-case experimental A-B-A-B phase design (SCED). The interviews in this study are designed to gain insight into the experiences and expectation of older adults on using wearables. While the study is not purely qualitative, as we are not aiming for data saturation, the focus is primarily on initial exploration. We want to assess how older adults interact with wearables and evaluate the feasibility of our protocol before conducting a larger study in the future.

The SCED allows for randomization and offers sufficient measurement moments within a single case. The What Works Clearinghouse's SCED standards recommend a minimum of four phases per case, with at least five data points per phase to ensure reliability (Kratochwill et al., 2010). By including three participants, rather than a single case (N=1), the study gains the potential to replicate findings, thereby enhancing its clinical relevance. More participants at this stage of the research should not be advantageous.

Procedure

Prior to the study, a baseline (Zero) phase was conducted to assess participant suitability and familiarize them with the device. This five-day trial allowed participants to wear the moodmetric® ring and receive feedback. Participants showing no fluctuations in moodmetric® levels or lacking motivation/self-reflection were excluded. Demographic data were collected during this phase. *Figure 1* shows the Moodmetric® ring with the app and the interface of the app (*Figures 2a, 2b, and 2c*).

Eligible participants then wore the ring for 28 consecutive days and performed the daily STEPPS intervention. Phase duration was randomized, with a minimum of five days each. Before each intervention, participants completed the self-assessment questionnaire (SAM, see section Measurements) to assess mood.

In phases A, the spouse uploaded the ring data daily. At the end of phase A1, the investigator and participant discussed data use and possible impediments. The same procedure was applied in phase B1, except the participant uploaded data and received feedback. During B phases, the practice function of the ring provided immediate feedback on stress levels during

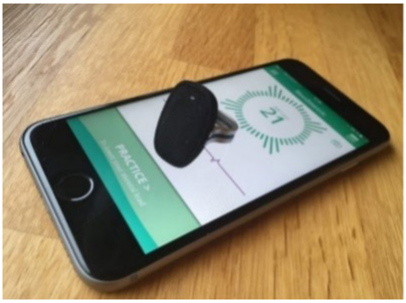

Figure 1. The moodmetric® ring

STEPPS, allowing participants to monitor and adjust practice. Phases A2 and B2 followed the same procedures as A1 and B1.

Before and after the study, interviews were held to explore expectations and experiences with the ring (average duration: 45 minutes). See *Figure 3* for details of the procedure.

Measurements

Semi-structured interviews

To achieve the study objectives, semi-structured interviews were employed, offering both consistency and flexibility by addressing key themes while exploring participants' individual experiences.

The initial interview (introduction), conducted after the baseline measurement, focused on stress management, expectations of the wearable, cognitive abilities, and motivation (see Appendix I). Interviews lasted about 45 minutes.

The second interview (evaluation), conducted after the study, explored participants' experiences

Figure 2a Displays the user's current stress level

with the wearable (see Appendix II). These interviews, also averaging 45 minutes, were audio-recorded for analysis. Questions addressed usability, feasibility, suitability, and acceptance of the wearable. Usability relates to user-friendliness and ease of operation; feasibility concerns cost, support, and training; suitability considers alignment with therapeutic goals and daily life; acceptance refers to participants' willingness to adopt the technology.

SAM-questionnaire

To determine participants' mood, they were asked to complete the SAM questionnaire (approximately one minute) before the start of the daily STEPPS intervention. The SAM is a nonverbal pictorial assessment tool that directly measures the pleasantness, arousal, and dominance associated with a person's affective responses to various stimuli, requiring only three assessments. The SAM is a useful tool in determining the subjective experience of emotion (Bradley et al., 1994; see Appendix III).

A low score (0) represents negative feelings, increased arousal (more arousal), and little control over the situation. A high score (9) represents positive feelings, increased calmness, and a lot of control over the situation.

Wearable device

In selecting a wearable measuring stress-indicators, we deliberately focused on EDA rather than heart rate variability (HRV). Although HRV can be measured with photoplethysmography (PPG) sensors in smartwatches, reliable HRV data can typically only be obtained during the night or when the user is completely still (i.e., stationary measurements; Georgiou et al., 2018). Daytime measurements are easily contaminated by movement artifacts. Chest straps provide more reliable HRV signals but are uncomfortable for prolonged daily use. EDA, in contrast, is a robust and well-validated proxy of sympathetic nervous system activity (Boucsein, 2012), and therefore more suitable for continuous stress monitoring in daily life.

While wristbands in principle could be acceptable for older users, the models available at the time did not meet our requirements. For example, the Empatica E4, widely used in research, does measure EDA but required a continuous Bluetooth connection, provided no user-friendly feedback to the wearer, and was considerably more expensive. Consumer-grade devices such as Fitbit and Garmin included CE marking and are unobtrusive, but at the time of study initiation, their EDA functionalities were not available or not validated for research or clinical use, and raw data access was limited. In contrast, the

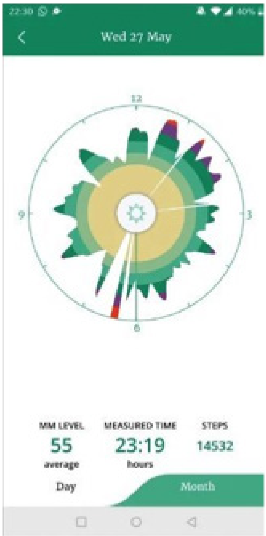

Figure 2b Visualizes the stress level over a 12-hour period, with the position within the circle indicating the intensity of the stress level; the closer to the center, the lower the stress level, and the farther out and more colorful, the higher the stress level. The center of the circle indicates whether the period relates to day or night.

Moodmetric® ring (produced by the Finnish company Vigofere Oy) combined several practical advantages: it is validated for EDA measurement (Torniainen et al., 2015), is legally compliant (i.e. CE marked), relatively inexpensive, unobtrusive, easy to put on and remove, and allowed local storage with later synchronization, enabling participants to move freely without continuous

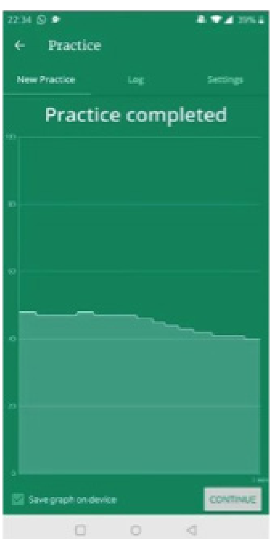

Figure 2c Shows the practice function used in our study, tracking how the stress level changed during the relaxation exercise.

phone connectivity while still providing GDPR-compliant cloud access. These features made it particularly feasible and acceptable for daily use by older adults. Importantly, the accompanying Moodmetric® app was user-friendly and provided immediate, understandable biofeedback to participants, which was essential for integrating the device into daily relaxation exercises alongside care as usual.

The Moodmetric® ring quantifies arousal on a scale from zero to one hundred, with higher scores indicating heightened arousal, irrespective of whether the stimulus is positive or negative. The model does not provide a specific threshold for stress; values are standardized for each individual. A daily average of 46–50 indicates a good balance of the autonomic nervous system, suggesting sufficient recovery relative to exertion. A daily average between 51 and 55 reflects increased stress, whereas a score of 56 or higher indicates significantly elevated stress levels, which may point to chronic stress (Vigofere Oy, 2021). Participants wore the ring continuously throughout the study to ensure sufficient data collection. Daily averages for both daytime and nighttime stress levels were calculated based on participants' reported wake-up and bedtime schedules. Although the device is not water-resistant and requires periodic charging—factors that can temporarily interrupt wear—sufficient data were obtained. In addition to daily averages, the physiological data for the five minutes before and after each STEPSS intervention were extracted, enabling a comprehensive understanding of both objective and subjective stress levels.

Tools and resources

The manuscript text was structured and the language optimized with the assistance of ChatGPT, and critically reviewed and edited by the authors. Evidence Hunt was used to identify relevant scientific articles, and DeepL was utilized for translations.

Data analysis

Qualitative data

The interviews were subjected to deductive content analysis, as delineated in Moser and Korstjens (2018). All interviews were transcribed verbatim by one researcher (NB) and thoroughly examined. Based on the predefined topic list and questionnaire, a summary of key points was prepared and returned to participants for verification (member check).

The transcripts were coded according to four predefined themes: suitability, usability, acceptance, and feasibility. Codes were clustered into

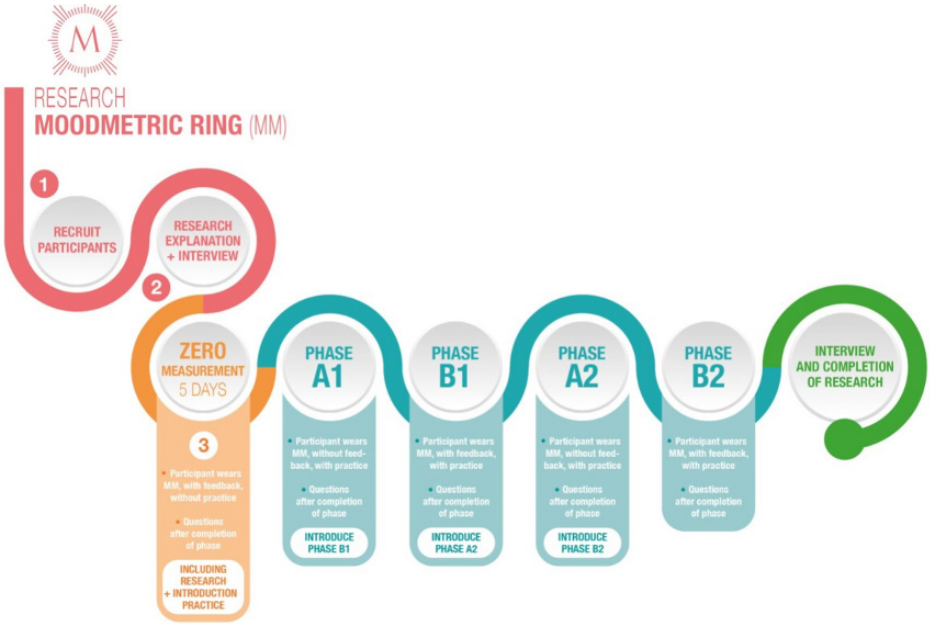

Figure 3. Timeline of the study procedure. Participants started with a 'zero phase' (orange) as habituation phase, measurements phase (blue) during measurements without (phase A1 and A2) and with (phase B1 en B2) feedback and a final interview (green).

categories within these domains. Initial coding was conducted by NB and reviewed by the supervisor (LS). Differences in interpretation were discussed until consensus was reached.

To enhance trustworthiness, several strategies were employed. Credibility was strengthened through member checks and consensus discussions. Dependability was supported by systematic documentation of the analytic process. Confirmability was enhanced through regular supervision meetings (monthly between NB and LS; bi-monthly with the wider research team) and transparent reporting of analytic steps. Transferability was facilitated by the use of illustrative quotes and a detailed description of the study context.

Quantitative data

Quantitative research was added to investigate whether participants' expectations and experiences could be supported by the data collected. This was done to assess the suitability of the ring (is the relaxation exercise used correctly more in the ring feedback phased than without ring feedback) and to evaluate the effectiveness of the moodmetric® ring within the context of emotion regulation (is there a greater reduction in stress levels with ring feedback than without ring feedback).

The analyses followed the guidelines for SCED research, combining both visual inspection and statistical methods (Barlow et al., 2009; Tate et al., 2016). Visual inspection was used to identify trends and patterns in stress levels over time, graphically displaying the primary outcome variable (arousal levels) for each participant. This technique provided a quick observation of differences between stages (A1, B1, A2, B2) and allowed for an initial impression of the effectiveness of the intervention. To complement the visual inspection, the randomisation test (RT) was used, a statistical method particularly suited to SCEDs. This test assesses the probability that the observed results are due to chance by randomly varying the duration of the phases. The RT thus provides a robust way of determining whether the observed outcomes are significantly different from what would be expected under random conditions (Bulte & Onghena, 2013).

Quantitative data analysis was performed using the Shiny SCDA (De, Michiels, Vlaeyen & Onghena, 2020) app from The Catholic University of Leuven (Belgium) to analyze the moodmetric® data. Statistical comparisons were made between phases A (without feedback from the moodmetric® ring) and phases B (with feedback), allowing for an evaluation of the effect of real-time stress feedback on stress reduction. Additionally, we calculated the correlation between stress levels and the days of the study to

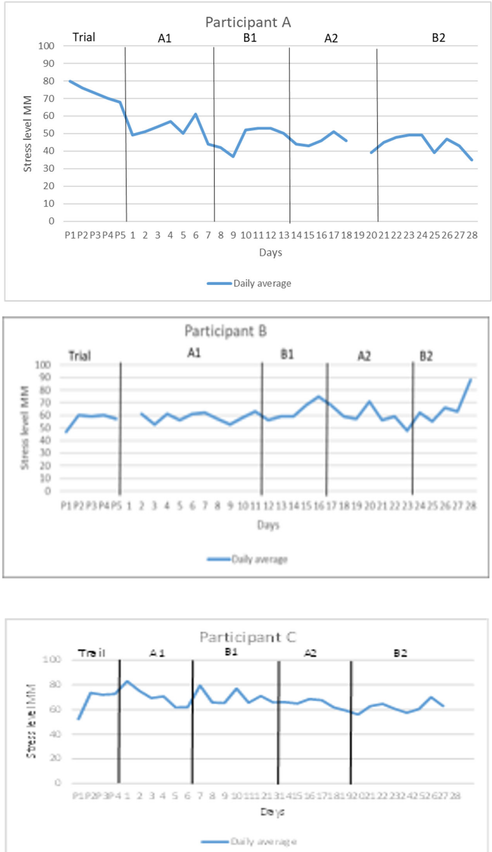

Figure 4. Daily stress levels of participants A, B, and C. The x-axis shows the five baseline days (zero measurements) and days 1-28 of the study. The y-axis shows the MM level scores from 0-100. Each graph is divided into five phases: Trial (zero measurement), A1 (first period without ring feedback), B1 (first period with ring feedback), A2 (second period without ring feedback), and B2 (second period with ring feedback)

observe any trends in stress development over time. Reported p-values indicate the probability that observed differences occurred by chance; these should be interpreted cautiously, given the exploratory nature and small sample size.

We examined suitability by investigating the relationship between the subjectively experienced stress (via the SAM questionnaire) and the objective measurements of the moodmetric® ring. For the objective stress measurement with the moodmetric® ring, the average of the moodmetric® values over the five minutes prior to the exercise was used. This average gives an indication of the stress level just before the start of the exercise.

The Shapiro-Wilk test was used to assess the normality of the data, which indicated that the data were not normally distributed. To further substantiate this, we employed histograms and QQ plots to visually evaluate the distribution of the data. Given the non-normal distribution, we calculated Spearman correlations between the SAM scores and the mean objective arousal levels prior to the start of the exercise. Furthermore, Spearman correlations were calculated between the daily objective arousal levels and the study days to assess trends over time. We applied a Wilcoxon signed-rank test to compare stress levels across phases. These statistical methods were used to provide quantitative evidence to complement the qualitative insights.

Ethical considerations

Ethical approval for this study was obtained from the Internal Scientific Committee, and all participants provided written informed consent, ensuring that they were fully aware of the study's purpose, procedures, potential risks, and benefits before participation. Participants have consented to the publication of their data. The procedures used in this study adhere to the tenets of the Declaration of Helsinki.

Results

Between February 2023 and June 2024, seven patients were approached based on the inclusion and exclusion criteria. Four participants were not included based upon experiences during the zero phase: one participant found wearing the ring too stressful, one participant could not operate the app properly, one participant had difficulty finding time to participate, and another participant could not participate because a suitable ring size was not available.

Additional challenges during the recruitment phase included an admission freeze within XXX, as well as Vigofere Oy's rebranding and discontinuation of support for the moodmetric® wearable as of August 2024. Furthermore, maintaining the visibility of the study among healthcare professionals required repeated efforts. Three older participants with features of BPD symptoms (one woman aged 51, another aged 52, and a third aged 69) participated in the present study, all receiving treatment focusing on arousal.

Participant A is a 69-year-old married woman with autism spectrum disorder and dependent personality disorder with borderline traits. She has stress management difficulties, particularly in relation to her husband. She freezes under stress and appears calm externally, but struggles internally. Her motivation for participating

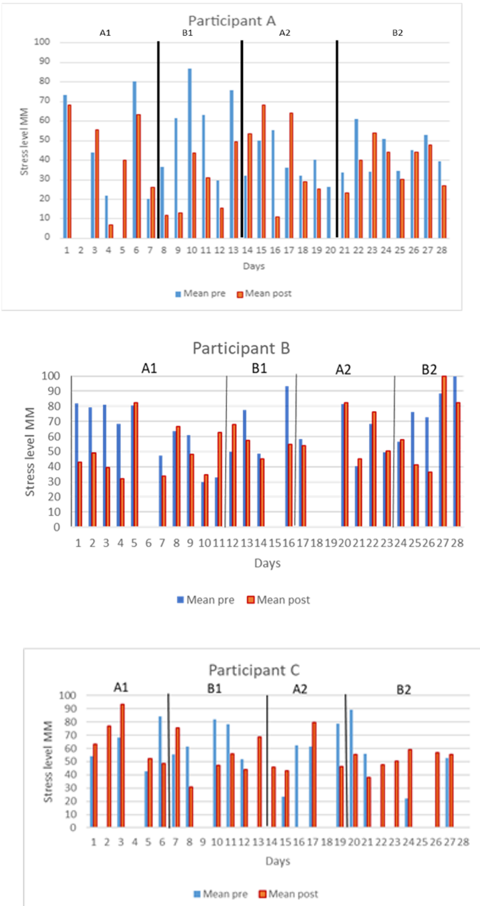

Figure 5. Mean MM levels before and after relaxation exercise across phases for the three participants The x-axis represents the days of the study, and the y-axis shows the MM levels for participants A, B, and C. The graph illustrates the daily MM levels of each participant before and after the exercise across phases without feedback (A1, A2) and with feedback (B1, B2). The blue bars represent the mean MM levels 5 minutes before the relaxation exercise, while the orange bars show the mean MM level 5 minutes after the exercise for each participant

is that mindfulness and counselling could help her manage her stress conditions.

Participant B is a 51-year-old woman with BPD and impulse-control issues. She struggles with trauma-related complaints, emotion regulation, self-harm, anger outbursts and physical complaints. She experiences fatigue and insomnia due to stress. She uses hobbies for distraction and seeks methods to understand and control stress, hoping the ring will help.

Her motivation for participating is to improve her treatment plan and contribute to making the ring accessible to others in need.

Participant C is a 52-year-old married woman with a diagnosis of unspecified personality disorder with borderline traits and binge-eating disorder. She faces emotional challenges and relationship problems. She internalizes emotions, leading to stress build-up. Criticism is a major stressor, and she hopes to learn better emotional expression. Her motivation for participating in the study is to contribute to the research and help others with those insights. The practice function malfunctioned (device near decommissioning) at participant C. Therefore, during B phases, stress levels were recorded manually at the beginning and end of each intervention.

All participants expect the ring to provide insight into their stress levels, thereby enabling them to better manage or express their emotions. No participants reported any issues with their cognitive abilities.

Suitability outcomes

The suitability of the moodmetric® ring depends on its ability to meet the specific needs and circumstances of users in clinical practice. All three participants found the ring suitable for people with emotional regulation problems. All three participants indicated a desire to use the ring under the guidance of a therapist. Without guidance, they felt unable to make the necessary behavioral changes.

Although there was confidence in the app's feedback, Participants A and C sometimes perceived a discrepancy between their subjective feelings and the app's data.

Participant C shared, “Sometimes I had the impression that the feedback from the app was delayed.

In addition to the feedback from participants, it is essential to examine whether their experiences are supported by objective data from the sensor.

Therefore, monitoring how often the relaxation exercise was implemented appropriately and whether it led to stress reduction of at least 10 moodmetric® (MM) points (*Table 1*). Additionally, statistical analysis using the shiny SCDA app was conducted to determine whether support during the B phases had a significant effect on perceived stress levels.

Table 1. Effectiveness of exercises on stress reduction by phase participant A

Participant A	Proportion of deployed exercises MM level > 50 [a]	Reduction of MM level > 10[b]
Fase A1	40 % (2/5)	50 % (1/2)
Fase B1	67 % (4/6)	100 % (4/4)
Fase A2	33 % (2/6)	50 % (1/2)
Fase B2	38 % (3/8)	100 % (3/3)

a) The proportion of instances in which the exercise was completed at an MM level of 50 or above.
b) This indicator denotes whether the MM value exhibited a decline of at least 10 points subsequent to the exercise.

Based on the moodmetric® ring manual, which considers a daily average MM level above 50 as elevated, participant A showed more often a larger decrease in stress levels (i.e. >10 MM) in the phases with feedback (i.e. phases B1 and B2; 67% and 38%, respectively), compared to phases without feedback (i.e. phases A1 and A2 40% and 33%, respectively) (Table 1). All those deployed exercises resulted in the feedback phase (B1 and B2) for a stress reduction of more than 10 MM points (75% and 100%, respectively) compared to the phases without feedback (A1 and A2; 70% and 60%, respectively). However, no significant effect of support during the B phases on perceived stress levels was observed for participant A (RT testing; p =0.0606). Participant B also showed a larger decrease in stress levels (i.e.,>10 MM) in the feedback phases (75% and 100%) compared with 70% and 60% in the no feedback phases (*Table 2*). Phases A1, B1 and B2 leading to the greatest stress reduction, 71%, 67% and 60% respectively. No reduction in stress was found in phase A2. Also, no significant effect of support during the B phases on measured stress levels was observed for participant B (RT testing; p= 0.2182). Participant C performs 75% of the exercises without feedback when the MM value exceeds 50, and 100% and 67% of the exercises with feedback. The highest stress reduction is measured in phases B1 (67%) and A2 (67%) (*Table 3*). No stress reduction of at least 10 points is observed in phase B2. No significant effect of support during B phases on perceived stress levels was observed for participant C (RT testing; p=0.7083).

The correlations between SAM scores (subjective stress) and MM values (objective stress) before exercise were not significant (p>0.05; r ranging from -.111 to .195), indicating that there was no relationship between objective stress and subjective stress before exercise (see *Tables 4,5,6*).

Table 2. Effectiveness of exercises on stress reduction by phase participant B

Participant B	Proportion of deployed exercises MM level > 50 [a]	Reduction of MM level > 10 [b]
Fase A1	70 % (7/10)	71 % (5/7)
Fase B1	75 % (3/4)	67 % (2/3)
Fase A2	60% (3/5)	0 % (0/3)
Fase B2	100 % (5/5)	60 % (3/5)

a) The proportion of instances in which the exercise was completed at an MM level of 50 or above.
b) This indicator denotes whether the MM value exhibited a decline of at least 10 points subsequent to the exercise.

Acceptance outcomes

Acceptance refers to the extent to which users are willing to use the ring and integrate it into their daily lives including treatment. As time passed, participants became more familiar with the ring.

As participant B indicated in an interview, "I would like to use the ring more often, but periodically, so that I don't feel like a 'prisoner' of the app."

In terms of wearing time, participant A wore the ring for a total of 558 hours, representing 83% of the maximum possible 672 hours. Of these hours, 291 (53%) were accumulated during daytime, while 266 (48%) were accumulated overnight. Participant B wore the ring for a total of 574 hours (85%), with 285 hours (50%) spent during the daytime and 288 hours (50%) spent overnight. Participant C wore the ring for a total of 541 hours (80%), including 280 hours (52%) during the day and 260 hours (48%) overnight. These wearing times reflect the extent to which the Moodmetric® ring was integrated into the participants' daily routines. Considering that the ring is not water-resistant and requires periodic charging, these wearing times can be considered notably high.

Feasibility outcomes

Feasibility is about the practicality of using the ring in daily life and within a treatment context, including possible limitations and requirements. All participants experienced problems with connecting and synchronizing the ring. The Moodmetric® app does not notify users that the ring must be in close proximity for synchronization, which could impact its feasibility in practice. This limitation may lead to missed data synchronization and could hinder effective use of the wearable within a therapeutic setting. In addition, participants advised that the ring should be affordable or reimbursed. Participant B noted: "An alarm would be helpful to remind the user to put the ring back on when it is off." Also, concerns were raised regarding the ring's non-water resistance. Participants A and C both indicated that the lack of water resistance was inconvenient and sometimes impractical.

Usability outcomes

Usability concerns how easily and effectively the ring can be applied by users. Although the app and manual were generally clear, technical issues (such as synchronization and connection) were mentioned as factors affecting usability.

Table 3. Effectiveness of exercises on stress reduction by phase participant C

Participant C	Proportion of deployed exercises MM level > 50 [a]	Reduction of MM level > 10 [b]
Fase A1	75 % (3/4)	50 % (2/4)
Fase B1	100 % (3/3)	67 % (2/3)
Fase A2	75 % (3/4)	67 % (2/3)
Fase B2	67 % (2/3)	0 % (0/1)

a) The proportion of instances in which the exercise was completed at a MM level of 50 or above.
b) This indicator denotes whether the MM value exhibited a decline of at least 10 points subsequent to the exercise.

Participant B stated in the interview, “It would be nice if the app was available in Dutch.”

Participant A noted: “I missed explanations in the manual about why only acute stress moments are recorded".

Finally, the qualitative data reveal important insights about participants' experiences. Participant C noted: “Performing alternate relaxation exercises would have helped to reduce my resistance, increase my curiosity and promote more relaxation. I'm always restless, it's in my nature.” This comment highlights both the challenges the participant faced and the potential benefits of additional techniques to her experience with the moodmetric® ring.

Effectiveness of feedback moodmetric® ring

To investigate the effectiveness of feedback from the moodmetric® ring, we visualized the stress patterns throughout the study. *Figure 4* illustrates the daily mean MM levels for each participant across phases, offering insight into both the patterns of stress reduction and the suitability of the moodmetric® ring for clinical practice. The daily mean MM values were calculated based on participants' reported times for getting up and going to bed: for participant A between 7:30 and 22:00, for participant B between 6:00 and 22:00, and for participant C between 11:30 and 00:00. In addition to visualizing the MM levels, we analyzed the correlation between the daily MM values and the study days for each participant using Spearman's rank correlation to examine trends over time.

For participant A and participant C, we observe a significant negative effect of daily MM values in relation to study days, with a correlation of -0.515 (p = 0.006) for participant A and -0.576 (p = 0.002) for participant C, respectively, suggesting that stress levels decreased significantly over the course of the study. For participant B, the correlation was 0.256 (p = 0.197), indicating a non-existent relation in stress levels over time.

Table 4. Correlation SAM-Questionnaire and MM value Mean Pre-Participant A

SAM-Questionnaire	Correlation	p-value
SAM 1[a] – Mean MM value Pre	-0.109	.596
SAM2[b] – Mean MM value Pre	0.148	.470
SAM3[c] – Mean MM value Pre	-0.111	.589

Note. [a]Measures positive or negative mood. [b]Measures arousal. [c]Measures the degree of control over the situation.

To investigate the effectiveness of the feedback, the participants' objective stress levels were gauged before and after the exercise, with and without feedback. It is imperative to determine whether deployment of the exercise results in a significant reduction in stress and to what extent feedback affects this outcome. By visualization these dynamics, we gain insight into the effectiveness of the feedback moodmetric® ring and the potential impact on participants' stress levels. *Figure 5* shows each participant's stress levels before and after the relaxation exercise. In most cases, performing the exercise at high tension (>50 MM) led to a reduction in tension (y) when the initial tension was high (x). Conversely, when the initial tension was low (<50 MM), performing the exercise often led to an increase in tension (y) as the initial tension remained low (x). The Wilcoxon signed-rank test was used to assess the effect of the relaxation exercise on stress reduction by comparing stress levels before and after the exercise in all phases (A1, B1, A2, B2). The results showed no significant differences for participant A (p = 0.101), participant B (p = 0.408) or participant C (p = 0.317).

Discussion

The aim of the study was to explore expectations and experiences of using wearables in older adults with BPD, specifically regarding their potential to support emotional regulation within a therapeutic context.

The interviews suggested that participants viewed the objective arousal levels measured by the wearable as a potentially valuable tool for emotion regulation with older adults with BPD symptoms, despite the aforementioned challenges, including those pertaining to connectivity and the absence of water resistance, which could potentially impede the device’s usability in a treatment context. The participants appreciated that the device gave them insight into their stress triggers and helped them to identify which situations or factors contributed to their elevated stress levels. However, the participants indicated that they were unable to implement the necessary behavioural modifications to effectively manage stress and integrate the insights gleaned from the wearable device into their daily lives in the absence of therapeutic guidance.

In line with the exploratory nature of this study, the quantitative data were

Table 5. Correlation SAM-Questionnaire and MM value Mean Pre-Participant B

SAM-Questionnaire	Correlation	p-value
SAM 1[a] – Mean MM Value Pre	0.122	.571
SAM2[b] – Mean MM Value Pre	0.195	.361
SAM3[c] – Mean MM Value Pre	0.153	.476

Note. [a]Measures positive or negative mood. [b]Measures arousal. [c]Measures the degree of control over the situation.

intended to complement the primary qualitative insights rather than provide definitive evidence of effectiveness. Consequently, the lack of significant quantitative effects cannot be conclusively interpreted and highlights the need for further research using a larger N and a more controlled or experimental design to examine the relationship between subjective experiences, objective measurements, and intervention effects.

Recruitment was challenging due to interpersonal difficulties commonly observed in older adults with BPD, such as difficulties in providing a close relative for inclusion. This led to the exclusion of several candidates and may have introduced selection bias, limiting generalizability. Nevertheless, our study demonstrates that conducting research in naturalistic home settings with older adults is feasible. Although all three participants highlighted practical challenges, including connectivity issues and a lack of water resistance. While these comments are specific to the Moodmetric® ring, participants noted that it could be beneficial if the accompanying app were also available in Dutch, to enhance accessibility for users not proficient in English. These observations provide guidance for future device development: stable connectivity, water resistance, user-friendly interfaces, interpretable feedback, and integration with therapy or relaxation goals could enhance usability and feasibility, especially for older adults with BPD.

Our choice of the Moodmetric® ring should be seen in the broader context of wearable technologies for biofeedback. As shown in recent systematic comparisons (Schoenmakers et al., 2025), no single device optimally balances validity, usability, data access, and affordability. For this study, usability in older participants, affordability, CE marking, GDPR-compliant storage, and provision of direct biofeedback were decisive factors. Although the Moodmetric® ring has been discontinued, its successor (Nuanic®) uses the same core technology, illustrating that our findings are not tied to one commercial product but reflect broader opportunities and challenges in implementing validated EDA-based wearables in routine clinical care.

Most research on wearables has been conducted in controlled settings with healthy young populations. This study demonstrates that research in naturalistic home settings with older adults is feasible. However, further research with larger, more diverse samples, controlled designs, attention to floor effects, habituation, usability issues and user support is needed to determine the effectiveness of wearable biofeedback. Establishing standardized guidelines and assessing reliability and validity are essential for advancing clinical use (Raugh et al., 2019).

Although our explorative study suggests that the use of wearable technology can be beneficial for understanding stress management in people with BPD, there seems to be an important role for healthcare professionals in determining which interventions are appropriate at which moments to reduce stress effectively.

Table 6. Correlation SAM-Questionnaire and MM value Mean Pre-Participant C

SAM-Questionnaire	Correlation	p-value
SAM 1[a] – Mean MM Value Pre	-0.288	.280
SAM2[b] – Mean MM Value Pre	-0.320	.227
SAM3[c] – Mean MM Value Pre	0.079	.771

Note. [a]Measures positive or negative mood. [b]Measures arousal. [c]Measures the degree of control over the situation.

Author contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Nicky Baselmans-van Limpt. The first draft of the manuscript was written by Nicky Baselmans-van Limpt and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Appendix I. Interview introduction

Participant data

ID nr:………………………………… Moodmetric® Ring nr:………………………………………..

Diagnosis:………………………………………………………………

Gender: Mr/Mrs

Medication:………………………………………………………

Date of birth:…………………………………………………

Questions about your stress management

1 What problems do you experience in relation to stress? And how do you deal with them?

....

2 Is there anything you would like to change regarding your stress management?

....

3 Do you have insight into what factors affect your stress level?

....

4 How is your mood in general?

....

Questions about your expectations regarding the moodmetric® ring

5 How do you feel about moodmetric® ring being used?
....

6 To what extent do you think the moodmetric® ring will affect your daily life?
....

7 How do you feel about being observed while wearing the moodmetric® ring?
....

8 What could be advantages in relation to the moodmetric® ring?
....

9 What could be disadvantages regarding the moodmetric® ring?
....

Questions about your cognitive skills

10 What is your highest level of education?
....

11 Do you know what your daily schedule looks like today?

....

12 Do you use an aid for this, such as a calendar? And can you use it independently?
....

13 Can you operate appliances well, such as a telephone or washing machine?

Appendix II. Interview evaluation

Personal data

ID number: ....

Testing period: ....

Evaluation moodmetric® ring

You recently tested the moodmetric® ring for four weeks. By answering the questions below, we can identify your experiences and improve the product. If you have kept a diary, please refer to it when answering the questions.

Part 1: General questions

1. The moodmetric ring measures your tension level based on skin conductance. For this, you have worn the moodmetric ring.

a. What are your experiences wearing this ring and what, if anything, would you like to see changed?

....

b. Are the results obtained (provided in the app) clear and helpful to you?

....

2. The moodmetric ring transports data to the moodmetric ring app, in which you can see your current level of tension but also observe fluctuations of tension levels. What are your experiences with this app and what, if anything, would you like to see changed?

....

3. What do you think is the ideal time to spend on the app?

....

4. At least twice a day it is advised to transfer data from the ring to the moodmetric ring. How did you experience this? And how did your loved one experience this?

- What were the main problems?

....

- Do you have any ideas for improvements?

....

Part 2: Theses
Now 19 statements follow. Can you indicate to what extent you agree or disagree with these statements? If necessary, could you explain your answer?

1. I would like to use the moodmetric® ring more often.

Completely disagree	Disagree	Not disagree/Not agree	Agree	Completely agree
1	2	3	4	5

If not, when would you like to continue using the moodmetric® ring for a longer period?

Explanatory note:

……………………………………………………………………………………………………

2. I find moodmetric® ring unnecessarily complicated.

Completely disagree	Disagree	Not disagree/Not agree	Agree	Completely agree
1	2	3	4	5

Explanatory note:

……………………………………………………………………………………………………

3. I can use the moodmetric® ring easily.

Completely disagree	Disagree	Not disagree/Not agree	Agree	Completely agree
1	2	3	4	5

Explanatory note:

……………………………………………………………………………………………………

4. I need support to use the moodmetric® ring.

Completely disagree	Disagree	Not disagree/Not agree	Agree	Completely agree
1	2	3	4	5

If so, what kind of support?

Explanatory note:

……………………………………………………………………………………………………

5. The different functions of the moodmetric® ring form a beautiful whole.

Completely disagree	Disagree	Not disagree/Not agree	Agree	Completely agree
1	2	3	4	5

Explanatory note:

....

6. Controlling the moodmetric® ring is obvious.

Completely disagree	Disagree	Not disagree/Not agree	Agree	Completely agree
1	2	3	4	5

Explanatory note:

....

7. I imagine most people quickly figure out how to use the moodmetric® ring.

Completely disagree	Disagree	Not disagree/Not agree	Agree	Completely agree
1	2	3	4	5

Explanatory note:

....

8. I find the moodmetric® ring very impractical to use.

Completely disagree	Disagree	Not disagree/Not agree	Agree	Completely agree
1	2	3	4	5

Explanatory note:

....

9. I have confidence in the information provided by the moodmetric® ring.

Completely disagree	Disagree	Not disagree/Not agree	Agree	Completely agree
1	2	3	4	5

Explanatory note:

....

10. I need to learn a lot about the moodmetric® ring before I can use it properly.

Completely disagree	Disagree	Not disagree/Not agree	Agree	Completely agree
1	2	3	4	5

Explanatory note:

....

11. I felt confident while using the moodmetric® Ring.

Completely disagree	Disagree	Not disagree/Not agree	Agree	Completely agree
1	2	3	4	5

Explanatory note:

....

12. The text in the app is not easy for me to read.

Completely disagree	Disagree	Not disagree/Not agree	Agree	Completely agree
1	2	3	4	5

Explanatory note:

....

13. The language I can understand well.

Completely disagree	Disagree	Not disagree/Not agree	Agree	Completely agree
1	2	3	4	5

Explanatory note:

....

14. The manual is clear and provides sufficient support.

Completely disagree	Disagree	Not disagree/Not agree	Agree	Completely agree
1	2	3	4	5

Explanatory note:

....

15. The practice function is too difficult.

Completely disagree	Disagree	Not disagree/Not agree	Agree	Completely agree
1	2	3	4	5

Explanatory note:

....

16. The moodmetric® ring boosts my stress management capabilities.

Completely disagree	Disagree	Not disagree/Not agree	Agree	Completely agree
1	2	3	4	5

Explanatory note:

....

17. The moodmetric® ring is suitable for people with emotion regulation problems.

Completely disagree	Disagree	Not disagree/Not agree	Agree	Completely agree
1	2	3	4	5

Explanatory note:

....

18. Wearing the moodmetric® ring was uncomfortable.

Completely disagree	Disagree	Not disagree/Not agree	Agree	Completely agree
1	2	3	4	5

Explanatory note:

....

19. The moodmetric® ring affected my daily life in a negative way.

Completely disagree	Disagree	Not disagree/Not agree	Agree	Completely agree
1	2	3	4	5

Explanatory note:

....

Part 3: concluding questions

1. If you could give the moodmetric® ring a grade (1-5), what grade would it be?

1=excellent 2=good 3=satisfactory 4=moderate 5=unsatisfactory

2. When the moodmetric® ring will soon be available, could it cost anything? If so, how much?

€ ....

3. Would you like to test the moodmetric® ring again?

Yes / No

4. Finally, do you have any questions and/or comments?

Thank you very much for your participation in this survey.

Appendix III. SAM-questionnaire

First and last name/number:
…………………………………………………………………………………..
Date and time:
…………………………………………………………………………………..

With the mood meter below, you can determine your mood.

- *With the first row of pictures you can describe whether you feel positive or negative.*
- *With the second row of pictures you can indicate how excited or calm you are.*
- *The third row is about dominance. Dominance describes the extent to which you feel in control of a situation.*