The Influence of Sleep Duration Measured by Digital Biomarkers on Self-Esteem Levels in Young Adults: An Experience Sampling Method Study

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M12 BSc Thesis PSY 202000384

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June 14,2024

Abstract

Background: Prior research suggested an association between insufficient or excessive sleep with lower self-esteem and mental health issues. However, these studies often rely on self-reported sleep data, which can be biased and inaccurate.

Aim: The present study aimed to investigate the relationship between sleep duration and self-esteem levels in young adults, overcoming the limitations of self-reported data by using digital biomarkers and the Experience Sampling Method (ESM).

Methods: 34 participants between the ages of 18 and 27 wore the EmbracePlus smartwatch for seven days to measure sleep duration objectively and completed daily diaries assessing self-esteem using Experience Sampling Method for eight days. The data was then visualized and analyzed by using a multilevel model.

Results: Contrary to the hypothesis and previous studies finding a significant association, this study found no significant association between sleep duration and self-esteem levels, suggesting a more complex relationship between the two variables.

Conclusion: The findings highlight the need for future research to explore additional factors and assessment methods influencing self-esteem levels, as well as the potential of digital biomarkers and ESM in psychological research. Several factors, including higher resilience and compensatory behaviors, can explain these findings. Methodological differences, such as the objective measure of sleep duration and narrower age ranges, also impact results. Despite non-significant findings, this study contributes to the growing literature on digital biomarkers and ESM methods in psychological research.

Keywords: *Experience Sampling Methods (ESM), Sleep Duration, Self-Esteem, Digital Biomarker, Young Adults*

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1. Introduction

According to a study conducted by the National Sleep Foundation, 45 % of young adults aged 18-29 report not getting enough sleep at least four nights a week in self-report questionnaires and week-long sleep diaries (Gradisar et al., 2013). In the same study. 29 % of participants reported waking up once or twice throughout the night, and 37 % of participants reported receiving less than six and a half hours of sleep per night. In line with this research, it was found that insomnia affects 20-25 % of young adults, which is still assumed to be underestimated (Uccella et al., 2023). Bingham & Kaplan (2014) characterize insomnia as the difficulty of initiating or maintaining sleep. The prevalence of the delayed sleep phase syndrome suggests that up to 10 % of young adults suffer from persistent instability in falling asleep at a socially acceptable time, causing difficulty waking up and sleepiness during wake time (Bingaham & Kaplan, 2014). An example cause for young adults' problematic sleep patterns can be the use of technology. 90 % of young adults are found to use their phones or comparable technological devices within one hour before bedtime, which can disturb sleep patterns by being exposed to blue light and engaging content (Gradisar et al., 2013). Even after falling asleep, around 40 % of young adults disrupt their sleep by answering texts or calls causing a total disruption of sleep for 45.88 minutes per week (Adams & Kisler, 2013). Sleep problems and problematic sleep patterns can have multiple effects on young people. The effect on mental health and specifically self-esteem levels will be explored in the following.

Impact of Sleep Duration on Overall Mental Health

Sleep duration refers to the total amount of sleep obtained over 24 hours (Kline, 2013). Results of a systematic review and meta-analysis by Zhang et al. (2024) including 52 research papers suggest that short sleep duration significantly increases the risk of mental illnesses, especially increasing the risk for anxiety and depression. Contrary, adequate sleep supported by an intervention that improved sleep, had a significant effect on reducing specific difficulties such as stress, anxiety, depression, suicidal ideation, and Post Traumatic Stress Syndrome Cortisol levels play a crucial role in the effect of sleep on anxiety. Sleep is found to lower cortisol levels in the human body reducing stress and anxiety (Banner Health, 2019). Adequate sleep improves cognitive functions such as concentration, problem-solving, memory, and judgment abilities (Diekelmann, 2014). Through lowered cortisol levels and less anxiety, the mental flexibility of individuals is improved, meaning the ability to examine different perspectives and adjust to

shifting circumstances in life (Blanchard, 2024). Furthermore, studies have found that sleep duration plays a significant role in mood regulation and mental health (Jansen, 2020). Next to stress, anxiety, and depression, sleep duration is found to influence self-esteem levels as well, which is further examined in the following paragraphs.

Self-esteem as a Core Component of Mental Health

Self-esteem refers to an individual's overall sense of value and personal worth (Cherry, 2023). Although self-esteem is a known term it is found to be too simplistic as it stands for varying and complex mental states (Bailey, 2003). Bailey (2003) states, that there is extensive literature on the term, but inconsistencies can be found throughout various definitions. Thus, core concepts and varying definitions are stated, to gain insight on the concept of self-esteem and to provide an overview. Concepts often associated in research with self-esteem are self-confidence, feelings of security, a sense of belonging, and identity (Cherry, 2023). According to Jordan (2020, p.4738), "Self-esteem is an overall assessment of the value of oneself or self-worth. It reflects a continuum, with people ranging from 'low' to 'high' self-esteem. Those with low self-esteem, in extreme cases, actively dislike themselves and feel worthless. Those with high self-esteem like themselves and believe strongly in their inherent worth as individuals." Overall, self-esteem is found to impact young individuals' mental health, later life such as personal goals, and life satisfaction (Zhang et al., 2024). Despite the lack of agreement, self-esteem can be operationalized with self-reported questionnaires, for example by using the Rosenberg self-esteem scale, which is elaborated on in the following.

Linking Sleep Duration with Self-Esteem Levels

Self-reported sleep duration has been found to have a significant effect on self-esteem levels. Research by Lemola et al. (2012) has shown that both excessive sleep, defined as more than nine hours, and insufficient sleep, defined as less than six hours, are associated with lower levels of optimism and self-esteem. Results remained after controlling for demographic factors and symptoms of depression. This research provided experimental evidence for the gradually reduced self-reported optimism and self-esteem caused by sleep deprivation. On the other hand, according to the same research, those who slept for seven or eight hours had the highest levels of self-esteem. This shows that desirable personality qualities like self-esteem are favorably connected with the ideal sleep length, which is between seven and eight hours. In addition, a

study conducted in 2023 by Liu et al. examined the connection between depression in college students during the COVID-19 epidemic and several variables, including sleep length. The results showed that the amount of sleep was a major predictor of depression, which is linked to low self-esteem. Other research presents that sleep enhances the ability to cope with emotional stress during daily life, consequently contributing to higher self-esteem (Vandekerckhove & Wang, 2017). Overall, Armand et al. (2021) found that sleep impacts the well-being of individuals in a sample of undergraduate students. As life satisfaction is associated with self-esteem and self-esteem is found to predict well-being, adequate sleep is essential for young adults' self-esteem (Du et al., 2017). As the relationship between sleep and self-esteem is found to be bidirectional, self-esteem influences sleep duration. Individuals with higher self-esteem tend to have better coping mechanisms, leading to less sleep disturbance and better overall sleep quality. Self-efficacy, which is closely related to self-esteem, is found to help individuals regulate their positive and negative emotions and stress effectively (Doménech, 2024). A study by Rezaie et al. (2023) found positive correlations between emotion regulation and sleep quality, meaning that better emotion regulation is correlated with better sleep quality, subsequently caused by higher self-efficacy.

The Relationship Between Self-Esteem and Sleep Duration in Young Adults

Despite self-esteem being critical in young adults' life and development, there is a lack of research about self-esteem and its relation to sleep duration in previous research. As suggested by a meta-analysis by Gao et al. (2021), focusing on young adults can lead to valuable and new insights, as this age group differs from other age groups concerning self-esteem levels and self-esteem formation and was not extensively studied before in this context. Young adults often go through critical phases in their development with new challenges and choices where self-esteem has an impact. For example, the opportunities to explore their identity, work fields, areas of love, and engagement in adult responsibilities (Wood et al., 2017). Their self-esteem in this period influences their decision-making and later achievements in life and thus needs to be investigated (Magnusson & Nermo, 2018). For example, high self-esteem is found to be associated with resilience, enabling individuals to withstand setbacks and challenges (Bogaerts et al., 2023). On the other hand, the same study found that identity formation itself positively impacts young adults' self-esteem levels. Through forming an identity, young adults can develop an increased self-esteem by getting a clearer and more stable sense of who they are. Achieving a sense of

identity and f identity and accomplishing the process of identity formation results in a feeling of accomplishment and purpose in life. This relationship is highlighted in the context of education for example, where identity formation is linked to better mental health outcomes, resilience, and a sense of purpose (Talusan, 2022). Overall, young adults with a more robust identity and thus higher self-esteem make healthier life choices (Stephonson, 2023). Thus, young adults need to be investigated separately and insights can be a valuable contribution to the literature about young adults' self-esteem.

Challenges in Measuring Sleep and Self-Esteem

While there are studies about sleep duration and self-esteem, the results often are based on self-reported sleep duration (Salters-Pedneault, 2023). Through self-reports, subjective and retrospective data is collected which has multiple limitations. According to Salters-Pedneault (2023), recall bias suggests that people often may not accurately remember how long they have slept, which possibly falsifies the data. Secondly, due to the social desirability bias, individuals may report a sleep duration they think is the "correct" or socially desirable amount of sleep. Overall, sleep duration is susceptible to subjectivity as the perception of sleep duration greatly varies across individuals. This was confirmed by a study investigating actigraphy-assessed sleep duration compared with self-reported sleep duration, finding significant reclassifications when comparing both data, suggesting differing results (Santos et al., 2021). Santos et al. (2021) study, presents poor correlations between self-reported and actigraphy-measured sleep duration, with participants self-reporting sleep duration approximately half an hour too much compared to objective measures. Thus, passively measured sleep duration allowing no self-interpretation can contribute to a better and more accurate understanding of the effect of sleep duration on self-esteem levels.

Previous research such as the Swiss Primary Hypersomnolence and Narcolepsy Cohort Study made use of digital biomarkers as reliable instruments for long-term monitoring of sleep patterns and sleep durations of healthy individuals compared to patients with narcolepsy (Gnarra et al., 2024). The results of this study demonstrated that digital biomarker wearables are feasible in monitoring sleep parameters and play a role in future diagnosing and sleep research. As previously stated, Santos et al., (2021), highlighted that actigraphy measures did yield different, and more accurate, sleep duration results compared to self-reports. Thus, wearables allow the blending of unintrusive biological markers and psychological states, such as self-esteem, as data

collected are typically used to explain, influence, and/or predict health-related outcomes such as personality characteristics like self-esteem levels (Alonso et al., 2024).

Measuring self-esteem reliably in research settings also has challenges. According to Monsonet et al. (2020), previous research on the construct of self-esteem often relies on retrospective reports in laboratory or clinical settings. Assessing self-esteem one time and retrospectively can have multiple limitations. As these assessments occur in laboratory or clinical settings, the participant's report is not in a natural context, lowering the ecological validity. The environmental factor of participants' answers is not explored, and a retrospective bias can occur, like with retrospective reports of sleep duration.

To measure self-esteem levels in young adults, this study makes use of ESM in the form of daily diary questionnaires. Daily Diary questionnaires are a form of Experienced Sampling Methods (ESM) measures, which focus on a more reflective picture of self-esteem levels compared to self-reports (Monsonet et al., 2020). Using this intensive longitudinal method participants are asked to answer one short questionnaire a day for eight days. Daily diary questionnaires are structured moment-to-moment diaries focusing on participants' effects, thoughts, behavior, and perception of their day (Csikszentmihalyi and Larson,1987). Through apps like mpath, used in this study, participants can answer the diaries in real-time by using their smartphones to increase compliance. Csikszentmihalyi and Larson (1987), present evidence for the short- and long-term reliability of ESM when assessing individuals' psychological states. Through these self-reports over an extended period, the self-esteem levels of young individuals can be measured each day.

Present Study

The current study seeks to investigate the relationships between sleep duration objectively measured with smartwatches and prospective, self-reported self-esteem levels in the context of young adults. By using objective measures of sleep duration this study differs from previous research, investigating sleep duration bypassing limitations of self-reports. Subjective measures of self-esteem, measured by daily diary questionnaires for a reflective, ecologically valid measure also aimed at reducing retrospective bias. By combining the two, the following research question is stated: “Can sleep duration measured by digital biomarkers predict self-esteem levels in young adults?”

As previously stated, previous findings suggest that sleep duration can predict individuals' self-esteem levels (Lemola et al., 2012). Short sleep duration is often associated with lower self-esteem and so is long sleep duration. Based on these previous findings, the following exploratory hypothesis to set the ground for further investigations is stated:
H1: Sleep duration is statistically associated with self-esteem levels in young adults.

2. Methods

2.1 Study Design

The current study was part of a larger extensive longitudinal study that investigated the relationship between digital biomarkers of meaning in everyday life, involving wearing a smartwatch and filling in daily diaries about constructs related to meaning in life. This specific study was part of this larger project and focused on whether sleep duration measured by digital biomarkers could predict self-esteem levels in young individuals. Digital biomarkers captured by the Empatica EmbracePlus smartwatch were worn by participants for seven consecutive days. Self-esteem was measured using an experience sampling method, gathering data using repeated assessments in the individual's natural environment. Participants had to fill in questionnaire items in an end-of-the-day daily diary related to self-esteem, meaning in life, stress, and positive and negative affect for eight days. Ethical approval for the study was obtained from the Ethics Committee, University of Twente of Behavioral Sciences, on the 23rd of February 2024 (project 240133). The study adhered to the STROBE guidelines for cross-sectional observational studies for transparency reasons (Cuschieri, 2019).

2.2 Setting

Data collection took place between the 18th of March 2024 and the 12th of April 2014. Digital biomarker data using EmbracePlus and ESM data using the m-path APP were collected during participants' daily lives over eight days and sleep periods, providing real-world data. The m-path app is further described in the measurements section of this study.

During intake meetings, a researcher met with one participant at a time to explain the study design, and procedures and to administer the setup of mobile applications. Researchers handed out smartwatches including a charger to the participants and explained to wear the smartwatch on their non-dominant hand approximately one finger's width from the wrist.

Participants were instructed to always wear the watch except when showering or in situations where the watch would be submerged in water. Then, participants were also informed about potential errors and the procedures to follow in case of errors, loss, or damage to the watch. Furthermore, a manual instruction form was handed out to the participants to clarify any further questions (Appendix B)

Next, participants were asked to download the apps Empatica Care Lab and M-Path. The m-Path app was used to distribute daily questionnaires and collect informed consent through a consent form, which was handed out before the following steps (Appendix A). Subsequently, participants filled in a landing survey (Appendix C) to collect sociodemographic information. Questionnaires for the next eight days were scheduled every evening between 6:00 PM and 9:00 PM, (Table 1). This questionnaire included four self-esteem items measuring the self-esteem level of the participants (Table 1). A description of the items is provided below.

Participants were instructed to install the "Care Lab" mobile application to enable Bluetooth and have an internet connection as much as possible. Downloading the Empatica Care Lab app was needed to connect the watch to the participants' phones Bluetooth. By doing this, the watch could synchronize sleep data collected with the account of the participant on the app and upload it to the Empatica website. After creating participant credentials on the Empatica researcher's website, participants could connect the smartwatch to their smartphone and start the data collection. When problems such as the lack of Bluetooth connection or when the participant is not wearing the device correctly might occur, the app automatically alerts the participant. After ensuring that participants were familiar with the technical features, the digital biomarker was worn for seven days except for when the participant was showering or charging the watch. Data collected was stored in the Care Lab Portal and later pseudonymized and moved to the UT server.

The data collection then continued the following days in the participants' natural environment by wearing the watch and answering the daily diary questionnaires on the phone, not bound to a fixed location.

After 7 days of wearing the watch, participants returned the watches to the researchers around the same time the watch was given to participants seven days earlier.

2.3 Participants

Participants were recruited via convenience sampling, with researchers asking friends, family, and acquaintances to take part in the study. Inclusion criteria included age and the ability

to speak English or German, and to be a young adult, namely, to be aged between the age of 18 and 30. The ability and willingness to wear the EmbracePlus for most of the day was also an inclusion criterion. Participants who did not own a smartphone, or a smartphone with an Android 11 or up and were not willing to use a smartphone were excluded from the study. Participants who were hindered from wearing the watch due to (e.g., work policies regarding dress codes) were excluded.

2.4 Variables and Data Sources

2.4.1 Sleep Duration Measured by EmbracePlus

Sleep duration was measured using the medical grade wearable EmbracePlus smartwatch, which continuously and automatically measured physiological data non-invasively. The EmbracePlus was available for rent at the BMS Lab (www.utwente.nl/bmslab) at the University of Twente. It was selected for this study because it is easy to use and through the non-invasiveness of the wearable it functions as a wear-and-forget device worn on the wrist (Erdem et al., 2024).

The validity of the sleep measures provided by the Embrace Plus by Empatica is supported by several factors. Empatica has conducted various validation studies to ensure their device provides reliable data. For example, a clinical validation study demonstrated the accuracy of the Embrace Plus in measuring peripheral oxygen saturation, a key indicator of sleep quality and respiratory health, with results meeting FDA and ISO standards for medical devices (Gerboni, 2023). FDA-cleared means that it is cleared for use in large-scale clinical research and at-home medical monitoring. This clearance indicates that the device meets stringent requirements for accuracy and reliability in measuring physiological parameters, including those related to sleep (Staff, 2024).

The wearable also used multiple sensors such as accelerometer and gyroscope sensors to detect body movement, indicating sleep periods. Additionally, the heart rate was monitored using optical photoplethysmogram sensors, with a steady and slow heart rate often associated with sleep. The wearable detected sleep on a minute-by-minute basis and was recognized as reliable and valid in detecting sleep by the American Academy of Sleep Medicine in 2007 (Empatica, 2023). Provides two measures: still and *restless sleep*, which are explained in the preprocessing part of this study, were analyzed independently. The raw data, consisting of sleep measures for each hour, could later be used for the analysis of sleep duration.

2.4.2 Self-Esteem Levels Measured by Mpath

Self-esteem levels were measured using an adaptation of the Rosenberg Self-Esteem Scale (Rosenberg, 1979), a widely used tool to identify an individual's level of self-esteem. Four items from the RSES were incorporated into the daily diary questionnaire to reduce its size and increase participants' compliance. Two positively framed items and two negatively framed items were chosen. The items were chosen based on the items that were used in a similar study by Hadden and Smith (2019) because they are easily translated into the daily diary design, and the factor loadings (Bouhi et al., 2022). Thus, self-esteem items measured both negative and positive feelings about oneself, with higher numbers associated with higher self-esteem levels. As the present study makes use of daily diary questionnaires, the four items were adjusted to fit into the ESM method by specifying the question to the present day. This was done by adding the word “today" to each of the items. The participants were given a response option from one (strongly disagree) to 4 (strongly agree). Table 1 shows the exact items and their wording used in the daily diary questionnaires.

Table 1

Self-esteem Items Used in the Daily Diary Questionnaire

Construct	Original Formulation	Formulation in accordance with DD design
Self-esteem	On the whole, I am satisfied with myself	On the whole, I was satisfied with myself today
Self-esteem	All in all, I am inclined to feel that I am a failure	All in all, I was inclined to feel like a failure today
Self-esteem	I certainly feel useless at times	I certainly felt useless today
Self-esteem	I feel that I have a number of good qualities	I feel that I had a number of good qualities today

Note. The items used are adapted from the Rosenbergs self-esteem scale, but the formulation was altered to fit into the daily diary design.

Daily diary questionnaires were sent to participants via the M-Path smartphone application in the evening, allowing them to answer 18 items related to meaning in life, and four specific to self-esteem (Table 2) between 6 pm and midnight (m-path, 2024). M-path is designed for psychological research and allows real-time self-report responses in the participant's natural environment, increasing the ecological validity of the data. Through this ESM approach researchers were able to capture self-esteem levels among other variables assessed in the broader study (Hernandez et al., 2016). Thus, M-Path provided a reliable and accurate measure of self-esteem levels by reducing recall bias and capturing dynamics and changes in self-esteem levels over the span of seven days. Additionally, the app was designed to be easy to use on the participant's smartphone, simplifying the task for participants.

2.4.3 Sample Description

The following socio-demographic variables were included in the intake survey through the m-path landing survey at the start of the data collection of each participant: Age, gender, nationality, and occupation status (student/student and working/working). They were used to describe the sample, as no covariate adjustment in the models was performed.

2.5 Potential Biases

To address potential sources of bias from the beginning of the data collection, participants were informed about the procedure, and it was emphasized that the data obtained would be pseudonymized. A potential bias can be low adherence to the study protocol, which was minimized by including an intake survey to explain the motivations of the study, creating a daily diary survey with a limited number of items, as well as a 50-euro voucher which was raffled based on participation. To further ensure an increase in the response rate, personal reminders were sent frequently from researchers (Muñoz-Leiva, 2010).

2.6 Study Size and Adherence Rate

In total 34 participants were recruited (Figure 1). Participants needed to complete at least 50% of the daily diary questionnaires and wear the EmbracePlus wearable for at least 50% of the data collection period of seven days for wearing the EmbracePlus and eight days for completing the daily diaries.

2.7 Statistical Methods

2.7.1 Data

After collecting the data by using m-path, the data was downloaded from the m-path website (www.m-path.io) in an Excel format. Similarly, the EmbracePlus data was downloaded from the Empatica website (www.empatica.com) in an Excel format using an access key generated on the website. Both the m-path and EmbracePlus data were uploaded to the University of Twente server with pseudo-anonymized participant IDs.

2.7.2 Preprocessing

To preprocess the data, the downloaded and anonymized physiological data measured by EmbracePlus, sampled every minute, was grouped and processed on an hourly basis for sleep detection. The hourly sleep data for each participant was derived by summarizing sleep counts for each hour.

Variables of *still sleep* and restless sleep in the raw Excel data set indicate sleep for each participant. The value *still sleep* in the dataset indicates sleep itself. *Restless sleep* on the other hand also indicates that the participant is sleeping but is in a wake state. This means the participant's sleep is interrupted by movement for example a turn or toss, which is still associated with being asleep (support@empatica, personal communication, April 24, 2024).

Additionally, data from a mobile application (m-path) were read from Excel files for each participant and were unified into a single data frame with all participants and all items and their answers. The timestamp column was parsed into a proper date-time format and rounded to the nearest hour. The m-path data was then pivoted to a long format and subsequently joined with the sleep detection data to form a comprehensive dataset, necessary for analyzing the data according to its nested structure. After cleaning and merging the dataset contained hourly measures of sleep and self-reported mean self-esteem levels per participant. After calculating the adherence rate, participants with an adherence rate under 50% were removed from the dataset.

2.7.3 Statistical Methods

To conduct the statistical analysis RStudio-2023.12.1-403 was used. A mixed-effects model was utilized to assess the relationships between the physiological measure of sleep duration and the mean self-esteem level to investigate hypothesis 1 using the R lme4 (version

1.1-27, Bates et al., 2015). Thus, sleep duration was used as an independent fixed effect variable, and self-esteem levels as the dependent variable. This statistical method helped analyze repeated measures from one unit of observation over a long time, where multiple observations per participant were available and nested hierarchically. In this dataset, observations were nested within a day and within participants. Furthermore, this model included the participants as random effects, accounting for individual differences in baseline self-esteem levels. Additionally, the model fit was improved by acknowledging that participants' self-esteem could be influenced by other unmeasured factors. Consequently, by choosing this approach, the model captured the inherent variability of self-esteem levels across young adults in this sample.

The model used fixed slopes, based on the reasonable assumption that sleep duration, both still and restless, had a uniform effect on all participants. Using fixed slopes not only simplified the model but also made the output easier to generalize across the whole study population.

2.7.4 Handling Missing Data

Missing data were systematically addressed to ensure the integrity of the dataset. For the data measured by the digital biomarker, any "NaN" entries were removed specifically for cases where sleep duration measurements, *restless sleep*, and *still sleep*, or awake, were absent.

Additionally, missing questionnaire data for self-esteem items (SE1, SE2, SE3, SE4) and other variables were filled using the Last Observation Carried Forward (LOCF) method. As described by Xu (2009), the missing value is replaced with the last observed non-missing value before the missing value occurs in the data. This was necessary because this study used hourly measures of sleep throughout the day but only one measure of self-esteem at the end of the day, so the LOCF method is assumed to adequately reflect the structure of this study. The LOCF method is commonly used in longitudinal studies with repeated measures over time for the same subjects under the assumption that response remains constant at the last observed value. It ensures continuous data and minimizes data loss for further analysis by avoiding dropping participants with incomplete data if their adherence rate is above 50%, which is especially important for longitudinal analyses (Toumi & Lamure, 2010).

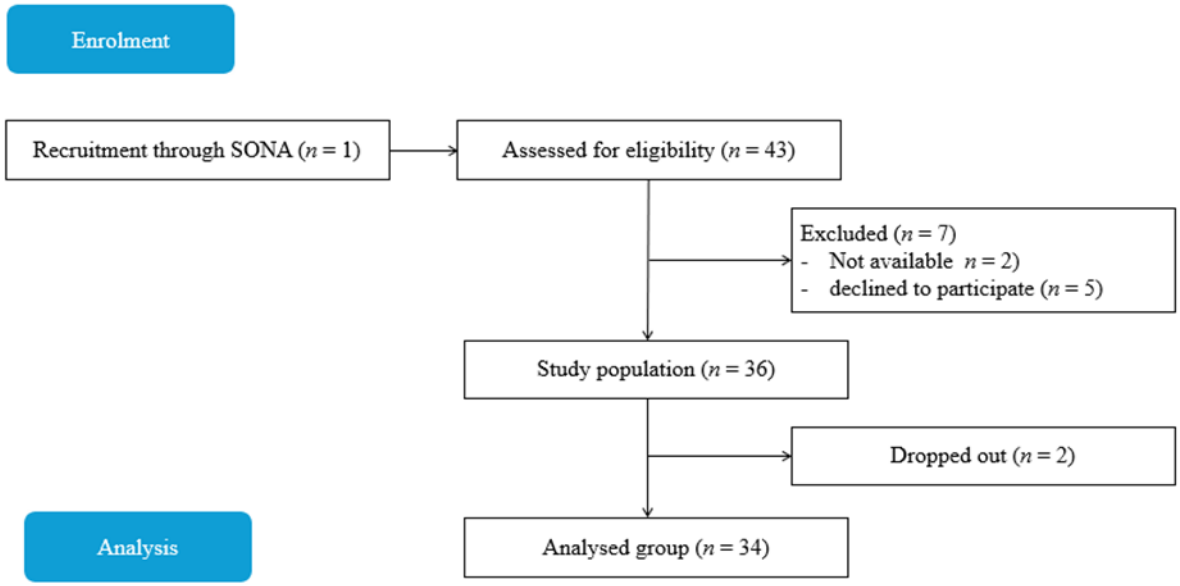
3. Results

3.1 Participants

For the present study, a total of 42 potential participants were contacted by the researchers personally, and one person was contacted on the platform SONA. Five potential participants were not interested, two people were not available to wear the watch during work hours or not available at all. Consequently, the study population existed out of 36 participants. Whereas the final sample consisted of 34 participants due to two participants dropping out.

Figure 1

Flow chart of Study Population and Study Size



Note.

3.2 Descriptive Data

The participants' average age was 21.45 years (SD = 2.05). Of the participants, 94.1 % were of German nationality, 2.9 % were natural Dutch nationality, and 2.9 % of Vietnamese nationality. Additionally, half of the participants (n = 17) reported being a full-time student, 17 (35.3 %) working students, and 5 (14.7 %) reported to be working (see table 2). 50 % of the participants were female (n = 17), and the other half of the participants were male (n= 17).

Table 2

Sociodemographic Characteristics of Participants

Baseline characteristic	**Participants**	
	n	*%*
Gender		
Female	17	50.0
Male	17	50.0
Age		
Mean (SD)	21.45 (2.05)	
Occupation		
Student	17	50.0
Student &working	12	35.3
Working	5	14.7
Nationality		
German	32	94.1
Dutch	1	2.9
Vietnamese	1	2.9

Note. The total number of participants included in the study is N=34

The overall data was almost complete, as the adherence rate was 90.47%, with the m-Path adherence rate at 93.06% and the watch-wearing adherence at 87.88%. The adherence rate of individual participants can be found in Appendix C.

3.2.1 Sleep Duration Tendencies and Summaries

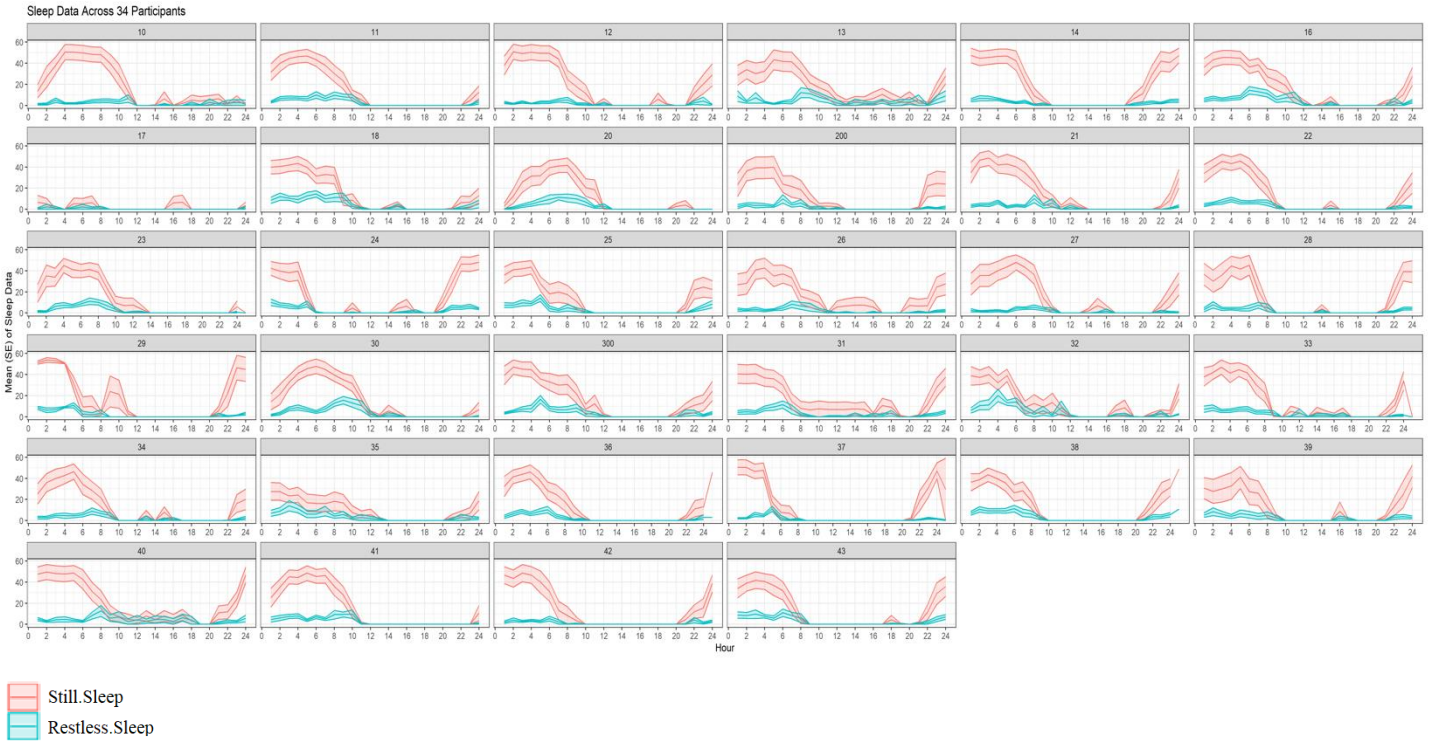
Figure 2 visualizes patterns revealed in *still sleep* and *restless sleep* measured by the digital biomarker. Still, sleep indicates uninterrupted sleep and *restless sleep* indicates sleep with movement interruptions. Each panel in Figure 2 visualizes data from one participant to check the hypothesis that sleep duration is statistically associated with self-esteem levels in young adults (H1). The x-axis represents sleep in minutes whereas the y-axis indicates the hours of each day.

The sleep data visualized in Figure 2 shows consistent cyclical patterns across participants. Peak sleep occurs at night between the hours 0 and 6, and occasional naps during the day for approximately half of the participants. This consistency suggests a robust daily rhythm in sleep behavior among young adults. Despite these consistencies, individual variations in sleep duration and patterns can be observed. Larger within-participant variability in sleep patterns,

indicated by higher standard errors, highlights issues with maintaining consistent sleep patterns. Generally, *still sleep* and *restless sleep* is tracked closely, with higher spikes in *still sleep* indicating more uninterrupted sleep.

Figure 2

Sleep Data Across 34 Participants



Note. This figure represents the mean sleep patterns of all 34 participants hourly. Sleep restless represents participants being asleep and not moving, while *still sleep* represents movement while sleeping. The solid line in the middle represents the mean. The ribbon around it indicates the SE.

3.2.2 Self-Esteem: Overall Trends, Observations, and Summaries

This study investigated self-reported self-esteem levels of young adults over a time span of eight days. Four different adjusted items from Rosenberg's self-esteem scale were used. Figure 3 displays participants' mean scores of the four self-esteem items on the y-axis and their standard error illustrated by shadow areas over days indicated by the x-axis.

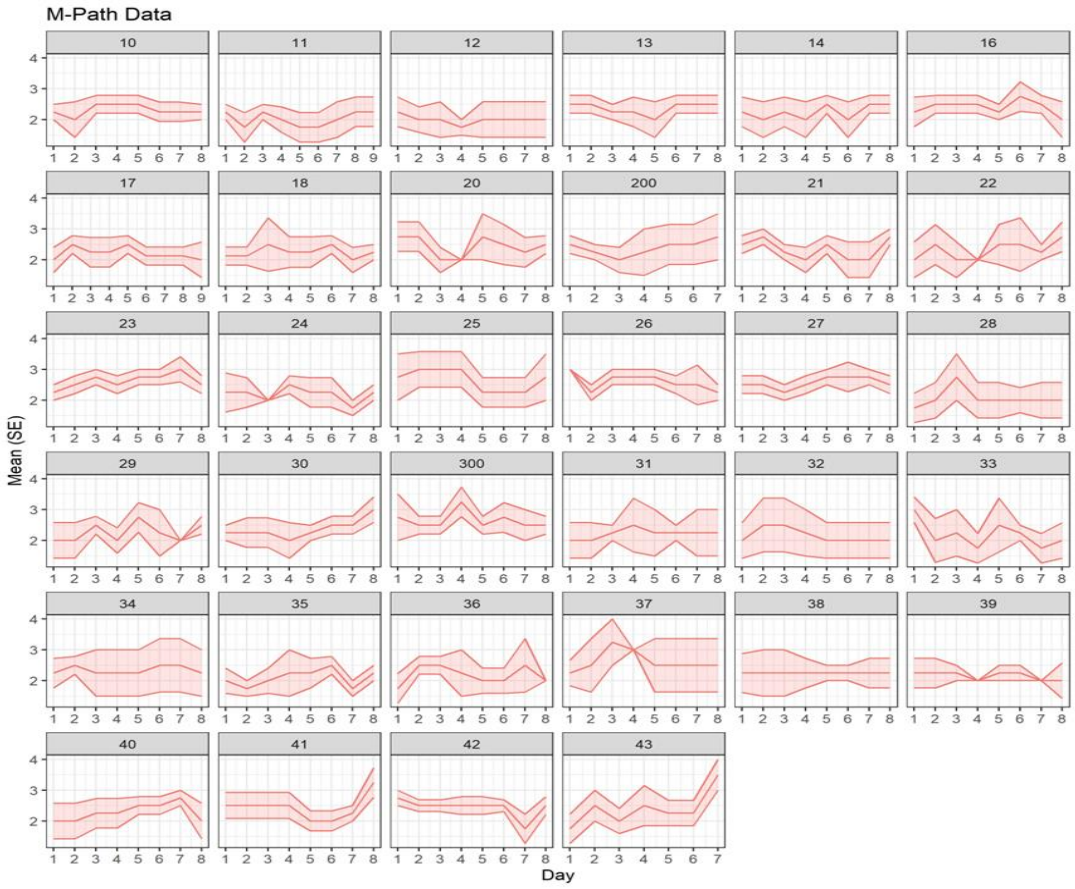
Overall, the daily variability across all participants and within each participant is illustrated across all days. This indicates self-esteem levels fluctuate daily, and every participant

has a unique self-esteem baseline level. These daily fluctuations are represented by dips and peaks in Figure 3. Across participants and days, no consistent trend can be observed, indicating that self-esteem levels are highly unique and dynamic.

The shadowed areas, indicating the standard error, provide a visual clue of the variability or consistency of participants' self-esteem scores. Wider standard deviations indicate greater variability in the self-esteem scores of that participant, which can be seen in Participant 34 for example. Generally, this indicates more day-to-day variability, which can be seen across almost all participants. Narrower standard deviations on the other hand indicate a more stable self-esteem, for which Participant 23 can be an example.

Figure 3

Mean Self-esteem Levels Measured by Daily Diaries Across 34 Participants



Note. The solid line in the middle represents the mean. The ribbon around it indicates the SE.

3.3 Main Results of Mixed-Effect Model Considering Hypothesis 1

A linear fixed effect model was used to examine how sleep duration measured by two sleep counts (*restless sleep* and *still sleep*) is associated with mean self-esteem scores in young adults (table 4). The study hypothesized that either long sleep duration can be positively associated with higher self-esteem levels in young individuals or that extremely long sleep duration is statistically associated with self-esteem levels in young individuals (H1).

The statistically significant intercept of the model is 2.32 (95% CI [2.26, 2.37] $p < 0.001$), meaning that the self-esteem level of young adults is around 2.32 when sleep counts are zero.

Rejecting hypothesis 1, the effect size for the *still sleep* for when participants are sleeping and not moving is zero (0.00) and statistically not significant (95% CI [0.00, -0.00] $p > 0.001$). This indicates that still, sleep does not reliably predict the mean self-esteem level for young adults in this sample. Similarly, the effect size of *restless sleep* is null (0.00) and, not statistically significant (95% CI [0.00, -0.00] $p > 0.001$). Thus, neither restless nor *still sleep* is associated with SE according to the model. Regarding the statistical significance, neither of the sleep variables was significantly associated with self-esteem level, thus this study did not find evidence for H1.

Overall, a conditional r squared of 0.327 indicates that around 33% of the variance in mean self-esteem levels of young adults in this sample is explained by the model's random and fixed effects. The marginal r squared (0.000) indicates that no variance of mean self-esteem levels is explained by the fixed effect of sleep duration, measured by still and *restless sleep*.

Table 4

Linear Mixed Model for the Impact of Sleep Duration on Self-esteem Levels

Predictors	*Estimates*	*std. Error*	*std. Beta*	*SE*	*CI*	*standardized CI*	*p*
(Intercept)	2.32	0.03	-0.01	0.10	2.26 – 2.37	-0.21 – 0.19	**<0.001**
Still sleep	0.00	0.00	-0.01	0.01	-0.00– 0.00	-0.03 – -0.02	0.527
Restless sleep	0.00	0.00	-0.02	0.01	-0.00– 0.00	-0.04 – 0.01	0.258
Observations	5170						

Marginal R^2 / Conditional R^2	0.000 / 0.327

Note. CI = Confidence Interval, standardized CI = standardized Confidence Interval, p = P-value, std. Beta = Standardized beta coefficients, SE = Standard Error

4. Discussion

The present study investigated whether sleep duration impacts self-esteem levels in young adults using objective and prospective ESM and digital biomarkers. To address this research question, an observation study was conducted measuring the association between sleep duration and self-esteem levels in young adults. Contrary to the hypothesis stated, that sleep duration would be statistically associated with self-esteem levels, the results indicated that neither nor *restless sleep* were significant predictors of self-esteem in this sample. The findings suggest that while sleep patterns exhibit a consistent daily rhythm among participants, the duration and quality of sleep, as captured by the EmbracePlus smartwatch, do not have a significant direct impact on self-esteem levels measured by m-path.

These findings are in contrast with the findings of Lemola et al. (2012), who reported a significant association between sleep duration and self-esteem, this study did not find a significant association between sleep duration and self-esteem levels. Similarly, the findings of the present study did not confirm the results of the meta-analysis of Zhai et al. (2020) stating that there is a significant association between sleep duration and self-esteem in young adults. This discrepancy might be attributed to methodological differences, such as the reliance on only self-reported sleep duration in Lemola et al.'s study versus the use of digital biomarkers in the present study. Similarly, the meta-analysis by Sowislo and Orth (2013) highlighted the importance of other mediating variables, when exploring the predictive role of self-esteem such as self-blame or emotion regulation strategies. Moreover, this study aligns with the growing body of literature that emphasizes the complexity of self-esteem and its multifaceted determinants (Bailey, 2003; Cherry, 2023).

Differing results could also be explained by other factors for example, this exploratory study used items of the Rosenberg self-esteem scale in the daily diary questionnaires. While there is previous research on self-esteem also making use of this scale, this present study did not validate the Rosenberg self-esteem scale for the use of ESM daily diary studies. The null findings

might be caused by the scale not being sensitive enough to detect the effect of sleep duration on self-esteem. The Rosenberg scale lets participants answer on a scale from one to four, not allowing much variability. Slight fluctuations in self-esteem levels might be captured more accurately on a larger scale allowing more variability in answers used in other studies (Preston & Colman, 2000). This is in line with a study by Liu et al. (2017) stating that many individuals prefer to answer moderate response options in psychological assessments, suggesting that some individuals might tend to only choose between two and three on the Rosenberg self-esteem scale.

In contrast to existing studies, this study specifically focused on a sample of young adults between the ages of 18 and 27. Meta-analyses usually include a wide range of age groups in the study samples, except for single studies focusing on young adults because of their heightened social media use (Gao et al., 2021; Valkenburg et al. 2021). The present study aimed to investigate whether the same influences of sleep on self-esteem can be observed in the specific age group of young adults. Results did not confirm the hypothesis and rejected the assumption that sleep duration is statistically associated, thus can either positively or negatively influence self-esteem level if the sleep duration is extremely long. Several potential reasons can be reasons. Firstly, Young adults generally exhibit higher physiological resilience to sleep deprivation than other age groups. Thus, young adults might mitigate the effects of less or extremely long sleep duration (ScienceDirect, 2021). Secondly, this age group is more likely to engage in compensating behaviors. Increased social interaction or stimulants like caffeine can be examples of ways to boost young adults' moods and compensate for inadequate sleep (Twenge et al., 2019).

4.1 Strengths of the Present Study

Compared to previous studies on sleep duration, this study makes use of an objective measure of sleep duration by using digital biomarkers. Using digital biomarkers provides objective and accurate data that is free from recall biases caused by the reliance on self-reports of participants (Salters-Pedneault, 2023). Furthermore, using digital biomarkers allows continuous monitoring of participants, providing a comprehensive and more detailed picture of participants' sleep patterns. The variances and details captured in participants' sleep behavior are not able to be captured by self-reports.

Another distinctive feature of this study is the use of ESM methods, namely daily diaries, whose benefits are stated previously. Real-time data are captured in naturalistic settings, increasing the ecological validity of the study.

The longitudinal design of the study as well as the high adherence rate are strengths of the present study. The longitudinal design allows patterns in sleep behavior and self-esteem levels to occur across participants. The high adherence rate on the other hand strengthens the validity of the findings, indicating that the data collected is representative of the participants' typical sleep behavior (Biron & van Veldhoven, 2012).

4.2 Limitations

This study made use of a simple model with a random intercept, without a random slope, which can be considered a limitation of this study. By doing so, potential differences in individuals' baseline self-esteem levels are considered, but it is assumed that sleep length has a consistent impact on all participants. This presumption might undermine individual variations in the way that sleep duration impacts individuals' self-esteem levels, as sleep duration may impact some individuals more than others. Furthermore, the model used for the analysis assumes a linear association between sleep and self-esteem levels, although previous studies show that the extremes of sleep duration are more relevant for lower self-esteem (Lemola et al., 2012).

Unlike some other studies, for example in Valkenburg et al.s (2021) study also measuring the construct self-esteem, m-path data measures of self-esteem levels were collected once a day in the evening. As self-esteem levels may vary over the day, this could be a limitation of this study, as developmental and self-esteem studies argue that self-esteem can fluctuate not only daily but also on an hourly basis caused by negative or positive experiences (Valkenburg et al., 2021). Thus, measuring only a small fraction of self-esteem and self-esteem variability can impact the findings of this study, by not capturing all the data needed to answer the research question accurately

4.3 Implications for Future Research

Future research should aim to continue using objective measures such as digital biomarkers to validate findings from self-reported data used in previous studies. As previously stated, there is a low agreement between self-reported and actigraphy-measured sleep duration (Santos et al., 2021). Thus, objective measures of sleep yield different results compared to self-reported data and therefore allow a more accurate base for research. For this reason, longitudinal studies using digital biomarkers could be beneficial. Furthermore, future research can explore the association between sleep duration and self-esteem levels not assuming a linear relationship. For

example, Generalized Additive Models (GAMs) can be used. Models that assume a linear relationship could oversimplify the relationship between self-esteem and sleep duration overlooking variations in the effect of extremely low or extremely high sleep duration. GAMs could offer a more accurate data analysis, allowing to inclusion of ranges and thresholds for the predictor variable sleep duration (Basheer, 2023). This might be useful in future studies to potentially show that extreme sleep duration might have another effect on self-esteem than moderate sleep duration.

To capture variability in self-esteem levels within a day, multiple assessments of self-esteem via ESM can be useful in future research. Through multiple measurements a day context specific self-esteem measures can be observed, and self-esteem instability based on experiences prior to the daily diary entry is considered (Valkenburg et al., 2021). In addition to that, a broader scale could be useful to capture more variability within and between participants. Approving that, Preston & Colman (2000) state that larger scales, for example, 10-point scales, have a higher reliability and allow more detailed responses.

Future research could also explore the impact of circadian rhythms on self-esteem. Circadian rhythms, which regulate sleep-wake cycles, are related to the straightforward approach to sleep duration. Incorporating the study of circadian rhythms can provide a more comprehensive understanding of how sleep quality and timing influence self-esteem. For example, how disruptions in the circadian rhythm are related to self-esteem (Fishbein, 2021). Addressing circadian disruptions through interventions like light therapy or behavioral adjustments could also be beneficial (Czeisler, 2013).

4.4 Conclusion

The present study investigated the association between sleep duration and self-esteem levels in young adults, using digital biomarkers to objectively measure sleep duration and m-path for self-reported self-esteem levels. 34 participants wore a digital biomarker for seven days and answered a daily diary questionnaire for eight days. Participants' high adherence rates ensure that reliable data was used. Contrary to previous research, this study did not find a statistically significant association between sleep duration and self-esteem levels in young individuals. Several factors, such as higher resilience and compensatory behaviors might explain these findings. Furthermore, methodological differences, such as the objective measure of sleep duration and narrower age ranges, can explain the results found. Despite the non-significant

findings, the present contributes to the growing body of literature on the use of digital biomarkers and ESM methods in sleep and self-esteem research. Future research should consider investigating a non-linear relationship between sleep duration and self-esteem levels using for example Generalized Additive Models. Adding multiple assessments throughout the day or using a broader scale to increase variability in answers could capture more fluctuations and reveal potential patterns more accurately.

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"During the preparation of this work the author(s) used [ChatGPT and Grammarly] in order to correct grammer/spelling, summarise and get an overview. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the work."

Appendicies

Appendix A

This was provided in a digital format in the mPath application

Consent Form for *BioMean*- Digital Biomarkers of Meaning in Everyday Life

Researchers: Carolina Annabell Klingebiel (s2704161), Leonie Döhrmann(s2682818), Sophie Spierenburg(s2664682)

Introduction:
You are invited to participate in a research bachelor thesis study exploring the use of digital biomarkers for exploring the connection to the variables of positive and negative affect, self-esteem and meaning in life. Before you decide whether to participate, it is important that you understand the purpose, procedures and potential risks.

Study Purpose:
The purpose of this study is to investigate the meaning of digital biomarkers in everyday life. In particular, the variables of positive and negative affect, self-esteem and meaning in life will be assessed through daily questionnaires and correlated with the assessment of the biomarkers. The examination of these relationships allows for a deeper understanding of the role of digital biomarkers in everyday human experience and provides valuable insights into the dynamics between psychological states and biological markers.

Duration:
Your participation in this study is expected to last eight days.

Procedures:
If you agree to participate, you will be asked to wear the Embrace Plus watch which measures physiological and behavioural parameters. In detail the watch will measure:

- *Blood Oxygen Saturation (SpO2)*
- *Sleep Detection*
- *Electrodermal Activity (EDA)*
  - *Skin Conductance Level (SCL)*
- *Temperature*
- *Pulse Rate*
- *Respiratory Rate*
- *Pulse Rate Variability*
- *Wearing Detection*
- *Actigraphy Measures:*
  - *6MWT*
  - *Advanced Gait Analysis*
  - *Raw 3-axis Accelerometer Data*
  - *Wearing Detection*
  - *Sleep Detection*
  - *Activity Counts*
  - *Energy Expenditure*
  - *Body Position*

No harms are expected from this experiment and participants can contact the researchers in case of expected side effects or questions (contact information are listed below).

Please tick the appropriate boxes	**Yes**	**No**	
Taking part in the study			
I have read and understood the study information dated [08/04/2024], or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction.	□	□	
I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.	□	□	
I understand that taking part in the study involves wearing the Embrace Plus watch all day (except when being in the water) and filling in a questionnaire once a day.	□	□	
Use of the information in the study			
I understand that information I provide will be used for a bachelor thesis…	□	□	

I understand that personal information collected about me that can identify me, such as [e.g. my name or where I live], will not be shared beyond the study team. □ □

Future use and reuse of the information by others

The data will be anonymised. If future publications utilise this study's data only groups estimates (e.g., mean, median, standard deviations, max, min, etc) will be reported. By clicking this box, I give permission for the questionnaire data and biomarker data that I provide to be archived in the UT data storage so it can be used for future research and learning. □ □

Signature

I understand what taking part in this study will involve. I agree to take part in this study □ □

Study contact details for further information:
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Contact Information for Questions about Your Rights as a Research Participant

If you have questions about your rights as a research participant, or wish to obtain information, ask questions, or discuss any concerns about this study with someone other than the researcher(s), please contact the Secretary of the Ethics Committee/domain Humanities & Social Sciences of the Faculty of Behavioural, Management and Social Sciences at the University of Twente by ethicscommittee-hss@utwente.nl

Appendix B

Manual for Participants

Everything you require to participate in this research should be covered in this manual.
Take your time going over everything, and don't hesitate to get in touch with the researchers if you have any questions, are experiencing technical problems or if you want to withdraw from the study:

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What is the purpose of the study?
The purpose of this study is to investigate the meaning of digital biomarkers in everyday life. In particular, the variables of positive and negative affect, self-esteem and meaning in life will be assessed through daily questionnaires and correlated with the assessment of the biomarkers. The examination of these relationships allows for a deeper understanding of the role of digital biomarkers in everyday human experience and provides valuable insights into the dynamics between psychological states and biological markers.

What is to be expected during the research?
Every day for 7 days you will be asked to answer a questionnaire via the app ***mPath*** on your mobile phone. The daily questionnaire will appear every evening at 18-21.00.
During these 7 days you will additionally be asked to wear the ***EmbracePlus*** watch **day and night**.
You will additionally be asked to download the ***EmpaticaCareLab app*** *f*or the upload of your watch's data. Ensure that your phone always has an internet and Bluetooth connection and ensure the watch is connected, which can be checked through the EmpaticaCareLab app, this will ensure a continuous synchronisation of data.
When you are requested to set up an account using your email but prefer not to use your personal email, you have the option to utilize *Proton Email* service at no cost (link on last page). This allows you to quickly establish a secure, anonymous, encrypted email account.
If you adhere to the protocol (wearing the watch for > 80% of the time and completing > 80% of daily diaries) you will go to a pool (of all participants of this study) where a 50-euro Amazon gift card will be raffled.

How does *mPath* work?
MPath is a mobile application through which questions can be sent to you.

1. First you download the mPath app
2. You are then asked to provide a nickname (you do not have to provide your real name, to protect your privacy you can also provide numbers or an alias)
3. After accepting the terms, you can connect to our study through clicking on “Your practitioner” and then on the plus symbol, where you can then look for **@zcfp9** to add us as your practitioner.
4. Enable notifications for this app on your phone
5. For this study, you will be sent a consent form and a landing survey once at the start the study.

After these first steps you will receive a daily questionnaire between 18.00-21.00 (at the time you prefer in the landing survey) consisting of 18 items for 8 days. You can click on the notification or go to the app manually within this time frame. You will see “start the questionnaire“on the bottom of the page. We ask you to answer each question as truthfully as possible. Your answers are automatically and securely processed and stored in the researcher's dashboard.

How does the *EmpaticaCareLab app* work?
The EmpaticaCareLap app is part of the monitoring system of the EmbracePlus. Through this application you as a participant can check if the data is synchronising and if you are wearing the watch correctly. Please, activate the Bluetooth function of your device to connect the app to

the EmbracePlus wearable. Additionally, your wearing time, pulse rate and skin temperature are displayed in the app.

The charge of the watch lasts approximately two days, so please recharge the wearable for about 1 ½ hours, when necessary, with the included charger.

Please do not wear the EmbracePlus during showers and when swimming. It is advised against to use it in water (despite the IP67 certification).
If the EmbracePlus **gets damaged** at any point, please notify the researchers **immediately,** there will be **no repercussions** for you, but we are required to inform the lending institutions of its damage.

How does the *EmbracePlus* work?
The EmbracePlus is a smartwatch designed for continuous health monitoring.
Place the EmbracePlus wristband top-down on a surface. Wrap the band around the wrist while making sure that the button is on the outside of your wrist. For reference look at the picture below. The EmbracePlus should be worn behind the knuckle. Make sure it is fixed and can't wriggle back and forth. Wear it on your non-dominant hand with a finger-width from your wrist bone. Check the underside if you want to make sure the wearable is recording, you should be able to see a green light.

Place the EmbracePlus on your wrist

Wear it on your non-dominant hand for more accurate monitoring. Your EmbracePlus should be a finger's width from your wrist bone.

How can I be sure the EmbracePlus is correctly recording?
Look out for the following signs

CARE LAB APP

Open the application and check that:

- ☑ The background is teal;
- ☑ The Status card reads 'Care is running smoothly';
- ☑ Wearing time is increasing;
- ☑ The Participant has the correct EmbracePlus. You can check this by looking at the serial number on the EmbracePlus, and comparing it to the serial number in the Settings menu of the Care Lab App

EMBRACEPLUS

Check the EmbracePlus and verify that:

- ☑ The display is light;
- ☑ The Empatica heart icon is visible;
- ☑ The sensor is on (there is a green light from t bottom of the device)

The Empatica heart icon tells you if the watch is connected to the app. If the watch is momentarily not connected to the app (no heart icon) the watch will upload the missing data when you are connected to the app again. Make sure your device with the Care Lab App has Bluetooth activated and is close to the EmbracePlus wearable.

What does the *EmbracePlus* measure?

In detail the watch will measure:

- Blood Oxygen Saturation (SpO2)
- Sleep Detection
- Electrodermal Activity (EDA)
    - Skin Conductance Level (SCL)
- Temperature
- Pulse Rate
- Respiratory Rate
- Pulse Rate Variability
- Wearing Detection
- Actigraphy Measures:
    - 6MWT
    - Advanced Gait Analysis
    - Raw 3-axis Accelerometer Data
    - Wearing Detection
    - Sleep Detection
    - Activity Counts
    - Energy Expenditure
    - Body Position

Links:

For more information about the applications and EmbracePlus:

EmbracePlus and EmpaticaCareLab: https://www.empatica.com/en-gb/

MPath: https://m-path.io/landing/

Proton E-mail free account: Proton Mail: Registrierung

Appendix C

Landing Survey Items

Welcoming text (ethics approved, researchers, what the study is about, informed consent form (first page study description, duration, randomized price voucher send by email, second page consent-only can continue when boxes are checked))

Landing survey items:

1. What is your gender Identity?
    a. Male
    b. Female
    c. Other

2. How old are you?

3. What is your nationality?
    a. Dutch
    b. German
    c. Other

4. What is your current occupation?
   a. Student
   b. Working
   c. Student and working
   d. other

5. What time in the day would be suitable for you to answer the daily survey?

Appendix D

Adherence Rates for Daily Diary Completion and Digital Biomarker Usage

	Mpath adherence	**Watch adherence**
Participant	**Adherence (%)**	**Adherence (%)**
30	100	90.1
20	100	89.6
21	100	85.4
31	100	88
32	100	87.5
10	86	85.4
11	100	95.3
12	100	92.2
13	100	88.5
33	100	83.9
22	100	84.9
34	100	84.4
23	100	85.4
24	88	89.6
35	100	88
26	100	87.5
36	88	87.5
37	100	87
38	75	87
25	50	87
27	100	88.5
28	100	94.4

14	100	85.4
39	100	87.5
29	100	93.3
300	100	87
200	88	85.7
16	88	90.1
17	50	88.5
18	100	92.2
40	100	87
41	75	88
42	88	85.7
43	88	87.5
Overall adherence: 90.47%	**Total Mpath:** 93.06%	**Total watch:** 87.88%