# Analysis project: Daily Activity as Predictors of Sleep Quality

**CS-C4100 - DIGITAL HEALTH & HUMAN BEHAVIOUR**
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## 1. Introduction

Sleep quality has always been an interesting topic to study about, since it affects an individual's daily life in many aspects, and it is also being strongly influenced by the intensity of physical activities during the day. The increasing development of wearable sensors and multimodal monitoring has made it possible to examine how physical activity shapes a person's sleep quality. Sleep quality, including metrics such as total sleep time (TST), sleep efficiency, and wake after sleep onset (WASO), is a crucial aspect of health. In previous research, not only intensity but also timing and type of daytime activity can influence a person's sleep outcomes.

Prior research suggests that daytime physical activity has a positive impact on night-time sleep quality, whereas evening activity may have variable effects depending on intensity and individual chronotype (Buman & King 2010; Kredlow et al., 2015). Chronotype, the natural preference for activity in the morning or evening, also interacts with physical activity to influence sleep patterns, with evening active individuals potentially benefiting less from late-day exercise (Adan et al., 2012).

The dataset from Multilevel Monitoring of Activity and Sleep in Healthy People (MMASH) will be used in this project. The dataset provides synchronized accelerometer data, heart-rate measures, sleep metrics, saliva biomarkers, and psychological questionnaires from 22 healthy male adults over a continuous 24-hour period (Rossi et al., 2020). The analysis focuses on comparing daytime versus evening activity levels and their relationship with sleep duration and quality.

## 2. Problem formulation

While it is known that exercise generally improves sleep quality, the relationship between daytime versus evening activity and subsequent sleep outcomes remains unclear. The main problem addressed in this project is: **Do individuals who are more active during the day differ in sleep duration and quality compared to those more active in the evening?** Understanding this relationship could inform lifestyle recommendations for improving sleep and overall health, especially in populations with irregular activity schedules or sleep disturbances.

In specific, the project has three goals: quantify the timing of daily physical activity for each participant (daytime vs evening); examine associations between activity timing and key sleep metrics, including total sleep time (TST), sleep efficiency, and wake after sleep onset (WASO); and explore potential patterns or trends in the data that could inform recommendations for optimizing activity schedules to improve sleep quality.

## 3. Dataset Description

The MMASH dataset includes data from 22 healthy male adult participants during the timespan of 24 hours. Each participant folder contains seven CSV files, out of which three files will be focused on: Actigraph.csv (contains main time-series activity signal), Activity.csv (helpful for categorizing and validating activity intensity throughout the day), and sleep.csv (contains sleep outcome variables).

During the process of data cleaning and preprocessing:

- There is missing and duplicate data. User 11 is excluded due to missing sleep data. On the other hand, user 1 has two nearly continuous sleep records with a 20-minute gap; these are merged into a single record.
- Relevant columns are converted to appropriate data types.
- Sleep periods are categorized based on total sleep duration into predefined sleep quality classes
- Daily activity is divided into daytime (before 18:00) and evening (18:00-23:00). Mean activity levels are calculated for each period
- Activity and sleep data are combined for each participant to study correlations between activity timing and sleep outcomes.

## 4. Research Methods

This project focuses on one main research direction: *Time-series analysis of activity during the day and its relationship to sleep quality.* For this direction, the research will utilize continuous accelerometer and activity annotations from the MMASH dataset. To be more specific, the analysis will examine how activity intensity, movement variability in 24 hours relate to sleep quality such as sleep efficiency, total sleep time, wake after sleep onset (WASO).

The analysis follows three main steps: data processing, visualization, and statistical analysis.

### 4.1. Data processing

- Sleep periods were categorized based on total sleep time (TST) into three groups: inadequate, adequate, and oversleep (according to CDC)
- Daily activity was divided into daytime (before 18:00) and evening (18:00–23:00) periods.
- Mean activity levels were calculated for each participant in both daytime and evening periods.
- Activity and sleep data were combined to enable correlation analysis and comparison across groups.

### 4.2. Visualization

- A bar chart is used to visualize the distribution of sleep categories to learn about the overall sleeping quality of the whole group
- Combined bar and line plots show the relationship between activity timing groups (day active versus evening active) and total sleep time. This visualization aims to highlight the differences in sleep outcomes between the groups.

### 4.3. Statistical analysis

- Pearson correlation coefficients assess the relationship between mean activity and sleep outcomes within each activity timing group
- Descriptive statistics (mean, minimum, maximum) are computed for sleep metrics and activity levels to summarize differences between day-active and evening-active participants
- Individual-level analysis for one participant to explore personalized activity-sleep patterns.

These methods enable a multi-level understanding of how the active timing of participants affects their sleep duration and quality, both at the group and individual level.

## 5. Results

### 5.1. Group analysis

According to the Centers for Disease Control and Prevention (CDC), adults should aim for seven or more hours of sleep per night. (Centers for Disease Control and Prevention, n.d.) Based on this guideline, participants' sleep durations were categorized into three conditions: oversleep, adequate, and inadequate, using the following criteria:

- **Oversleep:** Sleep duration > 8 hours
- **Adequate:** Sleep duration > 6 hours and ≤ 8 hours
- **Inadequate:** Sleep duration ≤ 6 hours

Analysis of the MMASH dataset showed that the majority of participants slept less than 6 hours, falling into the inadequate category. Only 14% participants achieved adequate or oversleep durations (Figure 1). The result indicates that the sample, on average, experienced short sleep durations, which may influence the relationship between activity timing and sleep quality.

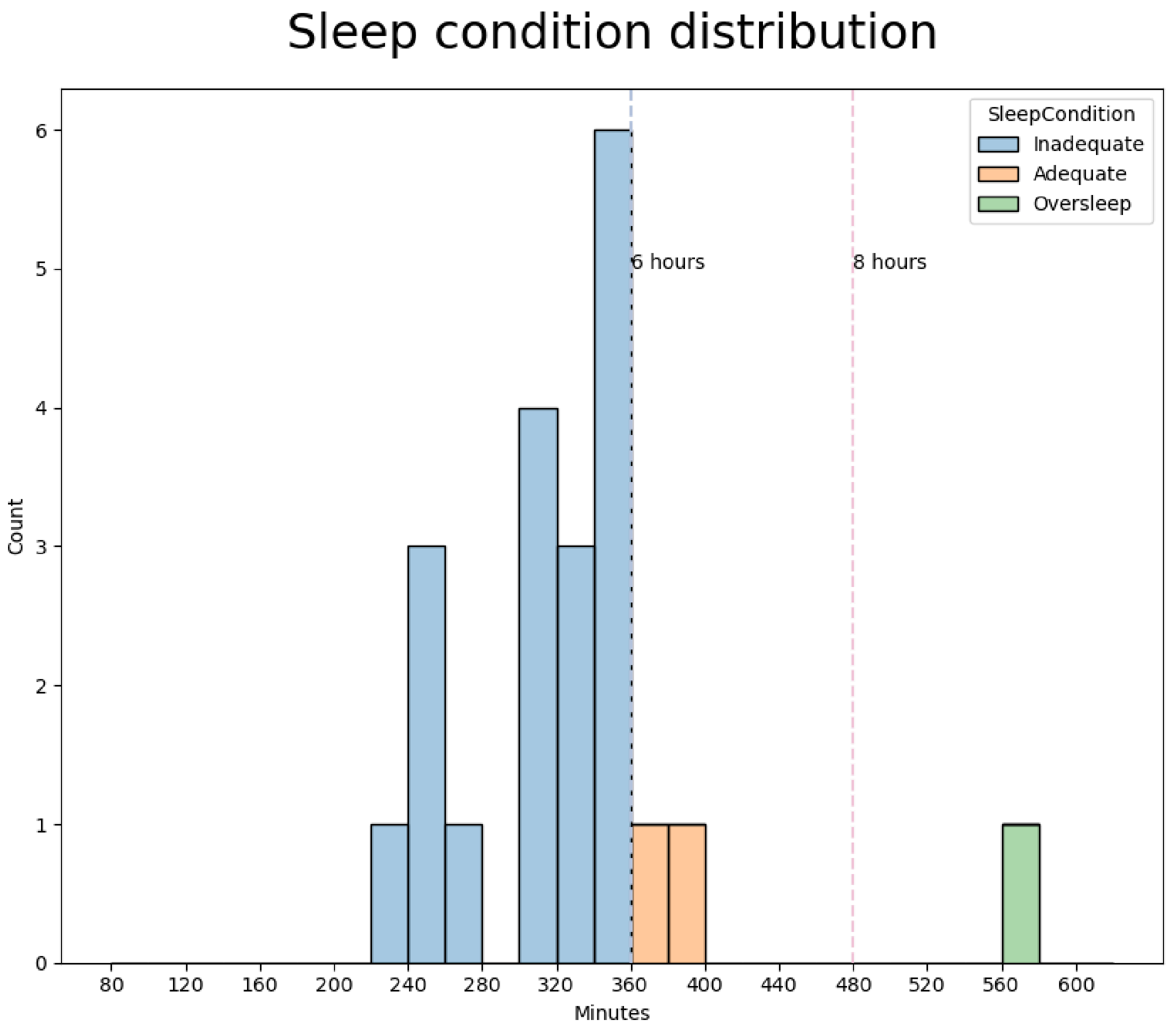


Figure 1. Sleep condition distribution in the whole group

Descriptive analysis further examined differences based on activity timing. The mean total sleep time for the day-active group is 321.3 minutes, slightly lower than the evening-active group, which averaged at 336.7 minutes. This suggests a minor difference in sleep duration between participants who are more active during the day versus in the evening. These findings provide context for the subsequent correlation analysis and visualizations, which explore how activity timing relates to total sleep time and overall sleep quality.

### 5.1.1. Day active group analysis

According to figure 2, the total sleep time fluctuates considerably across participants, showing no clear trend between activity level and sleep duration. This suggests that daytime activity alone may not strongly predict sleep duration, as other factors may play a significant role. Further correlation and descriptive analysis are conducted to explore these relationships more systematically.

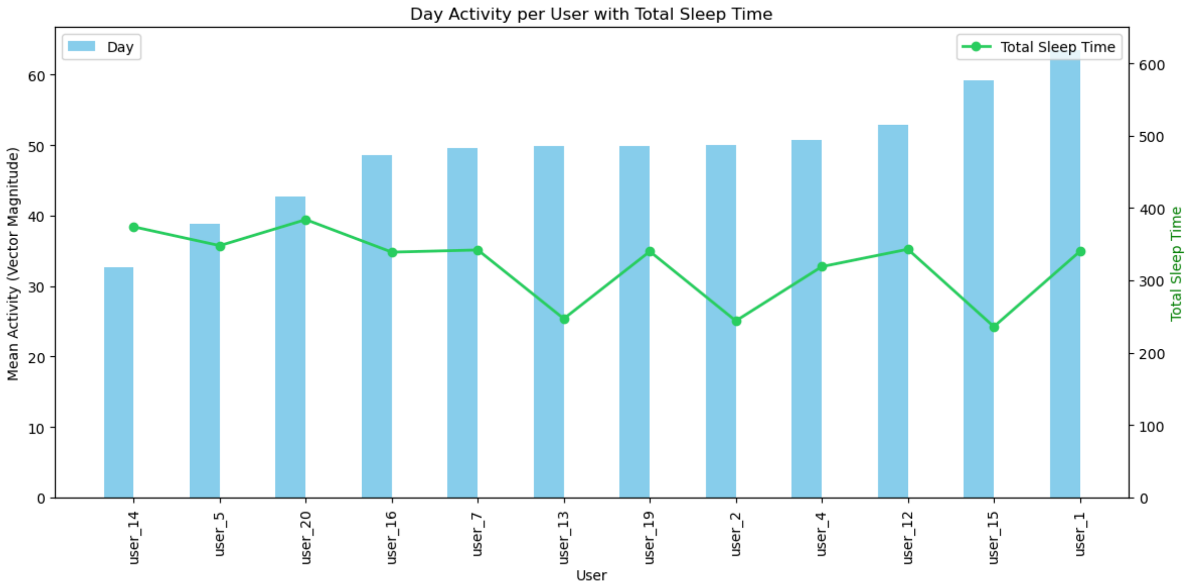


Figure 2. Day active users and their total sleep time

The Pearson correlation analysis (Figure 3) reveals several interesting patterns between activity levels and sleep outcomes in the day-active group. In the day-active group, daytime and evening activity levels are strongly positively correlated (r = +0.63), indicating that participants who are active during the day tend to remain somewhat active in the evening. Higher daytime activity is moderately associated with better sleep efficiency (r = +0.50), and evening activity also shows a slight positive effect on sleep efficiency (r = +0.48), suggesting that light evening activity does not disrupt sleep. Interestingly, both daytime and evening activity are negatively correlated with total sleep time (r = -0.47 and r = -0.35, respectively), indicating that more active participants sleep shorter durations but maintain efficient sleep. Wake After Sleep Onset (WASO) shows little to no correlation with activity (r = -0.10 for daytime, r ≈ 0.00 for evening), while higher WASO strongly reduces sleep efficiency (r = -0.48). Overall, the day-active group tends to sleep less but more efficiently, and their activity, whether during the day or evening, does not meaningfully disrupt sleep continuity.

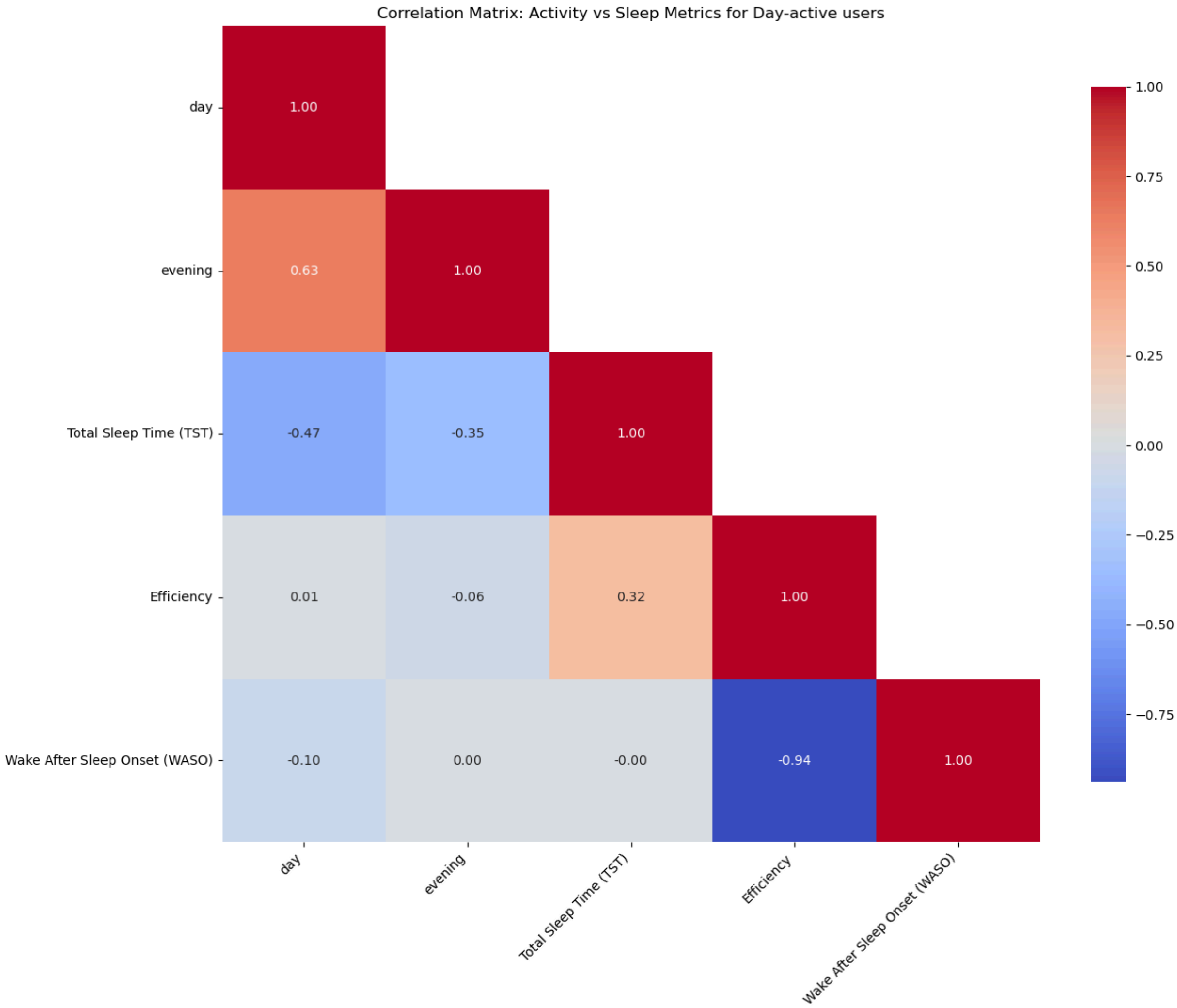


Figure 3. Correlation matrix of day-active users

In the next part, the analysis focuses on the evening-active group and compares the result with the day-active participants.

### 5.1.2. Evening active group analysis

In the evening-active group, evening activity is strongly positively correlated with total sleep time (r = +0.74), suggesting that participants who are more active in the evening tend to sleep longer. However, evening activity also shows a moderate positive correlation with Wake After Sleep Onset (WASO, r = +0.45), indicating that higher evening activity is associated with more nighttime awakenings. Daytime activity in this group is negatively correlated with both total sleep time (r = -0.47) and sleep efficiency (r = -0.45), suggesting that higher daytime movement is linked to shorter and less efficient sleep. Consistent with sleep physiology, sleep efficiency and WASO are strongly negatively correlated (r = -0.87), reflecting that more nighttime awakenings reduce overall sleep quality. These results are illustrated in figure 4.

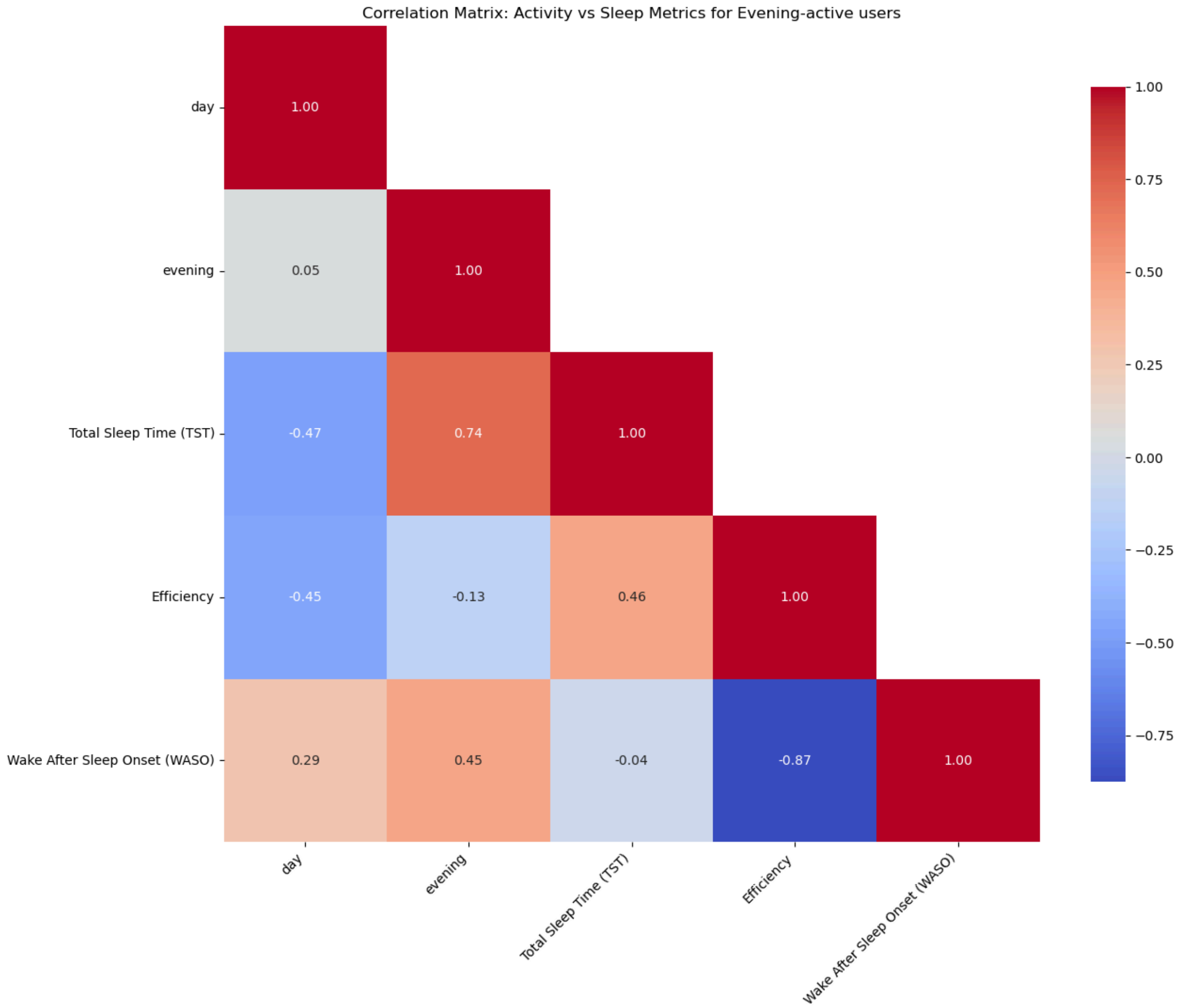


Figure 4. Correlation matrix of evening-active users

Overall, the results suggest a clear distinction between day-active and evening-active participants. For evening-active individuals, higher evening activity is associated with longer sleep durations but also more night time awakenings, leading to more fragmented sleep and no clear improvement in sleep efficiency compared with the day-active group. In contrast, being more active earlier in the day is linked to better sleep efficiency, even if total sleep time is slightly shorter. These findings indicate that the timing of activity may be more influential for sleep quality than the total amount of activity, highlighting the importance of considering when physical activity occurs in relation to sleep outcomes.

In addition to the correlation matrix, the combined bar-and-line plot shows the relationship between evening activity levels and total sleep time for the evening-active group (Figure 5). In general, participants with higher evening activity tend to have longer total sleep time, indicating a positive association between evening movement and sleep duration. An exception is User 10, whose total sleep time is unexpectedly low despite high evening activity. This outlier will be investigated individually later to better understand their sleep-activity pattern.

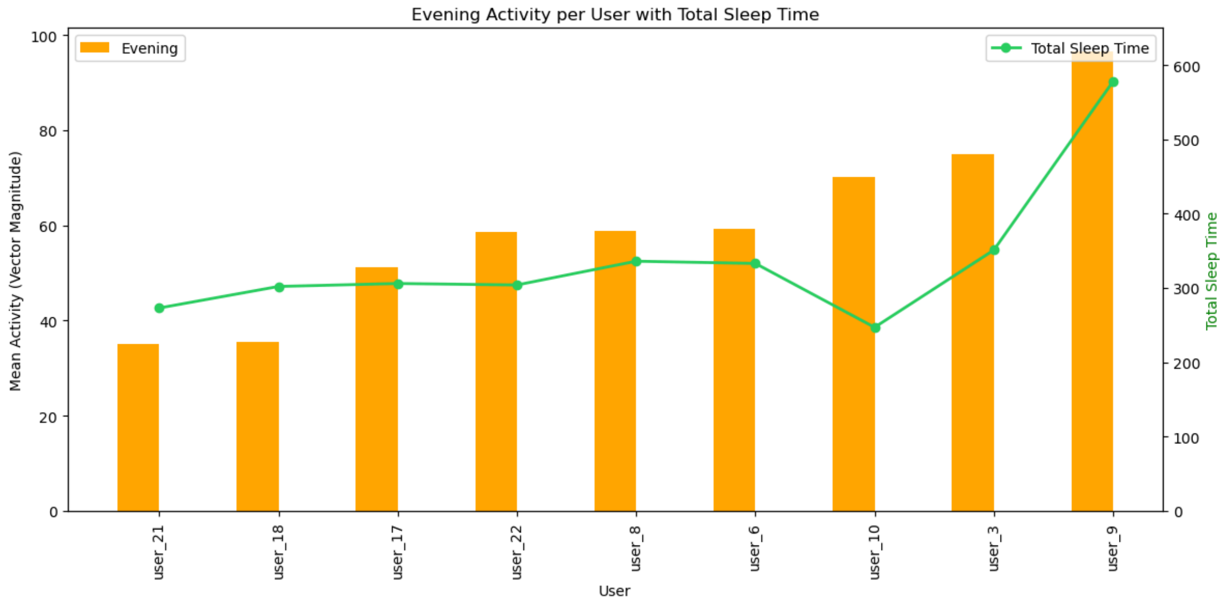


Figure 5. Evening active users and total sleep time

This analysis examines their activity distribution, sleep duration, and sleep quality in detail to identify potential factors contributing to the unexpectedly low total sleep time despite high evening activity.

## 5.2. User 10 analysis

User 10 exhibits an atypical sleep-activity pattern, with short total sleep time (247 minutes), which is substantially lower than the evening-active group mean total sleep time of 336.7 minutes. Sleep efficiency is moderate at 75.08%, but frequent awakenings (WASO = 78 minutes, 13 awakenings) indicate fragmented sleep (Figure 6).

| Activity | Start | End | Day | user | Activity_Label |
|---|---|---|---|---|---|
| 6 | 20:00 | 20:20 | 1 | user_10 | Heavy Activity |
| 6 | 21:30 | 21:40 | 1 | user_10 | Heavy Activity |
| 2 | 22:10 | 22:30 | 1 | user_10 | Laying Down |
| 2 | 22:50 | 23:10 | 1 | user_10 | Laying Down |
| 10 | 23:07 | 23:12 | 1 | user_10 | Caffeine |
| 11 | 23:17 | 23:30 | 1 | user_10 | Smoking |
| 10 | 23:30 | 23:35 | 1 | user_10 | Caffeine |
| 10 | 23:55 | 00:00 | 1 | user_10 | Caffeine |
| 11 | 00:05 | 00:15 | 2 | user_10 | Smoking |
| 10 | 00:28 | 00:33 | 2 | user_10 | Caffeine |
| 2 | 00:40 | 01:00 | 2 | user_10 | Laying Down |
| 7 | 01:30 | 02:30 | 2 | user_10 | Eating |
| 6 | 02:00 | 02:10 | 2 | user_10 | Heavy Activity |
| 0 | 02:30 | 06:50 | 2 | user_10 | Undefined |

| In Bed Time | Out Bed Time | Efficiency | Total Sleep Time (TST) | Wake After Sleep Onset (WASO) | Number of Awakenings |
|---|---|---|---|---|---|
| 02:40 | 08:09 | 75.08 | 247 | 78 | 13 |

Figure 6. Sleep and activity data (from 20:00) of User 10

Despite high evening activity, generally associated with longer sleep in this group, User 10's late-night behaviors, including caffeine intake, smoking, eating, and intermittent activity, likely disrupted sleep continuity (Smith, 2015; Jaehne et al., 2024). This case illustrates that individual lifestyle factors can override typical group-level activity-sleep trends, emphasizing the need to consider personal habits when interpreting sleep-activity relationships.

## 6. Conclusion & Discussion

This study investigated the relationship between daily activity timing and sleep quality using the MMASH dataset, focusing on differences between day-active and evening-active participants. In general, the findings indicate that the timing of the activity has a stronger influence on sleep quality than the total amount of activity. Based on the results, participants who were more active during the day tended to have higher sleep efficiency, despite having slightly shorter total sleep time. This suggests that daytime activity supports more restorative and consolidated sleep.

In contrast, evening-active users generally experienced longer sleep durations, however, this was accompanied by more fragmented sleep and increased nighttime awakenings, leading to no clear improvement in overall sleep efficiency. These findings are consistent with prior research indicating that timing of exercise and chronotype interact to influence sleep outcomes (Buman & King, 2010; Kredlow et al., 2015; Adan et al., 2012).

In addition to group-level analysis, the individual analysis for user 10 highlights the role of personal lifestyle factors in shaping sleep patterns. Despite high evening activity, user 10 experienced short, fragmented sleep, which is likely caused by late-night caffeine intake, smoking, eating, and irregular activity. This case demonstrates that group-level trends may not apply uniformly to all individuals, and personal behaviors can significantly modulate the relationship between activity and sleep. These findings also underscore the importance of considering both activity and individual daily habits when designing lifestyle recommendations aimed at improving sleep quality.

Furthermore, the results align with broader literature suggesting that daytime activity promotes better sleep efficiency, while evening activity may increase sleep duration but not necessarily quality (Buman & King, 2010; Kredlow et al., 2015). The current analysis further highlights that moderate evening activity is not inherently harmful, but excessive or irregular late-night behaviors can compromise sleep outcomes.

Although interesting findings can be drawn from this dataset, the study still faces some limitations. First, the sample size is small (n = 21 after excluding the missing data). This limits the statistical power and generalizability of the findings, as individual variations may not proportionally influence group-level results. Second, the dataset covers only two consecutive days, which may not capture well the habitual sleep and activity patterns. Short-term monitoring could be influenced by atypical daily routines, special events, or participant behavior during the study, reducing the representativeness of the results.

Another factor that affects the representativeness is the study population consisting of solely healthy male adults, limiting applicability to females, older adults, or individuals with health conditions that may affect sleep or activity patterns. While activity was measured with accelerometers, the analysis did not differentiate between types of physical activity, such as aerobic exercise, resistance training, or light movements, which may have distinct effects on sleep. External lifestyle factors, including caffeine intake, smoking, eating habits, work schedules, stress levels, or screen time, are not systematically controlled or quantified in the group level analysis, although they clearly influenced individual outcomes, which was proved by User 10 case.

The analysis focused on linear relationships using Pearson correlation, which may not fully capture non-linear or complex interactions between activity timing, intensity, and sleep outcomes. While there is still more to be explored with the given data, however, due to time constraints, the findings focus primarily on group-level correlations and selected individual cases, leaving additional analyses, such as detailed activity intensity patterns, chronotype interactions, and multivariate modeling of lifestyle factors for future work.

These limitations suggest that while the study provides useful insights into activity timing and sleep, the findings should be interpreted with caution, and further research with larger, more diverse populations and longer monitoring periods is needed to confirm and extend these results.

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