Exploring the Relationship between Physical Activity and Sleep Quality in Daily Life: An Experience Sampling Study

Ignacio Picón Rattel (s2821710)

Department of Psychology, University of Twente

202000375 - Health Psychology and Technology (HPT)

First supervisor: Dr. Peter ten Klooster

Second supervisor: Dr. Stans Drossaert

Date: 30/06/2024

Abstract

Background: Sleep is a crucial factor in human lives. The relationship between sleep and physical activity has been explored for decades, without finding clear and consistent results. That may be because most studies exploring these two variables have used cross-sectional or retrospective designs. For that reason, this study aimed at exploring the temporal reciprocal association between physical activity and sleep quality using Experience Sampling Methodology (ESM), an intensive longitudinal research design.

Methods: This study used a convenience sample of 21 participants (*M* = 29, *SD* = 15.08) of the general population who responded to four daily questionnaires over 14 days in the application "SEMA3". One daily morning questionnaire focused on sleep quantity (amount of hours of sleep) and quality (rate from 0 to 10) and the other three questionnaires focused on the amount of hours spent performing physical activity at different times of the day (morning, afternoon and evening). Visualisations of average values of both variables over time were created to observe potential trends. To analyse the data and statistically test potential relationships between physical activity and sleep quantity and quality, linear mixed models were employed.

Results: One statistically significant temporal association was found between physical activity and sleep quantity. More specifically, physical activity was associated with a longer sleep quantity the following night ($B = 0.23$, $SE = 0.09$, $t = 2.47$, $p = .01$). However, no significant temporal associations were found between physical activity and sleep quality, nor between sleep quantity and physical activity levels the following day.

Discussion: In line with previous cross-sectional research, this study found that physical activity is positively associated with sleep duration the following night. In addition, it is the first study to exclusively focus on physical activity and sleep using ESM and, therefore, brings some clarity about this association. Nevertheless, future research is suggested to focus on more specific samples or confounding variables to ultimately understand the temporal associations between different types of physical activity and dimensions of sleep quality in the general population.

Introduction

Sleep is a crucial aspect of our daily functioning. Human beings spend, on average, about one third of our lives sleeping (Canto et al., 2017). The study of sleep has had an extensive research tradition in different health sciences disciplines for several decades (Schulz, 2022). Especially since the development of physiology and psychology fields at the beginning of the 20th century and the discovery of different sleep stages (Schulz & Salzarulo, 2016).

It is currently well-established that there are multiple health consequences related to having insufficient sleep. Insufficient sleep can result in a reduction in executive functioning, emotional dysregulation or depression (Owens & Weiss, 2017). There are various societal implications of sleep as well. Insufficient sleep has been linked to different detrimental personal and social outcomes, including poor work performance and safety risks, and negative health outcomes such as obesity, diabetes, cardiovascular disease, and even early mortality which indirectly increase healthcare costs and negatively impact society and its functioning (Chattu et al., 2018).

In the Netherlands, the prevalence of poor sleep seems to be high, with estimates suggesting that up to one third of the adult population suffers from general sleep disturbance (Kerkhof, 2017). More globally, restless sleep is reported by 10 to 20% of the population across Europe and western countries (Baranowski & Jabkowski, 2023). This high prevalence, coupled with the significant societal and health implications of poor sleep quality, underlines the importance of understanding the dynamics of sleep quality and its possible antecedents and consequences.

In today’s fast-paced world, poor sleep is considered a major concern. Especially because current lifestyles are characterised by long or continuous work hours, high stress levels, and the constant use of electronic devices which have greatly impacted our traditional sleep patterns (Lastella et al., 2020). For instance, exposure to artificial light from screens has been proven to impair the production of melatonin, a hormone that regulates sleep-wake cycles, leading to disrupted sleep (Green et al., 2017). In addition, societal expectations and common beliefs have strongly emphasised values such as productivity and activeness which according to Matricciani et al. (2012), has led to a culture of sleep deprivation.

Sleep quality is a multi-dimensional concept and its conceptualization has been heavily debated. Its definition has emerged as a critical factor when evaluating our overall sleep experience (Fabbri et al., 2021). Research done in the last decade has considered two categories to explain and measure sleep quality. On the one hand, there is a more objective perspective (also called medical), which primarily uses polysomnography, a technique focused on sleep stages and considered to be the gold standard for diagnosing sleep-related disorders (Rundo & Downey, 2019). On the other hand, a more subjective way of measuring sleep quality exists, which takes self-reported measures of people into account (Krystal & Edinger, 2008). It focuses on indices such as total sleep time, sleep onset latency wakefulness after sleep onset or sleepiness during the day, which are usually fairly easily recalled by people (Crivello et al., 2019). Following these subjective measures, many questionnaires have been created and used as gold standards in later studies. According to Harvey et al. (2008), who asked participants with and without insomnia to define sleep quality, people mostly use three categories to evaluate their sleep quality: awakenings in the night, total sleep time and tiredness on waking and throughout the day. By taking similarities from previous research and different questionnaires, sleep quality will be defined in this study as one’s satisfaction of the sleep experience that integrates sleep quality rate and sleep quantity.

The dynamics of sleep quality are complex and multifaceted, involving links between biological, psychological, and environmental or lifestyle factors. Research has explored and identified a vast and wide range of potential predictors and correlates of poor sleep quality, especially those that concern certain lifestyles. One of the potential predictors that has received much attention is physical activity (Martínez-de-Quel et al., 2021). Lifestyle factors like physical activity can be something potentially changeable which might provide a solid starting point to intervene in order to improve people’s sleep quality.

Physical activity, a broad term that has been studied for a long time, has been closely linked with having a positive effect on sleep quality (Alnawwar et al., 2023). Physical activity can be defined as “any body movement that raises energy expenditure above resting metabolic rate” (Torgerson et al., 2018). Kredlow et al. (2015), who conducted a meta-analysis on the relationship between physical activity and sleep quality, concluded that both acute and regular physical activity have a beneficial impact on sleep quality. In a systematic review, they found that moderate activities seem to have more promising results than vigorous activities in relation to sleep quality (Wang & Boros, 2019). As walking and counting steps has become very popular due to the use of wearables (Patel et al., 2017), a recent study that focused on the relationship of simple walking on sleep quality showed that low-impact physical activity already positively contributes to sleep (Bisson et al., 2019). Nonetheless, a study by Pesonen et al. (2022) concluded that the more exercise, the less time people sleep, which is something to consider when aiming to improve sleep quality. In addition, according to Memon et al. (2021), more longitudinal studies are needed in order to investigate the variability in the association between physical activity and sleep quality.

While there is already much research conducted on the topic of how physical activity might affect sleep quality, there is still no clear consensus about the dynamics and temporal nature of this association over time. That is because most of the previous research is based on cross-sectional studies, using retrospective measures of physical activity and sleep. The main limitation of conducting a cross-sectional study is that it cannot determine causal or temporal associations. For that reason, this study uses the Experience Sampling Method (ESM) which allows researchers to capture real-time data in the participants' natural environment. The ESM involves participants reporting their experiences, behaviours, and thoughts at multiple points throughout the day, providing a rich, context-sensitive dataset (Van Berkel et al., 2017). In the context of physical activity and sleep quality, ESM can help capture the variability and unpredictability of these behaviours across different times and settings. This is particularly important as both physical activity and sleep patterns can fluctuate significantly from day to day and even within the same day.

Moreover, ESM enables researchers to examine variables, like physical activity and sleep quality, more accurately over time. Traditional survey methods often rely on retrospective recall, which can be subject to memory biases and may not accurately reflect the corresponding behaviours. With ESM, researchers can track the immediate effects of physical activity on subsequent sleep quality, or vice versa, providing more precise insights into the causal links these two health behaviours possess (Larson & Csikszentmihalyi, 1983). Therefore, the use of ESM may provide a more detailed insight on the complex temporal relationship between physical activity and sleep quality.

The term reciprocal gets importance in this ESM study as it makes reference to the fact that both variables, sleep and physical activity, can act as both independent and dependent variables (e.g. sleep can affect physical activity and vice versa) and this can just occur when variables are examined over time. To date, no studies have examined the reciprocal temporal association between sleep and physical activity using ESM, likely due to the relative novelty of ESM in this field. Nonetheless, two different studies with interesting results were published recently. A study by Hachenberger et al. (2022), explored physical activity, sleep and affective well-being the following day using a sample of young adults. Based on their analyses, they found that increased physical activity before 2 p.m. was associated with longer sleep duration the following night (Hachenberger et al., 2022). The other study by McGowan et al. (2022) focused on physical activity, sleep and well-being as well, specifically in college students. In relation to the relevant variables for this present study, they however concluded that an increase in physical activity resulted in a decrease of the sleep duration the next night (McGowan et al., 2022). Thus, these two studies, even though they did not fully examine reciprocal associations and did not use the same variables and sample, found contradictory results for the effect of physical activity on sleep the following night.

This research aims to further explore the temporal reciprocal association between physical activity and sleep quality in daily life using ESM. To assess this, the following research questions will be addressed:

Research question 1: How is sleep quantity related with next-day daily physical activity and how is physical activity related to sleep quantity the night before and the night after?

Research question 2: How is sleep quality related with next-day daily physical activity and how is physical activity related to sleep quality the night before and the night after?

Methods

Design

To investigate the different research questions, this study used the Experience Sampling Method (ESM) to collect data (Myin-Germeys & Kuppens, 2021). ESM is a quantitative intensive longitudinal research design which gathers self-reported data directly from the individual's natural environment over a period of time. A major advantage of ESM is that it is suitable for accurately assessing the dynamics and reciprocal relations between experiences such as perceived sleep quality and behaviours such as physical activity (Ellison et al., 2020). Sleep quality or quantity and physical activity are the variables of interest in this study and they can serve as both the independent and dependent variables, which is typical for such cross-lagged types of studies. The main objective of the current study was to analyse how these two variables affect each other over time. This study (240445) was approved by the Ethics Committee of the Faculty of Behavioural, Management and Social sciences at the University of Twente.

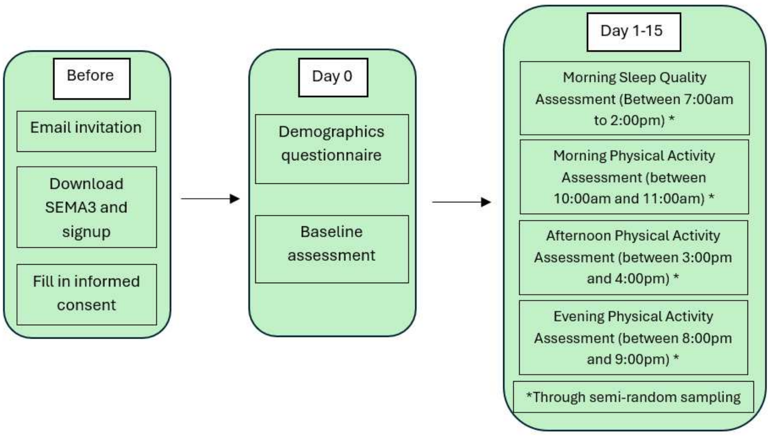
This ESM study used short questionnaires in order to measure the two variables using an application on the respondents' smartphones prompting them to answer questions at specific times of the day using semi-random sampling. Data were collected between 11-04-2024 until 25-04-2024, totalling 15 days of measurement. Self-report measurements were administered four times a day. There was one morning assessment each day measuring the participants' perceived sleep quality in the previous night, which was randomly prompted between 7:00 am and 10:00 am and could be answered until 14:00 pm. Participants received a reminder exactly one hour after they received the first notification. The other three daily assessments asked about the participants' physical activity, and these occurred in the morning, which was randomly prompted between 10:00 am and 11:00 am and could be filled in until 11:30 am, in the afternoon, which was prompted between 3:00 pm and 4:00 pm and could be filled in until 4:30 pm and in the evening, which was prompted between 8:00 pm and 9:00 pm and could be filled in until 9:30 pm. Each physical activity assessment had its particular time slot, and the participants received a reminder half an hour later if the assessment had not been filled in.

Semi-random sampling scheme is often used in ESM studies as it results in a relatively high ecological validity, a relatively low participant burden, and relatively small negative consequences for compliance (Myin-Germeys & Kuppens, 2022). The sampling protocol was designed in this way, to assess their physical activity more frequently in order to reduce recall biases and to randomise the questionnaires within specific time slots, to increase the ecological validity. Nonetheless, participants were given a reasonable amount of time to fill in the questionnaires, since it was assumed that both sleep quality and physical activity can be recalled for a longer period of time than, for instance, mood.

The sampling lasted for two weeks (15 days), which is a common practice within ESM studies, and it allows researchers to get a high response rate and to avoid unnecessary burden of participants (Dogan et al., 2022). Figure 1 illustrates the study design. Before the data collection part started, an email was sent to all participants with a link to download an ESM application on their phone and they received their unique participant number which was needed to log into the application and keep their anonymity. Once the participants downloaded the app, they could sign up to the study in order to read the general instructions and give their consent (Appendix A). On day 0, the study began, and the participants were asked to fill in both the demographics questionnaire and the baseline assessment. From day 1 until day 15, they had to fill in the corresponding four ESM questionnaires (Appendix B).

Figure 1

Flowchart of the study design



The questionnaires were programmed and administered through the software application “SEMA3” (O’Brien et al., 2023). This software was especially created in order to design ESM studies. No prior programming knowledge is needed in order to use this software, since all the information can be found on the website in an extensive user guide. The app the participants had to download on their smartphone is fairly easy to use as well, as the questionnaires can be filled in within a few minutes. In addition, SEMA3 only lets participants proceed to the next question if the previous one has been responded to, which eliminates the chance of filling in the questionnaires partly.

Participants

The participants were recruited via convenience sampling which is a non-probability sampling method where members of the target population that are easily accessible or are willing to participate are included for the purpose of the study (Etikan et al., 2016). Participants were relatives, friends, or social contacts, especially people in the university setting, who were contacted either in person or through social media. The intended sample size was 20 participants, as Van Berkel et al. (2017) found a median of 19 participants in their review of several ESM studies. Participants needed to perform some type of physical activity at least three times a week. Individuals who do not practise any physical activity at all, individuals who are under 18 years old and those who do not speak/understand English were excluded from participation in this study.

Materials

For this study, the participants needed a smartphone with a stable internet connection at some point of the day to process their responses to the questionnaires. This study collected data regarding sleep quality jointly with another bachelor thesis which used caffeine intake as its variable of interest. Questionnaires regarding this variable were included in the app SEMA3 and completed by participants in the same way (Appendix B).

Measures

Demographics. The first questionnaire that was administered in this study concerned demographics. Information about their age, gender (male, female or other), nationality and occupation (employed, unemployed, student or other). In case they responded “employed”, the sector where they work in was asked.

Baseline assessment. The baseline assessment had as its main objective to get a more detailed insight into people’s general behaviours with respect to sleep and physical activity. This made it possible to check if the participant’s sleep behaviour had significantly changed during the study when analysing the final results. Every question concerned their averaged behaviours and experience in the last week. Participants were asked how many hours they slept each night, how long it took them to fall asleep and how would they rate their quality of sleep. Regarding the physical activity, they were asked how many times they exercise and what type of physical activity they usually perform.

Daily sleep quality. To examine the participants’ sleep quality, they received a notification every morning with a questionnaire consisting of three questions to fill in. Since this study focused on sleep quality, rather than mere sleep quantity, there were no validated short questionnaires found specifically for ESM research. For that reason, a part of a general sleep questionnaire was adapted for

ESM sampling. The questionnaire that served as inspiration was The Pittsburgh Sleep Quality Index (PSQI). Since sleep quality has been often described using three categories (quantity, awakeness and quality), three questions were asked (Harvey et al., 2008). The first question was “How many hours did you sleep last night?”, which was a fully open question for the participants to be specific (e.g. 7.5 hours). The second question was “On a scale from 0-10, how would you rate your sleep?”, which they could slide between numbers from 0 until 10, the latter being excellent sleep. The third and last question was “How would you rate your energy level right now?”, which was also evaluated on a scale from 0-10.

Daily physical activity. To assess physical activity among participants, a survey was sent out three times a day (morning, afternoon and evening). Since the intention was to keep the questionnaires short and avoid potential burdens from participants, the International Physical Activity Questionnaire - Short Form served as an inspiration to create three questions. The first question was “How much have you moved since you woke up (in minutes)?” in the morning or “How much have you moved since the last survey (in minutes)” in the afternoon and evening. This question was open so that participants could type exactly how much they moved. The other two questions were not included in the data analysis and therefore, can be found in Appendix B.

Data analysis

The statistical software RStudio version 2024.04.1+748 was used to analyse the data. The code used in this software is fully described and shown in Appendix C. The cut-off point for participant inclusion in the analyses was set at a 33% response rate. This percentage commonly used in ESM studies was chosen to include as many participants as possible since randomly missing data in intensive longitudinal studies is expected and does not have a major negative impact on the outcome results (Myin-Germeys & Kuppens, 2021). Out of the 24 participants who were invited to participate in the study, 21 participants had a higher response rate than 33%. That means 3 participants were excluded from the data analysis.

First, the data from all the different surveys was downloaded from SEMA3 and saved as csv files. Those csv files were then imported into RStudio in order to be analysed. The data from the participants with a response rate over the cut-off estimate were merged using their unique ID number. Answers in the different surveys containing characters other than numbers were renamed as “NA” to exclusively have valid responses. The baseline questionnaire including the different demographic questions was analysed through descriptive statistics.

The sleep survey was specifically analysed separating the two questions that were taken into account in the data analysis, regarding hours of sleep and quality of sleep. The physical activity surveys had to be separated into 3 different surveys for a more accurate analysis, these being morning, afternoon and evening. Since the physical activity variable was asked in minutes, it was converted into hours for the analysis in order to have better interpretable numbers in a similar scale to sleep.

A summed variable accounting for the total amount of daily physical activity was created. The average amount of physical activity per day and the average amount of sleep (hours of sleep) was first plotted in a graph to explore any potential associations over the days of the study. Next, a random intercept Linear Mixed Model (LMM) to statistically analyse the association between number of hours of sleep as fixed covariate and total amount of physical activity the next day as the dependent variable was computed. The LMM used restricted maximum likelihood estimation, an unstructured covariance matrix for the repeated measures and a random intercept only for the participants. LMM's are useful in these situations since they are able to process structures with missing values. Mixed-effects models can account for missing data by adding additional random effects, which create estimates based on previous responses, and analyse within-subject variability (Myin-Germeys & Kuppens, 2022). Next, the amount of physical activity in relation to the number of hours of sleep the next night was analysed through another LMM with the same settings. This was done by lagging the daily total amount of physical activity by one day within each person using their specific participant ID so that physical activity was now associated with sleep quality the night after.

The two LMM's previously mentioned were then computed again in the same way but using sleep quality instead of hours of sleep to find potential associations with physical activity. For all the analyses previously mentioned, a significance level of $p < .05$ was used.

Results

Characteristics of the study group

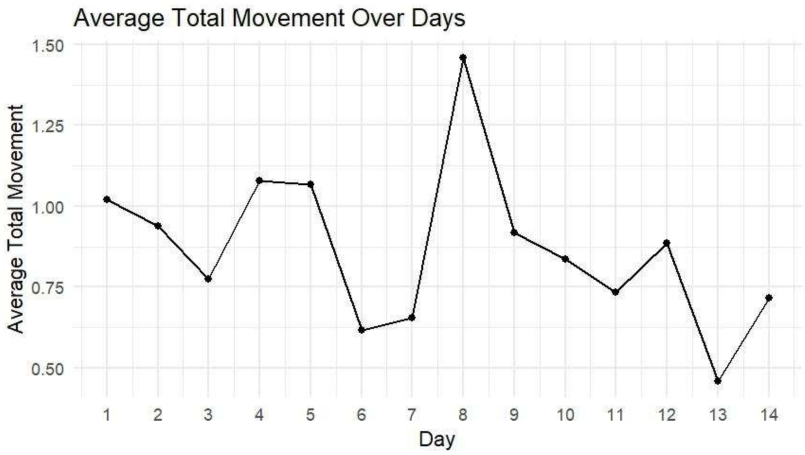
The final sample consisted of 21 individuals, from whom 10 were male and 11 female between the ages of 19 and 55 (*M* = 29, *SD* = 15.08). Ten (47.6%) of them reported to be Dutch, four (19%) indicated that they are Spanish and seven (33.3%) were of other origin or did not report their nationality. As for their current occupation, 10 participants reported to be a student, 6 of them reported to be employed and the other 5 did not report their occupation status. In the baseline assessment, participants responded that the week before the data collection started, they slept on average 7-8 hours and they rated their quality of sleep a 7.25 (*SD* = 1.08) on average. Regarding physical activity, the participants indicated that they exercised 4 times a week on average.

Daily physical activity

In figure 2, the average total activity of the 21 participants over the 14 days is illustrated. The x-axis represents the 14 days the study lasted and the y-axis represents the average amount of physical activity in hours. The participants performed an average of 52 minutes (*SD* = 14.39) of physical activity a day. The graph shows a noticeable variability in the participants' daily amount of physical activity. On day 4, the second day with the most physical activity performed on average occurs. After experiencing a slight increase on day 7, a clear peak is achieved on day 8, this being the day with the highest amount of physical activity performed. After this day, the amount of physical activity tended to decrease until day 13, where the lowest amount of physical activity had been practised.

Figure 2

Average Total Physical Activity Over Days in Hours



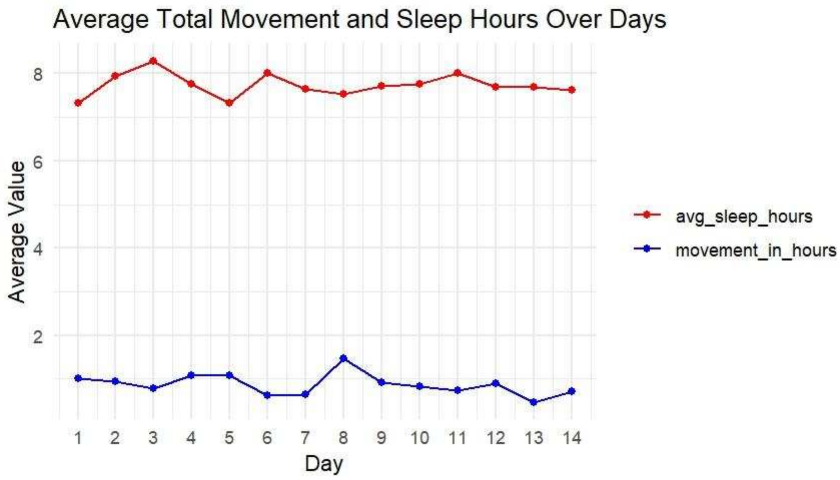
Note. This figure illustrates physical activity in hours to be more visually understandable.

Reciprocal associations between sleep quantity and physical activity

Figure 3 shows the average daily physical activity combined with average daily hours of sleep over the 14 days. The average daily hours of sleep (red line) remained fairly constant around 8 hours with minor fluctuations mainly occurring the first 6 days of the data collection period. Notably, over the 14 days, physical activity and hours of sleep seem to show some trend towards an inverse association, as when one of them increases, the other one tends to decrease. A clear example of this occurs on day 8, when the average physical activity peaks and the average hours of sleep (in the past night) decreased, reaching the lowest point on the second week of the study. Overall, the graph suggests that while there seems to be a trend indicating inverse relationships between movement the next day and sleep hours on specific days, these associations are not consistent across the entire 14-day period.

Figure 3

Average Total Movement (In Hours) and Sleep Hours Over Days



To statistically test the relationship between average daily average hours of sleep (sleep quantity) and daily average physical activity two LMMs were used. The first model tested the potential association between number of hours of sleep and the amount of physical activity the next day. The result indicates that there was no evidence of a significant relation between the variables ($B = -0.01$, $SE = 0.06$, $t = -0.11$, $p = .91$). The LMM showed an Intraclass Correlation Coefficient (ICC) of 0.466, which means that there was both a substantial between-participant variability (46.6%), and within-participant variability (54.4%) in daily physical activity, confirming the strong observed day-to-day fluctuations in activity levels.

The second model tested if the daily amount of physical activity was related to the number of hours of sleep the next night. For this, the LMM was fitted with the lagged variable of total daily physical activity. The analysis showed that the amount of physical activity was significantly positively associated with the number of hours of sleep the night after ($B = 0.23$, $SE = 0.09$, $t = 2.47$, $p = .01$). This indicates that, on average, each additional hour of physical activity was associated with an increase of about 0.23 hours (roughly 14 minutes) of sleep. The LMM showed an adjusted ICC of

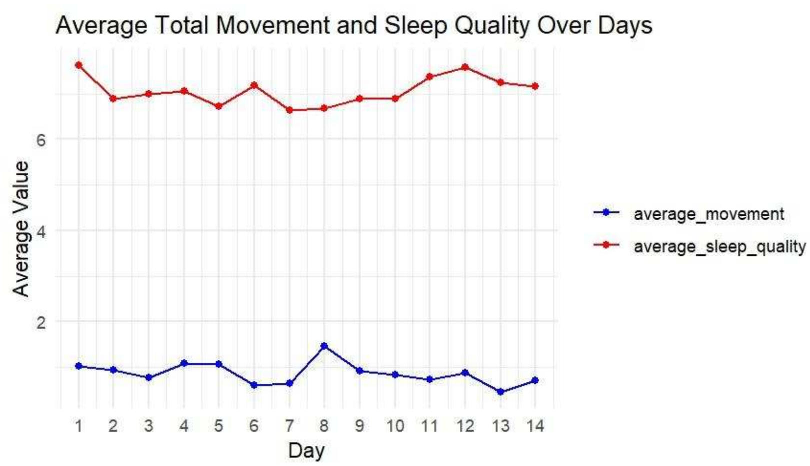
0.362, which means the variance in the amount of sleep was mostly accounted for by fluctuation at the within-participant level.

Reciprocal associations between sleep quality and physical activity

Next, the potential association between sleep quality and physical activity was explored. In Figure 4, these two variables are plotted over the 14 days in order to observe possible trends. In the graph, sleep quality and physical activity seem to remain rather stable over time. However, according to the ICCs that will be later discussed, this stability over time is not confirmed, as they show a great variability of both variables. This discrepancy might be due to the scaling of the variables in the figure. On day 8, there is a noticeable peak in average movement, but sleep quality does not show any increase or decrease. Conversely, on day 6, sleep quality has a peak, while the average physical activity shows a moderate decrease. Over the 14 days, as a general trend, there seem to be some indications that the variables could have some association but it is inconclusive.

Figure 4

Average Total Movement (In hours) and Sleep Quality Over Days



In order to statistically test their association over time, the next set of LMMs focused on daily sleep quality and daily amount of physical activity. The first model explored the potential association between sleep quality and physical activity the next day. The result of this analysis showed that this relationship was not statistically significant (B = 0.04, SE = 0.04, t = 0.87, p = .39, ICC = 0.46).

The second LMM in this set focused on the potential association between physical activity and sleep quality the next night. The outcome of the analysis, even though Figure 4 suggested a potential positive association between daily physical activity and daily sleep quality the next night, showed that this association was also not statistically significant (B = 0.16, SE = 0.09, t = 1.69, p = .09). The ICC in this model was 0.115, which means that the vast majority of the variability occurred at the within-person level.

Congruence between retrospective and daily sleep quantity measurements

Finally, a last post-hoc LMM used in this study explored how accurately participants responded to their daily average hours of sleep in the baseline assessment and how many hours of sleep they actually had throughout the 14 days. The result of this LMM (B = 0.97, SE = 0.34, t = 2.89, p = .01) indicated that baseline hours of sleep were significantly and strongly associated with hours of sleep during the data collection period. The estimate indicates that for every hour of sleep in general reported at baseline, the sleep hours throughout the 14 days increased by approximately 0.97 hours (roughly 58 minutes), suggesting that the ESM measurements accurately captured sleep over the 14-time period.

Discussion

This ESM study aimed to explore the temporal reciprocal relationships between physical activity and sleep quality in daily life. To do that, daily measurements of both sleep duration and sleep quality rate were used to find potentially different temporal associations with physical activity over 14 days in 21 participants. Only one association was found which indicated a positive association between daily physical activity and sleep duration (hours of sleep) the next night. No significant temporal associations were found between physical activity and sleep quality, nor between sleep quantity and physical activity levels the following day.

The significant positive association found between daily physical activity and sleep duration the following night is in line with several previous studies that have indicated physical activity is positively associated with sleep duration. For instance, a study that focused on the relationship between low-impact daily physical activity and sleep quality and quantity in healthy adults, found that on days when physical activity was higher than usual, participants reported a higher sleep quantity the night after regardless of sex (Bisson et al., 2019). Similarly, a study by Pesonen et al. (2022) found that vigorous physical activity predicted a longer sleep duration the following night. The current study provides both more and better evidence for the positive association between physical activity and sleep duration the next night, as it has explored the association over time with quite a broad sample representing part of the general population.

In previous ESM studies the association between physical activity and sleep have not been thoroughly investigated and results are also contradictory to each other. While a study by Hachenberger et al. (2022) also found this positive directionality of physical activity and sleep quantity, another study by McGowan et al. (2022) found the opposite indication. The reason behind these inconclusive results can be due to their specific variables of interest, since none of these two ESM studies focused solely on physical activity and sleep and they used other measurements for these two specific variables. The current findings, despite the little amount of ESM studies focused on sleep and physical activity, suggest the possible existence of a clear directionality where physical activity facilitates a more prolonged sleep. One explanation for this finding may be that physical activity has been shown to boost the production of melatonin, which directly regulates circadian rhythms (Xie et al., 2017). Next to that, according to a meta-analysis by Moyers and Hagger (2023), physical activity has demonstrated in different studies to reduce cortisol secretion before both during the day and night, therefore reducing stress and leading to a more optimal sleep. Based on this current study and previous findings, it can be stated that more physical activity enhances sleep quantity, possibly due to physiological matters or changes in the body.

In addition, no significant association was found between sleep quantity and physical activity the next day. This finding cannot be contrasted with other previous ESM studies, since the ones previously mentioned did not focus on this potential direction of the association. However, other types of longitudinal studies have explored these variables. According to several studies, which focused on adolescents and young adults, longer sleep duration is associated with less physical activity the next day (Mead et al., 2019). Next to that, other longitudinal studies have put their attention into distinguishing low, moderate and vigorous physical activity and have found that longer than usual sleep duration is associated with more vigorous physical activity but not the other types (Pesonen et al., 2022).

The first ever systematic review to focus exclusively on these variables by Atoui et al. (2021), suggested that sleep quantity and its associations, when analysed at an intra- and inter-individual level, might have to do with an idiosyncratic phenomenon, meaning that the effect can greatly vary in magnitude and direction from one person to another. That is why it is important to increase the sample average age to better reflect the diversity of the general population, and for future studies to analyse results at an individual level. To examine data at an individual level, the researcher needs to focus exclusively on a single subject and observe what results that subject shows. By adding up what is found in every single participant, trends or patterns can be extrapolated. This was done in a study by Bei et al. (2017), who studied sleep and physiological dysregulation at an intra-individual level and were able to find that those people with a more variable sleep pattern were associated with blunted diurnal cortisol, which can directly affect daily-life duties. Specifically in ESM methodology, some studies have used an intra-individual approach. An example is the study by Gadosey et al. (2021), which explored emotions that play a role in procrastination over time, and who found individual tendencies to procrastinate, as well as demographic and situational features that could trigger procrastination.

Despite the significant positive association found in this study regarding physical activity and sleep quantity the next night, there were no other significant temporal links between sleep quality and physical activity. Nevertheless, it is worth noting that in the analysis for physical activity and sleep quality the following night, some visual association seemed to be found, but on a group level this association was not statistically significant. This non-significant result can be due to many factors such as the multidimensionality of the concept of sleep quality or simply, a power problem due to, for instance, sample size. Several studies have found significant positive results towards physical activity and sleep quality (Jiao, 2021). Systematic reviews have revealed that moderate physical activity is effective in improving sleep quality for the whole general population (F. Wang & Boros, 2019; Alnawwar et al. 2023). Thus, it is important to take these into consideration and examine them closer, especially in longitudinal studies, where the association needs to be further examined (Semplonius & Willoughby, 2018).

With regards to the generalizability of the outcome results, it is worth mentioning that the sample used in this study may have been well-aware of a healthy lifestyle since they displayed quite healthy behaviours overall regarding both sleep and physical activity. Although the use of ESM does not intend to generalise to the broader population, but to bring some clarity about how certain things or associations work in daily life, it is important to keep in mind the selective sample used in this study if compared to in future findings.

Furthermore, as can be seen in Appendix B, there was one question in the daily sleep survey that was not used in the data analysis. That question focused on the energy of the participants at awakeness, which they could rate from 0 to 10. This question was not taken into account in the results since it did not show much variability and it can also be considered as a consequence or a dependent factor of the quality and quantity of sleep. The other two questions in the daily sleep survey that were used in the analyses could have some reliability concerns since they were just a small selection of the original validated instrument. This could ultimately affect the outcome of this study but ESM aims at having short questionnaires that are asked a few times a day over a span of several days. Thus, ESM finds it necessary to have variability in the data, something that cannot occur in highly valid and reliable questionnaires. Next to that, there were two other questions in the surveys regarding physical activity that were not used in the data analysis. Those questions focused on the participant specific type of physical activity performed and the location of that activity, whether it was performed indoors or outdoors. These two questions were not used because of technical issues with the data. In the survey, the type of physical activity was asked as an open question, which led to many grammatical errors or typos and therefore it was complex to recode and analyse it as a quantitative variable. At the same time, the activities participants entered were too broad and to meaningfully classify in a limited number of activity types. The second question also brought issues because, even though it was a multiple choice question where participants either chose “Indoors” or “Outdoors”, they always had to choose one or the other, and if they had not performed any physical activity, they could not skip the question and therefore those answers could not be reliable.

Strengths and limitations

The first and most important strength of this study is its intensive longitudinal design, which made it possible to examine physical activity and sleep in detail and in a temporal way. By continuously collecting data over a period of 14 days, this study was able to analyse daily variations on both variables and provide a more insightful understanding of the potential associations compared to cross-sectional studies, increasing the validity of the measurements as well (Myin-Germeys & Kuppens, 2021). In relation to this, ESM is the only methodology able to measure temporal reciprocality, as, in this case, both sleep and physical activity act as dependent and independent variables. The ESM methodology is also intended to minimise possible recall biases, which can be a problem when using self-reported measures. This is done by asking participants to respond to a survey close to when it takes place in their natural environment (Houtveen & Oei, 2007), which this study applied to both variables asking participants to respond to the sleep survey each day in the morning and to the physical activity surveys three times a day to receive accurate estimates. Collecting data in real-world settings increases ecological validity, as the results are more likely to reflect actual behaviours and experiences, making the findings more generalizable (Hermans et al., 2019). This type of electronic ESM study has become available due to the wide availability of smartphones, which most people in the general population now possess. Another strength of this study is that it defined sleep quality in a multi-dimensional way and it looked to separate these dimensions to measure them later on. These two dimensions were sleep quantity and sleep quality, which made it possible to have more specific findings. The third strength of this study is the sample age. Since many previous studies have focused on children, adolescents or young adults, this study wanted to bring to light the possibility of investigating it using the general population, ranging from young to older adults. Although the average age of the final sample turned out to be rather young, it is a starting point to establish solid results about the associations in the general adult population.

Besides the strengths, this study has some limitations that need to be explained and considered when interpreting the results. Firstly, the sample mostly consisted of people who are closely related to the researcher, recruited using a convenience sampling method. This might have provoked participants to display more socially desirable behaviours to some extent, since the study was based on self-report measures (Bäckström & Björklund, 2021), even though results could not be linked to identifiable participants. Secondly, and following the previous limitation, self-reported measures may produce subjective answers and therefore, not be fully reliable. Perhaps using some more objective measures of sleep and physical activity can produce answers and data which are a more accurate reflection of reality. According to Bate et al. (2023), it is already possible to measure both sleep and physical activity objectively in daily life by passive sensing using smartphones or other wearables in the general population. A combination of both more objective measures and more subjective measures, such as the study by Pieters et al. (2023) which used actigraphy and ESM in a study focused on physical activity and sleep, can lead to more holistic and accurate results. In the third place, even though a duration of two weeks is common in ESM studies, it might be still short to explore the long-term associations, especially due to the variability of sleep and physical activity which can depend on factors such as seasonal changes. Lastly, although physical activity and sleep can be directly associated with each other, it is important to conduct other studies that take into consideration potential confounding or moderating contextual variables such as screen time or mental well-being that could have a major effect on the results. Thus, future studies should take these limitations into account in order to establish a greater understanding of the relationship between physical activity and sleep quality.

Conclusion

In conclusion, while this study supports the beneficial impact of physical activity on sleep duration, it also highlights the complexity of the temporal links between physical activity and sleep quality. The findings support the need for further research to put the focus on other samples, confounding variables or methodology in order to discover, step by step, how different types of physical activity and different dimensions of sleep quality interact with each other.

References

Ács, P., Veress, R., Rocha, P., Dóczi, T., Raposa, L. B., Baumann, P., Ostojić, S. M., Pérmusz, V., & Makai, A. (2021). Criterion validity and reliability of the International Physical Activity Questionnaire – Hungarian short form against the RM42 accelerometer. *BMC Public Health*, *21*(S1). https://doi.org/10.1186/s12889-021-10372-0

Alnawwar, M. A., Alraddadi, M. I., Algethmi, R. A., Salem, G. A., Salem, M., & Alharbi, A. (2023). The Effect of Physical activity on sleep quality and sleep Disorder: A Systematic review. *Curēus*. https://doi.org/10.7759/cureus.43595

Atoui, S., Chevance, G., Romain, A., Kingsbury, C., Lachance, J., & Bernard, P. (2021). Daily associations between sleep and physical activity: A systematic review and meta-analysis. *Sleep Medicine Reviews*, *57*, 101426. https://doi.org/10.1016/j.smrv.2021.101426

Bäckström, M., & Björklund, F. (2021). Socially desirable responding in experience sampling. *Journal of Individual Differences*, *42*(4), 157–166. https://doi.org/10.1027/1614-0001/a000342

Baranowski, M., & Jabkowski, P. (2023). Gender and socioeconomic patterning of self-reported sleep problems across European countries. *European Journal of Public Health*, *33*(2), 242–248. https://doi.org/10.1093/eurpub/ckad012

Bate, G. L., Kirk, C., Rehman, R. Z. U., Guan, Y., Yarnall, A. J., Del Din, S., & Lawson, R. A. (2023). The role of wearable sensors to monitor physical activity and sleep patterns in older adult inpatients: A Structured review. *Sensors*, *23*(10), 4881. https://doi.org/10.3390/s23104881

Bisson, A. N., Robinson, S. A., & Lachman, M. E. (2019). Walk to a better night of sleep: testing the relationship between physical activity and sleep. *Sleep Health*, *5*(5), 487–494. https://doi.org/10.1016/j.sleh.2019.06.003

Canto, C. B., Onuki, Y., Bruinsma, B., Van Der Werf, Y. D., & De Zeeuw, C. I. (2017). The sleeping Cerebellum. *Trends in Neurosciences*, *40*(5), 309–323. https://doi.org/10.1016/j.tins.2017.03.001

Chattu, V. K., Manzar, M. D., Kumary, S., Burman, D., Spence, D. W., & Pandi-Perumal, S. R. (2018). The global problem of insufficient sleep and its serious public health implications. *Healthcare*, *7*(1), 1. https://doi.org/10.3390/healthcare7010001

Crivello, A., Barsocchi, P., Girolami, M., & Palumbo, F. (2019). The Meaning of Sleep Quality: A Survey of Available Technologies. *IEEE Access*, *7*, 167374–167390. https://doi.org/10.1109/access.2019.2953835

Dogan, G., Akbulut, F. P., Çatal, Ç., & Mishra, A. (2022). Stress Detection using Experience Sampling: A Systematic Mapping study. *International Journal of Environmental Research and Public Health/International Journal of Environmental Research and Public Health*, *19*(9), 5693. https://doi.org/10.3390/ijerph19095693

Ellison, W. D., Trahan, A. C., Pinzon, J. C., Gillespie, M. E., Simmons, L. M., & King, K. Y. (2020). For whom, and for what, is experience sampling more accurate than retrospective report? *Personality and Individual Differences*, *163*, 110071. https://doi.org/10.1016/j.paid.2020.110071

Etikan, İ., Musa, S. A., & Alkassim, R. S. (2016). Comparison of convenience sampling and purposive sampling. *American Journal of Theoretical and Applied Statistics*, *5*(1), 1. https://doi.org/10.11648/j.ajtas.20160501.11

Green, A., Cohen-Zion, M., Haim, A., & Dagan, Y. (2017). Evening light exposure to computer screens disrupts human sleep, biological rhythms, and attention abilities. *Chronobiology International*, *34*(7), 855–865. https://doi.org/10.1080/07420528.2017.1324878

Fabbri, M., Beracci, A., Martoni, M., Meneo, D., Tonetti, L., & Natale, V. (2021). Measuring Subjective sleep Quality: A review. *International Journal of Environmental Research and Public Health*, *18*(3), 1082. https://doi.org/10.3390/ijerph18031082

Hachenberger, J., Li, Y., & Lemola, S. (2022). Physical activity, sleep and affective wellbeing on the following day: An experience sampling study. *Journal of Sleep Research*, *32*(2). https://doi.org/10.1111/jsr.13723

Harvey, A. G., Stinson, K., Whitaker, K. L., Moskovitz, D., & Virk, H. (2008). The Subjective Meaning of Sleep Quality: A Comparison of Individuals with and without Insomnia. *Sleep*, *31*(3), 383–393. https://doi.org/10.1093/sleep/31.3.383

Hermans, K., Achterhof, R., Myin-Germeys, I., Kasanova, Z., Kirtley, O., & Schneider, M. (2019). Improving ecological validity in research on social cognition. In *Elsevier eBooks* (pp. 249–268). https://doi.org/10.1016/b978-0-12-815315-4.00010-0

Houtveen, J. H., & Oei, N. Y. (2007). Recall bias in reporting medically unexplained symptoms comes from semantic memory. *Journal of Psychosomatic Research*, *62*(3), 277–282. https://doi.org/10.1016/j.jpsychores.2006.11.006

Jiao, Y. L. Z. Z. X. (2021). Relationship between daily physical activity and sleep quality among college students. *Chinese Journal of School Health*, *42*(7), 1047–1051. https://doi.org/10.16835/j.cnki.1000-9817.2021.07.020

Kerkhof, G. (2017). Epidemiology of sleep and sleep disorders in The Netherlands. *Sleep Medicine*, *30*, 229–239. https://doi.org/10.1016/j.sleep.2016.09.015

Kline, C. (2013). Sleep quality. In *Springer eBooks* (pp. 1811–1813). https://doi.org/10.1007/978-1-4419-1005-9_849

Kredlow, M. A., Capozzoli, M. C., Hearon, B. A., Calkins, A. W., & Otto, M. W. (2015). The effects of physical activity on sleep: a meta-analytic review. *Journal of Behavioral Medicine*, *38*(3), 427–449. https://doi.org/10.1007/s10865-015-9617-6

Krystal, A. D., & Edinger, J. D. (2008). Measuring sleep quality. *Sleep Medicine*, *9*, S10–S17. https://doi.org/10.1016/s1389-9457(08)70011-x

Larson, R., & Csikszentmihalyi, M. (1983). The Experience Sampling Method. *New Directions for Methodology of Social & Behavioral Science, 15,* 41–56.

Lastella, M., Rigney, G., Browne, M., & Sargent, C. (2020). Electronic device use in bed reduces sleep duration and quality in adults. *Sleep and Biological Rhythms*, *18*(2), 121–129. https://doi.org/10.1007/s41105-019-00251-y

Martínez-de-Quel, Ó., Suárez-Iglesias, D., López-Flores, M., & Pérez, C. A. (2021). Physical activity, dietary habits and sleep quality before and during COVID-19 lockdown: A longitudinal study. *Appetite*, *158*, 105019. https://doi.org/10.1016/j.appet.2020.105019

Matricciani, L., Olds, T., Blunden, S., Rigney, G., & Williams, M. (2012). Never Enough sleep: A Brief History of sleep recommendations for children. *Pediatrics*, *129*(3), 548–556. https://doi.org/10.1542/peds.2011-2039

McGowan, A. L., Boyd, Z. M., Kang, Y., Bennett, L., Mucha, P. J., Ochsner, K. N., Bassett, D. S., Falk, E. B., & Lydon-Staley, D. M. (2022). Within-Person Temporal Associations among Self-Reported Physical Activity, Sleep, and Well-Being in College students. *Psychosomatic Medicine*, *85*(2), 141–153. https://doi.org/10.1097/psy.0000000000001159

Mead, M. P., Baron, K., Sorby, M., & Irish, L. A. (2019). Daily associations between sleep and physical activity. *International Journal of Behavioral Medicine*, *26*(5), 562–568. https://doi.org/10.1007/s12529-019-09810-6

Moyers, S. A., & Hagger, M. S. (2023). Physical activity and cortisol regulation: A meta-analysis. *Biological Psychology*, *179*, 108548. https://doi.org/10.1016/j.biopsycho.2023.108548

Myin-Germeys, I., & Kuppens, P. (2021). *The Open Handbook of Experience Sampling Methodology: A Step-by-step Guide to Designing, Conducting, and Analyzing ESM Studies*.

Myin-Germeys, I., & Kuppens, P. (Eds.). (2022) *The open handbook of experience sampling methodology: A step-by-step guide to designing, conducting, and analyzing ESM studies* (2nd ed.). Leuven: Center for Research on Experience Sampling and Ambulatory Methods Leuven.

O'Brien, S. T., Dozo, N., Hinton, J. D. X., Moeck, E., Susanto, R., Jayaputera, G., Sinnott, R. O., Vu, D., Álvarez-Jiménez, M., Gleeson, J., & Koval, P. (2023). SEMA3: A Free Smartphone Platform for Daily Life Surveys. *PsxArXiv*. https://doi.org/10.31234/osf.io/cnar8

Owens, J., & Weiss, M. (2017). Insufficient sleep in adolescents: causes and consequences. *Minerva Pediatrics*, *69*(4). https://doi.org/10.23736/s0026-4946.17.04914-3

Patel, M. S., Foschini, L., Kurtzman, G. W., Zhu, J., Wang, W., Rareshide, C. a. L., & Zbikowski, S. M. (2017). Using wearable devices and smartphones to track physical activity: initial activation, sustained use, and step counts across sociodemographic characteristics in a national sample. *Annals of Internal Medicine*, *167*(10), 755. https://doi.org/10.7326/m17-1495

Pesonen, A., Kahn, M., Kuula, L., Korhonen, T., Leinonen, L., Martinmäki, K., Gradisar, M., & Lipsanen, J. (2022). Sleep and physical activity – the dynamics of bi-directional influences over a fortnight. *BMC Public Health*, *22*(1). https://doi.org/10.1186/s12889-022-13586-y

Pieters, L. E., Deenik, J., De Vet, S., Delespaul, P., & Van Harten, P. N. (2023). Combining actigraphy and experience sampling to assess physical activity and sleep in patients with psychosis: A feasibility study. *Frontiers in Psychiatry*, *14*. https://doi.org/10.3389/fpsyt.2023.1107812

Rundo, J. V., & Downey, R. (2019). Polysomnography. In *Handbook of clinical neurology* (pp. 381–392). https://doi.org/10.1016/b978-0-444-64032-1.00025-4

Schulz, H. (2022). The history of sleep research and sleep medicine in Europe. *Journal of Sleep Research*, *31*(4). https://doi.org/10.1111/jsr.13602

Schulz, H., & Salzarulo, P. (2016). The Development of Sleep Medicine: A historical sketch. *Journal of Clinical Sleep Medicine*, *12*(07), 1041–1052. https://doi.org/10.5664/jcsm.5946

Semplonius, T., & Willoughby, T. (2018). Long-Term Links between Physical Activity and Sleep Quality. *Medicine and Science in Sports and Exercise*, *50*(12), 2418–2424. https://doi.org/10.1249/mss.0000000000001706

Torgerson, D., Tremblay, A., Genin, P., Panahi, S., Rivière, D., & Duclos, M. (2018). Physical Activity, Inactivity, and Sedentary Behaviors: Definitions and Implications in Occupational Health. *Frontiers in Public Health*, *6*. https://doi.org/10.3389/fpubh.2018.00288

Van Berkel, N., Ferreira, D., & Kostakos, V. (2017). The experience sampling method on mobile devices. *ACM Computing Surveys*, *50*(6), 1–40. https://doi.org/10.1145/3123988

Van Dalen, M., Snijders, A. C., Dietvorst, E., Bracké, K., Nijhof, S. L., Keijsers, L., Hillegers, M. H. J., & Legerstee, J. S. (2023). Applications of the experience sampling method (ESM) in paediatric healthcare: a systematic review. *Pediatric Research*, *95*(4), 887–900. https://doi.org/10.1038/s41390-023-02918-2

Wang, F., & Boros, S. (2019). The effect of physical activity on sleep quality: a systematic review. *European Journal of Physiotherapy*, *23*(1), 11–18. https://doi.org/10.1080/21679169.2019.1623314

Wang, L., Wu, Y., Lin, Y., Wang, L., Zeng, Z., Xie, X. S., Chen, Q., & Wei, S. (2022). Reliability and validity of the Pittsburgh Sleep Quality Index among frontline COVID-19 health care workers using classical test theory and item response theory. *Journal of Clinical Sleep Medicine*, *18*(2), 541–551. https://doi.org/10.5664/jcsm.9658

Xie, Z., Chen, F., Li, W. A., Geng, X., Li, C., Meng, X., Feng, Y., Liu, W., & Yu, F. (2017). A review of sleep disorders and melatonin. *Neurological Research*, *39*(6), 559–565. https://doi.org/10.1080/01616412.2017.1315864

Appendix A

Invitation information and informed consent

General information about the study: As sleep is very important for everyone to function in daily life, you might be interested in getting more insight into what factors can influence your sleep. In this study we will specifically focus on how caffeine intake and physical activity are related to sleep.

Inclusion criteria

In order to prevent having to exclude people from the study after they have participated, we kindly ask you to only continue with the study if you...

...are 18 years or older

...have a proficient understanding of English

...drink at least one of the following stimulants at least once a week: coffee, tea, soda* or energy drinks.

...engage in physical activity** at least 3 times a week

Do you fit with these criteria (please answer below)?

* Soda includes: coca cola, fanta, sprite, 7-up, bitter lemon, ginger ale, ice tea, tonic or root beer.

**Physical activity includes: participating in activities and/or sports, which increase your heart rate, for at least 3 times a week (such as biking to the store, going for a walk at a moderate/fast pace or engaging in weekly sports trainings).

The data gathered in this study will be anonymous and deleted after completion of this thesis. Only the researchers and their supervisor will have access to your answers.

You are asked to participate for 2 weeks (14 days) by using the app 'Sema3'. Via this app we kindly ask you to fill in the demographics survey within 2 days after the start of the survey. Furthermore, for the next two weeks, you will receive a morning survey about how you slept the past night, followed by a few short survey questions at 3 fixed moments of each day.

Be aware that you can withdraw from the study at any time.

For questions, please contact: i.d.bouwer@student.utwente.nl OR j.i.piconrattel@student.utwente.nl.

Please answer below: I agree with the terms and give consent to participate in this study.

We thank you for participating. Make sure to allow the app to send you notifications when installing the app on your phone. Or check if notifications are allowed, by turning on the notifications of the app. This in order to have less possibilities of missing surveys at certain time slots. If you are not sure how to put on the notifications of an app, please refer to How to Enable and Disable Push Notifications on Android - Make Tech Easier for Android and to Use notifications on your iPhone or iPad – Apple Support (UK) for iOS.

Appendix B

Surveys in SEMA3

1. Demographic questions

What is your age? (range from 18-70)

What do you identify as?

- Male
- Female
- Other

What is your occupation?

- Employed
- Unemployed
- Student
- Other

If you selected 'employed' in the previous question, please specify in which sector you work. If not selected, leave an 'x' or another small icon to continue.

What is your nationality? (Open question)

2. Baseline assessment

How long did it usually take you to fall asleep during the past week?

- 0-15 minutes
- 16-30 minutes
- 31-45 minutes
- 46-60 minutes
- More than 60 minutes

On average, how many hours did you sleep each night during the past week?

- 3 to 4 hours
- 5 to 6 hours

- 7 to 8 hours
- 9 to 10 hours
- More than 10 hours

How would you, on average, rate the quality of your sleep over the past week? (range from 0 to 10)

How many cups of coffee do you normally drink during one day? (range from 0 to 10)

How many cups of tea do you normally drink during one day? (range from 0 to 10)

How many glasses of soda do you normally drink during one day? (range from 0 to 10)

How many cans of energy drink do you normally drink during one day? (range from 0 to 10)

How many times do you exercise every week on average? (range from 3 to 10)

What type of physical activity do you usually perform? Please specify (Open question)

3. Daily sleep survey

How many hours did you sleep last night? (Open question)

On a scale from 0-10, how would you rate your sleep? (Range from 0 to 10)

How would you rate your energy level right now? (Range from 0 to 10)

4. Daily morning survey (AM survey)

How do you feel right now? From “very tired” (0) to “full of energy” (10)

How many cups of coffee have you had since you woke up? (Range from 0 to 10)

How many cups of tea have you had since you woke up? (Range from 0 to 10)

How many glasses of soda have you had since you woke up? (Range from 0 to 10)

How many cans of energy drink have you had since you woke up? (Range from 0 to 10)

How much have you moved since you woke up (in minutes)? (Open question)

Could you specify the activity? (Open question)

Where did you practise that activity?

- Indoors
- Outdoors

5. Daily afternoon and evening survey (PM survey)

How do you feel right now? From “very tired” (0) to “full of energy” (10)

How many cups of coffee have you had since the last survey? (Range from 0 to 10)

How many cups of tea have you had since the last survey? (Range from 0 to 10)

How many glasses of soda have you had since the last survey? (Range from 0 to 10)

How many cans of energy drink have you had since the last survey? (Range from 0 to 10)

How much have you moved since the last survey (in minutes)? (Open question)

Could you specify the activity? (Open question)

Where did you practise that activity?

- Indoors
- Outdoors

Appendix C

R Code for data analysis

```
setwd("C:/2024_SEMA3_sleep")

install.packages("readr")
install.packages("dplyr")
install.packages("tidyr")
install.packages("ggplot2")
install.packages("scales")
install.packages("nlme")
install.packages("lme4")
install.packages("performance")
install.packages("psych")
library(readr)
library(dplyr)
library(tidyr)
library(ggplot2)
library(scales)
library(nlme)
library(lme4)
library(performance)
library(psych)

# Download the data from the the different surveys as separate .csv files from SEMA3

# Define a list of the PARTICIPANT_ID values you want to keep, for instance based on compliance rate
of >33% in SEMA3
selected_ids <- c("s027726465", "s077062546", "s143806477", "s159381842",
          "s230084949", "s244004245", "s283444806", "s330222955", "s392553353",
          "s595575588", "s662830324", "s683002070", "s694160992", "s728977899",
          "s762447320", "s775955172", "s822401278", "s828965218", "s870035860",
          "s963624552", "s993509399")
```

```
# Load the separate surveys from SEMA3 in R

# Informed consent survey

# Read data from CSV file
ic <- read_delim("informed_consent.csv",
         col_types = cols(
          CREATED_TS = col_datetime(format = "%d-%b-%Y %H:%M"),
          SCHEDULED_TS = col_datetime(format = "%d-%b-%Y %H:%M"),
          STARTED_TS = col_datetime(format = "%d-%b-%Y %H:%M"),
          COMPLETED_TS = col_datetime(format = "%d-%b-%Y %H:%M"),
          EXPIRED_TS = col_datetime(format = "%d-%b-%Y %H:%M"),
          UPLOADED_TS = col_datetime(format = "%d-%b-%Y %H:%M"),
          TOTAL_RT = col_double(),
          RAND_PROB = col_integer(),
          GEN.INFO = col_integer(),
          GEN.INFO_RT = col_double(),
          INCL.CRIT = col_integer(),
          INCL.CRIT_RT = col_double(),
          INF.CONS = col_integer(),
          INF.CONS_RT = col_double()
         )) %>%
 # Sort by participant ID and scheduling
 arrange(PARTICIPANT_ID, SCHEDULED_TS) %>%
 # Group by participant ID and keep only the first entry for each
 group_by(PARTICIPANT_ID) %>%
 slice(1) %>%
 # Rename columns except for PARTICIPANT_ID
 rename_with(~ paste0("ic_", .x), .cols = -c(PARTICIPANT_ID))

#  Filter the dataframe to keep only the cases with the defined PARTICIPANT_ID values
ic_filtered <- ic %>%
 filter(PARTICIPANT_ID %in% selected_ids)
```

```
# Define the relevant column names you want to keep
relevant_columns <- c("PARTICIPANT_ID", "ic_STUDY_ID", "ic_SURVEY_ID",
                "ic_COMPLETED_TS", "ic_GEN.INFO", "ic_INCL.CRIT", "ic_INF.CONS")
# Select only the relevant columns
ic_filtered <- select(ic_filtered, relevant_columns)

# Baseline survey

# Read data from CSV file
bl <- read_delim("baseline_questions.csv",
          col_types = cols(CREATED_TS = col_datetime(format = "%d-%b-%Y %H:%M"),
                   SCHEDULED_TS = col_datetime(format = "%d-%b-%Y %H:%M"),
                   STARTED_TS = col_datetime(format = "%d-%b-%Y %H:%M"),
                   COMPLETED_TS = col_datetime(format = "%d-%b-%Y %H:%M"),
                   EXPIRED_TS = col_datetime(format = "%d-%b-%Y %H:%M"),
                   UPLOADED_TS = col_datetime(format = "%d-%b-%Y %H:%M"),
                   TOTAL_RT = col_double(),
                   RAND_PROB = col_integer(),
                   AGE = col_double(),
                   AGE_RT = col_double(),
                   ID = col_integer(),
                   ID_RT = col_double(),
                   JOB_0 = col_integer(),
                   JOB_1 = col_integer(),
                   JOB_2 = col_integer(),
                   JOB_3 = col_integer(),
                   JOB_RT = col_double(),
                   JOB_1 = col_integer(),
                   SECTOR = col_character(),
                   NAT. = col_character(),
                   SLP.WK = col_integer(),
                   SL.HOURS = col_double(),
                   SL.HOURS_RT = col_double(),
```

```
                    SL.QLTY = col_double(),
                    SL.QLTY_RT = col_double(),
                    DAY_COF = col_double(),
                    DAY_COF_RT = col_double(),
                    DAY_TEA = col_double(),
                    DAY_TEA_RT = col_double(),
                    DAY_SODA = col_double(),
                    DAY_SODA_RT = col_double(),
                    DAY.ENDR = col_double(),
                    DAY.ENDR = col_double(),
                    WKLY_EXRSE = col_double(),
                    WKLY_EXRSE_RT = col_double(),
                    SPRT_ACTVTY = col_double(),
                    SPRT_ACTVTY_RT = col_double(),
                    ))

# Set <no-response> to NA for all character columns
bl <- bl %>%
  mutate(across(where(is.character), ~ifelse(. == "<no-response>", NA, .))) %>%
  arrange(PARTICIPANT_ID, COMPLETED_TS) %>%
  group_by(PARTICIPANT_ID) %>%
  slice(1) %>%
  rename_with(~ paste0("bl_", .x), .cols = -c(PARTICIPANT_ID))

# Filter the dataframe to keep only the cases with the defined PARTICIPANT_ID values
bl_filtered <- bl %>%
  filter(PARTICIPANT_ID %in% selected_ids)

# Define the relevant column names you want to keep
relevant_columns <- c("PARTICIPANT_ID", "bl_COMPLETED_TS", "bl_AGE", "bl_ID",
              "bl_JOB_0", "bl_JOB_1", "bl_JOB_2", "bl_JOB_3", "bl_SECTOR",
              "bl_NAT.", "bl_SLP.WK", "bl_SL.HOURS", "bl_SL.QLITY",
              "bl_WKLY_EXRSE", "bl_SPRT/ACTVTY")
# Select only the relevant columns
```

```
bl_filtered <- select(bl_filtered, relevant_columns)

# Sleep survey

sleep <- read_csv("sleep_survey.csv",
        col_types = cols(CREATED_TS = col_datetime(format = "%d-%b-%Y %H:%M"),
                SCHEDULED_TS = col_datetime(format = "%d-%b-%Y %H:%M"),
                STARTED_TS = col_datetime(format = "%d-%b-%Y %H:%M"),
                COMPLETED_TS = col_datetime(format = "%d-%b-%Y %H:%M"),
                EXPIRED_TS = col_datetime(format = "%d-%b-%Y %H:%M"),
                UPLOADED_TS = col_datetime(format = "%d-%b-%Y %H:%M"),
                TOTAL_RT = col_double(),
                RAND_PROB = col_integer(),
                SL.HRS.NIGHT = col_double(),
                SL.HRS.NIGHT_RT = col_double(),
                QLTY = col_double(),
                QLTY_RT = col_double(),
                ENRGYLVL = col_double(),
                ENRGYLVL_RT = col_double()
                ))%>%
#Sort by participant ID and scheduling
arrange(PARTICIPANT_ID, SCHEDULED_TS)

# Set <no-response> to NA for all character columns
char_cols <- sapply(sleep, is.character)
sleep <- sleep %>%
  mutate_if(char_cols, ~ifelse(. == "<no-response>", NA, .))%>%
  rename_with(~ paste0("sleep_", .x), .cols = -c(PARTICIPANT_ID))

#  Filter the dataframe to keep only the cases with the defined PARTICIPANT_ID values
sleep_filtered <- sleep %>%
  filter(PARTICIPANT_ID %in% selected_ids)

# Define the relevant column names you want to keep
```

```
relevant_columns <- c("PARTICIPANT_ID", "sleep_CREATED_TS", "sleep_SCHEDULED_TS",
                "sleep_STARTED_TS", "sleep_COMPLETED_TS", "sleep_SL.HRS.NIGHT",
                "sleep_QLTY", "sleep_ENRGYLVL")
# Select only the relevant columns
sleep_filtered <- select(sleep_filtered, relevant_columns)

# Count unique PARTICIPANT_IDs in the dataframe
unique_participants <- n_distinct(sleep_filtered$PARTICIPANT_ID)

# Physical activity (AM survey)

am <- read_delim("am_questions.csv",
           col_types = cols(CREATED_TS = col_datetime(format = "%d-%b-%Y %H:%M"),
                     SCHEDULED_TS = col_datetime(format = "%d-%b-%Y %H:%M"),
                     STARTED_TS = col_datetime(format = "%d-%b-%Y %H:%M"),
                     COMPLETED_TS = col_datetime(format = "%d-%b-%Y %H:%M"),
                     EXPIRED_TS = col_datetime(format = "%d-%b-%Y %H:%M"),
                     UPLOADED_TS = col_datetime(format = "%d-%b-%Y %H:%M"),
                     TOTAL_RT = col_double(),
                     RAND_PROB = col_integer(),
                     SLEEPINESS = col_double(),
                     SLEEPINESS_RT = col_double(),
                     COFFEE_1 = col_double(),
                     COFFEE_1_RT = col_double(),
                     TEA_1 = col_double(),
                     TEA_1_RT = col_double(),
                     SODA_1 = col_double(),
                     SODA_1_RT = col_double(),
                     ENERGY_DRINK_1 = col_double(),
                     ENERGY_DRINK_1_RT = col_double(),
                     MVNT_MIN.1 = col_double(),
                     MVNT_MIN.1_RT = col_double(),
                     SP.ACT.1_RT = col_double(),
                     PLACE.1 = col_integer(),
```

```
                    PLACE.1_RT = col_double()
                    ))%>%
  #Sort by participant ID and scheduling
  arrange(PARTICIPANT_ID, SCHEDULED_TS)

  # Remove redundant (old?) columns
  am <- am %>%
   select(1:which(colnames(am) == "PLACE.1_RT"))

  # Set <no-response> to NA for all character columns
  char_cols <- sapply(am, is.character)
  am <- am %>%
   mutate_if(char_cols, ~ifelse(. == "<no-response>", NA, .))%>%
   rename_with(~ paste0("am_", .x), .cols = -c(PARTICIPANT_ID))


#  Filter the dataframe to keep only the cases with the defined PARTICIPANT_ID values
am_filtered <- am %>%
  filter(PARTICIPANT_ID %in% selected_ids)

# Define the relevant column names you want to keep
relevant_columns <- c("PARTICIPANT_ID", "am_CREATED_TS", "am_SCHEDULED_TS",
             "am_STARTED_TS", "am_COMPLETED_TS", "am_SLEEPINESS", "am_MVNT_MIN.1",
"am_SP.ACT.1",
             "am_PLACE.1")

# Select only the relevant columns
am_filtered <- select(am_filtered, relevant_columns)

# Physical activity (PM surveys)
# This data set contains both the afternoon and evening survey!!!

pm <- read_delim("pm_questions.csv",
             col_types = cols(CREATED_TS = col_datetime(format = "%d-%b-%Y %H:%M"),
```

```
                    SCHEDULED_TS = col_datetime(format = "%d-%b-%Y %H:%M"),
                    STARTED_TS = col_datetime(format = "%d-%b-%Y %H:%M"),
                    COMPLETED_TS = col_datetime(format = "%d-%b-%Y %H:%M"),
                    EXPIRED_TS = col_datetime(format = "%d-%b-%Y %H:%M"),
                    UPLOADED_TS = col_datetime(format = "%d-%b-%Y %H:%M"),
                    TOTAL_RT = col_double(),
                    RAND_PROB = col_integer(),
                    FEEL.PM = col_double(),
                    FEEL.PM_RT = col_double(),
                    COF.PM = col_double(),
                    COF.PM_RT = col_double(),
                    TEA.PM = col_double(),
                    TEA.PM_RT = col_double(),
                    SODA.PM = col_double(),
                    SODA.PM_RT = col_double(),
                    EN.DR.PM = col_double(),
                    EN.DR.PM_RT = col_double(),
                    PM_MVMT = col_double(),
                    PM_MVMT_RT = col_double(),
                    COF.PM = col_double(),
                    COF.PM_RT = col_double(),
                    SP_PM_ACTVTY = col_character(),
                    SP_PM_ACTVTY_RT = col_double(),
                    PLACE_PM = col_integer(),
                    PLACE_PM_RT = col_double(),
                    ))%>%
# Sort by participant ID and scheduling
  arrange(PARTICIPANT_ID, SCHEDULED_TS)

# Set <no-response> to NA for all character columns
char_cols <- sapply(pm, is.character)
pm <- pm %>%
  mutate_if(char_cols, ~ifelse(. == "<no-response>", NA, .))%>%
  rename_with(~ paste0("pm_", .x), .cols = -c(PARTICIPANT_ID))
```

```
#  Filter the dataframe to keep only the cases with the defined PARTICIPANT_ID values
pm_filtered <- pm %>%
  filter(PARTICIPANT_ID %in% selected_ids)

# Define the relevant column names you want to keep
relevant_columns <- c("PARTICIPANT_ID", "pm_CREATED_TS", "pm_SCHEDULED_TS",
                      "pm_STARTED_TS", "pm_COMPLETED_TS", "pm_FEEL.PM",
                      "pm_PM_MVMT", "pm_SP_PM_ACTVTY", "pm_PLACE_PM")

# Select only the relevant columns
pm_filtered <- select(pm_filtered, relevant_columns)

# Reshape the `pm_filtered` data frame into wide format, so that the evening questions are listed
after the morning questions
# Evening questions will be denoted with an additional 2 to the variable names

# Convert pm_CREATED_TS to a POSIXct object if it is not already
pm_filtered <- pm_filtered %>%
  mutate(pm_CREATED_TS = as.POSIXct(pm_CREATED_TS, format = "%Y-%m-%d %H:%M:%S"))

# Extract the date part and create a column to distinguish between afternoon and evening
measurements
pm_filtered <- pm_filtered %>%
  mutate(
    Date = as.Date(pm_CREATED_TS),
    TimeOfDay = ifelse(format(pm_CREATED_TS, "%H") < 18, "Afternoon", "Evening")
  )

# Split the data into afternoon and evening measurements
afternoon_data <- pm_filtered %>%
  filter(TimeOfDay == "Afternoon") %>%
  select(-TimeOfDay)

evening_data <- pm_filtered %>%
```

```
  filter(TimeOfDay == "Evening") %>%
  select(-TimeOfDay)

# Rename the columns in afternoon and evening data to distinguish them
afternoon_data <- afternoon_data %>%
  rename_with(~ paste0(.x, "_Afternoon"), -c(PARTICIPANT_ID, Date))

evening_data <- evening_data %>%
  rename_with(~ paste0(.x, "_Evening"), -c(PARTICIPANT_ID, Date))

# Join the afternoon and evening data on PARTICIPANT_ID and Date
pm_wide <- left_join(afternoon_data, evening_data, by = c("PARTICIPANT_ID", "Date"))

# Joining the am and pm dataframes.
am_filtered <- am_filtered %>%
  mutate(am_CREATED_TS = as.POSIXct(am_CREATED_TS, format = "%Y-%m-%d %H:%M:%S"))

pm_wide <- pm_wide %>%
  mutate(pm_CREATED_TS_Afternoon = as.POSIXct(pm_CREATED_TS_Afternoon, format =
"%Y-%m-%d %H:%M:%S"))

# Extract the date part from the timestamps
am_filtered <- am_filtered %>%
  mutate(Date = as.Date(am_CREATED_TS))

pm_wide <- pm_wide %>%
  mutate(Date = as.Date(pm_CREATED_TS_Afternoon))

# Join the dataframes on PARTICIPANT_ID and Date
combined_df <- left_join(am_filtered, pm_wide, by = c("PARTICIPANT_ID", "Date"))

# Now join this combined_df dataframe with the sleep_filtered survey.
sleep_filtered <- sleep_filtered %>%
  mutate(sleep_CREATED_TS = as.POSIXct(sleep_CREATED_TS, format = "%Y-%m-%d %H:%M:%S"))
```

```
# Extract the date part from the sleep_CREATED_TS timestamp
sleep_filtered <- sleep_filtered %>%
  mutate(Date = as.Date(sleep_CREATED_TS))

# Join the combined_df with sleep_filtered on PARTICIPANT_ID and Date
final_df <- left_join(combined_df, sleep_filtered, by = c("PARTICIPANT_ID", "Date"))

# Now join this final_df dataframe with the bl_filtered survey.
# Join combined_df with bl_filtered on PARTICIPANT_ID
final_df <- left_join(final_df, bl_filtered, by = "PARTICIPANT_ID")

# Move the columns from bl_filtered to the front of the final_df dataframe
bl_columns <- names(bl_filtered)
other_columns <- setdiff(names(final_df), bl_columns)
final_df <- final_df[, c(bl_columns, other_columns)]

# Make a new variable for the day number within each participant, both a numerical (Day) and a
factor variable (fDay)

final_df <- final_df %>%
  group_by(PARTICIPANT_ID) %>%
  arrange(PARTICIPANT_ID, Date) %>%  # Ensure data is sorted by PARTICIPANT_ID and Date
  mutate(Day = row_number()) %>%     # Create the numerical Day variable
  ungroup() %>%
  mutate(fDay = as.factor(Day))      # Create the factor fDay variable

# Move PARTICIPANT_ID, Day, and fDay to the front
final_df <- final_df %>%
  select(PARTICIPANT_ID, Day, fDay, everything())

# Remove all rows from the dataframe with values on Day >14.
# Remove rows where Day > 14
final_df <- final_df %>%
  filter(Day <= 14)
```

```
# Frequency table for Day using dplyr
day_freq_table <- final_df %>%
  count(Day) %>%
  arrange(Day)

# ANALYSES
# Total amount of physical activity per day
# Add the total_movement variable, accounting for missing values
final_df <- final_df %>%
  mutate(total_movement = rowSums(across(c(am_MVNT_MIN.1, pm_PM_MVMT_Afternoon,
pm_PM_MVMT_Evening)), na.rm = TRUE))

# Plot the average amount of physical activity, sleep quantity and sleep quality per day
# Calculate the average total_movement for each Day
average_movement <- final_df %>%
  group_by(Day) %>%
  summarize(avg_total_movement = mean(total_movement, na.rm = TRUE))

average_sleep <- sleep_filtered %>%
  group_by(Date) %>%
  summarize(sleep_SL.HRS.NIGHT = mean(sleep_SL.HRS.NIGHT, na.rm = TRUE))

average_sleep_quality <- sleep_filtered %>%
  group_by(Date) %>%
  summarize(sleep_QLTY = mean(sleep_QLTY, na.rm = TRUE))

# Plot the average total_movement over Days with labels for each Day
ggplot(average_movement, aes(x = Day, y = avg_total_movement)) +
  geom_line() +
  geom_point() +
  labs(title = "Average Total Movement Over Days",
       x = "Day",
       y = "Average Total Movement") +
  scale_x_continuous(breaks = average_movement$Day) + # Ensure each Day value is labeled
```

```
  theme_minimal()

# Sleep quantity and sleep quality together with total movement in two figures
# Calculate the average total_movement and sleep_SL.HRS.NIGHT for each Day
average_values <- final_df %>%
  group_by(Day) %>%
  summarize(average_movement = mean(total_movement, na.rm = TRUE),
    avg_sleep_hours = mean(sleep_SL.HRS.NIGHT, na.rm = TRUE))

average_values_final <- final_df %>%
  group_by(Day) %>%
  summarize(average_movement = mean(total_movement_hours, na.rm = TRUE),
           average_sleep_quality = mean(sleep_QLTY, na.rm = TRUE))

# Reshape the dataframe to long format for plotting
average_values_long <- average_values %>%
  pivot_longer(cols = c(average_movement, avg_sleep_hours),
             names_to = "variable",
             values_to = "value")

average_values_long_final <- average_values_final %>%
  pivot_longer(cols = c(average_movement, average_sleep_quality),
             names_to = "variable",
             values_to = "value")
# Plot the values with the correct labels for Total Coffee and Sleep Hours
ggplot(average_values_long, aes(x = Day, y = value, color = variable)) +
  geom_line() +
  geom_point() +
  labs(title = "Average Total Movement and Sleep Hours Over Days",
      x = "Day",
      y = "Average Value") +
  scale_x_continuous(breaks = average_values$Day) + # Ensure each Day value is labeled
  theme_minimal() +
  scale_color_manual(values = c("average_movement" = "blue", "avg_sleep_hours" = "red"),
```

```
              labels = c("Total Movement" = "blue", "Sleep Hours" = "red")) +
  theme(legend.title = element_blank())

ggplot(average_values_long_final, aes(x = Day, y = value, color = variable)) +
  geom_line() +
  geom_point() +
  labs(title = "Average Total Movement and Sleep Quality Over Days",
     x = "Day",
     y = "Average Value") +
  scale_x_continuous(breaks = average_values$Day) + # Ensure each Day value is labeled
  theme_minimal() +
  scale_color_manual(values = c("average_movement" = "blue", "average_sleep_quality" = "red"),
              labels = c("Total Movement" = "blue", "Sleep Quality" = "red")) +
  theme(legend.title = element_blank())

#Convert minutes into hours of movement
average_movement <- average_movement %>%
  mutate(movement_in_hours = avg_total_movement / 60)

#Run similar graphs but with the movement in hours

ggplot(average_movement, aes(x = Day, y = movement_in_hours)) +
  geom_line() +
  geom_point() +
  labs(title = "Average Total Movement Over Days",
     x = "Day",
     y = "Average Total Movement") +
  scale_x_continuous(breaks = average_movement$Day) + # Ensure each Day value is labeled
  theme_minimal()

average_values_final <- final_df %>%
  group_by(Day) %>%
  summarise(average_movement = mean(total_movement, na.rm = TRUE),
         avg_sleep_hours = mean(sleep_SL.HRS.NIGHT, na.rm = TRUE))
```

```
average_values_final <- average_values_final %>%
  mutate(movement_in_hours = average_movement / 60)
average_values_final <- average_values_final %>%
  select(-average_movement)

average_values_final_long <- average_values_final %>%
  pivot_longer(cols = c(movement_in_hours, avg_sleep_hours),
               names_to = "variable",
               values_to = "value")
View(average_values_final_long)

ggplot(average_values_final_long, aes(x = Day, y = value, color = variable)) +
  geom_line() +
  geom_point() +
  labs(title = "Average Total Movement and Sleep Hours Over Days",
       x = "Day",
       y = "Average Value") +
  scale_x_continuous(breaks = average_values$Day) + # Ensure each Day value is labeled
  theme_minimal() +
  scale_color_manual(values = c("movement_in_hours" = "blue", "avg_sleep_hours" = "red"),
                     labels = c("Total Movement in Hours" = "blue", "Sleep Hours" = "red")) +
  theme(legend.title = element_blank())

# Run a lMM to statistically the association between number of hours sleep and total_movement the
next day
model_sleep_movement <- lme(total_movement ~  1 + sleep_SL.HRS.NIGHT,
                            data = final_df,
                            random = ~ 1 | PARTICIPANT_ID, # random intercept only
                            method = "REML",
                            na.action = na.exclude,
                            )
summary(model_sleep_movement)
icc(model_sleep_movement)
```

```
final_df <- final_df %>%
  mutate(total_movement_hours = total_movement / 60)

model_sleep_movement_final <- lme(total_movement_hours ~  1 + sleep_SL.HRS.NIGHT,
                    data = final_df,
                    random = ~ 1 | PARTICIPANT_ID, # random intercept only
                    method = "REML",
                    na.action = na.exclude,)
summary(model_sleep_movement_final)
icc(model_sleep_movement_final)

model_sleep_quality_movement_final <- lme(total_movement_hours ~  1 + sleep_QLTY,
                        data = final_df,
                        random = ~ 1 | PARTICIPANT_ID, # random intercept only
                        method = "REML",
                        na.action = na.exclude,)
summary(model_sleep_quality_movement_final)
icc(model_sleep_quality_movement_final)


# To test how amount of movement is related to number of hours sleep the next night
# Create the lagged variable for total_movement within each PARTICIPANT_ID
final_df <- final_df %>%
  group_by(PARTICIPANT_ID) %>%
  arrange(PARTICIPANT_ID, Day) %>%
  mutate(lagged_total_movement = lag(total_movement)) %>%
  ungroup()

final_df <- final_df %>%
  group_by(PARTICIPANT_ID) %>%
  arrange(PARTICIPANT_ID, Day) %>%
  mutate(lagged_total_movement_hours = lag(total_movement_hours)) %>%
  ungroup()
```

```
# Fit the mixed-effects model with the lagged total_movement variable
lagged_model_sleep_quality_movement_hours <- lme(sleep_QLTY ~ 1 +
lagged_total_movement_hours,
                    data = final_df,
                    random = ~ 1 | PARTICIPANT_ID, # random intercept only
                    method = "REML",
                    na.action = na.exclude,
                    )
summary(lagged_model_sleep_quality_movement_hours)
icc(lagged_model_sleep_quality_movement_hours)

lagged_model_sleep_movement <- lme(sleep_SL.HRS.NIGHT ~ 1 + lagged_total_movement,
                     data = final_df,
                     random = ~ 1 | PARTICIPANT_ID, # random intercept only
                     method = "REML",
                     na.action = na.exclude,
)
summary(lagged_model_sleep_movement)


# Model predicting daily sleep from baseline sleep
model_sleep_blsleep <- lme(sleep_SL.HRS.NIGHT ~ 1 + bl_SL.HOURS,
                    data = final_df,
                    random = ~ 1 | PARTICIPANT_ID, # random intercept only
                    method = "REML",
                    na.action = na.exclude,
                 )
summary(model_sleep_blsleep)

# Compute the overall mean and standard deviation of a numerical variable like bl_AGE
overall_mean_bl_AGE <- mean(unique_df$bl_AGE, na.rm = TRUE)
overall_sd_bl_AGE <- sd(unique_df$bl_AGE, na.rm = TRUE)

# Display the mean and standard deviation
```

```
cat("Mean of bl_AGE:", overall_mean_bl_AGE, "\n")
cat("Standard Deviation of bl_AGE:", overall_sd_bl_AGE, "\n")

overall_mean_bl_NAT <- mean(unique_df$bl_NAT., na.rm = TRUE)

# Compute the frequency of each bl_NAT response of a categorical variable like bl_ID
freq_bl_ID <- unique_df %>%
  group_by(bl_ID) %>%
  summarize(freq = n()) %>%
  ungroup()
# Compute the total number of responses to calculate the percentage
total_responses <- sum(freq_bl_ID$freq)
# Add the percentage to the dataframe
freq_bl_ID <- freq_bl_ID %>%
  mutate(percentage = (freq / total_responses) * 100)
# Display the frequency and percentage of each bl_NAT response
cat("Frequency and Percentage of bl_NAT responses:\n")
freq_bl_ID %>%
  mutate(percentage = round(percentage, 2)) %>%
  print()
```