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Network Analysis of within-person temporal associations among physical activity, sleep, and wellbeing *in situ*

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Citation Diversity Statement

Recent work in several fields of science has identified a bias in citation practices such that papers from women and other minority scholars are under-cited relative to the number of such papers in the field (1–9). Here we sought to proactively consider choosing references that reflect the diversity of the field in thought, form of contribution, gender, race, ethnicity, and other factors. First, we obtained the predicted gender of the first and last author of each reference by using databases that store the probability of a first name being carried by a woman (5,10). By this measure (and excluding self-citations to the first and last authors of our current paper), our references contain 16.46% woman(first)/woman(last), 17.12% man/woman, 20.3% woman/man, and 43.39% man/man. This method is limited in that a) names, pronouns, and social media profiles used to construct the databases may not, in every case, be indicative of gender identity and b) it cannot account for intersex, non-binary, or transgender people. We look forward to future work that could help us to better understand how to support equitable practices in science.

CRediT authorship contribution statement

Amanda L. McGowan: Conceptualization, Methodology, Software, Validation, Formal Analysis, Resources, Data Curation, Writing—Original Draft, Writing—Review & Editing, Visualization, Project Administration. **Zachary M. Boyd:** Validation, Resources, Writing—Review & Editing. **Yoona Kang:** Investigation, Resources, Data Curation, Writing—Review & Editing, Project Administration. **Logan Bennett:** Writing—Review & Editing. **Peter J. Mucha:** Resources, Writing—Review & Editing, Project Administration, Funding Acquisition. **Kevin N. Ochsner:** Resources, Writing—Review & Editing, Project Administration, Funding Acquisition. **Dani S. Bassett:** Resources, Writing—Review & Editing, Project Administration, Funding Acquisition. **Emily B. Falk:** Resources, Writing—Review & Editing, Project Administration, Funding Acquisition. **David M. Lydon-Staley:** Conceptualization, Methodology, Data Curation, Resources, Writing—Original Draft, Writing—Review & Editing, Supervision, Project Administration, Funding Acquisition.

Abstract

Physical activity, sleep, affect, and purpose in life are part of a system that reflects wellbeing in daily life. A holistic understanding of the naturalistic dynamics of the interactions within this system is key to promoting wellbeing. Using self-reported affect (happy, sad, angry, anxious) and physical activity periods collected twice per day via smartphone-based experience sampling over 28 days as young adult participants (n = 226 young adults; M = 20.2 years, SD = 1.7 years; 75% women) went about their daily lives, we examined the within-day associations between physical activity and affect that form a network of wellness behaviors and outcomes. Adding once per day reports of sleep duration, sleep quality, and purpose in life, we additionally examined day-to-day temporal dynamics among physical activity, sleep, affect, and purpose in life. Multilevel modeling showed that when individuals reported engaging in more than their usual level of physical activity, they reported increased happy and reduced anxious affect at the next prompt. At the daily level, multilevel vector autoregressive models that consider the network of wellness together showed that higher physical activity on a given day predicted an increase of happy affect the next day. In parallel, higher sleep quality on a given night predicted a decrease in negative affective states the next day. We found that purpose in life predicted decreased sad, anxious, and angry affect up to two days later. Collectively, these findings suggest that while the effects of sleep and physical activity on affective states and purpose in life may be shorter term (up to one day), a sense of purpose in life is a critical component of wellbeing that can have slightly longer effects, bleeding into the next few days.

Keywords: network analyses, health behavior, ecological momentary assessment, emotions, physical activity

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Wellbeing refers to optimal psychological functioning and experience (11). Wellbeing consists of an affective component encompassing the experience of happiness and pleasure (12) as well as a eudaimonic component emphasizing experiences of meaning, purpose, and self-actualization (13). Globally, people rate being happy as important (14,15) and cultivating states of wellbeing through positive psychological interventions is policy-relevant and holds the potential to alter population health (11,16–18). Physical activity and sleep have emerged as key modifiable health behaviors that may have both immediate and persistent impacts on wellbeing (19). However, less is known about the temporal associations among affective and eudaimonic components of wellbeing in everyday life. Here, we consider how health behaviors (physical activity and sleep) and wellbeing (positive and negative affect and purpose in life) form a complex dynamic system, reinforcing one another in daily life.

Physical activity, sleep, and affective aspects of wellbeing

Both physical activity and sleep support positive affect and alleviate negative affect. For example, people who endorse experiencing short sleep duration and poor sleep quality also have increased depressive and anxiety symptoms, as well as decreased happiness (20–22). On the other hand, regular physical activity is associated with decreased anxiety, depression, and fatigue in addition to increased happiness (23–29). Such cross-sectional studies provide preliminary evidence that physical activity and sleep play a key role in promoting affective aspects of wellbeing. However, single time point, retrospective studies that largely describe static between-person differences in wellbeing provide only limited evidence for establishing associations between health behaviors and wellbeing (30).

Laboratory studies offer greater evidence for causal effects of physical activity and sleep on affective aspects of wellbeing. There is a robust body of evidence demonstrating the immediate influence of physical activity on affective states in highly controlled laboratory settings (31–34). These studies have generally demonstrated that physical activity alleviates negative affect and enhances positive affect immediately and up to one day following the experimental session (32,34). These studies have also established the effects of sleep on subsequent affective states. Following one night of sleep deprivation in the laboratory, individuals reported increased negative affect and lower positive affect relative to mornings following their habitual sleep schedule (35).

However, it is unclear whether the processes observed in the laboratory generalize to real-world settings (36). *In situ* intensive repeated measures study designs can complement laboratory-based findings, testing the extent to which findings from these highly controlled settings generalize into the real world (37,38). In naturalistic settings, sleep, physical activity, and wellbeing are *dynamic*, fluctuating *within* the same person from one day to the next. A growing body of research has focused on within-person associations between physical activity and affect in everyday life (39). These studies have begun to untangle the bidirectional associations between physical activity and affective states. In these studies, positive affect and increased affective arousal has generally predicted increased physical activity over the next few hours (40–44) whereas negative affect predicted a decrease or no change in subsequent physical activity (41,44–46).

The evidence replicating laboratory findings of increased positive affect and decreased negative affect following physical activity in everyday life, however, are inconsistent. Some experience-sampling studies observed increased positive affect following physical activity

(40,47–49) whereas others found no such association (42,45,50,51). Similar mixed findings have been observed for negative affect, with some studies finding reduced negative affect following physical activity (47,49), others observing no associations (42,45,46,52), and one study demonstrating evidence for no association at the within-person level but a significant negative association at the between-person level (53). During the early months of the COVID-19 pandemic, one experience-sampling study found that on days when people engaged in more physical activity than usual, they reported increased positive affect and decreased negative affect in the evening (54). Experience-sampling studies also allow for an examination of the time-varying effects of physical activity (55,56). Thus, the current evidence for physical activity supporting affective components of wellbeing in naturalistic settings is less clear-cut than laboratory findings and varies based on the timescale examined.

In contrast, the association between sufficient sleep duration (57–59) and adequate sleep quality (57,58,60–62) with elevated next-day positive affect and lower next-day negative affect has been consistently observed in experience-sampling studies. Sleep plays an important role in restoring connectivity between brain systems underlying emotion generation (i.e., limbic system) and emotion regulation (i.e., prefrontal cortex; van der Helm & Walker, 2009). Thus, sleep facilitates neural and cognitive resources to effectively deal with emotional experiences and maintain balance in the face of everyday stressors (59). In general, inadequate sleep leads to a heightened experience of negative affect and a reduction in positive affect (64). In sum, existing evidence suggests physical activity and sleep are associated with affective components of wellbeing.

Physical activity, sleep, and eudaimonic aspects of wellbeing

Yet, wellbeing not only encompasses the extent to which we feel happy and sad, calm or anxious, but also includes the extent to which we judge our lives to be meaningful (65). The benefits of physical activity and sleep may extend from affective to eudaimonic components of wellbeing, and vice versa. For example, people reporting higher levels of self-reported physical activity report a higher sense of purpose in life up to four years later (66) and objectively measured physical activity is associated with higher purpose in life when averaged across three days (67). Furthermore, people who are more likely to practice health-promoting behaviors report a greater sense of purpose in life (68). Cross-sectional evidence suggests physical activity supports attainment of a higher goal of health or giving direction and meaning to life across longer timescales beyond immediate change (66,67,69,70). In older adults, people endorsing a higher level of meaning and purpose in life report better sleep quality (71) and every unit increase in self-reported purpose in life was associated with 16% reduced odds of developing sleep disturbances over four years (72). Indeed, people with high purpose in life had 24% decreased risk of becoming physically inactive and 33% reduced risk of developing sleep problems across an eight-year follow-up period in a prospective US national sample of adults (73).

A growing body of experimental work has further increased our understanding of the associations among physical activity, sleep, and eudaimonic wellbeing. For example, an 8-week Zumba intervention improved purpose in life in a small sample (n = 22) of women (74). However, short duration interventions also appear effective for influencing daily wellbeing. One such study examined the impact of a two-and-a-half day workshop targeting employee wellbeing by teaching techniques to optimize daily energy expenditure, set short- and long-term goals, and review feedback from important people in their lives (e.g., coworkers and family). Employees randomized to the intervention group demonstrated greater six-month gains in general and mental health, social functioning, purpose in life, and sleep quality relative to the waitlist control group (75). These studies offer preliminary evidence to suggest that sleep and physical activity are health behaviors that may be related to wellbeing in everyday life.

Sleep and physical activity may support individuals in reaching a goal of health that supports other life goals and values (76). However, whether physical activity is associated with subsequent increases in one's sense of purpose in life—similar to how physical activity has mood-brightening effects—in naturalistic settings is less certain. Experience-sampling studies observed that physical activity was positively associated with happiness, positive mood, and purpose in life on the following day (77) and that people endorse greater life satisfaction on days when they engage in more minutes of overall physical activity (78). Though an important empirical foundation has been established for the transient effects of physical activity on eudaimonic components of wellbeing, there is need to concurrently measure sleep, physical activity, affect, and purpose in life concurrently in everyday life to gain a holistic understanding of the naturalistic dynamics of interactions within this system.

Health behavior and well-being as a complex system

Complicating the relationships among physical activity, sleep, and wellbeing are the presence of potential bidirectional associations between health behaviors and wellbeing and the complex, networked interplay between sleep and physical activity in real life contexts. As reviewed above, health behavior interventions designed to promote wellbeing focus on the effects of physical activity and sleep on wellbeing (32,39,59,64,67,75), but the degree to which we judge our lives to be meaningful and experience happiness also likely impacts the extent to which we get a good night's sleep (79) and move throughout the day (41,46,78).

An additional complication is that physical activity and sleep, while generally examined independently (20,41,73,80–82) likely influence one another in naturalistic contexts. For example, regular physical activity at or above recommended levels (600 MET [metabolic equivalent] minutes per week) mitigates the detrimental effects of poor sleep on wellbeing (83) and a single bout of physical activity increases neuroelectrical indices of relaxation in individuals with anxiety (i.e., EEG alpha wave activity) (84). Greater consideration of the mutual dependencies between physical activity and sleep will provide a more complete account of how physical activity and sleep engender lasting changes on wellbeing in daily life. To push forward our understanding of health behaviors and wellbeing, this complex systems perspective entailing bidirectional associations and dependencies among a web of individual health behaviors (i.e., physical activity and sleep) can be accommodated by coupling intensive repeated measures with network science.

Accommodating a complex systems approach to health behaviors and wellbeing using network science

A network approach has emerged to better understand the dynamic relationships among multiple behaviors and psychological processes in daily life (85–88). For example, poor sleep may result in heightened negative affect, which in turn may lead to more daytime sleepiness, which in turn may lead to negative affect states. In contrast, being active may result in increased positive affect, which in turn may lead to feeling a greater sense of purpose in life, which in turn may lead to reduced negative affect. Network analysis can be applied to experience-sampling data using vector autoregression (VAR) techniques. These approaches predict autoregressive effects: a variable (i.e., sleep quality) at a certain time point is predicted by the same variable at the previous time point as well as all other variables at the previous time point (cross-lagged effects; (86). Network analysis extends standard time series analyses by offering a visual representation of the relations among all assessed variables. The network approach also allows for the estimation and visualization of the co-occurrence of multiple variables simultaneously on lagged (previous day), contemporaneous (same day), and between-person trait levels, thus it is possible to capture the dynamics among variables of interest while considering multiple timescales.

The present study

Understanding how physical activity and sleep influence wellbeing in everyday life necessitates approaches that consider how these behaviors fluctuate within a day and across days as well as how these behaviors support components of wellbeing in everyday life. To address these gaps, we test momentary associations among physical activity and affect to examine to what extent how much we move throughout the day bolsters affective components of wellbeing, just as laboratory studies have shown physical activity enhances positive affect and alleviates negative affect (32,34). Additionally, given that these associations do not occur in isolation and are likely influenced by nightly sleep characteristics and eudaimonic components of wellbeing, we move to the daily level and leverage the strengths of network analysis to explore the temporal relationships among physical activity, sleep, and wellbeing in everyday life.

Method

We use data from the Social Health Impact of Network Effects (SHINE) Study, which was designed to provide insight into health behaviors and social interactions among young adults. The University of Pennsylvania served as the Institutional Review Board of record, following reliance agreements and local context review approvals at Columbia University. This study was approved by the University of Pennsylvania Institutional Review Board and the Army Research Lab Human Research Protection Office.

Participants

The present study used data from 226 young adult participants (169 women, 56 men, 1 unreported, $Mean_{age}$ = 20.2 years, SD_{age} = 1.7, age range: 18–42) who completed the study from May to October 2020. The racial/ethnic composition of the sample was 42% white, 33.6% Asian, 7.1% Black or African American, 10.2% multiracial, 1.3% other, and 9.3% of participants identified as Hispanic or Latino.

Procedure

Recruitment materials advertised a study titled "Social Health Impact of Network Effects Study (SHINE)" to undergraduate students who were members of on-campus social groups (e.g., sports teams, clubs, sororities and fraternities) at the University of Pennsylvania and Columbia University. We refer readers to Supplemental Methods for additional information about the larger study. Data and code are available from the corresponding author upon reasonable request.

We used the LifeData (https://www.lifedatacorp.com/) company's RealLife Exp smartphone app for experience sampling. Experience-sampling assessment was deployed between 30 May 2020 and 27 October 2020 in response to the emergence of the COVID-19 pandemic. For this data collection, all participants contacted initially as part of the larger study and any new members that joined the groups were invited to complete an online survey to understand the impact of the COVID-19 pandemic on a variety of psychosocial factors (see codebook on the Open Science Foundation: https://osf.io/gkahy/). Interested participants provided their consent and completed the COVID survey. At the end of the COVID survey, participants were asked for their interest and consent to partake in a 28-day Ecological

Momentary Assessment (EMA) and Ecological Momentary Intervention (EMI) protocol. This second protocol was similar to the first protocol (see Supplemental Methods), though it contained additional items and was completed entirely online. Interested participants were emailed a Qualtrics survey with instructions on how to set up the EMI and EMA protocol on their phone, and then began the protocol. We focus on the baseline survey measures and COVID-19 experience-sampling period. Participants received $60 Amazon gift card for answering at least 70% of the second experience-sampling period.

Measures

The present study made use of participants' reports of demographic characteristics from the baseline survey (age, gender, race, and ethnicity) and the experience-sampling data collected on their smartphones in day-to-day life during the COVID-19 pandemic. During the experience-sampling period, a morning survey was sent at 8AM and an evening survey was sent at 6PM. The surveys remained open until the next notification: after the 8AM survey, there was a prompt at 2PM and after the 6PM survey there was a prompt at 9PM as part of the EMI (see Supplemental Methods).

Momentary Physical Activity

Physical activity was measured using a modified version of the Godin Leisure Time Exercise Questionnaire (LTEQ; Godin et al., 1986; Godin & Shephard, 1985). The LTEQ is a validated measure of adult physical activity (91). Although typically administered as a previous-week recall measure, the measure has been modified to assess physical activity *in situ* over a period of hours (92–94), thus reducing potential recall bias and reliance on personal heuristics to estimate physical activity (95,96). During the EMA surveys, participants were asked "Since your MORNING/EVENING survey, how many times did you engage in exercise for more than 10 minutes in (1) vigorous exercise (e.g., running, vigorous swimming), (2) moderate exercise (e.g., fast walking, volleyball), (3) mild exercise (e.g., easy walking, yoga). Using the LTEQ scoring procedure, responses were weighted by standard metabolic equivalents (MET; vigorous = 9; moderate = 5; mild = 3) and summed to create a total momentary MET or energy expenditure score. Higher scores indicate greater physical activity energy expenditure.

Momentary Affect

Momentary affect (happy, sad, anxious, angry) was measured using items from the Profile of Mood States (POMS; 97). The POMS is a validated measure of mood that has been previously used in experience-sampling studies with adults (98,99).

Happiness. We measured happiness using one item asking participants to respond on a sliding scale from 1 (“Not at all”) to 100 (“Extremely”) to the following prompt: “Right now, I feel HAPPY”.

Sadness. We measured sadness using one item asking participants to respond on a sliding scale from 1 (“Not at all”) to 100 (“Extremely”) to the following prompt: “Right now, I feel SAD”.

Anxiety. We measured anxiousness using one item asking participants to respond on a sliding scale from 1 (“Not at all”) to 100 (“Extremely”) to the following prompt: “Right now, I feel ANXIOUS”.

Anger. We measured anger using one item asking participants to respond on a sliding scale from 1 (“Not at all”) to 100 (“Extremely”) to the following prompt: “Right now, I feel ANGRY”.

Daily Purpose in Life

We measured purpose in life with an item adapted from Ryff (100). In the morning survey, we measured purpose in life using one item asking participants to respond on a sliding scale from

1 (“Not at all”) to 100 (“Extremely”) to the following prompt: “I feel that I have a sense of direction and purpose in my life”.

Nightly Sleep

We measured sleep using items adapted from the Pittsburgh Sleep Quality Index (101) that have been used in previous daily diary studies (102). Typically used as previous-month recall measures, two items were configured for daily assessment as previous-night recalls. These measures are more strongly correlated with actigraphy-based measures of sleep than retrospective, previous month reports (103).

Sleep duration. In the morning survey, we measured sleep duration using one item asking participants to answer the following question: “How many hours and minutes of sleep did you get last night (This may be different from # of hours spent in bed)?”. Participants responded based on a hours and minutes number wheel.

Sleep quality. In the morning survey, we measured sleep quality using one item asking participants to report on a scale from 1 (“Very bad”) to 100 (“Very good”) to the following question: “Last night, how would you rate your quality of sleep?”.

Data Preparation and Statistical Analysis

Using the EMA data, we tested the extent to which physical activity was associated with each of the discrete affective states (happy, sad, anxious, angry) using separate multilevel models that accommodated the nested nature of the data (up to 56 observations per participant in 228 participants in 24 groups; Snijders & Bosker, 2011). As we were interested in within-person momentary associations among physical activity and affect (105) and to accommodate the difference in scales in these variables, we within-person standardized the predictor variable in the multilevel models using the stdz function from the weights package in R (106). Such an approach allowed us to focus on within-person associations and reduced any potential confounding of between-person differences in reporting. The resulting predictor variable indexes the extent to which a person's physical activity, for example, deviates relative to their own typical levels. Thus, zero indicates usual levels of physical activity behavior for that person whereas positive values indicate more than usual levels and negative values indicate less than usual levels for that person. By creating a within-person standardized variable, each individual's physical activity time series had a mean of 0 and a standard deviation of 1. Additionally, this approach mitigated the extent to which scale and variance differences across variables would render coefficients comparable to one another (107–110). We specified all multilevel models using the nlme package in R (111). All models included age, gender, and weekend (Saturday and Sunday) as covariates.

Momentary Associations between Physical Activity and Wellbeing

The considered physical activity-wellbeing associations are prospective such that the association between current affect is examined *following* self-reported physical activity. Weekend (Saturday, Sunday) was a categorical variable (0 = weekday; 1 = weekend), gender was a categorical variable (man = 0; woman = 1), and age was sample-mean centered. We tested the extent to which a moment's physical activity was associated with subsequent discrete emotions (i.e., happy, sad, angry, anxious) in separate multilevel models of the form (using happy as an example):

$$Happy_{it} = \beta_{0i} + \beta_{1i} physicalactivity_{it-1} + \beta_{2i} weekend_{it} + e_{it}$$

where $happy_{it}$ is the level of happiness for person i on moment t; β_{0i} indicates the expected *happiness* for an individual experiencing an average level of physical activity for that person; β_{1i} indicates within-person differences in happiness associated with prior moment's physical activity; β_{2i} indicates the effect of weekends on happiness in order to account for day-of-week differences in happiness (112,113); and e_{it} are moment-specific residuals allowed to be autocorrelated (AR1).

Person-specific intercepts and associations from the Level 1 model were specified at Level 2 as:

$$\beta_{0i} = \gamma_{00} + \gamma_{01} age_i + \gamma_{02} gender_i + u_{0i}$$
$$\beta_{1i} = \gamma_{10} + \gamma_{11} age_i + \gamma_{12} gender_i + u_{1i}$$
$$\beta_{2i} = \gamma_{20}$$

where γs are sample-level parameters and us are the residual between-person differences that may be correlated but are uncorrelated with e_{it}. Parameters γ_{11} and γ_{12} indicate how between-person differences in the within-person association of moment's affect and physical activity were moderated by age and gender (114,115).

For the reversed sequence, we tested the extent to which within-person standardized momentary wellbeing (happy, sad, angry, anxious) predicted physical activity by fitting separate multilevel hurdle models using the glmmTMB package in R (116), specifying a gamma distribution. Physical activity data reported on this manuscript (i.e., energy expenditure MET values) have three features that violate the assumptions of linear mixed models: excess zeroes, data that are always positive when not zero, and a large positive skew (117). Given these data, we can predict 1) whether someone was active and 2) the energy expenditure if they were active. Hurdle models use a logistic regression to model the zeroes (active/inactive) in the data in addition to a gamma regression to model the amount of physical activity (in this case MET energy expenditure). The zero-inflation submodel of the hurdle model estimates the probability of an extra zero (no physical activity) such that a positive estimate indicates a higher chance of no physical activity. The conditional submodel of the hurdle model estimates the positive process, providing insight into variables that increase physical activity (i.e., MET energy expenditure) during moments when someone was physically active.

Daily Interactions among Physical Activity, Sleep, and Wellbeing

To accommodate the once per day rating of sleep and purpose in life (in contrast to the other variables which could be measured more than once per day), we used a multilevel vector autoregressive model to isolate within- and between-person relationships among multiple variables (Epskamp et al., 2018, 2019; see Supplemental Material). This approach generates three networks describing the relationships among variables of interest (day's physical activity, sleep, happiness, sadness, anger, anxiousness, and purpose in life): 1) a directed temporal network revealing within-person time-lagged (previous day) relationships among variables, 2) an undirected network revealing within-person same-day (contemporaneous) relationships among variables, and 3) an undirected between-person network identifying variables that fluctuate at the between-person level. We computed daily values of physical activity, affect, and purpose in life by calculating the mean values of physical activity, affect, and purpose in life across the two reports for each day to be used in these models. Eight multilevel models are sequentially estimated (one for each variable of interest). In this step, each variable (i.e., physical activity, sleep quality, sleep duration, happy, sad, anxiety, angry, purpose in life all assessed at the daily level) at time t is predicted by the 8 within-participants lagged ($t-1$) variables and the 7 trait-level predictors (the mean of the predicted variable is not included; see Supplemental Data Analysis).

Results

Descriptive Statistics

We provide descriptive statistics of the experience-sampling variables in Table 1.

Momentary Within-Person Associations between Physical Activity and Affective Wellbeing

We ran separate multilevel models to examine whether previous physical activity was associated with current happiness, anxiety, anger, and sadness. Higher than usual physical activity at the last prompt was associated with increased happy (b = 1.67, p < 0.001, d = 0.19; see Figure 1A) and lower anxious affect (b = -0.74, p < 0.001, d = -0.09; see Figure 1B). In terms of covariates, weekends were associated with increased happy (b = 1.23, p = 0.006, d = 2.8) and decreased anxious affect (b = -1.89, p < 0.001, d = -0.08). We provide details of these three models in Table 2. Previous physical activity was not significantly associated with subsequent angry or sad affect (*p's* ≥ 0.08; see Table S1).

We ran separate multilevel hurdle models to examine whether previous happiness, anxiety, anger, and sadness was associated with current physical activity. Moments of higher than usual sad affect were more likely to be followed by moments of not being physically active (b = 0.06, p = 0.02; see Figure 1C). However, current sad affect was unrelated to subsequent amount of physical activity (p =0.21; see Table S5). There were no significant associations between current happy, anxious, or angry affect and probability of not being physically active or amount of physical activity (*p's* ≥ 0.15; see Tables S2-S4).

Daily Interactions among Physical Activity, Sleep, and Wellbeing

We used a multilevel vector autoregressive model to estimate within and between-person relationships among multiple variables (86,87). Because sleep and purpose in life are reported once, we move to the daily level to investigate these associations by estimating temporal, contemporaneous, and between-participant networks.

Temporal Network

Results from the within-participants temporal network are depicted in Figure 2A. We found the following significant temporal relationships with physical activity: when physical activity was higher than usual on a given day, happy affect was higher than usual the next day ($b = 0.07$, $p = 0.005$). We found the following significant temporal relationships with sleep quality: higher than usual sleep quality on a given night predicted next-day increases in purpose in life ($b = 0.07$, $p < 0.002$) and happy affect ($b = 0.17$, $p < 0.001$) as well as a decrease in sad ($b = -0.07$, $p < 0.001$), anxious ($b = -0.05$, $p < 0.001$), and angry ($b = -0.09$, $p < 0.001$) affect the next day. We found the following significant temporal associations with sleep duration: longer than usual sleep duration on a given night predicted lower than usual sleep quality ($b = -0.04$, $p = 0.049$), purpose in life ($b = -0.05$, $p < 0.001$), and happy affect ($b = -0.06$, $p < 0.001$) the next day. We found the following significant temporal associations with affect: when sad affect was higher than usual on a given day, physical activity was lower than usual ($b = -0.05$, $p = 0.01$) and anxiety was higher than usual ($b = 0.04$, $p = 0.034$) the next day; when happy affect was higher than usual on a given day, purpose in life was higher than usual the next day ($b = 0.06$, $p = 0.002$); when anxiety was higher than usual yesterday, sad affect ($b = 0.10$, $p < 0.001$) and purpose in life ($b = 0.05$, $p = 0.03$) were higher than usual the next day.

Contemporaneous Network

Results from the within-participants contemporaneous network are depicted in Figure 2B. We found the following significant relationships for a given day: on days when people experienced higher happy affect than usual, sad ($r_p = -0.29$), anxious ($r_p = -0.14$) and angry affect ($r_p = -0.21$) were lower than usual. On days when physical activity was higher than usual, sleep duration on the same night was shorter ($r_p = -0.04$) and happy affect was lower ($r_p = -0.04$) on the same day. Longer sleep duration than usual was associated with increased sleep quality ($r_p = 0.45$) on the same evening. Higher happiness than usual was associated with increased purpose in life ($r_p = 0.17$). The negative affective states were positively associated (r_p's ≥ 0.10).

Between-participants Network

Results from the between-participants network are depicted in Figure 2C. People who on average were happier tended to endorse a higher sense of purpose in life ($r_p = 0.31$), experience higher sleep quality ($r_p = 0.45$) and lower sad affect ($r_p = -0.19$). People who on average were sadder tended to have higher anxiety ($r_p = 0.50$) and anger ($r_p = 0.55$). People who on average had longer sleep duration had higher sleep quality ($r_p = 0.19$).

Length of Temporal Effects

Given that physical activity on a given day corresponds with higher happy affect the next day and sleep alleviates negative affect the following day, a natural question is how long this temporal relationship persists. Thus, we next assessed the temporal network with a time lag of two days (rather than one day; see Figure 3A). Physical activity two days prior did not predict happy affect ($b = 0.001$, $p = 0.96$). Likewise, sleep quality did not predict negative affect at a lag of two days (*b's* ≤ -0.03, *p's* ≥ 0.05). However, sleep quality predicted increased happy affect at a lag of two days ($b = 0.07$, $p = 0.001$). Similarly, purpose in life predicted decreased sad ($b = -0.04$, $p = 0.03$), anxious ($b = -0.04$, $p = 0.02$), and angry ($b = -0.05$, $p = 0.02$) affect at a lag of two days. Anxiety's positive autocorrelation was significant at the two-day lag ($b = 0.07$, $p = 0.002$) and anxiety predicted longer sleep duration at a lag of two days ($b = 0.06$, $p = 0.046$). Angry affect predicted increased anxiety at a lag of two days ($b = 0.05$, $p = 0.006$). At a lag of three days, sleep and physical activity were not predictive of any behaviors, yet there were associations among happy, anxious, and angry affect (*p's* ≤ 0.037; see Figure 3B). Collectively, these findings suggest that while the effects of physical activity on affect and purpose in life may be shorter term (e.g., up to one day), a sense of purpose in life and negative affective states can be slightly longer lasting, bleeding into the next few days.

Discussion

Sleep, physical activity, affect, and purpose in life are parts of a system of wellbeing and health behaviors. The extent to which components of this system interact and mutually influence one another during everyday life is not clear, due in part to the challenge of concurrently measuring these states and behaviors and due to the complex, mutual dependencies that exist within this health behavior-wellbeing system. Here, we capitalized on smartphone-based experience sampling approaches across one month and network analytic approaches to reveal the pairwise interplay and to simultaneously estimate associations among sleep, physical activity, affect, and purpose in life naturalistically, in real-world settings.

Focusing on twice per day assessments of physical activity and affect, we found that higher than usual physical activity reported at a prompt was associated with increased happy and lower anxious affect at the next prompt. This association is consistent with animal models and human laboratory studies of sleep and physical activity behavior (32,34,35,118,119) and with experience-sampling studies observing increased positive affect (40,47–49,80) and decreased negative affect (47,49). It is also plausible that these short-term improvements in positive affect within a day may then subsequently support higher purpose in life on the daily level. Such findings support theories that suggest engaging in physical activity supports attainment of a higher goal of health and gives meaning or direction to life almost immediately (67,120). In line with social cognitive theory (121), physical activity provides structure and goals to daily life, supports the feeling of spending time doing something worthwhile, and aligns with the goal of living a meaningful healthful life (66,122). It may be that through improved positive affect following a brief period of physical activity, individuals may then experience higher purpose in their everyday lives.

The Affect and Health Behavior Framework suggests there exists a causal pathway from previous affective response to motivation to behavior (123). For example, positive or negative affective responses to physical activity increase or decrease the likelihood of engaging in future physical activity via effects on affective associations with implicit attitudes and automatic neurobiological substrates of motivation (e.g., dreading or wanting to engage in physical activity in the future; (124–127). Although prior experience-sampling work suggests that both positive and negative affective experiences predict subsequent physical activity (39), our findings found that moments of higher than usual sad affect were more likely to be followed by periods of any physical inactivity. Consistent with (42), we did not find that sad affect predicted subsequent amount of physical activity. We found no significant associations between current happy, anxious, or angry affect with chance of being physically active or amount of physical activity at the next prompt. Our findings may differ from prior experience-sampling work as we did not capture the arousal component of affective experience (128) and we did not use objective device-based measure physical activity (41,42,44,45,129). Moreover, prior work has shown that higher positive affect and lower negative affect predict subsequent physical activity within the 15 to 120 minutes following the affect report (42,129). The time delay between the two prompts in our study was longer than the acute period, which may have dampened the extent to which we could observe the association between positive affect and subsequent physical activity. Together, our findings suggest that sadness may be a negative affective state that persists longer to reduce subsequent likelihood of an individual deciding to be physically active or not.

Moving to the daily level allowed the incorporation of sleep and purpose in life into this health behavior and wellbeing system. It also allowed us to combine the intensive repeated measure data with a network analytic approach to build a more complete model of how health behaviors and wellbeing interact with one another *in situ* during daily life. In the within-person temporal network, which shows how sleep, physical activity, purpose in life, and affect relate to one another from one day to the next, we observed that higher than usual sleep quality is associated with decreased negative affective states (sad, angry, anxiety) the next day. Longer sleep duration yesterday was associated with decreased purpose in life and reduced happy affect the next day, which is consistent with prior work at the between-person level suggesting that longer sleep duration (≥ 10h) is associated with increased depressive symptoms that overlap with the current operationalization of purpose in life, e.g., “little interest or pleasure in doing things” (130). Collectively, findings are consistent with work demonstrating that sleep is a crucial health behavior supporting wellbeing in daily life (59,71,131–133) but extends it by examining the influence of sleep characteristics on both affective and eudaimonic components of wellbeing across a month at the within-person level.

The within-person temporal network also offered insight into associations between the physical activity and affective aspects of wellbeing. We observed that higher than usual physical activity yesterday predicted increased happy affect the next day, but these effects disappeared in the two- and three-day temporal networks. This finding is consistent with laboratory studies showing that a single bout of physical activity enhances positive affect up to one day following the experimental session (32). We extend prior experience-sampling work (40,42,47–49,54) by examining the effects of physical activity on affect up to 3 days later. This finding is further supported by interpreting it alongside the contemporaneous network showing that increased physical activity is associated with decreased happy affect on the same day, suggesting that there is a temporal precedence for the physical activity-affect association: people need to engage in physical activity *before* experiencing enhanced positive affect. Taken together, our findings show people must engage in physical activity regularly to accrue the mood-brightening effects of physical activity in everyday life because these effects are relatively short lived.

Findings from the within-person temporal network highlight sad affect as a particularly potent negative affective state influencing next-day physical activity. This is consistent with prior experience-sampling work demonstrating that heightened negative affective states immediately reduce subsequent physical activity (134). Importantly, our findings show that this relationship persists up to one day. Consistent with network perspectives of emotions suggesting that psychopathology results from the causal interplay between symptoms (88,135,136), we find that there is an interplay among sad, angry, and anxious affect. Within the same day, we observe that there is a positive interplay among sad, angry, and anxious affect whereas from one day to the next sad and anxious affect perpetuate one another. Consistent with these perspectives, we find sadness is a negative affective state that has a persistent influence on physical activity. In this way, negative affect may subsequently reduce the likelihood of being physically active, which is a potent moderator of positive affect. Thus, it is plausible that engaging in physical activity may briefly interrupt the interplay among negative affective states suggesting its utility in the management of negative affective states.

With respect to purpose in life as an indicator of eudaimonic wellbeing, our daily network models show that on days when purpose in life is higher than usual, happy affect is also higher than usual. This positive association is consistent with prior work demonstrating that purpose in life supports psychological wellbeing and is related with positive affect (29,137,138) but extends it by showing this association holds on a daily timescale. In this way, purpose in life is a renewable resource that physical activity can serve to enhance, thus bolstering wellbeing by supporting attainment of the greater goal of health or by simply engaging in enjoyable meaningful daily activities (67,120,139). Our findings did not support a bidirectional association between purpose in life and physical activity from one day to the next. Although prior work has shown a bidirectional association between physical activity and purpose in life, our findings may differ because these studies have used objective measures of physical activity. However, by using self-reported physical activity periods, it is possible that our participants were able to move beyond experimenter-defined notions of physical activity or exercise with the goal of improving fitness. Indeed, extant literature shows that the extent to which individuals find the physical activity enjoyable or meaningful influences the effects on affective experiences (32) and willingness to engage in the physical activity (140). Thus, the self-report nature of the physical activity periods may have enabled us to capture activities that participants would not typically associate with physical activity or that may not be captured by objective device-based measures (e.g., cycling to the grocery store).

Another interesting finding was that purpose in life appears to be particularly salient for reducing negative affect up to two days later. Thus, it is possible that a boost in daily meaning has an enduring impact on emotional health persisting beyond the activity bout—bleeding into the next few days. This finding has practical implications. Substantial public health efforts have highlighted physical activity as a means of enhancing population physical and mental health (141). However, efforts to disseminate these guidelines have focused on communicating the duration, frequency, and type of physical activity to receive optimal health benefits. Such an approach overlooks a critical component of the health behavior-wellbeing system: finding meaning or purpose in daily activities. Aristotle (142) first proposed that human behavior is likely better understood within the lens of phronesis or practical reasoning that aims to realize valued goals. This perspective is in contrast to the robust body of literature seeking to determine the antecedents and determinants of physical activity (143–146). Our findings highlight that the pathway from physical activity → purpose in life → affect may play a critical role in supporting everyday wellbeing and ought to be considered when translating physical activity guidelines to the general population. For instance, helping people identify daily physical activities that support their values and meaning-making and finding ways to help them understand how frequently to engage in these behaviors to support their health and wellbeing.

Our findings also emphasize that small steps each day matter. That is, going for that brisk walk you may have been contemplating could put you in a good mood and alleviate anxiety immediately, which may support a daily sense of accomplishment to be able to juggle multiple daily responsibilities of work, family, and life and endure for days to come. The decision to be physically active in that moment may boost positive affect, thus helping buffer against negative affect up to two days later when time constraints have made it difficult to engage in meaningful activities.

Given that health communication efforts highlight values affirmation as a critical component of health messaging and behavior change in daily life (147,148), future work that examines activity-promoting interventions incorporating aspects of self-affirmation and purpose in life combined with mobile sensing will help reveal whether, how, and the temporal nature by which these interventions influence components of the health behavior-wellbeing system in daily life. To this end, commercially available wearable devices already deploy nudges that incorporate self-affirmation messages to influence behavior; however, to what extent an activity-promoting intervention can be personalized to align with one's purpose and values may be more fruitful for influencing behavior in the moment. For instance, coupling a mindful nudge with brief bursts of movement may be beneficial (e.g., focus on your breath as you walk around the block; when your mind wanders bring it back to the sensations of the movement), though this goes beyond the current data. Future work may seek to understand how such mindful movement interventions can be personalized and the downstream impact on sustainable behavior change in peoples' daily lives.

Finally, days of higher than usual physical activity were associated with shorter than usual sleep duration later that night. These findings are in line with observations that physical activity and sleep represent two ends of a continuum in which prioritizing one behavior (e.g., physical activity) may occur at the expense of the other (e.g., sleep) due to time constraints (149). Although cross-sectional evidence suggests increased physical activity benefits sleep quality and duration (150), our findings highlight the need for examining how these relationships unfold in the course of daily life. Prior experience-sampling work has found equivocal findings for the association between physical activity and sleep. One study found that overweight adult women slept longer on days following higher than usual physical activity (151) whereas other studies found no association between sleep duration and physical activity in healthy physically active adults (152,153). Within the context of daily life, however, physical activity and sleep compete for time. That is, the time someone may commit to being physically active may come at the expense of time to sleep when juggling all the responsibilities of daily life (154). Indeed, people who exercise regularly sleep on average 15.5 minutes less than those who do not exercise (154), and our findings extend this work to the within-person level suggesting that on days when people engage in more physical activity than usual it may occur at the expense of sleep duration that night. Alternatively, it may be that since these data were collected during COVID-19, the observed longer sleep duration may be indicative of heightened negative affective states, which are associated with increased risk for depression (155).

Limitations

Despite the strength of the naturalistic reports of sleep, physical activity, affect, and purpose in life across one month in the present investigation, there are limitations that warrant further discussion. The sample is primarily white, college-aged adults identifying as women, making generalizations to other samples difficult. The self-report measures of sleep and physical activity were retrospective in nature (reporting on the previous timepoint's behavior). This approach allowed us to capture behaviors occurring after the evening survey (6:00pm) but may have introduced retrospective biases. An interval-contingent EMA protocol was used whereby participants responded at the same time everyday. This approach likely supported the high response rate (77.1%), but it may have led participants to anticipate the assessments in a way that may be mitigated by signal-contingent or variable time-based approaches. Future work may seek to incorporate mobile sensing techniques and physiological measures to corroborate self-report measures with objective measures of sleep and physical activity.

Conclusions

In summary, we helped bridge the gap between laboratory studies and experience-sampling work regarding the roles of physical activity, sleep, affect, and purpose in life on everyday wellbeing. Laboratory studies and animal models suggest a robust tendency for physical activity and sleep to enhance positive affect and alleviate negative affect and cross-sectional evidence points towards a bidirectional association between physical activity and purpose in life. We were able to test physical activity, sleep, affect, and purpose in life as components within a health behavior and wellbeing system and found that physical activity immediately boosts happy affect and reduces anxiety in everyday life. We found that physical activity predicted increased happy affect the next day and sleep predicted reduced negative affect the next day. We found that purpose in life predicted decreased sad, anxious, and angry affect up to two days later. More broadly, our results lay the groundwork for creating naturalistic, mobile-sensing based human models to further elucidate the interplay among real-world health behaviors and wellbeing as well as see how changes in some sets of nodes propagate to influence other nodes within the system, which would be useful for personalizing behavior change interventions and testing the feasibility of ecologically-relevant health-enhancing intervention programs.

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Table 1. Descriptive statistics for day-level experience-sampling measures.

Variable	***M***	***Median***	***SD***	**1**	**2**	**3**	**4**	**5**	**6**	**7**
1. Happy	60.02	64	19.89							
2. Anxiety	38.48	32	25.23	-.41**						
3. Angry	19.86	14	18.28	-.42**	.43**					
4. Sad	26.56	22	19.79	-.52**	.58**	.59**				
5. Purpose in life	55.47	60	24.09	.40**	-.21**	-.20**	-.24**			
6. Sleep duration (hours)	7.32	7.5	1.61	.05**	-.06**	-.08**	-.09**	.02		
7. Sleep quality	60.54	65	22.13	.38**	-.24**	-.21**	-.26**	.25**	.34**	
8. Physical activity (MET)	24.74	3	82.63	.08**	-.04**	-.03*	-.04**	.02	.03*	.05**

Note: MET = metabolic equivalents. For example, 1 MET is equal to the energy expended when seated at rest. *indicates $p < 0.05$. ** indicates $p < 0.01$. Affect, purpose in life, and sleep quality were measured on a scale from 1 to 100. Out of 12,656 prompts possible (2 prompts per day × 28 days × 226 participants), participants completed 9838 (77.7%) physical activity reports; 10,373 angry reports (82%), 10,388 anxious reports (82.1%); 10,397 happy reports (82.2%); and 10,396 sad reports (82.1%). Out of 6328 prompts possible (1 prompt per day × 28 days × 226 participants), participants completed 5121 sleep duration reports (80.9%) and 5137 sleep quality reports (81.2%) and 5206 purpose in life reports (82.3%). Participants completed an average of 49.3 prompts of up to 56 prompts (*SD* = 12.6) and reported being physically active on 40.9% of these reports. On the prompts during which physical activity was reported, the median duration reported was 20 minutes (*min* = 10, *max* = 3600 minutes).

Table 2. Results of the multilevel models examining associations of physical activity since the previous prompt with current moment's happy and anxious affect.

Effect	Estimate	Standard error	*p*	*d*	Confidence interval Lower	Confidence interval Upper
Model 1: Happy						
Fixed effects						
Intercept	60.71**	1.90	< 0.001		56.98	64.44
Physical activity	1.67**	0.18	< 0.001	0.19	1.33	2.02
Weekend	1.23*	0.44	0.006	0.06	0.36	2.10
Age	0.54	0.46	0.25	0.16	-0.38	1.45
Gender woman	-1.67	2.20	0.45	-0.10	-6.01	2.67
Random effects	Variance				Standard Deviation	
Intercept	89.92				9.48	
Residual	324.34				18.09	
Model 2: Anxiety						
Fixed effects						
Intercept	38.21**	2.76	< 0.001		32.80	43.61
Physical activity	-0.74**	0.17	< 0.001	-0.09	-1.08	-0.41
Weekend	-1.89**	0.46	0.001	-0.08	-2.79	-0.98
Age	-1.12	0.67	0.10	-0.22	-2.45	0.21
Gender woman	1.07	3.20	0.74	0.05	-5.22	7.37
Random effects	Variance				Standard Deviation	
Intercept	194.78				13.96	
Residual	336.24				18.34	

Note. 9753 observations nested within 226 participants. * $p < 0.05$, ** $p \leq 0.001$.

Figure Captions

Figure 1. Results of the multilevel models testing the association between physical activity and (A) happiness and (B) anxiousness. Physical activity at the previous time point is shown on the x-axis and current affect is shown on the y-axis. Physical activity was within-person standardized such that values of 0 are moments when physical activity is at its usual level, values below 0 indicate lower physical activity than usual, and values above 0 indicate higher physical activity than usual. When physical activity was higher than usual at the previous timepoint, happy affect was higher at the next prompt (A) and anxiety was lower at the next prompt (B). 95% confidence intervals are shown in grey. Graphic representation of the multilevel hurdle models showing (C) the association of current sad affect with likelihood of not being active at the subsequent prompt. 95% confidence intervals are represented in grey.

Figure 2. Temporal (A), contemporaneous (B), and between-participant (C) networks. Solid blue/dark blue edges represent positive associations whereas solid red edges represent negative associations. The thickness and shade of the edge represents the strength of the association. In panel A, arrows represent the direction of the effect (i.e., variable yesterday predicting a variable today) and edges represent partial β-coefficients. In Panels B and C, edges represent partial correlations. All shown edges are statistically significant $p < 0.05$.

Figure 3. Temporal lag of 2 days (A) and temporal lag of 3 days (B) networks. Solid blue/dark blue edges represent positive associations whereas solid red edges represent negative associations. The thickness and shade of the edge represents the strength of the

association. Arrows represent the direction of the effect (i.e., variable *n* days prior predicting a variable today) and edges represent partial β-coefficients.

Figure 1.

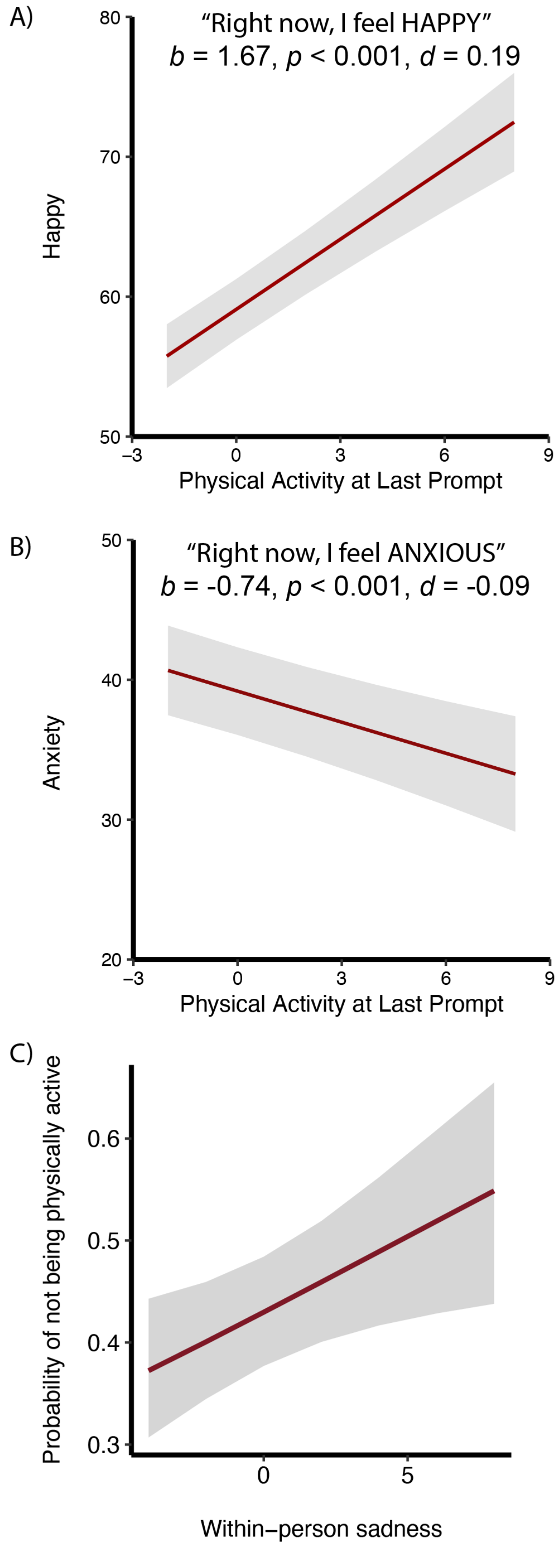

A)
"Right now, I feel HAPPY"
b = 1.67, p < 0.001, d = 0.19
Happy
80
70
60
50
–3
0
3
6
9
Physical Activity at Last Prompt
B)
"Right now, I feel ANXIOUS"
b = -0.74, p < 0.001, d = -0.09
Anxiety
50
40
30
20
–3
0
3
6
9
Physical Activity at Last Prompt
C)
Probability of not being physically active
0.6
0.5
0.4
0.3
0
5
Within–person sadness

Figure 2.

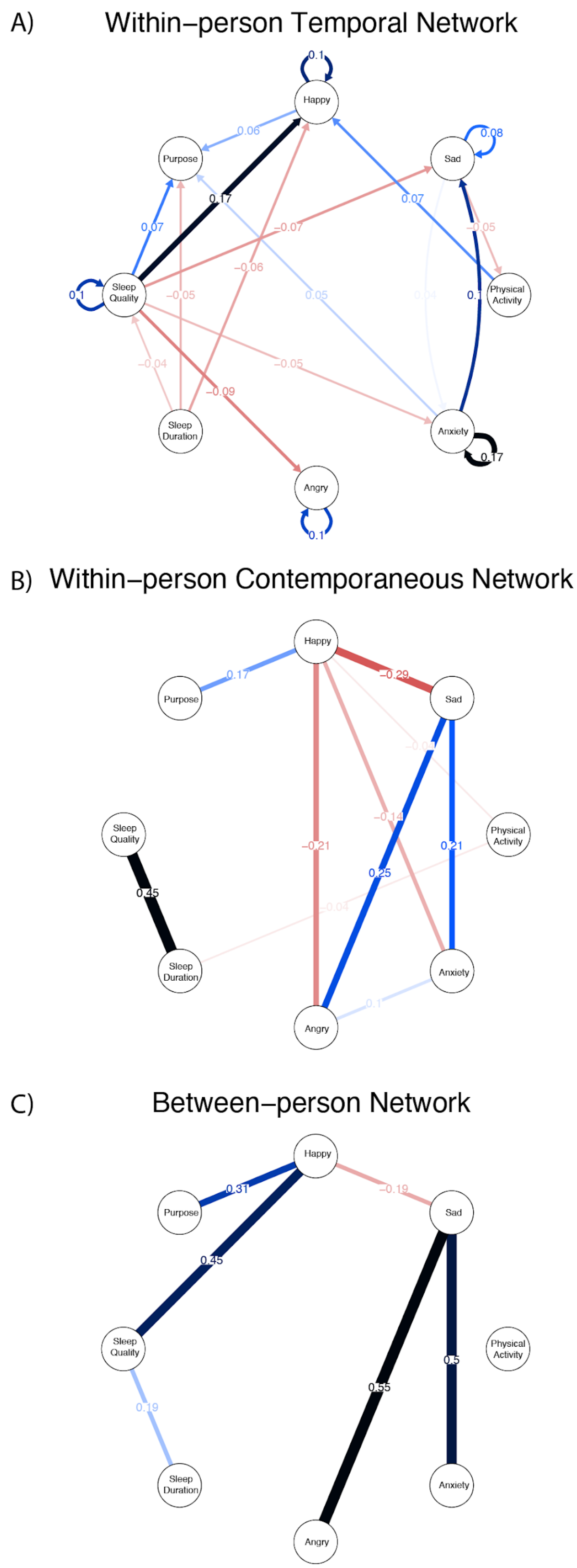
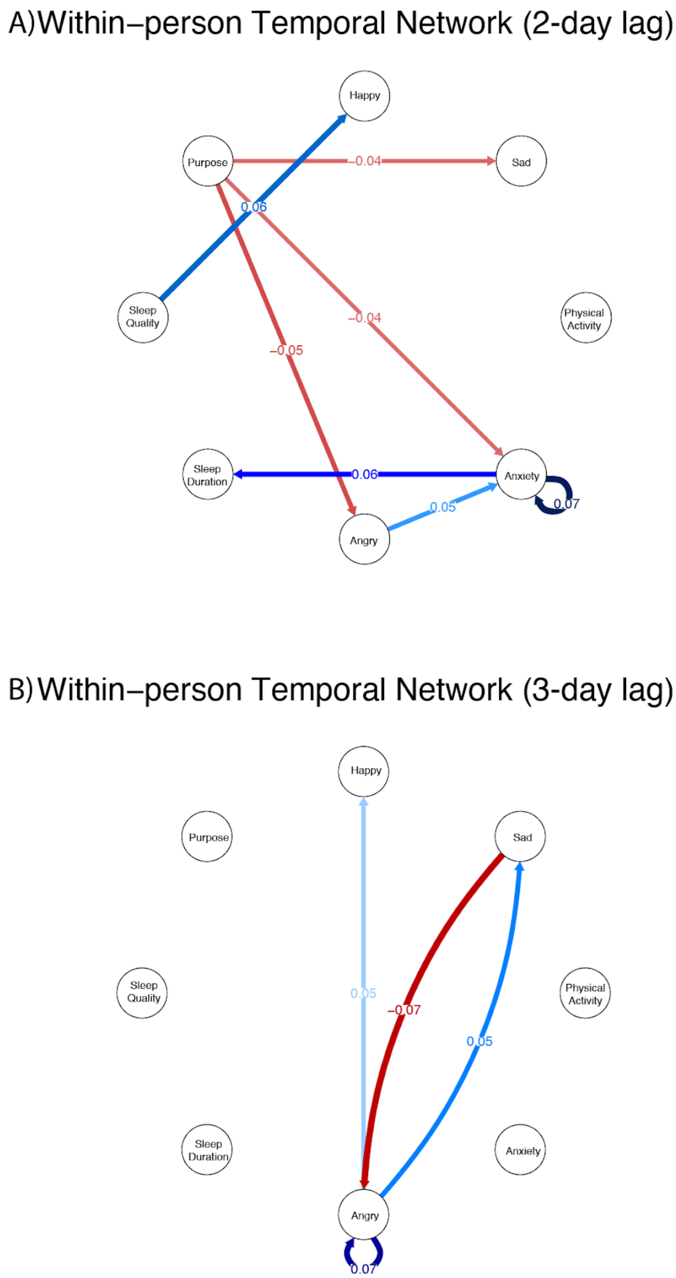

A) Within−person Temporal Network
Happy
Purpose
Sad
Sleep Quality
Physical Activity
Sleep Duration
Anxiety
Angry
B) Within−person Contemporaneous Network
Happy
Purpose
Sad
Sleep Quality
Physical Activity
Sleep Duration
Anxiety
Angry
0.17
−0.29
−0.21
0.21
0.25
0.45
C) Between−person Network
Happy
Purpose
Sad
Sleep Quality
Physical Activity
Sleep Duration
Anxiety
Angry
0.31
−0.19
0.45
0.55
0.5
0.19

Figure 3.


A) Within–person Temporal Network (2-day lag)
Happy
Purpose
Sad
Sleep Quality
Physical Activity
Sleep Duration
Anxiety
Angry
–0.04
0.06
–0.04
–0.05
0.06
0.05
0.07
B) Within–person Temporal Network (3-day lag)
Happy
Purpose
Sad
Sleep Quality
Physical Activity
Sleep Duration
Anxiety
Angry
0.05
–0.07
0.05
0.07