Supplementary materials for:

Sleepiness, sleep duration, and human social activity: An investigation into bidirectionality using longitudinal time-use data

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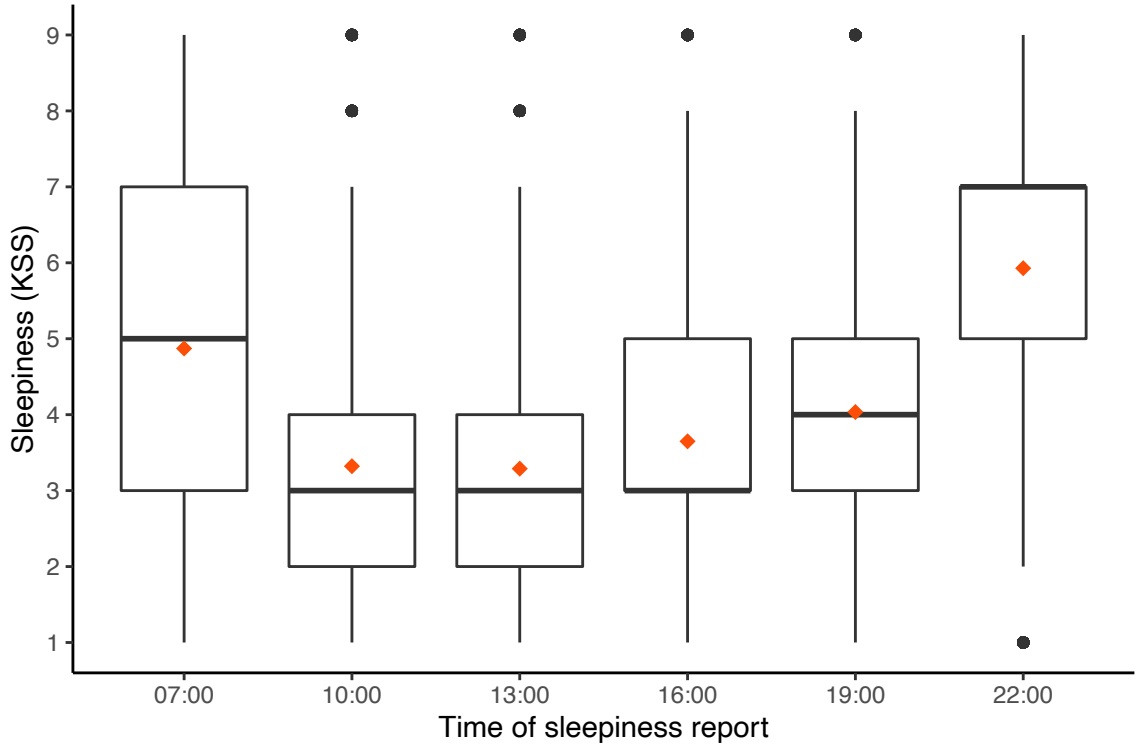

Figure S1. Box and whisker plot showing the distribution of sleepiness scores (raw KSS) at different times of day. The thicker horizonal black line within each box represents the median, the red diamond represents the mean, and the lower and upper edges of the box represent the lower (Q1/25%) and upper (Q3/75%) quartiles of the data. The distance between Q1 and Q3 represents the inter-quartile range (IQR). The ends of the "whiskers" represent the "minimum" (Q1-1.5*IQR) and "maximum" (Q3+1.5*IQR) of the data. Outliers are represented as dots.

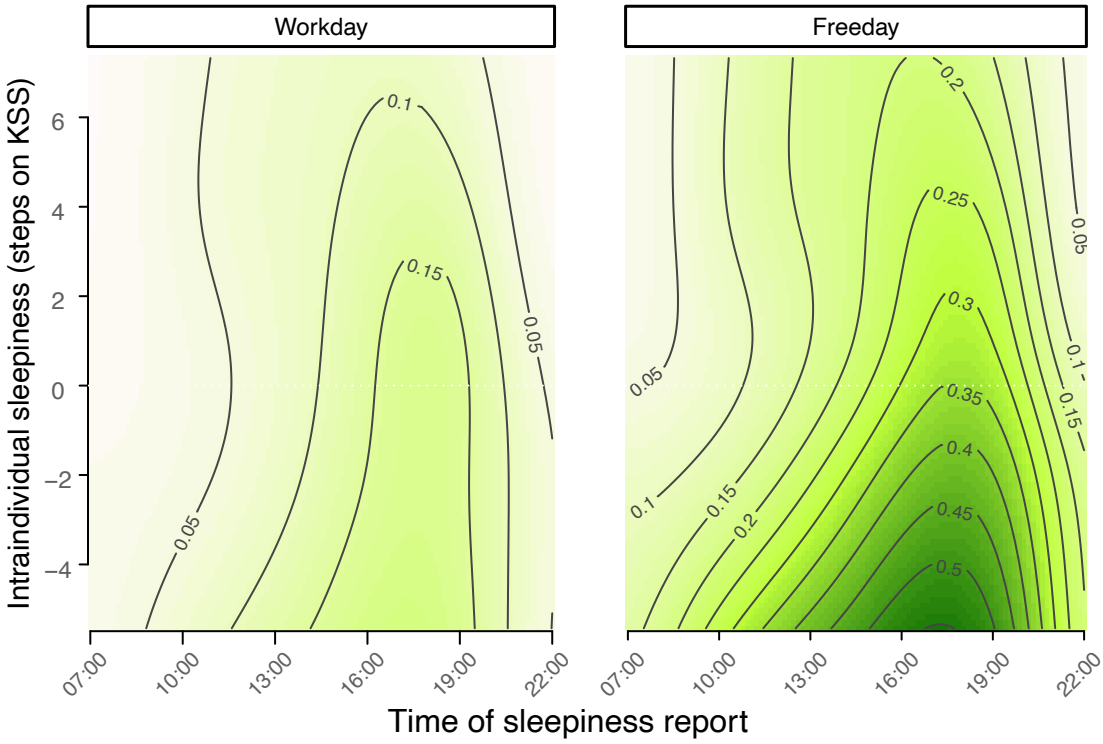

Figure S2. Contour plot showing the probability of being socially active, given sleepiness, time-of-day, and type-of-day. Increasing darkness of green colour represents increasing probability of reporting social activity. The y-axis represents within-subject mean-centered sleepiness scores, with positive values signifying greater than average sleepiness and negative values representing less than average sleepiness. The x-axis represents the change in relationship across different times of day.

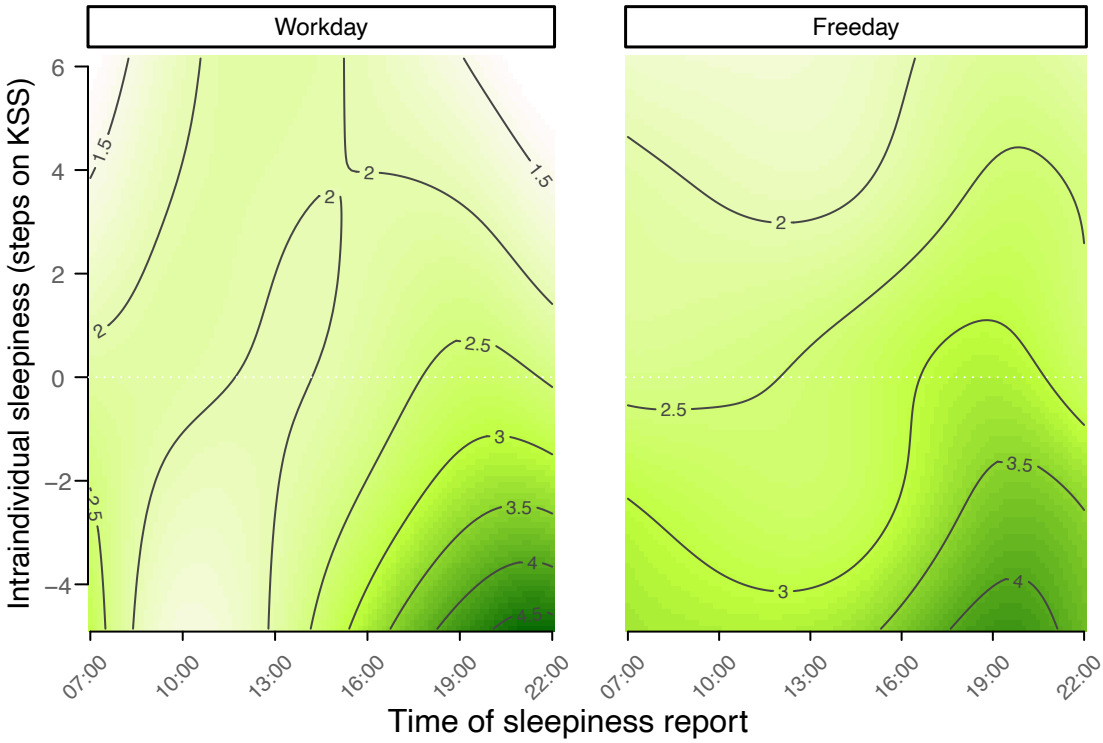

Figure S3. Contour plot showing the predicted number of 30-minute periods (per 3-hour time chunk) reported as social activity, given sleepiness, time-of-day, and type-of-day. Increasing darkness of green colour represents increasing predicted duration of social activity. The y-axis represents within-subject mean-centered sleepiness scores, with positive values signifying greater than average sleepiness and negative values representing less than average sleepiness. The x-axis represents the change in relationship across different times of day.

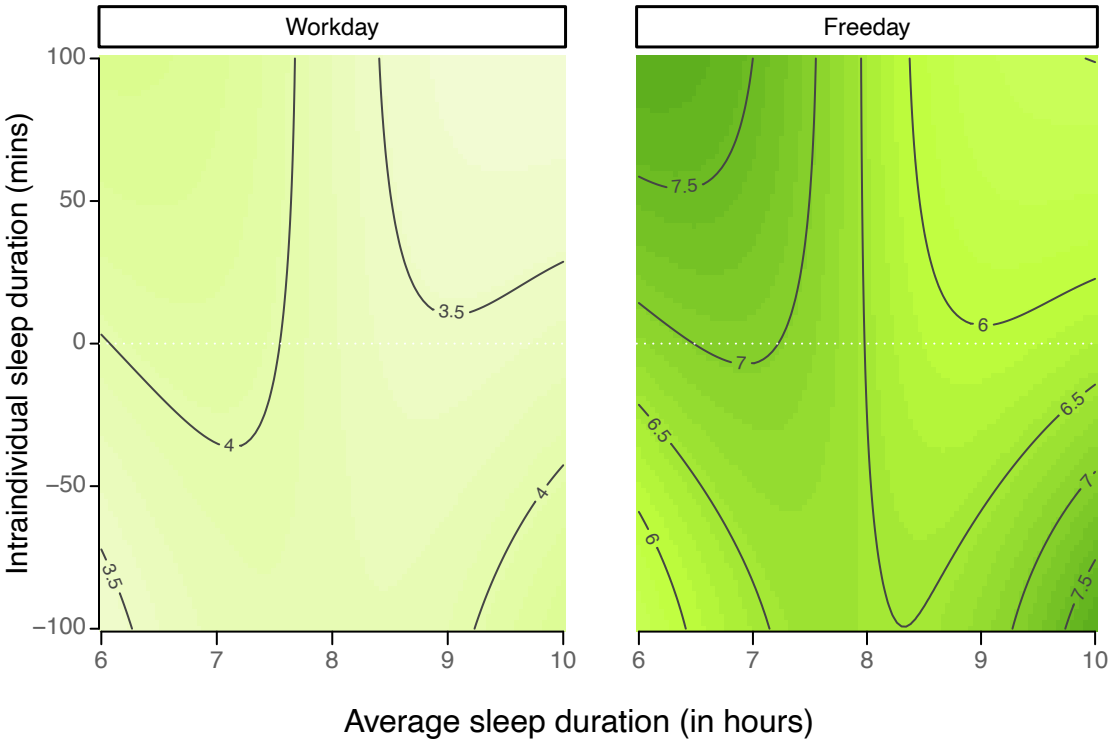

Figure S4. Contour plot showing how variation in sleep duration predicts how socially active one is the following day (number of 30-minute periods), given a three-way interaction between intraindividual sleep duration, average sleep duration, and type-of-day. Increasing darkness of green colour represents increasing probably of reporting social activity. The y-axis represents within-subject mean-centered sleep duration, with positive values signifying greater than subject-mean sleep duration and negative values representing less than subject-mean sleep duration. The x-axis represents the change in relationship across participants with different average sleep duration.

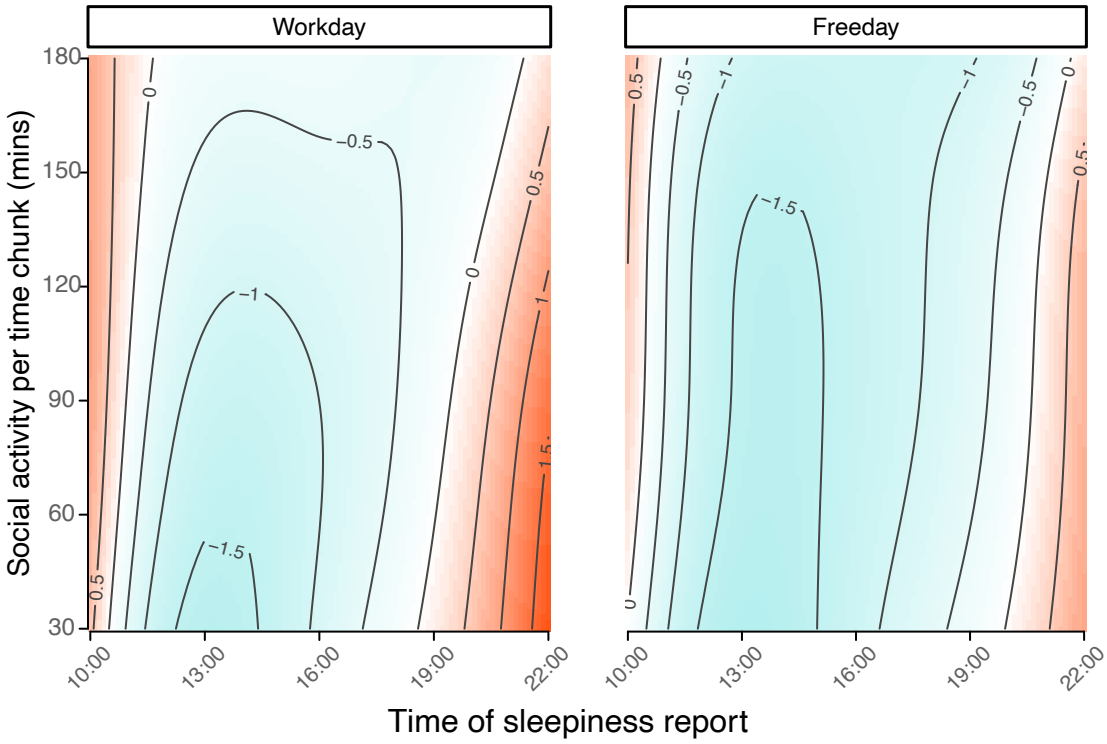

Figure S5. Contour plot showing how the amount of recent social activity (during the previous 3 hours) predict intraindividual sleepiness (compared to within-subject means) given time-of-day and type-of-day. Darker red represents increased sleepiness, and darker blue represents increased alertness. Values within the plot represent intraindividual sleepiness (i.e. 0 represents an individuals' average). The y-axis represents the number of 30 minute periods (per 3-hour time chunk) reported as social activity. The x-axis represents different times of day. To increase ease of interpretability, predicted 30 minute periods of social activity have been converted to predicted minutes of social activity.

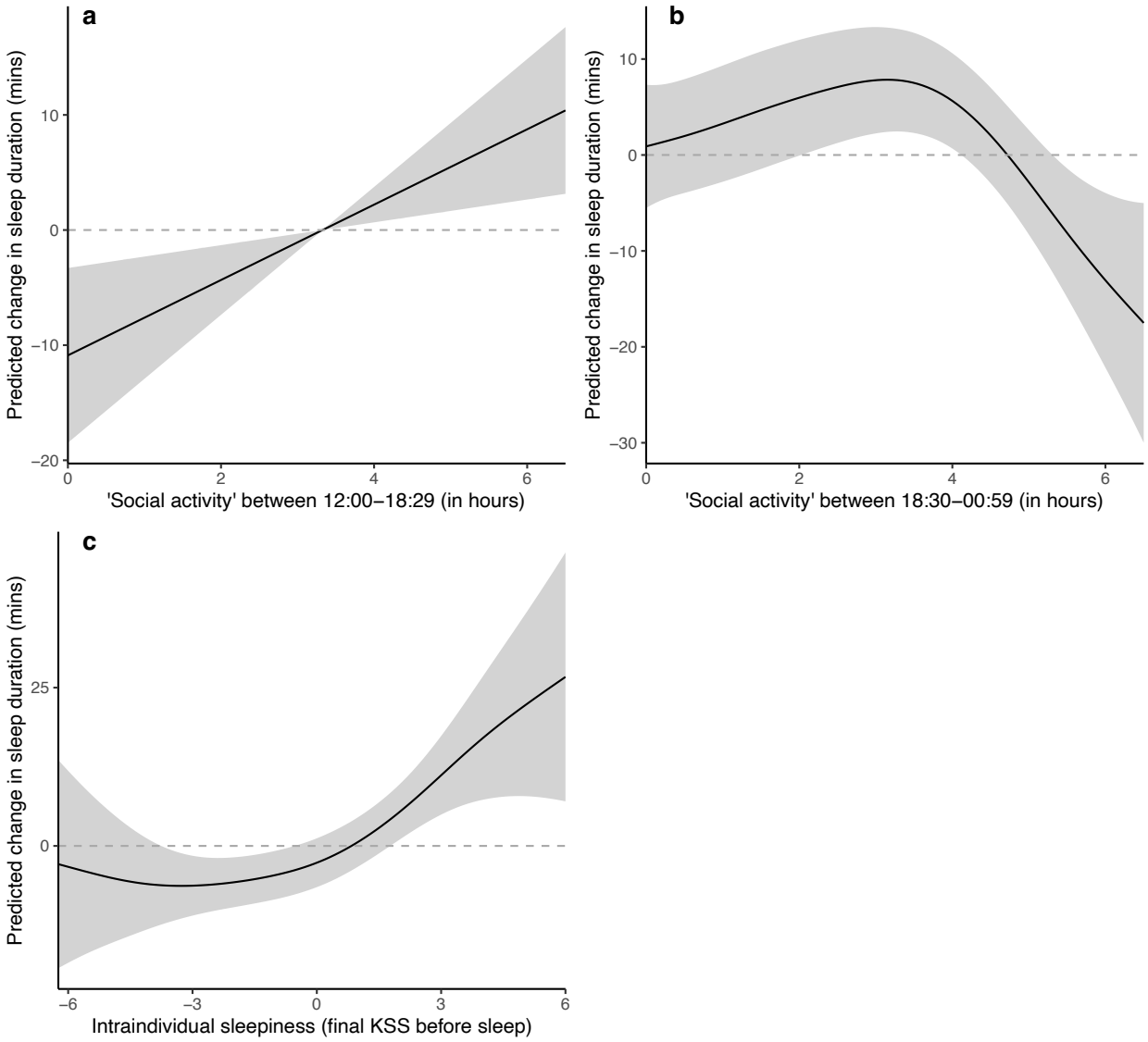

Figure S6. Visualizations of significant predictors of change in intraindividual sleep duration (sleep duration centered around an individuals' own average) in the GAMM model presented in Table S11. Figure S6a shows the positive relationship between social activity between 12:00-18:29 and subsequent change in intraindividual sleep duration. Figure S6b shows a curvilinear relationship of social activity between 18:30-00:59 and subsequent change in interindividual sleep duration. Figure S6c shows a curvilinear relationship between intraindividual sleepiness reported before sleep (relate to individuals' overall average) and subsequent change in interindividual sleep duration.

Table S1. Descriptive statistics

Demographic data reported by participants at baseline		**N**	**%**
Having children living at home		324	57.75
Shared household (with another adult)		488	76.61
Job specification:			
	Social Services	196	30.58
	Technical Services	199	31.05
	Care and welfare	170	26.52
	Call centre	76	11.86
Outcome variable during entire study		**Mean**	**SD**
Mean sleepiness (Karolinska Sleepiness Scale)			
	On workdays	4.22	2.03
	On freedays	3.98	2.18
Mean sleep duration (mins)			
	Preceding workdays	450.00	63.46
	Preceding freedays	513.25	84.02
Mean sleep quality			
	Preceding workdays	3.90	0.98
	Preceding freedays	4.02	0.96
Mean reported quantity (per day) of 30min social activity periods			
	On workdays	1.37	2.66
	On freedays	3.90	5.12
Mean reported quantity (per day) of 30min working periods			
	On workdays	14.53	3.77
	On freedays	0.07	0.35

Note. Values were calculated over the entire dataset, not accounting for differences in missing data between participants. These values additionally represent those following the data preparation procedures outlined in the *Missing Data* subsection of the main manuscript though prior to imputation.

Table S2. Description and examples for the 13 activity types

Activity	**Description or example**
Work	• Ordinary work in main job • Overtime work in main job • Other time spent at the workplace • Work travel
Work from home	• Work in main job that takes place at home
Household work	• Cooking, baking • Washing dishes, drying • Cleaning of home • Clothes washing and ironing • Maintenance of land and garden • Walking the dog, care of pets • Repairs and DIY in the home • Repairs and maintenance of vehicles • Unspecified maintenance • Building work, Reconstruction
Care of Children	• Supervision and help to children • Helping with homework • Playing with children • Talking to children • Reading to children • Parent meeting • Presence at children's activities • Other childcare activity
Care of others	• Helping adults in own household • Helping children in other households • Other types of help to other households • Visiting patients at hospital
Personal care	• Lying in bed because of illness • Personal hygiene, putting on / taking off clothes • Sauna, solarium • Other personal care
Mealtime	• Mealtime • Coffee, refreshments
Sleep	• Night sleep • Nap
Rest	• Rest, mediating, doing nothing

Table S2 continued

Free time	• Walking • Traveling • Hunting, fishing • Sport, physical activity • Outdoor life • Day trips • Club activity • Religious activity • Watching sport • Visiting the cinema • Theatre, concert, exhibition, museum • Visiting the library • Other entertainment
Social activity	• Party, celebration • Visiting friends and family • Visit by friends and family • Conversation, telephone conversation • Visit to restaurant, café, bar • Dancing, nightclub • Other social gathering
Own time	• Watching TV or video • Listening to the radio • Reading (newspaper, book) • Handicrafts, e.g. knitting • Using a computer (not work) • Technical hobbies, collecting • Playing games alone • Listening to music, CDs, records, tapes • Practicing an instrument • Other hobbies
Other	• Uncodable activity

Table S3. Logistic GAMM comparisons assessing the best model configuration for predicting the incidence of future social activity from within-subject changes in sleepiness

Model	New predictors over previous significant model	Deviance explained	AIC	EDF	fREML	Compared against	p-value
Baseline		18.1%	-	4	59641		
a	Sleepiness	20.3%	-	6	59039	Baseline	< .001
b	Sleepiness [by workday]	20.4%	-	8	59023	a	< .001
c	**Sleepiness x ToD**	**20.8%**	**-**	**10**	**58886**	**b**	**< .001**
d	Sleepiness x ToD [by workday]	22.2%	-	14	59090	c	1

Note. $N_{subject}$ = 484, N_{chunk} = 50148. GAMM = generalised additive mixed-effect model, EDF = estimated degrees of freedom, fREML = fast Restricted maximum likelihood score, ToD = time-of-day. All models compared had a quasibinomial response distribution (link = logit). AIC could thus not be calculated for models with a quasibinomial response distribution. The baseline model included a parametric effect of workday, a cubic regression smooth of ToD, random intercepts for participants, and an AR1 covariance structure. An 'x' between two variables represents the addition of the estimated interaction effect between the two variables, while 'by workday' represents that the estimated effect of the new predictor was calculated separately depending on the type-of-day. Bold rows represent models that best fit the data (compared using chi-square test on differences in fREML score).

Table S4. GAMM comparisons assessing the best model configuration for predicting the amount of future social activity (in individuals who socialise at least once) from within-subject changes in sleepiness

Model	New predictors over previous significant model	Deviance explained	AIC	EDF	fREML	Compared against	p-value
Baseline		13.5%	22873	3	6017		
a	Sleepiness	16.2%	22655	6	5913	baseline	< .001
b	Sleepiness [by workday]	16.2%	22654	8	5914	a	1
c	Sleepiness x ToD	16.9%	22593	8	5887	a	< .001
d	**Sleepiness x ToD [by workday]**	**17.3%**	**22573**	**10**	**5879**	**c**	**< .001**

Note. $N_{subject}$ = 463, N_{chunk} = 6513. GAMM = generalised additive mixed-effect model, AIC = Akaike information criterion, EDF = estimated degrees of freedom, fREML = fast restricted maximum likelihood score, ToD = time-of-day. All models had a tweedie response distribution. The baseline model included a parametric effect of workday, a cubic regression smooth of ToD, and random intercepts for participants. An 'x' between two variables represents the addition of the estimated interaction effect between the two variables, while 'by workday' represents that the estimated effect of the new predictor was calculated separately depending on the type-of-day. Bold rows represent models that best fit the data (compared using AIC and chi-square test on differences in fREML score).

Table S5. Logistic GAMM comparisons assessing the best model configuration for predicting the incidence of next-day social activity from within-subject changes in sleep duration

Model	New predictors over previous significant model	Deviance explained	AIC	EDF	fREML	Compared against	p-value
Baseline		**19.5%**	**9199**	**3**	**11978**		
a	Sleep duration	19.5%	9199	5	11978	baseline	1
b	Average sleep duration	19.5%	9200	5	11978	baseline	.99
c	Average sleep duration x sleep duration	19.5%	9203	10	11978	baseline	1

Note. $N_{subject}$ = 455, N_{day} = 7889. GAMM = generalised additive mixed-effect model, AIC = Akaike information criterion, EDF = estimated degrees of freedom, fREML = fast restricted maximum likelihood score. All models had binomial response distribution (logit link). The baseline model included a parametric effect of workday, random intercepts for participants, and an AR1 covariance structure. An 'x' between two variables represents the addition of the estimated interaction effect between the two variables, while 'by workday' represents that the estimated effect of the new predictor was calculated separately depending on the type-of-day. Bold rows represent models that best fit the data (compared using AIC and chi-square test on differences in fREML score).

Table S6. GAMM comparisons assessing the best model configuration for predicting the amount of next-day social activity (in individuals who socialise at least once) from within-subject changes in sleep duration

Model	New predictors over previous significant model	Deviance explained	AIC	EDF	fREML	Compared against	p-value
Baseline.		29.7%	16145	3	3638		
a	Sleep duration	29.7%	16145	5	3638	baseline	1
b	Average sleep duration	29.7%	16142	5	3635	baseline	.04
c	**Average sleep duration x sleep duration**	**30.0%**	**16136**	**10**	**3635**	**b**	**.78**

Note. $N_{subject}$ = 438, N_{day} = 3222. GAMM = generalised additive mixed-effect model, AIC = Akaike information criterion, EDF = estimated degrees of freedom, fREML = fast restricted maximum likelihood score. All models had a tweedie response distribution. The baseline model included a parametric effect of workday and random intercepts for participants. 'by workday' represents that the estimated effect of the new predictor was calculated separately depending on the type-of-day. Bold rows represent models that best fit the data (compared using AIC and chi-square test on differences in fREML score).

Table S7. GAMM comparisons assessing the best model configuration for predicting within-subject changes in future sleepiness from the amount of social activity (in individuals who socialise at least once).

Model	New predictors over previous significant model	Deviance explained	AIC	EDF	fREML	Compared against	p-value
Baseline.		30.5%	22945	4	11506		
a	Social activity	31%	22895	6	11478	baseline	< .001
b	Social activity [by workday]	31.2%	22874	8	11469	a	< .001
c	Social activity x ToD	33.3%	22716	10	11396	b	< .001
d	**Social activity x ToD [by workday]**	**33.6%**	**22699**	**12**	**11389**	**c**	**< .001**

Note. $N_{subject}$ = 463, N_{chunk} = 5929. GAMM = generalised additive mixed-effect model, AIC = Akaike information criterion, EDF = estimated degrees of freedom, fREML = fast restricted maximum likelihood score. All models had a Gaussian response distribution. The baseline model included a parametric effect of workday, a cubic regression smooth of ToD, and random intercepts for participants. An 'x' between two variables represents the addition of the estimated interaction effect between the two variables, while 'by workday' represents that the estimated effect of the new predictor was calculated separately depending on the type-of-day. Bold rows represent models that best fit the data (compared using AIC and chi-square test on differences in fREML score).

Table S8. GAMM comparisons assessing the best model configuration for predicting within-subject changes in subsequent sleep duration from the amount of social activity (in individuals who socialise at least once).

Model	New predictors over previous significant model	Deviance explained	AIC	EDF	fREML	Compared against	p-value
Baseline.		1.48%	31153	3	15570		
a	**Social activity**	**1.96%**	**31145**	**5**	**15567**	**baseline**	**.06**
b	Social activity [by workday]	1.95%	31146	7	15567	a	1

Note. $N_{subject}$ = 437, N_{day} = 2757. GAMM = generalised additive mixed-effect model, AIC = Akaike information criterion, EDF = estimated degrees of freedom, fREML = fast restricted maximum likelihood score. All models had a Gaussian response distribution. The baseline model included a parametric effect of workday and random intercepts for participants. 'by workday' represents that the estimated effect of the new predictor was calculated separately depending on the type-of-day. Bold rows represent models that best fit the data (compared using AIC and chi-square test on differences in fREML score).

Table S9. Logistic GAMM comparisons assessing the best model configuration for predicting the incidence of next-day social activity from within-subject changes in sleep quality

Model	New predictors over previous significant model	Deviance explained	AIC	EDF	fREML	Compared against	p-value
Baseline		19.1%	9234	3	11995		
a	**Sleep quality**	19.1%	**9229**	**5**	**11993**	**baseline**	**.106**

Note. $N_{subject}$ = 454, N_{day} = 7896. GAMM = generalised additive mixed-effect model, AIC = Akaike information criterion, EDF = estimated degrees of freedom, fREML = fast restricted maximum likelihood score. All models had binomial response distribution (logit link). The baseline model included a parametric effect of workday, random intercepts for participants, and an AR1 covariance structure. An 'x' between two variables represents the addition of the estimated interaction effect between the two variables, while 'by workday' represents that the estimated effect of the new predictor was calculated separately depending on the type-of-day. Bold rows represent models that best fit the data (compared using AIC and chi-square test on differences in fREML score).

Table S10. GAMM comparisons assessing the best model configuration for predicting the amount of next-day social activity (in individuals who socialise at least once) from within-subject changes in sleep quality

Model	New predictors over previous significant model	Deviance explained	AIC	EDF	fREML	Compared against	p-value
Baseline.		**31%**	**15600**	**3**	**3611**		
a	Sleep quality	31%	15600	5	3611	baseline	1

Note. $N_{subject}$ = 437, N_{day} = 3214. GAMM = generalised additive mixed-effect model, AIC = Akaike information criterion, EDF = estimated degrees of freedom, fREML = fast restricted maximum likelihood score. All models had a tweedie response distribution. The baseline model included a parametric effect of workday and random intercepts for participants. 'by workday' represents that the estimated effect of the new predictor was calculated separately depending on the type-of-day. Bold rows represent models that best fit the data (compared using AIC and chi-square test on differences in fREML score).

Table S11. GAMM showing the association between the amount of social activity (in individuals who socialise at least once) and subsequent sleep duration

A. parametric coefficients	Estimate	Std. Error	t-value	p-value
Intercept	17.02	3.59	4.74	< .001
Workday	14.31	3.16	4.52	< .001
B. smooth terms	**EDF**	**RefDF**	**F-value**	**p-value**
Social activity [early]	0.00	9	.000	1
Social activity [mid]	.8878	9	.88	.003
Social activity [late]	2.610	9	1.10	.008
KSS intraindividual	2.079	9	1.47	< .001
Random intercept for participant	0.00	428	0.00	1

Note. GAMM = generalised additive mixed-effect model, ToD = Time-of-day, EDF = effective degrees of freedom, RefDF = reference degrees of freedom. All smooth terms are centered at zero. P-values for smooth terms represent a test of whether the term is different to a flat line.

Table S12. GAMM of the association between preceding amount of social activity and future sleepiness at different times of day controlling for prior sleepiness

A. parametric coefficients	Estimate	Std. Error	t-value	p-value
Intercept	-0.26	0.04	-6.67	< .001
Workday	0.26	0.05	5.40	< .001
B. smooth terms	**EDF**	**RefDF**	**F-value**	**p-value**
Social activity [Workday]	0.72	4	0.35	0.151
Social activity [Freeday]	0.00	4	0.00	1
ToD	2.98	3	365.26	< .001
Social activity x ToD [Workday]	3.54	12	3.37	< .001
Social activity x ToD [Freeday]	5.02	12	6.78	< .001
Prior KSS intraindividual	3.84	4	281.68	< .001
Random intercept for participant	127.90	566	0.33	< .001

Note. GAMM = generalised additive mixed-effect model, ToD = Time-of-day, EDF = effective degrees of freedom, RefDF = reference degrees of freedom. Smooth terms with categorical moderators, as specified in square brackets, represent separate smoothing terms given the moderator's condition. An 'x' between two variables represents a continuous interaction. All smooth terms are centered at zero. P-values for smooth terms represent a test of whether the term is different to a flat line.