Daily associations between sleep and pain in patients with chronic musculoskeletal pain

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1. Abstract

Patients with chronic pain commonly report sleep problems, and the evidence for a relationship between sleep disturbance and pain seems robust. The day-to-day associations between these constructs are less well studied, particularly with objective sleep measures as actigraphy. Moreover, the concurrent presence of negative affective symptoms, as well as seasonality effects at extreme latitudes may complicate it further. Here, we studied 56 patients with chronic primary musculoskeletal pain conditions, contributing data in two separate seven-day data-collection periods, during summer and winter respectively. The effect of self-reported sleep quality, and actigraphy measured sleep duration, efficiency and timing on next-day pain, as well as the effect of pain on the same sleep indices were estimated by generalized linear mixed regression models. The models were additionally adjusted for age, sex, education, data collection period, weekend, season and mental distress, with the latter two also specified as moderators. We observed a significant effect of pain as predictor of next-night sleep quality (p=.003), and marginally of next-night sleep duration (p=.079). Conversely, sleep quality tentatively predicted next-day pain (*p*=.063). No other day-to-day associations were present. Mental distress was the strongest predictor of pain, but it did not modify the sleep-pain associations, nor did season. In conclusion pain, sleep quality and mental distress are closely related, underscoring the importance of encompassing this complexity in assessment and treatment of chronic pain patients.

Keywords: chronic musculoskeletal pain, insomnia, mental distress, actigraphy, multilevel modelling, season

2. Introduction

The evidence for a bidirectional pain-sleep relationship seems robust (Alfoldi, Wiklund, & Gerdle, 2014; Gerhart et al., 2017; Tang, Wright, & Salkovskis, 2007), yet the strength and direction of such associations within a shorter daily time-frame among pain patients are less well studied. Studies examining day-to-day associations between sleep and pain, suggest a dynamic relationship where worse pain may undermine next-night sleep, and poor sleep may aggravate pain the following day, most consistently reported for the effect of self-reported sleep quality on next-day pain (Alsaadi, McAuley, Hush, Lo, et al., 2014; Bromberg, Gil, & Schanberg, 2012; Edwards, Almeida, Klick, Haythornthwaite, & Smith, 2008; Gerhart et al., 2017; Lewandowski, Palermo, De la Motte, & Fu, 2010; O'Brien et al., 2011; Tang, Goodchild, Sanborn, Howard, & Salkovskis, 2012; Valrie, Gil, Redding-Lallinger, & Daeschner, 2008; Whibley, Braley, Kratz, & Murphy, 2019). Studies assessing sleep with actigraphy, indicate minor to non-existent effects of pain on next night total sleep time (TST), sleep efficiency (SE), wake after sleep onset (WASO) and sleep onset latency (SOL) (Lewandowski et al., 2010; O'Brien et al., 2011; Tang et al., 2012; Whibley et al., 2019). An exception is a study by Alsaadi (2014) where increased pain during the day predicted increased WASO and reduced SE the following night. Conversely, the effect of actigraphy-recorded sleep measures on pain levels the following day seems more variable, as effects of TST, SE and / or WASO have been reported by some (Alsaadi, McAuley, Hush, Lo, et al., 2014; Lewandowski et al., 2010; Tang et al., 2012), but not by others (O'Brien et al., 2011; Whibley et al., 2019).

Previous studies of daily sleep-pain associations have, to our knowledge, not included measures of sleep timing, although delayed sleep timing, as a trait, has been associated with increased pain (Merikanto et al., 2014; Zhang, Duffy, de Castillero, & Wang, 2018). In the present study we included the midpoint of sleep as a measure of sleep timing, and a variable

of interest. Sleep timing in the general population may be delayed in winter at higher latitudes (Friborg, Rosenvinge, Wynn, & Gradisar, 2014; Johnsen, Wynn, & Bratlid, 2012), which is relevant for the current study conducted in the sub-arctic. In a recently published study based on the same dataset as the current study, we unexpectedly observed a delay in sleep timing and mild increases in pain levels in summer compared to winter. (Abeler, Sand, Friborg, & Bergvik, 2020). The role of seasonality is in general an understudied factor in the associations between sleep and pain in pain populations.

A further complicating factor in studies of pain and sleep, is the substantial comorbidity of depression in chronic pain (Bair, Robinson, Katon, & Kroenke, 2003), so far the role of affective symptoms in day-to-day sleep-pain associations seems inconclusive, as some studies find a contribution of depressed mood to daily sleep and / or pain (Bromberg et al., 2012; Edwards et al., 2008; Lewandowski et al., 2010; Tang et al., 2012) whereas others do not (Alsaadi, McAuley, Hush, Lo, et al., 2014; Whibley et al., 2019). Studies examining if affective symptoms may modify any day-to-day associations have reported moderating effects in one or both directions (Bromberg et al., 2012; O'Brien et al., 2011; Valrie et al., 2008), or no moderation (Lewandowski et al., 2010). We therefore included affective symptoms both as a covariate and as a moderator in order to examine these potential respective directions.

The aim of this study was to examine day-to-day bidirectional relationships between sleep and pain among patients with chronic primary musculoskeletal pain by actigraphy and self-report sleep measures. More specifically, the objectives were to estimate whether daytime pain predicts self-reported sleep quality and actigraphy-recorded TST, SE and sleep-timing the following night, and whether the same sleep indices predict next-day pain levels. A second objective was to examine whether such day-to-day relationships were modified by season or daily fluctuations in mental distress.

3. Method

Study sample

Patients attending the outpatient clinic at the Rehabilitation Department or the Pain Clinic, both at the University Hospital of North Norway (UNN), and residing in the sub-arctic municipality of Tromsø (69° North), were invited by mail. Patients aged 18-65 years and diagnosed with chronic primary musculoskeletal pain (CMP), defined by selected ICD-10 codes, at the respective clinics during the last 18 months were included. As these conditions are usually treated in primary health care, the patients referred to specialist clinics are expected to be those with more persistent and longstanding (chronic) conditions. Patients were excluded if they had a major medical condition (cancer, inflammatory-, symptomatic heart or lung-, metabolic- or endocrine disease), neurologic condition, mental health condition, were drug abusers, pregnant or participated in ongoing intervention studies. Patients diagnosed with sleep disorders other than insomnia were also excluded.

Procedure

All participants provided data during two separate data-collection periods; summer (May-July, 2016 and 2017) and winter (November-February, 2016-2017). A nonrandomized counterbalancing scheme was employed, with half of participants entering the first data-collection period during the summer and the other half during the winter. Each data-collection period entailed one week of continuous actigraphy recording combined with daily paper and pencil questionnaire registrations (the first and the second data-collection periods are entitled T1 and T2, respectively). Perceived sleep quality the previous night was scored upon awakening in the morning, whereas mental distress and pain intensity experienced during the day were scored at bedtime in the evening. The first visit was scheduled at UNN, where subjects received detailed information, completed baseline questionnaires, and had the actigraph attached. Participants returned the actigraph and the completed questionnaires after

7 days. Participants were instructed to conduct their daily life as usual during the study periods without restrictions to sleep schedule, habitual medication or daily activities.

Measurements

Baseline measurements

Demographic variables: Age, gender, educational level (high school vs higher education), marital status (single vs married/cohabiting), employment (no, yes), receiving social benefit (no, yes) and self-rated perceived financial situation (poor/medium vs good) were registered.

Insomnia Severity Index (ISI): The ISI includes seven items assessing problems with sleep onset, maintenance and early morning awakening, as well as daytime functioning, sleep satisfaction and worrying about sleep during the previous 14 days (Charles M. Morin, 1993). Items are rated on a five-point Likert scale (0–4), with higher scores indicating worse insomnia (total range 0- 28). A cut off score of >14 suggests clinical insomnia (C. M. Morin, Belleville, Belanger, & Ivers, 2011), and ISI is a recommended research measure of insomnia symptoms (Buysse, Ancoli-Israel, Edinger, Lichstein, & Morin, 2006).

Pittsburg Sleep Quality Index (PSQI): The PSQI comprises 19 items probing sleep quality and disturbance during the previous month across seven components: 1) subjective sleep quality, 2) sleep latency 3) sleep duration 4) habitual sleep efficiency 5) sleep disturbance, 6) sleep medication and 7) daytime dysfunction. Each component receives a score of 0-3 based on a scoring algorithm, yielding a global score with a range of 0-21 (higher scores indicate more disturbed sleep), where a value > 5 indicates poor sleep quality (Buysse, Reynolds, Monk, Berman, & Kupfer, 1989). The PSQI is a recommended research measure of global sleep quality (Buysse et al., 2006).

Brief Pain Inventory (BPI): The pain severity items of the Brief Pain Inventory short form were applied (Cleeland, 1991; Klepstad et al., 2002). Participants estimated their worst,

least and average pain during the last week, as well as their current pain. Each of the four items were rated on an 11-point numeric rating scale (NRS) (from 0- no pain to 10- worst imaginable pain). We used the mean score of these four items in the analyses of pain severity.

Hopkins Symptom Checklist 25 (HSCL 25): The HSCL 25 is a self-report inventory designed to screen for symptoms of depression and anxiety, indicating mental distress the last 14 days (Derogatis, Lipman, Rickels, Uhlenhuth, & Covi, 1974). The 25 items are rated on a 4-point Likert scale (from 1-not at all to 4-very much), from which a global average score is calculated (range: 1-4).

Daily measurements

Sleep quality: Self-reported sleep quality the previous night was rated on a visual analog scale (VAS) in the morning ("last night I would describe as a good (0) - poor (100) night sleep). The term "sleep quality" (SQ) will pertain to this self-reported measure throughout the rest of this paper.

Brief Pain Inventory (BPI): Similar to the baseline measures, the BPI severity items with the timespan modified from "last week" to "today" were applied for the daily measures. Participants estimated their worst, least and average pain during that day, as well as their current pain before bedtime in the evening. We used the mean score of these four items in the analyses of pain severity.

Hopkins Symptom Checklist (HSCL)-10: The HSCL-10 comprises 10 of the original depression and anxiety items of the Hopkins Symptoms Checklist with good score reliability (Strand et al., 2003). Patients rated their mood according to the current day (modified from last week). The scoring was similar as for HSCL-25.

Actigraphy: The Actiwatch Spectrum Plus device, which is validated in musculoskeletal pain patients (Alsaadi, McAuley, Hush, Bartlett, et al., 2014), was used to register movement, and post-processing of the raw actigraphy data was conducted in the

Actiware version 6.0.9 software (both Phillips Respironics, Inc., Murrysville, PA). The Actiwatch was worn on the non-dominant wrist, only to be removed shortly during shower or if required at work (e.g. due to hygiene or safety considerations). Off-wrist periods were excluded from the analyses. The participants were instructed to register time of first sleep attempt and final morning awakening in the accompanying sleep diary and by pushing an event button on the actigraph. Rest intervals were scored by a trained research assistant (psychology student) supervised by a specialist in clinical neurophysiology (first author). Both were blinded to participant identity. A significant sustained reduction or increase in activity defined the start and end of a rest interval, respectively. If these two primary criteria were insufficient to define the rest interval, the event marker, sleep diary information and light intensity were additionally consulted. Sleep was scored automatically by the software within the defined rest interval, with the specification of 30 sec epochs, medium sensitivity (40 activity counts/ epoch) for activity detection and an inactivity threshold of 10 minutes to define sleep onset and offset. The variables total sleep time (TST, duration of sleep within the sleep interval) and sleep efficiency (SE, total sleep time/ time in bed) were recorded for each night. The midpoint of sleep $\left(\frac{sleep\ onset-sleep\ offset}{2}\right)$ was calculated as a measure of sleep timing (Roenneberg et al., 2004).

Statistical procedure

The IBM SPSS 25 was used for all analyses. Summary statistics were used to present demographic and baseline characteristics, separately for the first and second attendance.

Generalized linear mixed regression models were fit to examine the association between the bidirectional day-to-day observations. The dataset was rearranged such that each participant's daily measurements for the same and the next day appeared on the same row, thus allowing analyses of the temporal correlations between the current and the next day measures. The repeated data included several layers of dependency that was accounted for by

including random coefficient variables in addition to an estimation of any remaining residual correlational patterns. Two random intercept parameters were added: one for the seven-day repeated measures for each subject, and another, if substantially contributing, for the dependency in these measures across the two data-collection periods, T1 and T2. A reduction in the Bayesian Information Criterion (BIC) was deemed necessary to retain the second random intercept effect. We additionally estimated, if significant, a first order autoregressive covariance matrix for the fitted residual scores accounting for any left-over declining dependency. The standard errors were estimated using the robust sandwich estimator due to some heteroscedasticity in the error scores. The alpha level was set to .05.

We fitted separate regression models for the effects of the daily sleep measures SQ, TST, SE and midsleep on the next day pain level, as well as models for the effect of daily pain level on the same sleep variables the following night. The crude models were adjusted for the covariates age, sex, education, data-collection period, season and daily mental distress. The models with sleep as outcome were additionally adjusted for weekday vs. weekend. Season could be included as a covariate adjustment factor due to the seasonal study design, and the modifying effect of mental distress and season on the sleep-pain associations were assessed by sequentially including the interaction term predictor × HSCL and predictor × season. These higher-order interaction terms were only kept in the models if statistically significant.

Ethical approval

The study was approved by the Regional Committee for Medical and Health Research Ethics, Office North (reference number 2015/2473). Written informed consent was obtained from all participants.

4. Results

A total of 401 patients were invited to participate, of whom 91 responded. Based on criteria, 28 patients were excluded and 7 patients either moved or withdrew. The final sample consisted of 56 patients, of whom 53 participated at both data-collection periods. The repeated data collection yielded 763 individual observations for the SQ-pain and pain-actigraphy analyses (7 per participant per week), and 654 observations for the actigraphy-pain and pain-SQ analyses (6 per participant per week).

The sociodemographic characteristics are presented in Table 1, and the distribution of pain diagnoses is shown in Table 2. Table 3 presents descriptive data for the baseline, daily questionnaire and actigraphy recordings collected at T1 and T2 separately. Seasonality in this patient group has been described in a previous paper (Abeler et al., 2020) The ISI cut-score indicated possible clinical insomnia in 23 (41.1 %) and 13 (24.5 %) patients, and the PSQI indicated poor sleep quality in 43 (76.8 %) and 41 (77.4%) patients at T1 and T2, respectively.

The effect of daytime pain on the next-night SQ and TST are presented in Table 4. An increase of one point on the pain severity scale was associated with a close to 3-point deterioration in the SQ scale the next night (p adjusted= 0.003). Higher daytime pain ratings marginally predicted a longer TST the following night (a one-point increase in pain associated with about four minutes longer TST, p crude = .015); however, it turned non-significant in the full model (p = .079) model. There were no significant effects of daytime pain on sleep timing or sleep efficiency the next night (Supplementary Table 1). To assess whether the effect of daytime pain was still detectable on sleep quality two nights later, a post hoc test was conducted. In this analysis the effect was attenuated, but still statistically significant (*beta*=1.98, *CI*=0.60-3.36, *p*=.005)

The effect of SQ and TST on next day pain are presented in Table 5. Poorer SQ was associated with increased pain the next day, however a 10-point change on the 100-point VAS scale of SQ was associated with a minute 0.03 point change on the 11-point scale in pain severity. The effect was significant in the crude (p = .015), but not in the full model (p = .063). There was a nonsignificant trend towards a negative association between TST and next-day pain (p crude = .078, and p adjusted = .112). Sleep timing and sleep efficiency were not associated with pain levels the next day (Supplementary Table 2). Taken together, sleep variables predicted only a minor part of pain the next day.

None of the interaction terms in any models revealed a significant modifying effect of season or mental distress. The observed bidirectional associations were thus comparable across season (summer and winter) and across different levels of mental distress.

5. Discussion

The present study assessed the strength and direction of daily associations between sleep indices (sleep quality (SQ), sleep efficiency (SE), total sleep time (TST), and midsleep) and pain measures in patients with chronic primary musculoskeletal pain through a repeated measures design. Our main finding includes a clear observation of current pain as a predictor of next-night poorer SQ. Daily pain measures also predicted increases in next-night increased TST in the crude model, but turned into a marginal and non-significant effect in the fully adjusted model. A small effect of SQ on pain was found in the crude model, but turned non-significant after adjustment. Another main finding was that bidirectional sleep-pain associations were not modified by daily mental distress or by season.

In the analyses of daily associations between SQ and pain, mental distress was the single variable responsible for weakening this relationship, confirming its common role in both sleep and pain. It is worth mentioning that the magnitude of this adjusted association, i.e., the beta coefficient, was not much different from the crude magnitude; hence, the

relatively small sample size may have rendered this test underpowered, thus missing this effect as significant. An effect of sleep quality on next day pain seems to be the most consistently reported effect in previous studies of adults with chronic pain, adjusting for baseline affective symptoms (Alsaadi, McAuley, Hush, Lo, et al., 2014; O'Brien et al., 2011; Whibley et al., 2019) or not adjusted for such symptoms (Gerhart et al., 2017). In the current study, adjusting for daily level of mental distress rendered SQ non-significant as a predictor of next-day pain. Additionally, cognitive processes in patients with pain, such as tendencies to build appraisal of sleep quality in part on next-day pain levels, and attribute sleep quality to preceding pain more strongly than the opposite (Blagestad, Pallesen, Gronli, Tang, & Nordhus, 2016; Ramlee, Afolalu, & Tang, 2018), may influence associations between self-reported sleep and pain.

Sleep duration was the only actigraphy measure with a tendency to exhibit associations with pain, such that increased level of pain during the day was followed by increased total sleep duration the next night and increased sleep duration was followed by reduced pain the next day. These tentative associations could allude to a beneficial compensatory mechanism, however, this result remains exploratory and suitable for a future pain study that is better powered by recruiting more patients. Similar findings have been reported in perimenopausal women, where pain experienced during the course of the night was associated with increased sleep duration, albeit in combination with reduced sleep efficiency (Kravitz et al., 2015). Other studies did not find an association between daily sleep duration and pain (Alsaadi, McAuley, Hush, Lo, et al., 2014; O'Brien et al., 2011; Whibley et al., 2019), except in a study of adolescents which reported increased pain after longer sleep duration (Lewandowski et al., 2010). Taken together, there thus does not seem to be strong evidence for daily associations between actigraphy measured sleep duration and pain levels in adult patients with chronic pain.

Sleep timing has, to our knowledge, not previously been probed in day-to-day studies of sleep and pain. In the current study, sleep timing, assessed by the midpoint of sleep, was not associated with next-day pain, or vice-versa. Circadian rhythms are gaining attention in the field of sleep and pain research, since both processes are under circadian control (Palada, Gilron, Canlon, Svensson, & Kalso, 2020), and late chronotype is considered a trait feature which is proposedly associated with musculoskeletal pain conditions (Kantermann, Theadom, Roenneberg, & Cropley, 2012; Knutson & von Schantz, 2018; Merikanto et al., 2014; Zhang et al., 2018). Seasonal rhythms with delay of sleep-wake timing in winter are reported in healthy and general populations (Arendt, 2012; Friborg et al., 2014; Johnsen, Wynn, Allebrandt, & Bratlid, 2013), however in a previous study of the current clinical sample we observed a phase delay, and concurrent slight increase in pain severity in summer (Abeler et al., 2020). In the current study we could not confirm a modifying effect of season on the daily sleep-pain associations, yet the association between sleep timing and pain severity in clinical samples, and the possible benefits of targeting sleep timing in sleep behavioral approaches in pain patients, seem understudied.

In this study, the daily level of mental distress, explained unique variance in daily pain severity and self-reported sleep quality, however, none of the bidirectional sleep-pain associations were modified by levels of mental distress. Symptoms of depression are common in chronic pain patients, correlating with both sleep disturbance and pain severity (Abeler, Friborg, Engstrom, Sand et al., 2020 in press; Alfoldi et al., 2014; Bair et al., 2003; Bonvanie, Oldehinkel, Rosmalen, & Janssens, 2016; Bromberg et al., 2012; Lewandowski et al., 2010). In corroboration with the current study, most day-to-day studies that include psychological distress as a covariate, suggest associations with next-day sleep quality and / or pain (Bromberg et al., 2012; Lewandowski et al., 2010; O'Brien et al., 2011; Tang et al., 2012; Valrie et al., 2008), but not with objective sleep measures (Alsaadi, McAuley, Hush, Lo, et

al., 2014; Lewandowski et al., 2010), thus pointing to different measurement modalities (objective vs subjective) as a contributing factor. The studies probing psychological distress as a moderator have observed such effects on bidirectional sleep-pain associations (O'Brien et al., 2011), solely on the association of sleep quality on next day pain (Bromberg et al., 2012; Valrie et al., 2008) or on neither (Lewandowski et al., 2010), as in the present study. A potential moderating effect thus needs to be substantiated in future clinical studies.

There are several limitations to this study. The study may have been underpowered to show effects of clinical significance also as statistically significant. Another limitation is that participants only reported pain and mood in the evening. We may thus have missed potential effects as other studies have shown that mood and pain may be differentially associated with sleep at different time points during the day (Gerhart et al., 2017; Tang et al., 2012; Whibley et al., 2019). This procedure also prevented assessment of night-pain, which may have contributed to the observed association between daytime pain and sleep quality. Finally, daily medication use was not recorded and thus unavailable as adjustment variables.

Strengths of the study include the fairly homogenous pain sample and the inclusion of both self-report and actigraphy sleep measures since the sleep-pain association may differ between pain conditions (Bonvanie et al., 2016), and there may be discord between sleep measurement modalities (Wilson, Watson, & Currie, 1998). Additionally, we could control for several possible confounders to the sleep-pain association, where mental distress seems to be of particular importance. Finally, we assessed the bidirectional sleep-pain association at two time points enabling assessment of the stability of associations over time and season.

6. Conclusion

Sleep problems and negative affect are well-known complicating issues in the treatment of patients with chronic pain. The current study provides evidence for a significant effect of pain on the next-night sleep quality, and less convincing evidence for an effect of

sleep on next-day pain. Mental distress was the most robust predictor of pain severity, but did not modify the sleep-pain associations. Sleep function seems to be an important aspect of improvement in quality of life in chronic pain patients on its own right (Hush et al., 2009), yet, according to our results, an effect on pain following treatment of insomnia may be less likely. A meta-analysis of cognitive behavioral treatment for insomnia found only a marginal improvement in pain post-treatment, and no improvement at follow up (Tang et al., 2015), which converges with our finding. The strong association with pain supports that clinicians should be aware the close interrelations between sleep, negative affect, and pain, and provide treatment that encompass the complexity of these interrelations in chronic pain.

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Table 1
Sociodemographic characteristics, n=56

Age, *M* (*SD*)	41.7 (10.8)
Female, n (%)	42 (75.0)
Cohabitation, n (%)	35 (62.5)
Higher education, n (%)	35 (62.5)
Employment, n (%)	42 (75.0)
Social benefit, n (%)	28 (50.0)
Good financial situation, n (%)	16 (28.6)

Table 2
Distribution of ICD-10 diagnoses in pain sample

	n
M54.2 Cervicalgia	12
M54.5 Low back pain	11
M54.6 Pain in thoracic spine	1
M54.8 Other dorsalgia	2
M54.9 Dorsalgia, unspecified	11
M79.1 Myalgia	10
M79.6 Pain in limb	3
M79.7 Fibromyalgia	6

Table 3
Sleep, pain and mood characteristics, separate for each study period (T1 and T2)

	T1 (n=56)	T2 (n=53)
Baseline characteristics		
BPI, NRS 1-10	4.2 (1.4)	4.1 (1.5)
ISI, score-range 0-28	12.4 (7.1)	10.6 (6.5)
PSQI, score-range 0-21	10.0 (4.5)	9.2 (4.0)
HSCL 25, Likert 0-4	1.8 (0.5)	1.7 (0.6)
Average daily self-report measures		
BPI, NRS 1-10	3.41 (1.91)	3.41 (2.0)
SQ, VAS 0-100	36.3 (28.7)	31.9 (27.8)
HSCL 10, Likert 0-4	1.48 (0.51)	1.56 (0.61)
Average daily actigraphy measures		
TST, h	6.60 (1.45)	6.58 (1.32)
SOL, minutes	19.0 (35.7)	12.5 (18.5)
WASO, minutes	36.3 (22.3)	38.7 (24.2)
SE, %	85.8 (9.4)	86.8 (6.7)
Midsleep, h:min	04:24 (01:36)	04:20 (01:29)

Notes: BPI: Brief Pain Inventory, ISI: Insomnia Severity Index, PSQI: Pittsburgh Sleep Quality Index, HSCL 25: Hopkins Symptom Checklist with 25 items, HSCL 10: HSCL with 10 items, SQ: Sleep Quality, TST: Total Sleep Time, SOL: Sleep onset Latency, WASO: Wake After Sleep Onset, SE: Sleep Efficiency

Table 4
Daytime pain as predictor of the next-night sleep quality (SQ) and total sleep time (TST)

	Outcome variable: SQ* (range 0-100)			Outcome variable: TST (hours)		
Pain as predictor						
Fixed effects	*beta*	95% *CI*	*F*	*beta*	95% *CI*	*F*
Pain (0-10)**	**2.81**	**.98 to 4.63**	**9.15 (*p* = .003)**	**.07**	**-.01 to .14**	**3.09 (*p* = .079)**
Covariates						
Sex	5.46	-2.42 to 13.34	1.85 ns	-1.09	-1.43 to -.74	38.37 ($p < .001$)
Age	.23	-.01 to .47	3.59 ns	-.01	-.02 to .01	.55 ns
Education	-3.23	-9.87 to 3.42	.09 ns	.31	-.02 to .64	3.49 ($p = .062$)
Data-collection period	-4.32	-8.80 to .16	3.58 ns	.01	-.17 to -.20	.021 ns
Weekend	-5.22	-8.34 to -2.10	10.81 ($p = .001$)	.59	.36 to .81	25.99 ($p < .001$)
Season	.44	-4.00 to 4.88	.04 ns	-.00	-.19 to .19	0.00 ns
HSCL	9.16	3.16 to 15.17	8.98 ($p = .003$)	.063	-.21 to .33	.21 ns
Random effects	Estimate	*SE*	*Z*	Estimate	*SE*	*Z*
Intercept (subject)	103.44	36.94	2.80 ($p = .005$)	.30	.08	3.68 ($p < .001$)
AR1 variance	578.93	38.43	15.06 ($p < .001$)	1.51	.08	18.44 ($p < .001$)
AR1 correlation	.21	.054	3.83 ($p < .001$)	-.03	.04	-.78 ns

Notes: * SQ was rated on a visual analog scale (VAS) in the morning ("last night I would describe as a good (0)- poor (100) night sleep"). **Average of current pain before bedtime and worst, least and average pain during that day rated on a numeric rating scale (0-10). TST was measured by actigraphy. Sex: female=0, male=1. Education: 10 years or less=0, <10 years=1. Data collection period: T1=0, T2=1. Weekend: weekday=0, weekend=1. Season: summer=0, winter=1. HSCL=Hopkins Symptom Checklist, AR1=Residual covariance matrix estimated as first-order autoregressive. Crude beta for SQ regressed on pain was 3.47 (95% *CI* = 1.75-5.18, $F = 15.74$, $p < .001$), and for TST regressed on pain was .09 (95% *CI* = .02-.16, $F = 5.98$, $p = .015$).

Table 5
Sleep quality (SQ) and total sleep time (TST) as predictors of next-day pain

	Outcome variable: Next-day pain (0-10)*		
SQ as predictor			
Fixed effects	*beta*	95% CI	*F*
SQ (range 0-100)**	**.003**	**.000-.005**	**3.47 (p= .063)**
Covariates			
Sex	-.26	-1.05 to .53	.43 ns
Age	.02	-.02 to .05	1.10 ns
Education	-.32	-1.08 to .43	.70 ns
Data-collection period	-.07	-.34 to .20	.26 ns
Season	-.06	-.34 to .21	.20 ns
HSCL	1.30	.93 to 1.66	48.26 (p<.001)
Random effects	Estimate	SE	*Z*
Intercept (subject)	1.70	.39	4.33 (p<.001)
Interceps (subject*visit)	.35	.11	3.18 (p=.001)
AR1 variance	.90	.06	15.53 (p<.001)
AR1 correlation	.16	.05	3.05 (p<.002)
TST as predictor			
Fixed effects	*beta*	95% CI	*F*
TST (hours)	**-.04**	**-.10 to .01**	**2.53 (p= .11)**
Covariates			
Sex	-34	-1.18 to .51	.60 ns
Age	.02	-.02 to .06	1.30 ns
Education	-.38	-1.14 to .39	.94 ns
Data-collection period	.01	-.26 to .27	.00 ns
Season	-.03	-.29 to -24	.04 ns
HSCL	1.19	.78 to 1.60	32.16 (p<.001)
Random effects	Estimate	*SE*	*Z*
Intercept (subject)	1.89	.41	4.59 (p<.001)
AR1 variance	1.14	.08	13.52 (p<.001)
AR1 correlation	.37	.05	7.78 (p<.001)

Notes: *Average of current pain before bedtime and worst, least and average pain during that day, rated on numeric rating scale (0-10). ** SQ was rated on a visual analog scale (VAS) in the morning ("last night I would describe as a good (0)- poor (100) night sleep"). TST was measured by actigraphy. Sex: female=0, male=1. Education: 10 years or less=0, <10 years=1. Data collection period: T1=0, T2=1. Season: summer=0, winter=1. HSCL= Hopkins Symptom Checklist. AR1= Residual covariance matrix estimated as first-order autoregressive. Crude beta for pain regressed on SQ was .004 (95% *CI*=.001-.007, *F*= 5.9, *p*= 0.015) and on TST were -.05 (95% *CI*=-.10-.01, *F*=3.12, *p*=.078)

Supplementary Table 1
Daytime pain as predictor of next-night sleep timing (midsleep) and sleep efficiency (SE)

	Outcome variable: Midsleep (hours)			Outcome variable: SE (%)		
Pain as predictor						
Fixed effects	*beta*	95% *CI*	*F*	*beta*	95% *CI*	*F*
Pain (0-10)*	**.00**	**-.06 - .07**	**.02 ns**	**-.11**	**-.55 - .34**	**ns**
Covariates						
Sex	-.15	-.83 - .53	.19 ns	-4.18	-8.45 - .09	(p=.055)
Age	-.01	-.03 - .02	.29 ns	.11	.01 - .20	(p= .034)
Education	.08	-.54 - .71	.07 ns	1.72	-1.14 - 4.57	ns
Data-collection period	-.03	-.22 - .16	.08 ns	1.28	.13 - 2.43	(p = .029)
Weekend	1.31	1.07 - 1.54	26.57 (p < .001)	-56	-.83 - 1.95	ns
Season	-.47	-.65 - -.29	118.87 (p < .001)	-.14	-1.25 - .96	ns
HSCL	-.02	-.32 - .29	ns	-.78	-2.59 - 1.03	ns
Random effects	Estimate	*SE*	*Z*	Estimate	*SE*	*Z*
Intercept (subject)	1.01	.22	4.59 (p < .001)	22.35	5.04	4.44 (p < .001)
AR1 variance	1.02	.06	17.05 (p < .001)	40.54	2.22	18.26 (p < .001)
AR1 correlation	.20	.04	4.73 (p < .001)	.02	.04	.51 ns

Notes: *Average of current pain before bedtime and worst, least and average pain during that day rated on a numeric rating scale (0-10). Midsleep and SE was measured by actigraphy. Sex: female=0, male=1. Education: 10 years or less=0, <10 years=1. Data collection period: T1=0, T2=1. Weekend: weekday=0, weekend=1. Season: summer=0, winter=1. HSCL=Hopkins Symptom Checklist, AR1=Residual covariance matrix estimated as first-order autoregressive. Crude beta for midsleep regressed on pain was .03 (95% *CI* = -.03 - .09, *F* = .83, *p* = ns), and for SE regressed on pain was -.11 (95% *CI* = -.55 - .33 , *F* = .23, *p* = ns).

Supplementary Table 2
Sleep timing (midsleep) and sleep efficiency (SE) as predictors of next-day pain

	Outcome variable: Next-day pain (0-10)*		
Midsleep as predictor			
Fixed effects	*beta*	95% *CI*	*F*
Midsleep (hours)	**-.02**	**-.09 - .04**	**.47 ns**
Covariates			
Sex	-.29	-1.13 – .56	.44 ns
Age	.02	-.02 - .06	1.29 ns
Education	-.38	-1.15 - .38)	.97 ns
Data-collection period	.00	-.26 - .27	.00 ns
Season	-.04	-.31 - .23	.08 ns
HSCL	1.19	.78 – 1.60	32.27 (p < .001)
Random effects	Estimate	*SE*	*Z*
Intercept (subject)	1.88	.41	4.60 (p < .001)
AR1 variance	1.14	.08	13.55 (p < .001)
AR1 correlation	.37	.05	7.70 (p < .001)
SE as predictor			
Fixed effects	*beta*	95% *CI*	*F*
SE (%)	**-.004**	**-.02 - .01**	**.39 ns**
Covariates			
Sex	-.30	-1.14 - .54	.50 ns
Age	.02	-.01 - .06	1.37 ns)
Education	-.38	-1.14 - .38	.95 ns
Data-collection period	.01	-.26 - .27	.00 ns
Season	-.03	-.29 - .23	-06 ns
HSCL	1.19	.78 – 1.60	32.44 (p < .001)
Random effects	Estimate	*SE*	*Z*
Intercept (subject)	1.87	.41	4.60 (p < .001)
AR1 variance	1.14	.08	13.56 (p < .001)
AR1 correlation	.36	.05	7.64 (p < .001)

Notes: *Average of current pain before bedtime and worst, least and average pain during that day, rated on numeric rating scale (0-10). Midsleep and SE were measured by actigraphy. Sex: female=0, male=1. Education: 10 years or less=0, <10 years=1. Data collection period: T1=0, T2=1. Season: summer=0, winter=1. HSCL= Hopkins Symptom Checklist. AR1= Residual covariance matrix estimated as first-order autoregressive. Crude beta for pain regressed on midsleep was -.03 (95% *CI*= -.08 - .03 *F*=.74, *p*= ns), and on SE was -.01 (95% *CI*= -.02 - .01, *F*= .61, *p*= ns)