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RESEARCH REPORT

The Effects of Blue-Light Filtration on Sleep and Work Outcomes

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In this article, we investigate the effects of blue-light filtration on broad attitudinal and behavioral outcomes (i.e. work engagement, organizational citizenship behavior, and counterproductive work behavior). Drawing on recent developments in the circadian process literature and its related research on chronobiology, we propose that a cost-effective sleep intervention can improve multiple organizationally relevant outcomes. Specifically, we theorize that wearing blue-light filtering glasses creates a form of physiologic darkness, thus improving both sleep quantity and quality. We then argue that wearing blue-light filtering glasses is related to work engagement, task performance, and nontask performance via sleep quantity and sleep quality. Considering that individuals vary in the timing of their circadian process, we propose that chronotype is a first-stage moderator for our theoretical model. We tested these theoretical expectations in 2 experimental experience sampling studies. In Study 1a, we collected data from 63 managers (519 daily observations) and found that wearing blue-light filtering glasses is an effective intervention to improve physiological (sleep), attitudinal (work engagement), and behavioral (task performance, organizational citizenship behavior, and counterproductive work behavior) outcomes. In general, the effects were stronger for employees who tend to have sleep periods later in the day. In Study 1b, we collected data from 67 call center representatives (529 daily observations) and measured task performance from clients. We replicated most of the findings except for the interactions. Our model highlights how and when wearing blue-light filtering glasses can help employees to live and work better.

Keywords: circadian process, sleep, well-being, work engagement, task and nontask performance

Supplemental materials: http://dx.doi.org/10.1037/apl0000806.supp

The workforce broadly suffers from sleep deprivation (National Sleep Foundation, 2005) with clear detriments to work engagement, task performance, and nontask performance (organizational citizenship behavior [OCB] and counterproductive work behavior [CWB]; Barnes, Ghumman, & Scott, 2013; Christian & Ellis, 2011; Litwiller, Snyder, Taylor, & Steele, 2017). Considering that practitioners and scholars are constantly searching for ways to improve employees' work attitudes and behaviors, an important research question receiving attention within the applied psychology literature is how to improve employee sleep (e.g., Barnes, Jiang, & Lepak, 2016; Barnes, Miller, & Bostock, 2017) as a way to improve key attitudinal and behavioral outcomes.

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Researchers have highlighted several practices to help improve employee outcomes by improving employee sleep. For example, organizations can alter work shifts, make work scheduling more flexible, or minimize the use of night shifts (Barnes, 2018). However, in many contexts, these solutions are impractical to implement or limited in scope. Creating flexible or daytime-only shifts is impossible in some organizations. Hospitals, for example, must have multiple shifts to provide round-of-the-clock care. Indeed, nurses often work multiple long shifts to accommodate the increased demand for health care (Stimpfel & Aiken, 2013).

Fortunately, drawing from theory on the circadian process and the associated research on chronobiology (e.g., Dijk & Lockley, 2002), the sleep literature has indicated a new and cost-effective means to improve sleep. This literature indicates that sleep patterns are partially influenced by exposure to blue light (Burkhart & Phelps, 2009) and that wearing blue-light filtering glasses can improve sleep by providing a form of physiologic darkness (e.g., Kessel, Siganos, Jørgensen, & Larsen, 2011). Thus, this research indicates that filtering out blue light can improve sleep by advancing the phase of the circadian process. Although no research to date has applied this idea to the context of work outcomes, an integration of the sleep physiology literature and the burgeoning literature on sleep and work suggests that wearing blue-light filtering glasses may be a cost-effective (price range between $10 and $120) and easily implementable way to help employees sleep better and increase their effectiveness at work.

Accordingly, we draw from theory on the circadian process to develop a model in which blue-light filtration improves employee sleep quantity and sleep quality, with resulting beneficial effects on employees' work engagement, task performance, and nontask performance. Moreover, we suggest that the strength of these effects is a function of individual differences in typical sleep/wake patterns within the circadian process (chronotype). Specifically, we posit that the indirect effects of blue-light filtration on performance via sleep will be stronger for individuals who tend to have sleep periods later in the day than for individuals who tend to have sleep periods earlier in the day. To test our model, we invited managers and call center representatives to participate in a pair of within-subject field experiments (See Figure 1).

Circadian Process, Sleep, and Work Effectiveness

The circadian process is an internal 24-hr clock that regulates a broad range of cellular, physiological, and behavioral rhythms, including sleep–wake cycles (Dijk & Lockley, 2002). Researchers have shown that the circadian process generates a wake signal that generally increases through the day and declines toward the end of one's circadian cycle, during the biological night (Dijk & Czeisler, 1994). The wake signal sent by the circadian process is influenced in part by exposure to light (Moore & Eichler, 1972), especially blue light (Thapan, Arendt, & Skene, 2001). Light exposure late in one's biological day can delay natural sleep onset (e.g., Shigeyoshi et al., 1997) by suppressing melatonin production (Lucas, Freedman, Muñoz, Garcia-Fernández, & Foster, 1999), which is a key component in individuals' sleepiness and ability to fall asleep and stay asleep (Chellappa et al., 2013; Knufinke, Nieuwenhuys, Geurts, Coenen, & Kompier, 2018).

The effects of blue-light exposure on sleep are problematic because most of the technology the workforce commonly uses emits blue light (e.g., computer screens, smartphones, and tablets), which may be one of the causes related to the sleep crises in America (Marcus, 2005). Evidence that workers have become more dependent on blue-light emitting devices comes from work on telepressure (Barber & Santuzzi, 2015), the digital workforce (Reyt & Wiesenfeld, 2015), and remote work (Gajendran & Harrison, 2007). Fortunately, sleep clinicians and researchers have developed a cost-effective device that suppresses the pervasive effects of blue light in the evenings: blue-light filtering glasses.

Burkhart and Phelps (2009) posit that filtering blue light from technological devices creates a form of physiologic darkness, which aids the onset of sleep. They invited participants for a randomized test to compare blue-light filtration via the usage of blue-light filtering glasses to no blue-light filtration via placebo glasses. Results from their longitudinal data showed significant improvements in sleep quality for the participants in the blue-light filtration group. van der Lely and colleagues (2015) also found that blue-light filtration increased melatonin levels in the evening. These results have been replicated in adults; Ayaki and colleagues (2016) found that wearing blue-light filtering glasses improved sleep efficacy and latency. Accordingly, the previous paragraphs suggest that exposure to blue light is related to reduced sleep quantity and quality. We hypothesize the following:

> *H1:* Compared to the control condition days, on days which participants wear blue-light filtering glasses at night, they will have higher (a) sleep quantity and (b) sleep quality.

Researchers in sleep physiology and applied psychology have documented the effects of sleep quantity and sleep quality on numerous individual and organizational performance measures (recent review, see Barnes & Watson, 2019). We build on this evidence to develop our hypotheses for the effect of sleep quantity and quality on a set of the attitudes and behaviors that are critical for organizational effectiveness. Specifically, we focus on the outcomes of work engagement, task performance, OCB, and CWB. Each of these outcomes has been established in the literature as influenced by sleep. Accordingly, we keep our arguments here brief.

Producing high levels of work engagement, task performance, and OCB requires high levels of employee effort, attention, concentration, and self-control (Barnes, 2012; Fisk & Schneider, 1983; Kanfer & Ackerman, 1989; Rich, Lepine, & Crawford, 2010). Similarly, avoiding workplace deviance also requires effort and self-control (Barnes, Schaubroeck, Huth, & Ghumman, 2011; Christian, Garza, & Slaughter, 2011). Empirical evidence clearly shows that sleep has beneficial effects on each of these workplace

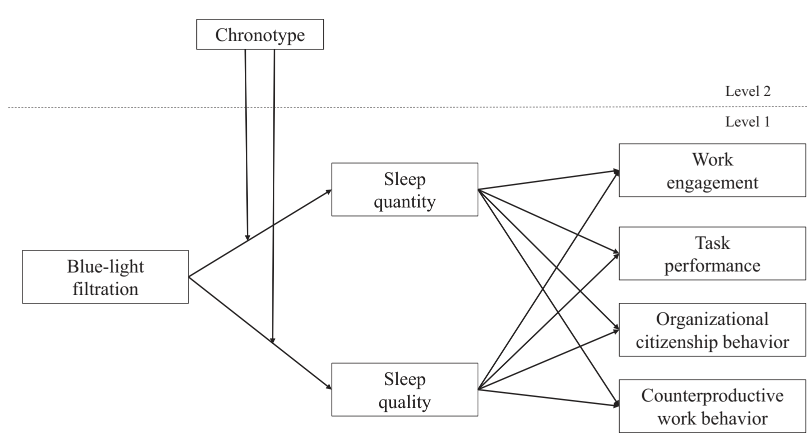

Figure 1. Conceptual model.

outcomes (Barnes et al., 2011; Barnes et al., 2013; Barnes & Watson, 2019; Lanaj, Johnson, & Barnes, 2014; Litwiller et al., 2017).

Building on this research, we predict that sleep quantity and quality will be related to employees' work engagement, task performance, OCB, and CWB. In addition, we hypothesize a mediating effect of sleep on the relationship between blue-light filtration and work outcomes. Specifically, we argue that within individuals blue-light filtration in the evening will be related with next day's work outcomes via sleep quantity and quality. Blue-light filtration in the evening creates a form of physiologic darkness, prompting the physiological conditions (melatonin production, lowered body temperature, and slowed heart rate) conducive to individuals' falling and staying asleep. By sleeping better and longer, employees potentially have the resources to engage in their work and perform at high levels. We hypothesize:

> *H2:* Following nights in which participants have higher sleep quantity, they will have higher next-day (a) work engagement, (b) task performance, and (c) OCB and (d) lower CWB.

> *H3:* Following nights in which participants have higher sleep quality, they will have higher next-day (a) work engagement, (b) task performance, and (c) OCB and (d) lower CWB.

> *H4:* Compared to the control condition days, on days which participants wear blue-light filtering glasses at night, they will have higher next-day (a) work engagement, (b) task performance, and (c) OCB and (d) lower CWB.

> *H5:* Daily sleep quantity mediates the relationship between wearing blue-light filtering glasses at night and next-day (a) work engagement, (b) task performance, and (c)OCB and (d) CWB.

> *H6:* Daily sleep quality mediates the relationship between wearing blue-light filtering glasses at night and next-day (a) work engagement, (b) task performance, and (c) OCB and (d) CWB.

Chronotype as a Boundary Condition

The circadian process is an internal clock that regulates our wake-sleep cycles. Although the presence and mechanisms of this internal clock are universal (Dijk & Lockley, 2002), the individual timing of the internal clock is not. Researchers refer to this individual difference in the circadian process as a chronotype (Horne & Östberg, 1976). Specifically, chronotypes are biological predispositions that influence the timing of wake-sleep cycles. Researchers in medicine have focused on three categories (morning, intermediate, and evening chronotypes [Adan et al., 2012]). However, these are arbitrary cutoffs that vary continuously and unidimensionally.

A large body of research in physiology shows that chronotype influences the timing of the peaks and valleys in an individual's attentional resources (Coogan & McGowan, 2017) and executive functions (Hahn et al., 2012). Researchers have found that chronotype is related to sleep and performance. Generally, performance suffers for individuals who tend to have sleep periods later in the day because their natural sleep onset time is often too late at night to allow sufficient sleep before they must wake in the morning. Van der Vinne and colleagues (2015), for example, investigated the relationship between chronotype and school performance. They found that individuals who had sleep periods later in the day performed worse than individuals who had sleep periods earlier in the day, especially with morning examinations.

This mismatch between chronotype and external social time also occurs in organizations in which most employees have fixed work shifts that may not match with their chronotypes. Many organizations create strong social norms for work schedules that match poorly with the circadian processes of individuals who tend to have a sleep periods later in the day (Yam, Fehr, & Barnes, 2014). Indeed, research has shown that chronotype is unrelated to waking time on work days (Roenneberg, Wirz-Justice, & Merrow, 2003) and the type of work shifts individuals engage in (Vetter, Fischer, Matera, & Roenneberg, 2015). Thus, individuals who have sleep periods later in the day may encounter more misalignments between their internal physiological clocks and the external social norms regarding work schedules. These mismatches may create sleep and performance difficulties for them.

Light therapy (e.g., blue-light filtration) has been shown to improve sleep quality (Burkhart & Phelps, 2009) by shifting individuals' sleep cycles (Brainard et al., 2001), thus addressing these mismatches. Filtering out blue light at night removes a cue indicating it is still too early to sleep, thereby allowing individuals to begin melatonin production earlier than they would otherwise and bringing about earlier sleep onset time. For individuals who tend to have a sleep periods later in the day, filtering blue light is particularly helpful because the earlier sleep onset time will allow for more time to be spent sleeping before waking in the morning. In contrast, individuals who tend to have sleep periods earlier in the day already tend to have an earlier increase in the production of melatonin and, therefore, an earlier sleep onset time. So moving their sleep onset time even earlier will be less likely to increase their total sleep time; in other words, they will be more likely to have an early enough sleep onset time that will allow sufficient sleep before they must wake, reducing the benefit of moving their sleep onset time further. We propose that wearing blue-light filtering glasses at night can particularly help individuals who have sleep periods later in the day sleep better and longer, which then is related to next-day work outcomes.[1] We hypothesize the following:

> *H7:* Chronotype moderates the relationship between wearing blue-light filtering glasses at night and (a) sleep quantity and (b) sleep quality in such a way that the relationships are stronger for individuals who tend to have a sleep periods later in the day than for those who tend to have sleep periods earlier in the day.

> *H8:* Chronotype moderates the indirect effects of wearing blue-light filtering glasses at night on the next-day (a) work engagement, (b) task performance, (c) OCB, and (d) CWB through sleep quantity. The indirect relationships are stronger for individuals who tend to have sleep periods later in the day than for those who tend to have sleep periods earlier in the day.

[1] Changing light patterns does not change the person's biological chronotype (tendency to sleep early or late within a given day/light cycle), but changing light patterns can still change people's sleep cycles by sending signals that a given time of day is occurring earlier or later.

Table 1
Means, Standard Deviations, and Correlations of Study 1a Variables

Variable	*M*	*SD*	1	2	3	4	5	6	7	8
1. Blue-light filtration	.50	.50	—	−.07	.24	−.15	−.13	.02	−.04	−.09
2. Sleep quantity	382.08	45.86	.20**	—	.26*	.11	.23	.27*	−.07	.02
3. Sleep quality	3.46	.79	.30**	.19**	(.80)	.34**	.09	.14	−.27*	−.21
4. Work engagement	3.54	.85	.17**	.13**	.28**	(.81)	.34**	.33**	−.49**	.05
5. Task performance	3.76	.84	.15**	.23**	.14**	.37**	(.81)	.49**	−.42**	.15
6. OCB	3.10	1.04	.24**	.25**	.19**	.30**	.44**	(.88)	−.19	.05
7. CWB	1.21	.27	−.28**	−.15**	−.28**	−.31**	−.28**	−.18**	(.71)	−.02
8. Chronotype	2.80	.88	−.01	.03	−.09*	.06	.12*	.05	−.01	(.93)

Note. Within individual correlations are shown below the diagonal and are based on within-individual scores ($N = 519$). Between-individual correlations are shown above the diagonal and are based on between-individual scores ($N = 63$). Means are based on within-individual scores. Coefficient alphas are reported in parentheses along the diagonal. OCB = organizational citizenship behavior; CWB = counterproductive work behavior.
* $p < .05$. ** $p < .01$.

H9: Chronotype moderates the indirect effects of wearing blue-light filtering glasses at night on the next-day (a) work engagement, (b) task performance, (c) OCB, and (d) CWB through sleep quality. The indirect relationships are stronger for individuals who tend to have sleep periods later in the day than for those who tend to have sleep periods earlier in the day.

Overview of Empirical Studies

We conducted two longitudinal, within-person field experiments. In Study 1a, we collected daily data from 63 managers (519 daily surveys). In Study 1b, we collected data from 67 call center employees (529 daily surveys). This data collection was exempted per the University of Washington Human Subjects Division (STUDY00004001: The Effects of Light on Sleep and Work Outcomes).

Sample and Procedure

The sample consisted of managers and call center representatives at a large multinational financial firm based in the United States. In this study, we collected data in Brazil, the largest operation in South America with more than 3,000 employees. We followed Brislin's (1986) back-translation procedure to translate the surveys into Portuguese. The online data collection effort took place over four workweeks (Monday-Friday) and consisted of two distinct phases. The first two weeks (recruitment phase) were the most logistically complex, and researchers worked closely with the HR department to deliver two pairs of glasses to participants. The glasses (200 blue-light filtering glasses [blue-light filtration treatment] and 200 sham glasses [control]) were donated by Swanwick (https://support.swanwicksleep.com/). The glasses looked essentially the same with the only difference being the yellow tone of the lenses.

For Study 1a, we then sent the recruitment survey to 120 managers, and for Study 1b, we sent the recruitment survey to 120 call center representatives. The recruitment survey explained the details of the research project. Employees were asked to wear the glasses for at least two hours before going to bed each night for two weeks (e.g., Ryan, Matsangas, Anglemyer, & Shattuck, 2017). We also asked participants to complete two daily surveys, one early in the morning and one late in the afternoon during the data collection. After reading the consent form, we asked if they agreed to participate in the study and collected demographic and chronotype data. Next, we randomly assigned participants to one of two conditions: treatment-first or control-first condition. On the Sunday before the beginning of the daily data collection, we informed the participants which pair of glasses they were to wear for the week.

In this second phase, we emailed the daily surveys to participants twice each day — morning and afternoon — for 10 consecutive workdays. We sent the early morning survey at 6 a.m. It included items to check participants' compliance with the procedures (which glasses they used and how long they used the glasses before going to bed) and measures of sleep quantity and sleep quality. We sent the late afternoon survey at 4 p.m. measuring daily work engagement, task performance (Study 1a only), OCB, and CWB. The financial firm provided daily performance data (based on customer ratings) of the call center representatives for Study 1b.

In Study 1a, after matching participants across the waves and eliminating participants who responded to only one or two surveys, or participants who wore the wrong glasses, we ended up with 63 managers (66% response rate) and 519 daily surveys (82% response rate; 40% female, mean age was 36.75 [$SD = 8.93$]). In Study 1b, after the matching process, we obtained data on 67 call center representatives (76% response rate) and 529 daily surveys (79% response rate; 64% female, mean age was 31.54 [$SD = 8.42$]). We also checked for order effects, and the results were not significant (see Appendix for details).

Measures

Blue-light filtration. We used blue-light filtering glasses as our operationalization of blue-light filtration. We dummy coded the blue-light exposure as 0 when participants wore the sham glasses and 1 when participants wore the blue-light filtering glasses.

Sleep quantity. We used the Pittsburgh Sleep Diary (Monk et al., 1994) to measure sleep quantity.

Sleep quality. We adopted two items from Karolinska Sleep Diary (Nordin, Åkerstedt, & Nordin, 2013). An example of the items is "How well did you sleep last night?" (Cronbach's alpha averaged across the days of data collection was .80 for Study 1a,

Table 2
Means, Standard Deviations, and Correlations of Study 1b Variables

Variable	*M*	*SD*	1	2	3	4	5	6	7	8
1. Blue-light filtration	.49	.50	—	−.12	.19	−.07	.15	.12	−.17	−.08
2. Sleep quantity	382.12	58.66	.19**	—	.16	.08	.15	.07	−11	.05
3. Sleep quality	3.51	.88	.23**	.22**	(.84)	.25*	.27*	.16	−.34**	−.10
4. Work engagement	3.55	.81	.17**	.15**	.28**	(.77)	.11	.33**	.11	−.07
5. Task performance	6.41	.29	.10*	.21**	.24**	.12**	—	−.01	−.16	−.13
6. OCB	2.54	.91	.23**	.25**	.23**	.27**	.15**	(.90)	−.08	−.16
7. CWB	1.17	.24	−.31**	−.23**	−.28**	−.02	−.12**	−.16**	(.71)	.16
8. Chronotype	2.96	.72	−.01	.04	−.06	−.03	.08	−.08	.06	(.90)

Note. Within individual correlations are shown below the diagonal and are based on within-individual scores ($N = 529$). Between-individual correlations are shown above the diagonal and are based on between-individual scores ($N = 67$). Means are based on within-individual scores. Coefficient alphas are reported in parentheses along the diagonal. OCB = organizational citizenship behavior; CWB = counterproductive work behavior.
* $p < .05$. ** $p < .01$.

and .84 for Study 1b; average correlation across the days between the two items was .67 for S1a, and .73 for S1b).

Daily work engagement. We measured daily work engagement with three items from Schaufeli, Bakker, and Salanova (2006). One example is "Today, I was immersed in my work" (Cronbach's alpha averaged across the days was .81 for S1a and .77 for S1b).

Daily task performance. In Study 1a, we measure daily task performance with three items from the scale developed by Williams and Anderson (1991). One example of the items is "I adequately completed my assigned duties today" (Cronbach's alpha averaged across the days was .81). In Study 1b, the financial firm provided objective daily data on the average performance of each participant. At the end of the call, the company asked clients to evaluate the performance of the call center representative. Specifically, the company asked "how satisfied are you with this call?" The answers could vary from 1 to 7. We aggregated the episode-level data for each representative to an overall day-level measure of daily task performance. This operationalization of task performance has been used by others (e.g., Batt & Colvin, 2011).

Daily OCB. We measured daily OCB with four items from Spector, Bauer, and Fox (2010). An example of the items is "Took time to advice, help, or mentor a coworker" (Cronbach's alpha averaged across they days was .88 for S1a, and .90 for S1b).

Daily CWB. We adopted four items from Bennett and Robinson (2000) to measure daily CWB. An example of the items is "Said something hurtful to someone at work" (Cronbach's alpha averaged across they days was .71 for S1a and .71 for S1b).

Chronotype. We adopted the 12-item scale developed by Smith, McEvoy, and Gevins (2002) to measure chronotype. Consistent with accepted practices, we asked participants to indicate their sleep/awake preferences relative to that of most people. An example of the items is "When would you prefer to go to bed?" Responses ranged from "Much earlier than most people" to "Much later than most people." Thus, we collected continuous data on chronotype and did not make any reference to the specific wake/bed times (Cronbach's alpha = .93 for S1a, and .90 for S1b).

Analyses

We performed multilevel path analyses (Preacher, Zyphur, & Zhang, 2010) in MPlus 8 (Muthén & Muthén, 2012), used a parametric bootstrap to assess the significance of the indirect effects, and used a Monte Carlo simulator (20,000 replications) to generate the confidence intervals for the indirect effects in our proposed mediation and moderated mediation models (Preacher & Selig, 2010). We modeled all paths as random slopes. To test the hypothesized within-individual relationships among wearing blue-light filtering glasses, sleep quantity, sleep quality, work engagement, task performance, OCB, and CWB, we followed Koopman, Lanaj, and Scott (2016) and group-mean-centered Level-1 predictors. Managers' chronotypes (a Level 2 variable) were grand-mean-centered (Hofmann, Griffin, & Gavin, 2000)[2].

Results

Tables 1 and 2 contain means, *SD*s and correlations for S1a and S1b variables.

We proposed that on days which participants wore blue-light filtering glasses at night, they would have higher sleep quantity and sleep quality than on days they wore the control glasses (H1a and H1b). Multilevel analysis results with simultaneous modeling of sleep quantity and sleep quality showed that the within-individual relationships between wearing blue-light filtering glasses and sleep quantity (S1a: $\gamma = 18.39$, $SE = 3.78$, $p < .01$; S1b: $\gamma = 23.58$, $SE = 5.46$, $p < .01$) and quality (S1a: $\gamma = .47$, $SE = .09$, $p < .01$; S1b: $\gamma = .37$, $SE = .07$, $p < .01$) were significant. Therefore, we found support for H1a and H1b.

We ran one multilevel model with both independent variables (sleep quantity and sleep quality) and all dependent variables (work engagement, task performance, OCB, and CWB) to test H2 and H3. H2 suggested that sleep quantity is related to daily work engagement (H2a), task performance (H2b), OCB (H2c), and CWB (H2d). The within-individual path between sleep quantity and daily work engagement was marginally significant in both studies (S1a: $\gamma = .02$, $SE = .01$, $p = .08$; S1b: $\gamma = .02$, $SE = .008$, $p = .06$). However, the paths from sleep quantity to daily task performance (S1a: $\gamma = .04$, $SE = .01$, $p < .01$; S1b: $\gamma = .01$, $SE = .01$, $p < .01$), OCB (S1a: $\gamma = .05$, $SE = .01$, $p < .01$; S1b: $\gamma = .06$, $SE = .01$, $p < .01$), and CWB (S1a: $\gamma = -.01$, $SE = .003$,

[2] See Appendix for the percentage of within-individual variance and confirmatory factor analyses.

Table 3
Multilevel Parallel Moderated Mediation Model Results for Study 1a

Variable	Sleep quantity		Sleep quality		Work engagement		Task performance		OCB		CWB	
	B	*SE*	*B*	*SE*	*B*	*SE*	*B*	*SE*	*B*	*SE*	*B*	*SE*
Intercept	−.41	4.31	−.12	3.40	17.80	22.23	5.90	36.71	3.82	86.96	1.16	8.57
Blue-light filtration[a]	1.80**	.38	.46**	.09	.23**	.09	.19*	.09	.31*	.13	−.11**	.03
Sleep quantity					.01	.01	.02**	.01	.04**	.01	−.01	.004
Sleep quality					.13*	.05	.08*	.04	.16**	.06	−.06**	.02
Chronotype	−.23	.24	−.20	6.80	.05	.29	.07	.19	.14	.60	−.001	.06
Int. Chronotype × Blue-Light	.48	.47										
Int. Chronotype × Blue-Light			.32**	.09								
Variance explained												
Level-1 pseudo-R^b					.19		.08		.12		.20	

Indirect effect	Parameter	95% CI (*LL*, *UL*)
Blue light → sleep quantity → work eng.	.01	[−.02, .04]
Blue light → sleep quality → work eng.	.06*	[.01, .11]
Blue light → sleep quantity → task perf.	.04*	[.01, .08]
Blue light → sleep quality → task perf.	.04*	[.01, .07]
Blue light → sleep quantity → OCB	.07*	[.01, .13]
Blue light → sleep quality → OCB	.07*	[.01, .14]
Blue light → sleep quantity → CWB	−.01	[−.03, .001]
Blue light → sleep quality → CWB	−.03*	[−.05, −.01]
Conditional indirect effect		
DV: Work engagement		
Mediator: Sleep quantity		
−1*SD* (−.88)	.01	[−.02, .03]
+1*SD* (.88)	.02	[−.02, .05]
Difference	.006	[−.01, .02]
Mediator: Sleep quality		
−1*SD* (−.88)	.02	[−.01, .05]
+1*SD* (.88)	.09*	[.01, .17]
Difference	.07*	[.001, .14]
DV: Task performance		
Mediator: Sleep quantity		
−1*SD* (−.88)	.03	[−.002, .07]
+1*SD* (.88)	.05*	[.003, .10]
Difference	.02	[−.02, .06]
Mediator: Sleep quality		
−1*SD* (−.88)	.01	[−.01, .03]
+1*SD* (.88)	.06*	[.01, .11]
Difference	.04†	[−.003, .09]
DV: OCB		
Mediator: Sleep quantity		
−1*SD* (−.88)	.06†	[−.002, .11]
+1*SD* (.88)	.09*	[.009, .17]
Difference	.03	[−.03, .10]
Mediator: Sleep quality		
−1*SD* (−.88)	.03	[−.02, .07]
+1*SD* (.88)	.12*	[.02, .21]
Difference	.09*	[.01, .16]
DV: CWB		
Mediator: Sleep quantity		
−1*SD* (−.88)	−.01	[−.02, .01]
+1*SD* (.88)	−.02	[−.04, .01]
Difference	.001	[−.02, .01]
Mediator: Sleep quality		
−1*SD* (−.88)	−.01	[−.02, .01]
+1*SD* (.88)	−.04*	[−.08, −.01]
Difference	−.03*	[−.06, −.001]

Note. $N = 519$ at the within-individual level (Level 1), $n = 63$ at the manager level (Level 2); We divided sleep quantity by 100 to allow the models to converge. OCB = organizational citizenship behavior; CWB = counterproductive work behavior; *LL* = lower limit; *UL* = upper limit; Int. = interaction; DV = dependent variable.
[a] blue-light filtering glasses = 1, control glasses = 0.
* $p < .05$. ** $p < .01$.

Table 4
Multilevel Parallel Moderated Mediation Model Results for Study 1b

Variable	Sleep quantity *B*	Sleep quantity *SE*	Sleep quality *B*	Sleep quality *SE*	Work engagement *B*	Work engagement *SE*	Task performance *B*	Task performance *SE*	OCB *B*	OCB *SE*	CWB *B*	CWB *SE*
Intercept	−.36	8.09	−.11	1.54	5.09	32.46	2.78	30.86	−2.54	24.31	2.16	87.80
Blue-light filtration[a]	2.34**	.54	.36**	.08	.19*	.08	.02	.02	.20*	.09	−.09**	.03
Sleep quantity					.01	.01	.01**	.002	.05**	.01	−.01**	.003
Sleep quality					.19**	.06	.04*	.02	.18**	.06	−.04**	.02
Chronotype	−.24	.41	−.05	.06	−.05	.15	−.05	.04	−.12	.11	.03	.03
Int. Chronotype × Blue-Light	.57	.86										
Int. Chronotype × Blue-Light			.11	.10								
Variance explained												
Level-1 pseudo-R^2					.12		.14		.25		.26	

Indirect effect	Parameter	95% CI (*LL*, *UL*)
Blue light → sleep quantity → work eng.	.02	[−.001, .05]
Blue light → sleep quality → work eng.	.07**	[.02, .12]
Blue light → sleep quantity → task perf.	.02**	[.01, .04]
Blue light → sleep quality → task perf.	.02*	[.01, .03]
Blue light → sleep quantity → OCB	.12**	[.04, .19]
Blue light → Sleep quality → OCB	.07*	[.01, .12]
Blue light → sleep quantity → CWB	−.03*	[−.05, −.01]
Blue light → sleep quality → CWB	−.01*	[−.03, −.001]
Conditional indirect effect		
DV: Work engagement		
Mediator: Sleep quantity		
−1*SD* (−.72)	.02	[−.01, .05]
+1*SD* (.72)	.03	[−.01, .06]
Difference	.01	[−.01, .01]
Mediator: Sleep quality		
−1*SD* (−.72)	.06*	[.01, .10]
+1*SD* (.72)	.08*	[.02, .14]
Difference	.02	[.02, .06]
DV: Task performance		
Mediator: Sleep quantity		
−1*SD* (−.72)	.02*	[.01, .03]
+1*SD* (.72)	.03*	[.01, .04]
Difference	.01	[−.01, .02]
Mediator: Sleep quality		
−1*SD* (−.72)	.02*	[.01, .02]
+1*SD* (.72)	.02*	[.01, .03]
Difference	.005	[−.01, .01]
DV: OCB		
Mediator: Sleep quantity		
−1*SD* (−.72)	.10**	[.01, .19]
+1*SD* (.72)	.13*	[.05, .21]
Difference	.03	[−.06, .12]
Mediator: Sleep quality		
−1*SD* (−.72)	.06*	[.01, .11]
+1*SD* (.72)	.08*	[.01, .14]
Difference	.02	[−.02, .06]
DV: CWB		
Mediator: Sleep quantity		
−1*SD* (−.72)	−.02*	[−.05, −.01]
+1*SD* (.72)	−.03*	[−.06, −.01]
Difference	−.01	[−.03, .02]
Mediator: Sleep quality		
−1*SD* (−.72)	−.01	[−.03, .01]
+1*SD* (.72)	−.02*	[−.03, −.01]
Difference	−.01	[−.01, .01]

Note. $N = 529$ at the within-individual level (Level 1), $n = 67$ at the representative level (Level 2); We divided sleep quantity by 100 to allow the models to converge. OCB = organizational citizenship behavior; CWB = counterproductive work behavior; *LL* = lower limit; *UL* = upper limit; Int. = interaction; DV = dependent variable.
[a] blue-light filtering glasses = 1, control glasses = 0.
* $p < .05$. ** $p < .01$.

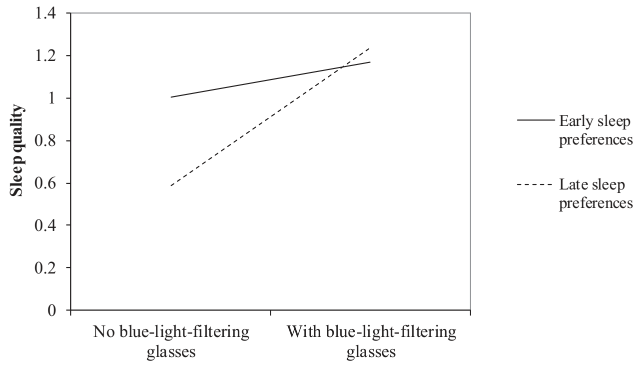

Figure 2. Interactive effect of blue-light filtration and chronotype on sleep quality for Study 1a.

$p < .01$; S1b: $\gamma = -.01$, $SE = .004$, $p < .01$) were significant. H2b, 2c, and 2d were thus supported.

Hypothesis 3 suggested that within-individual sleep quality is correlated with daily work engagement (H3a), task performance (H3b), OCB (H3c), and CWB (H3d). In S1a, we found support for the relationship between sleep quality and daily work engagement ($\gamma = .18$, $SE = .05$, $p < .01$), OCB ($\gamma = .24$, $SE = .06$, $p < .01$), and CWB ($\gamma = -.08$, $SE = .02$, $p < .01$). However, the path between sleep quality and daily task performance was marginally significant ($\gamma = .11$, $SE = .06$, $p = .06$). H3a, 3c, and 3d were supported. In S1b, we found similar results, except that we found significant results for the relationship between sleep quality and daily task performance (work engagement: $\gamma = .26$, $SE = .08$, $p < .01$, task performance: $\gamma = .05$, $SE = .02$, $p < .05$, OCB: $\gamma = .24$, $SE = .08$, $p < .01$, and CWB: $\gamma = -.06$, $SE = .02$, $p < .01$). We found support for H3a, 3b, 3c, and 3d.

Hypothesis 4 suggested that compared to the control condition days, on days which participants wore blue-light filtering glasses at night, they would have higher next-day (a) work engagement, (b) task performance, (c) OCB, and (d) lower CWB. Results showed that wearing blue-light filtering glasses at night had a significant relationship with work engagement (S1a: $\gamma = .31$, $SE = .08$, $p < .01$; S1b: $\gamma = .28$, $SE = .08$, $p < .01$), task performance (S1a: $\gamma = .27$, $SE = .09$, $p < .01$; S1b: $\gamma = .06$, $SE = .03$, $p < .05$), OCB (S1a: $\gamma = .49$, $SE = .10$, $p < .01$; S1b: $\gamma = .43$, $SE = .09$, $p < .01$), and CWB (S1a: $\gamma = -.15$, $SE = .02$, $p < .01$; S1b: $\gamma = -.14$, $SE = .03$, $p < .01$), supporting H4.

Turning to the indirect effects of wearing blue-light filtering glasses on next-day work engagement, task performance, OCB, and CWB via sleep, we predicted that sleep quantity (H5) and sleep quality (H6) will mediate the direct effects. We ran one comprehensive model with all direct and indirect effects (See Tables 3 and 4). In S1a, sleep quantity mediated the relationship between wearing blue-light filtering glasses and task performance (*estimate* = .04, $p < .05$; 95% CI [.01, .07]), and OCB (*estimate* = .07, $p < .05$; 95% CI [.01, .13]). The results of Monte Carlo simulation provided support for task performance (H5b) [.01, .04] and OCB (H5c) [.01, .12]. The indirect effects were similar for S1b, but with the indirect effects on CWB also being significant (task performance: *estimate* = .02, $p < .05$; 95% CI [.01, .04]; OCB: *estimate* = .12, $p < .05$; 95% CI [.04, .19]; CWB: *estimate* = −.03, $p < .05$; 95% CI [−.03, −.001]; Monte Carlo 95% CI: task performance = [.001, .04], OCB = .05, .18, and CWB = −.02, −.01) supporting H5b, H5c, and H5d.

We also found support for H6. For S1a, the indirect effects of wearing blue-light filtering glasses on work engagement (*estimate* = .06, $p < .05$; 95% CI [.01, .11]); task performance (*estimate* = .04, $p < .05$; 95% CI [.01, .08]), OCB (*estimate* = .07, $p < .05$; 95% CI [.01, .14]), and CWB (*estimate* = −.03, $p < .05$; 95% CI [−.05, −.01]) via sleep quality were significant. The results of Monte Carlo simulations were consistent with these findings (95% CI for work engagement [.01, .11]; task performance [.01, .07]; OCB: .01, .12; CWB: −.04, −.01). The results were similar for S1b (work engagement: *estimate* = .07, $p < .01$; 95% CI [.02, .12], Monte Carlo 95% CI [.02, .11]; task performance: *estimate* = .02, $p < .05$; 95% CI [.01, .03], Monte Carlo 95% CI [.001, .02]; OCB: *estimate* = .07, $p < .05$; 95% CI [.01, .12], Monte Carlo 95% CI [.01, .11]; CWB: *estimate* = −.01, $p < .05$; 95% CI [−.03, −.001], Monte Carlo 95% CI [−.04, −.01]). Therefore, we found support for H6a, H6b, H6c, and H6b.

Next, we examined the cross-level interaction. H7 suggested that the effects of wearing blue-light filtering glasses on sleep quantity (H7a) and sleep quality (H7b) would be stronger for individuals who have sleep periods later in the day than earlier in the day. We adopted the full spectrum of chronotype in our analysis and graphed the results from one standard deviation above and one standard deviation below the mean of chronotype (Aiken & West, 1991). The interaction term on sleep quantity was not significant in S1a ($\gamma = .47$, $SE = .46$, $p = .31$), and S1b ($\gamma = .57$, $SE = .86$, $p = .50$). The interaction term on sleep quality was significant ($\gamma = .32$, $SE = .08$, $p < .01$) in S1a but not in S1b ($\gamma =$

Table 5
Growth Model Slopes for Study 1a

Variable	Coefficient of the slope on manipulation	Control-slope	Control-95% CI	Treatment-slope	Treatment-95% CI
Sleep quantity	1.22 (2.66)	2.08 (1.98)	[1.59, 2.57]	3.45 (1.70)*	[3.03, 3.87]
Sleep quality	.00 (.05)	.02 (.03)	[.01, .03]	.023 (.04)	[.01, .03]
W. engagement	.07 (.04)†	.04 (.03)	[.03, .05]	.11 (.03)**	[.10, .12]
Task performance	.09 (.03)**	.02 (.03)	[.01, .03]	.10 (.02)**	[.09, .11]
OCB	.14 (.05)**	.009 (.03)	[.001, .016]	.14 (.04)**	[.13, .15]
CWB	.01 (.02)	−.002 (.01)	[−.004, .001]	.01 (.01)	[.001, .01]

Note. OCB = organizational citizenship behavior; CWB = counterproductive work behavior.
$^{\dagger}p < .10$. $^{*}p < .05$. $^{**}p < .01$.

Table 6
Growth Model Slopes for Study 1b

Variable	Coefficient of the slope on manipulation	Control-slope	Control-95% CI	Treatment-slope	Treatment-95% CI
Sleep quantity	5.46 (2.55)*	3.86 (1.66)*	[3.45, 4.27]	8.99 (1.79)**	[8.55, 9.43]
Sleep quality	.12 (.05)**	−.03 (.03)	[−.03, −.02]	.10 (.03)**	[.09, .11]
W. engagement	.02 (.01)†	.02 (.01)*	[.017, .022]	.06 (.02)**	[.05, .064]
Task performance	.16 (.05)**	.06 (.03)	[.05, .07]	.22 (.04)**	[.21, .23]
OCB	.01 (.03)	.04 (.02)	[.004, .04]	.06 (.02)**	[.05, .064]
CWB	−.03 (.01)*	.003 (.003)	[.002, .004]	−.02 (.006)**	[−.022, −.018]

Note. OCB = organizational citizenship behavior; CWB = counterproductive work behavior.
$^{\dagger}p < .10$. $^{*}p < .05$. $^{**}p < .01$.

.10, *SE* = .10, *p* = .29). Simple slopes analysis showed that the effect of wearing blue-light filtering glasses on sleep quality was significant for individuals who have sleep periods later in the day (*slope* = .75, *p* < .01); however, the effect did not reach significance for individuals who have sleep periods earlier in the day (*slope* = .17, *p* = .09; see Figure 2).

Finally, H8 and H9 predicted that chronotype is related to the strength of the indirect relationship (sleep quantity and quality, respectively). We tested for these hypotheses in S1a only because the interactions were not significant in S1b. Table 3 shows that H8a, H8b, H8c, and H8d were not supported. However, the indirect effect of wearing blue-light filtering glasses on work engagement via sleep quality was significant for individuals who have sleep periods later in the day (*estimate* = .09, *p* < .05; 95% CI [.01, .17]) but not for individuals who have sleep periods earlier in the day (*estimate* = .02, *p* > .05; 95% CI [−01, .05]; *difference* = .07; *p* < .05; 95% CI [.001, .14]). We found a similar pattern for OCB (sleep periods later in the day: *estimate* = .12, *p* < .05; 95% CI [.02, .21]; sleep periods earlier in the day: *estimate* = .03, *p* > 05; 95% CI [−.02, .07]; *difference* = .09; *p* < .05; 95% CI [.01, .16]) and CWB (sleep periods later in the day: *estimate* = −.04, *p* < .05; 95% CI [−.08, −.01]; sleep periods earlier in the day: *estimate* = −.01, *p* > 05; 95% CI [−.02, .01]; *difference* = −.03; *p* < .05; 95% CI [−.06, −.001]). The indirect effect on task performance was significant for individuals who have sleep periods later in the day (*estimate* = .06, *p* < .05; 95% CI [.01, .11]) but not for individuals who have sleep periods earlier in the day (*estimate* = .01, *p* > .05; 95% CI [−.01, .03]). However, the difference between the estimates approached significance (*estimate* = .04; *p* = .067; 95% CI [−.003, .09]), and the findings need to be interpreted with caution.

Additional Analysis

We ran latent growth models to investigate if the growth curves of the focal dependent variables changed over time (dosage effect) and were different across the days individuals wore blue-light filtering glasses and the control glasses. Although not theorized, it is possible that it takes multiple days for the glasses to lead to their full potential for circadian adjustment and that the slopes were the same regardless of blue-light filtration, which could indicate a day-of-the-week effect. We calculated the slopes for each dependent variable and then regressed the slopes on the manipulation. We next calculated the slopes and 95% CI for the treatment and control conditions. Tables 5 and 6 present these results. See Figure 3 for an example of the results pattern.[3]

The results show that although not every comparison reveals a statistically significant difference, in general, there is a clear overall pattern. Beyond having overall positive main effects on many of our outcome variables, the blue light blocking glasses also had increasing positive effects on many outcomes over the short span of a week. This is a relatively novel finding as existing studies have thus far focused on main effects of blue light filtration instead of trajectories of effects and have studied biological instead of workplace outcomes (e.g., Burkhart & Phelps, 2009; Esaki et al., 2016). This is also particularly noteworthy as these existing studies have found effects in samples of individuals with sleep disorders. We extend this literature by showing that the effects of blue light filtration generalize to nonclinical contexts.

Discussion

Across two studies, we used a within-individual experimental design to examine the relationships between wearing blue-light filtering glasses at night and sleep (quantity and quality), and its consequences for work engagement, task performance, OCB, and CWB. We also examined the moderating effect of employees' chronotypes because employees with different sleep cycles may experience different sleep-related responses to blue-light filtration. The results generally supported our hypotheses, highlighting that blue-light exposure is one reason for poor sleep and reduced work outcomes and that a cost-effective remedy can help employees.

Our study contributes to the literature in multiple ways. It has implications for research on chronobiological processes in organizations, particularly in relation to circadian theory. First, we contribute to research on work engagement, task, and nontask performance. Although past research has depicted various antecedents of daily variation in these constructs, their antecedents are predominantly related to psychological resources (e.g., Sonnentag, Binnewies, & Mojza, 2008). In contrast, we show that daily engagement, task performance, and nontask performance may be related to more underlying biological processes such as the circadian process. Also, we extend theory on the circadian process by showing the effects of blue light exposure on workplace outcomes. Our research pushes the chronotype literature to consider the

[3] Please see online supplemental material for the additional figures.

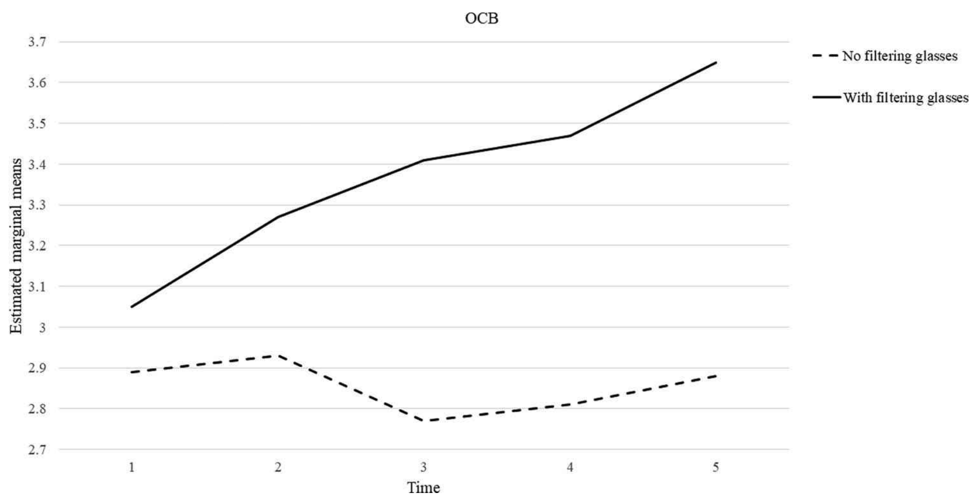

Figure 3. Linear growth curves for OCB in Study 1a.

relationship between the timing of circadian processes and employees' performance. Employees are often required to work early mornings, which may lead to a misalignment between their internal clock and the externally controlled work time. Finally, our post hoc analyses showed a general pattern that blue-light filtration can have a cumulative effect on key performance variables, at least in the short term.

Our findings have clear implications for practice. First, our intervention suggests that blue-light filtering glasses (a simple and cost-effective intervention) may be related to employees' performance at work and their well-being outside of work. This is especially important considering that exposure to blue light in the form of smartphones and other devices is steadily increasing around the world (Bucksch et al., 2016). We suggest blue-light exposure should also be of concern to organizations. The ubiquity of the phenomenon suggests that control of blue-light exposure may be a viable first step for organizations to protect the circadian cycles of their employees from disruption.

Although our research design had strengths (two longitudinal, within-person field experiments), our empirical approach still had some limitations, which create opportunities for future research. We theorized that blue-light filtration is related to sleep and work outcomes because of its effects on biological processes. Research from physiology have shown that exposure to blue light is related to hormonal (e.g., melatonin production; Lucas et al., 1999) and biological changes (e.g., decreases in core body temperature and heart rate; Cajochen et al., 2005). Although there is indirect support for the relationship between blue-light filtration on work outcomes via biological processes, we have not measured them and encourage future researchers to do so.

We also found that blue-light filtration is related to sleep quality and quantity as well as to work-related outcomes in two samples of employees' working regular hours. However, it is likely that our hypothesized effects would be even more powerful with employees whose work schedules are likely to be extremely misaligned with their circadian processes. We encourage scholars to investigate our model in the context of employees who work night shifts or schedules that appear to be in great conflict with natural circadian processes. Also, another potential area for light-therapy research is the effects of demographics and trait-like variables (e.g., consciousness) as contingencies for the model. A final potential line of inquiry may explore if wearing the glasses for different lengths of time might strengthen or weaken the effects.

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(*Appendix follows*)

Appendix

Additional Analyses

Order Effect Analyses

In our within-individual research design, all participants spent time in both the control and treatment conditions, with random assignments determining which condition each participant was assigned to first. However, to check the possibility of an order effect (i.e. were results different depending on whether a given participant was in the control condition first and then the treatment condition, or the treatment condition first and then the control condition), we conducted a *t* test comparing the means of the focal variables in our study across these two different orders of condition assignments. In Study 1a, there were no significant order effects (sleep quantity: $t_{(517)} = .16$, $p = .87$; sleep quality: $t_{(517)} = 1.61$, $p = .11$; work engagement: $t_{(517)} = .34$, $p = .73$; task performance: $t_{(517)} = 1.26$, $p = .21$; OCB: $t_{(517)} = 1.10$, $p = .27$; CWB: $t_{(517)} = 1.30$, $p = .20$). In addition, we conducted a series of *t* tests comparing the mean levels of age, tenure, and chronotype between participants included in the final sample and those who completed the recruitment scale. We found no significant differences (age: $t_{(540)} = .72$, $p = .47$; tenure: $t_{(540)} = .88$, $p = .38$; chronotype: $t_{(540)} = .03$, $p = .97$).

Similar to Study 1a, we did not find order effects in Study 1b (i.e. whether a given participant was in the control condition first and then the treatment condition or vice versa) in the focal variables means (sleep quantity: $t_{(527)} = .72$, $p = .47$; sleep quality: $t_{(527)} = 1.33$, $p = .18$; work engagement: $t_{(527)} = 1.52$, $p = .13$; task performance: $t_{(527)} = 1.61$, $p = .11$; OCB: $t_{(527)} = 1.07$, $p = .29$; CWB: $t_{(527)} = .50$, $p = .62$). We also did not find statistical differences in the mean levels of age, tenure, and chronotype between participants included in the final sample and those who completed the recruitment scale (age: $t_{(555)} = .66$, $p = .51$; tenure: $t_{(555)} = .57$, $p = .57$; chronotype: $t_{(555)} = .60$, $p = .55$).

Percentage of Within-Individual Variance Analyses

The percentage of within-individual variance for our focal variables for Study 1a (sleep quantity = 59%; sleep quality = 70%; work engagement = 47%; task performance = 51%; OCB = 54%; and CWB = 70%) and for Study 1b (sleep quantity = 60%; sleep quality = 58%; work engagement = 53%; task performance = 49%; OCB = 72%; and CWB = 51%) provided support for conducting multilevel analysis.

Confirmatory Factor Analyses

Before testing our hypotheses, we conducted a within- and between-individual confirmatory factor analysis (CFA) to assess the fit of the measurement model. The hypothesized model with seven factors showed acceptable fit to the data (Study 1a: $\chi^2(136) = 225.54$; CFI = .95; RMSEA = .04; and SRMR (between) = .04; Study 1b: $\chi^2(93) = 115.48$; CFI = .98; RMSEA = .02; and SRMR (between) = .03), and all loadings were significant ($p < .05$). The hypothesized model fit the data significantly better than all other models in which any two of the five factors at the within-individual level were combined (Study 1a: $150.91 \leq \Delta\chi^2\text{s}(\Delta df = 5) \leq 409.15$; Study 1b: $333.56 \leq \Delta\chi^2\text{s}(\Delta df = 5) \leq 77.56$). The findings show the discriminant validity of the measures of our key constructs.

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