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Sleep as a restorative process for self-control

by

Garrett Hisler

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Program of Study Committee:
Zlatan Krizan, Major Professor
Douglas Gentile
Christian Meissner
Alison Phillips
Daniel Russell

The student author, whose presentation of the scholarship herein was approved by the program of study committee, is solely responsible for the content of this dissertation. The Graduate College will ensure this dissertation is globally accessible and will not permit alterations after a degree is conferred.

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ABSTRACT

Sleep is conceptualized as a restorative factor in people's ability to exert self-control; however, this possibility has yet to be directly examined. It is likely that sleep replenishes self-control ability by restoring cognitive and motivational factors necessary for enacting self-control. By using daily diary methodology, this study assessed whether changes in self-control, as well as its relevant underlying mechanisms (inhibition, motivation, effort), from evening to the next morning is influenced by the intervening sleep period. To this end, 85 participants were recruited in a two week daily diary study to complete assessments of behavioral (eye blink inhibition) and self-reported self-control (self-control capacity scale) and underlying mechanisms. Sleep was assessed via actigraphy and morning diary entrees. Multilevel structural equation modeling was used to examine if change in self-control and theoretical mechanisms from evening to next morning was predicted by the duration, continuity, or subjective quality of the intervening sleep period. Overnight improvement in eye blink inhibition was predicted by the duration of sleep, which was partially due to co-occurring reductions in the temptation to blink. Additionally, overnight improvement in self-reported self-control capacity was independently predicted by both the duration and subjective quality of sleep, and both of these associations were fully explained by overnight reductions in sleepiness. These findings are the first to link overnight improvements in self-control to sleep, implicating sleep duration as a sleep characteristic that is particularly important for the restoration of self-control. Moreover, temptation, as opposed to motivation and inhibition, emerged as a critical factor explaining the sleep-self-control link.

CHAPTER 1. INTRODUCTION

Sleep is often assumed to restore people's ability to successfully restrain urges, resist desires, and persist in effort, that is, engage self-control (Baumeister, Heatherton, & Tice, 1994). Indirect evidence for this premise comes from findings that the day's demands on self-control predict self-control success later that same day, but do not predict self-control success or difficulty the next day (Muraven, Collins, Shiffman, & Paty, 2005; Park, Wright, Pais, & Ray, 2016). This is a violation of the tenant that using self-control now deteriorates the mechanisms necessary for future self-control. Presumably, this violation occurs because sleep revitalizes these mechanisms and thereby negates the relevance of self-control on one day for self-control the next day. However, despite the proposal of sleep as a replenishing factor for self-control originating at least two decades ago (e.g., Baumeister, Heatherton, & Tice, 1994), no study has sought to explicitly test it. While past studies have examined self-control across days, no study has examined changes in self-control at controlled times right before and after sleep. Such a test is needed because the lack of relation of self-control across days could be due to other intervening and restorative factors (e.g., waking rest) or differences in circadian rhythms at time of assessment (Ramirez, Garia, & Valdez, 2016; Zhang, Smolders, Lakens, IJsselsteijn, 2018).

In addition to this lack of controlled and direct examination of sleep as a restorative factor in self-control, there is an absence of studies examining how sleep independently impacts multiple mechanisms at the core of self-control, such as inhibition, motivation, and effort. Teasing apart how sleep independently impacts these mechanisms can better inform how sleep impacts self-control as well as provide applied insights by speaking to conditions under which self-control failures are most likely to occur and how these failures may be mitigated. For instance, perhaps sleep loss has a more pronounced effect on motivation for self-control than cognitive self-control processes like inhibition. This would suggest that engaging self-control when motivation is low (e.g., persisting with job engagement during a boring day of work) is especially likely to fail after a night of poor sleep and that interventions to restore motivation or reduce its importance for task outcome may reduce self-control failures. Overall, a direct test of sleep as a restorative process in self-control is needed as well as an examination of what self-control mechanisms are being restored. To test these possibilities, this study aimed to assess whether daily variation in sleep influences the restoration of self-control and its underlying mechanisms from evening to the next morning.

Sleep and Self-control

Sleep is a state of reversible disengagement from the external world during which processes vital to biological and psychological growth and restoration occur. For instance, during sleep, toxins are cleared from the brain, memories are consolidated, and metabolism is regulated (Diekelman & Born, 2010; Sharma & Kavuru, 2010; Xie et al., 2013). The architecture of normal sleep consists of alternating cycles of non-rapid eye-movement sleep (NREM) and rapid-eye movement (REM) sleep, alongside transitional stages (Carskadon & Dement, 2011). Overall, the initiation and maintenance of wakefulness is the function of three processes: (1) the homeostatic pressure to sleep that increases with wakefulness and decreases with sleep, (2) circadian rhythms in arousal that counterbalance accruement and dissipation of sleep pressure in a way that constrains wakefulness to the day and sleep to the night, and (3) the “waking up” process described as sleep inertia (Akerstedt & Folkard, 1997). While the focus of the current study is on how sleep may restore self-control, it is critical to keep in mind that cognitive and affective processes at any given time are a function of sleep pressure, circadian rhythm, and sleep inertia. Optimal functioning is generally promoted when sleep pressure and sleep inertia are low and when the circadian rhythm for wakefulness is near its peak (Burke, Scheer, Ronda, Czeisler, & Wright, 2015). As will be discussed later, it will be necessary to control or separate the contribution of these three sleep processes when evaluating differences in self-control across any two time periods.

The role of sleep in self-control has only recently gained the attention of researchers and growing evidence demonstrates that inadequate sleep interferes with the effortful control of behavior and emotion. After a night of short or fitful sleep, people are less able to restrain undesirable urges, such as stealing office supplies, cheating on tests, or insulting others (Barnes, Lucianetti, Bhave, & Christian, 2015; Barnes, Miller, & Bostock, 2017; Barnes, Schaubroeck, Huth, & Ghumman, 2011; Christian & Ellis, 2011; Meldrum, Barnes, Hay, 2013). People also have greater difficulty starting and continuing effortful behaviors, such as staying engaged in their job over the day or continuing exercise (Barnes, Schaubroeck, Huth, & Ghumman, 2011; Baron, Reid, & Zee, 2013; Khunel, Sonnentag, Bledow, & Melchers, 2017; Lanaj, Johnson, & Barnes, 2014). In addition to behavioral control, sleep loss also appears to disrupt the stability and control of emotion (Baum, Desai, Field, Miller, Rausch, & Beebe, 2014; Mauss, Troy, & LeBourgeois, 2013; Zohar Tzischinsky, Epstein, & Lavie, 2004).

While these previous findings have firmly established a link between lack of sleep and self-control failures, it remains unclear how sleep is leading to such self-control failures. Many of these past studies have attempted to answer this question using the State Self-control Capacity Scale and whether responses to this scale mediate the effect of sleep on self-control outcomes such as unethical behavior or interpersonal deviance (Barnes, Lucianetti, Bhave, & Christian, 2015; Barnes, Miller, & Bostock, 2017; Christian & Ellis, 2011; Lanaj, Johnson, & Barnes, 2014; Welsh, Ellis, Christian, & Mai, 2014; Welsh, Mai, Ellis, & Christian, 2018). However, validity information regarding scores on this scale is lacking and it is unknown what about self-control it measures. Likely as a consequence, just within these few studies this scale has been conceptualized as a myriad of self-control constructs such as ego depletion (Barnes, Lucianetti, Bhave, & Christian, 2015; Lanaj, Johnson, & Barnes, 2014; Welsh, et al., 2014; Welsh et al., 2018), state self-control (Barnes, Miller, & Bostock, 2017) and self-control resources (Christian & Ellis, 2011). Moreover, it is likely that the scale taps into both cognitive (e.g., greater difficulty in inhibition) and motivational (e.g., mental fatigue) antecedents to self-control. Thus, such findings do little to resolve the question of how does sleep uniquely influence the distinct mechanisms that drive self-control. Two other studies have assessed similar mediation models using different scales assessing self-reported cognitive fatigue (Barnes, Schaubroeck, Huth, & Ghumman, 2011) and willpower (Kuhnel, Sonnentag, Bledow, & Melchers, 2017). Again, these studies did not independently examine mechanisms behind self-control.

Overall, taking evidence that inadequate sleep weakens self-control alongside evidence that an intervening period of sleep suppresses the link between self-control assessed across days suggests a modulatory role of sleep for self-control. Additionally, while sleep is likely to play a modulatory role, it is unknown what about self-control is actually modulated. Before further considering how or why sleep may play a restorative role for self-control, it is first necessary to understand how the process of self-control operates. Such processes are succinctly described by Integrative Self-Control Theory, which synthesizes disparate lines of self-control research to explain when self-control attempts occur and the mechanisms that determine the outcome of these attempts (Kotabe & Hofmann, 2015). An overview of this theory also illuminates why it is necessary to assess the multiple components behind self-control when examining how sleep impacts self-control.

Integrative Self-Control Theory

In this theory, desires are visceral motivational forces that direct action towards an immediately rewarding stimulus (e.g., cursing out a neglectful boss). In contrast, goals are abstract cognitive concepts of desired end-states that are often pursued intentionally for their long-term benefits (e.g., keeping a job). A self-control attempt is initiated when a desire co-activates with an opposing goal (see Figure 1). Note that co-activation of the desire and goal relies upon *attention*; if neither the desire nor the relevant goal is attended to, then no conflict occurs and the enacted behavior is likely to result from the singularly activated desire or goal. When a desire-goal conflict occurs, there are two outcomes (with shades of success) for that self-control attempt: either the desire is pursued, or it is not. Although self-control conflicts can be resolved in a variety of ways that don't involve self-control (e.g., desire is removed by an external force), typical self-control involves engaging in effortful tactics to resist a desire.

The ultimate determinant of whether a desire is pursued depends on whether the amount of *effort* put into adhering to the goal is greater than the strength of the goal-opposing desire. However, the maximal amount of effort that could be put into controlling the desire is the combined product of current *cognitive abilities* leveraged to enact self-control and the *motivation* to control the desire (e.g., strength of higher order goal, affect in the moment). The cognitive abilities typically reflect "executive functions" (i.e., inhibition, task-switching, working memory ability) that are necessary for execution of self-control (Hofmann, Schmeichel, & Baddeley, 2012). Working memory is important for accurately activating and representing goals as well as shielding them from interference by desires. Task-switching is critical for switching between goals as they become relevant to changing desires and for switching between different methods for achieving the same goal (Hofmann, Schmeichel, & Baddeley, 2012). Inhibition is necessary for the active top-down suppression of conscious desires and goal-opposing habitual behavior (Hofmann, Schmeichel, & Baddeley, 2012). In contrast, motivation for self-control typically refers to how much a person aspires to obtain a goal; motivation influences the engagement of cognitive control functions and can be weakened by accrued perceptions of fatigue (Brewer, Lau, Wingert, Ball, & Blais, 2017; Inzlicht, Schmeichel, & Macrae, 2014)

The interaction between cognitive capacity and motivation defines the maximum amount of effort that could be exerted, but additional factors, such as competing higher order goals (e.g., avoiding self-control now to save resources for future self-control) or self-efficacy (e.g., feeling confident that self-control will be successful), influence the *actual* amount of self-control effort. Thus, cognitive capacities and motivation, alongside invested effort, are the primary processes underlying the exertion self-control once it is initiated. As a result, to the extent sleep restores self-control it should largely do so by affecting one or more of these key determinants. For this reason, the current study focuses on overt self-control performance as well as the cognitive, motivational, and effort processes that underlie self-control.

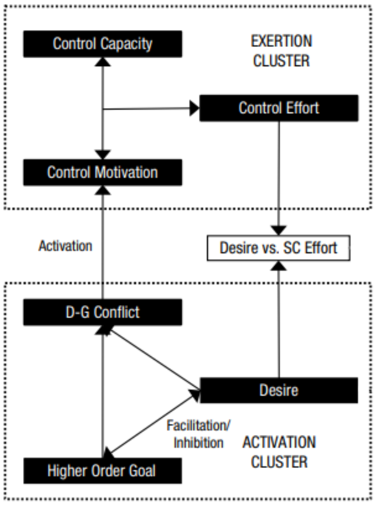

Figure 1.1. Determinants of desire strength and self-control effort. Adapted from Kotabe and Hofmann, 2015.

How Does Sleep Restore Self-control?

Broadly, there are two non-mutually exclusive ways that sleep may restore self-control. First, having a period of rest between acts of exerting self-control improves subsequent self-control performance, especially as time-on-task and task difficulty increase (Steinborn & Huestegge, 2016). Along this line, sleep may play a passive role by simply providing a long period of rest after exerting self-control throughout the waking day. Sleep may not actively restore cognitive capacities, motivation, and effort, but rather allow for these mechanisms to rest after use during waking activity. Second, sleep may play a direct role in repairing the wear and tear on self-control mechanisms accrued from use during wakefulness. In this case, processes only occurring during sleep (e.g., slow-wave sleep, neurological reorganization) should be critical for restoration. Although a definitive test of these two possibilities is beyond the scope of the current study, I review evidence relevant to both in order to provide the most comprehensive account of how sleep may revitalize self-control.

Sleep as Rest: Sleep Passively Restores Self-control

The primary evidence that sleep passively restores self-control comes from studies manipulating sleep duration. This research demonstrates that the longer someone remains, cognitive control and motivation factors decline and less stable, while perceptions of effort increase (Engle-friedman, 2014; Killgore, 2010).

Cognition. The most profound cognitive effect of sleep loss is on the limited capacity to maintain directed attention. For instance, the frequency and duration of attentional lapses increases the longer a person is awake in a 24-hour period (Lim & Dinges, 2008). Importantly, attentional performance begins approaching typical levels after recovery sleep, with longer recovery sleep leading to greater gains towards baseline attention ability (Belenky, et al., 2003; Jay, et al., 2006). Reductions in attention are insidious for self-control because directed attention is needed to detect when environmentally salient desires (e.g., a cake on the table) may be in opposition to less-salient goals (e.g., maintaining healthy diet; Mann & Ward, 2007). Moreover, the capacity to direct attention is hypothesized to be the main substrate of more complex cognitive control processes essential to self-control (Kaplan & Berman, 2010). Thus, sleep may provide rest for directed attention, which should improve the ability to keep in mind current goals that are in opposition to desires as well as indirectly enhance executive cognitive abilities that play a role in reigning in desires.

These executive cognitive abilities, namely, working memory, task-switching, and inhibition (i.e., executive functions) also show reductions in functioning as time awake increases. Less sleep results in worse working memory and inhibition as well as increased task-switching costs, though the effect on working memory may be due to concomitant attentional impairments (Lim & Dinges, 2010; Killgore, 2010; Tucker et al., 2010).

Importantly, these cognitive impairments begin to reverse after a period of recovery sleep, again suggesting that sleep restores these functions (Couyoumdjian, et al., 2010; Drummond, Paulus, & Tapert, 2006). Because these executive functions are integral for executing self-control, the extent that sleep influences these functions should be reflected in a person's ability to exert self-control.

Motivation. In addition to restoring cognitive performance, sleep should also reverse decreased motivation to engage self-control. Motivation is a key factor in maintaining good performance in many cognitive and behavioral domains. For instance, a person's ability to sustain attention declines over time, but this decline in performance can be ameliorated by increases in monetary compensation (Esterman et al., 2014, 2016). In other words, providing boosts in motivation counteracts routine declines in performance over time. These effects are even more pronounced in sleep deprived participants. Participants deprived of sleep have even worse sustained attention and these greater declines can be mitigated more by higher monetary rewards than rested participants, implicating that lack of motivation is accounting for part of the effect of sleep loss on performance (Massar, Lim, Sasmita, & Chee, 2019).

Along these lines, sleep is heavily linked to feelings of exhaustion and fatigue, which are theorized to play a substantial role in undermining self-control (Hockey, 2013; Inzlicht & Schmeichel, 2012; Kurzban, Duckworth, Kable, & Myers, 2013; Molden, Hui, & Scholer, 2016). Participants restricted to only four hours of sleep over five days in a lab had increasingly stronger feelings of fatigue over the course of the study (Banks, Van Dongen, Maislin, & Dinges, 2010). When finally allowed to sleep for longer, feelings of fatigue began to decline, demonstrating that sleep is critical to recovering from experiences of fatigue. Outside of the lab, sleep has been linked to people's day-to-day fatigue experiences. In a study both behaviorally and subjectively assessing fifty participants' sleep for six weeks, both longer nightly sleep duration and better subjective quality of sleep independently reduce next-day fatigue (Akerstedt et al., 2014). Altogether, this evidence suggests that sleep may reverse deteriorations in motivational factors in self-control.

Effort. Overlapping with some of the losses in motivation that can occur with sleep loss, inadequate sleep is linked to preferring less effortful goals and expending less effort. When given control over task difficulty, participants with insufficient or disrupted sleep will engage in easier tasks than when they were rested (Engle-Friedman & Riela, 2010; Engle-Friedman, et al., 2013). Importantly, participants reported putting the same amount of effort into the easier tasks they selected while sleep deprived as the harder tasks they selected while rested (Engle-Friedman, et al., 2003). The equal levels of effort expenditure suggest that when sleep deprived people are allowed to select their tasks, they do not necessarily shy away from expending the same amount of subjective effort, but will more easily reach their psychological threshold for typical effort level. Moreover, there were no differences in overall task performance between sleep deprived and rested states, suggesting that sleep deprived participants selected easier tasks to compensate for their compromised state.

When participants lack control over their environment, different patterns of effort expenditure and performance emerge. When forced to complete the same cognitive tasks with no control over task difficulty over three consecutive days of no sleep, performance of the sleep deprived participants was 55% that of participants who were allowed to sleep (Haslam, 1985). After the sleep deprived participants were informed they would be able to nap soon, their cognitive performance jumped to 85% that of the rested group. Thus, without task control, unrested people do withhold effort and performance suffers as a result. Additional evidence that people will adopt less effortful approaches to tasks comes from a study in which military officers adopted more passive/avoidant leadership styles after being deprived of sleep while also decreasing in effortful transformational and transactional leadership styles (Olsen, et al., 2016). Similarly, when given the forced choice to earn a small amount of money by completing a less effortful task or to earn a large amount of money by completing a more effortful task, sleep deprived participants prefer the less effortful option. (Libedinsky, et al., 2013). In terms of self-control, these findings implicate that sleep loss may lead to prioritizing less effortful self-control goals (e.g., prioritizing reading over exercising), exerting less effort towards inflexible goals, and reducing the maximum amount of effort exerted during self-control.

It is worth explicitly stating that performance on any test of cognitive performance depends on the motivation and effort put into the task. Therefore, sleep loss may not have easily separable effects on cognitive and motivational processes, though evidence does suggest some independence (Nilsson, et al., 2005). Nonetheless, the evidence reviewed here demonstrates that continued wakefulness reduces cognitive abilities, motivational priorities, and effort expenditures, all of which are key for enacting self-control. These declines in functioning begin to reverse after allowing a period of sleep, suggesting that, at a minimum, sleep restores these functions by offering a break from their use during wakefulness. However, as argued next, processes unique to sleep (vs. rest) are also vital to self-control and actively restore functioning of these underlying mechanisms.

Sleep as Restorative: Sleep Actively Restores Self-control

While direct evidence that sleep actively replenishes self-control mechanisms is scant, putting together disparate threads of research regarding sleep's regulatory role in biological systems which influence self-control provides indirect evidence for this possibility.

Sleep, stress, and the immune system. Sleep has been proposed to play an important role in the immune and stress systems by regulating inflammatory and stress signals (Bryant, Trinder, & Curtis, 2004). Heightened inflammation markers have been linked to decreased motivation and impaired executive functions (Shields, Moons, & Slavich, 2017). Sleep loss can also amplify stress responses by elevating the frequency of stressors encountered and increasing psychological perceptions of stress. For instance, when sleep duration was cut in half for a week, participants increasingly reported more complaints and stress each day (Dinges, et al., 1997). These psychological perceptions of stress are also accompanied by heightened physiological stress markers such as cortisol (Minkel et al., 2014). These amplified stress responses may occur because sleep loss lowers the psychological threshold needed to perceive an event as stressful and hyper-activates the Hypothalamus-Pituitary-Adrenal axis (Hirotsu, Tufik, & Anderson, 2015; Minkel et al., 2012). In turn, stress can impair inhibition and working memory as well as enhance preferences for immediately gratifying choices, leading to breakdowns in self-control (Inzlicht, McKay, & Aronson, 2006; Maier, Makwana, & Hare, 2015; Oaten & Cheng, 2005; Schoofs, Preuss, & Wolf, 2008). These effects arise, in part, because acute and prolonged exposure to stress corrodes the neural architecture required for optimal self-control (Arnsten, 2009). Importantly, this deprecating effect of stress may not carryover to next-day self-control, implicating that sleep may reverse stress-induced decrements, perhaps by restoring normal neural connectivity (Park, Wright, Pais, Ray, 2016).

Sleep and neural functioning. Sleep appears to play an active role in maintaining normal neural functioning and connectivity within the brain, especially in the prefrontal cortex areas which houses executive functions necessary for self-control (Krueger, et al., 2008). After sleep deprivation, patterns of decreased frontal activity with increased activity in other brain regions are seen at rest and during effortful tasks (Drummond & Brown, 2001; Thomas, et al., 2000; Wu, et al., 2006). These changes in activity begin to return to baseline after sleeping, with restoration of cognitive operations such as working memory and planning particularly dependent on amount of slow-wave sleep (Anderson & Horne, 2003; Wu et al., 2006). Because self-control relies on these functions, then restoring normal neural architecture for these functions should be one way sleep actively restores self-control. Note, however, that changes in neural activity do *not* necessitate impaired cognitive functioning. In fact, the increased activation of other brain regions (often parietal regions) during tasks that typically draw on frontal brain regions has been hypothesized to be a compensatory response to maintain performance during cognitive tasks (Killgore, 2012). For instance, participants in one study did not perform worse on a logical reasoning task after sleep deprivation, but as task difficulty increased so did activation in other brain regions not originally active during task performance when rested (Drummond, Brown, Salamat, & Gillin, 2004). Moreover, participants with greater compensatory activation performed better. Given the existence of compensatory neural responses to maintain performance during sleep deprivation, sleep may only restore cognitive self-control mechanisms that do not have compensatory brain activation during sleep loss.

In this vein, compensatory activation seems absent when a task involves a significant degree of emotional processing (Killgore, 2010, 2012). This has critical implications for self-control because desires, urges, and impulses at the heart of self-control conflicts are often emotionally or viscerally charged and require regulation of these affective responses (Lopez et al., 2017). Difficulty in controlling emotional desires after sleep loss is reflected in the increased activation of the amygdala to emotionally valanced stimuli, with concomitant deterioration in functional connectivity between the prefrontal cortex and the amygdala, implicating an impaired ability to exert top-down control of emotions (Gujar, Yoo, Hu, & Walker, 2011; Yoo et al., 2007). Increased pupil diameter when viewing negative stimuli and increased and greater risk-taking also supports amplified reactivity to emotional information after sleep loss (Franzen, et al., 2009; Killgore, Balkin, Wesenten, 2006). Again, because executing self-control relies on these mechanisms, the extent that sleep restores such mechanisms should be reflected in actual engagement of self-control.

While sleep loss clearly amplifies emotional reactivity, some evidence suggests that rapid-eye movement (REM) sleep may be key to reversing this reactivity. For instance, after extended wakefulness, participants rated angry and fearful faces as more negative and happy faces as more positive in comparison to their baseline ratings (Gujar, McDonald, Nishida, & Walker, 2011). After napping, however, amplified emotional ratings returned to baseline, but only for participants who achieved REM sleep (however, see Lara-carrasco, Nielsen, Solomonova, Levrier, & Popova for contrary REM findings).

Sleep and sleepiness. Finally, lack of sleep ultimately makes people sleepy and although caffeine and changes in time-of-day can temporarily reduce sleepiness, only sleep can truly alleviate sleepiness (Balkin & Wesensten, 2011). Sleepiness is a signal of the current physiological pressure to sleep and the associated impairments that occur with sleep loss (e.g., eye closures, Akerstedt, Anund, Axelsson, & Kecklund, 2014). As the strength of this signal grows, so does the desire to sleep. Importantly, the desire to sleep may motivate behavior away from the pursuit of important goals and could even create a self-control conflict itself (e.g., taking a nap over continuing to study). Behind the desire to eat, the desire to sleep has been found to be the second most common source of reported self-control conflicts (Hofmann, Baumeister, Forster, & Vohs, 2012). Thus, sleeping is key to reducing an extremely common demand on self-control.

Altogether, the role of sleep in maintaining optimal functioning and biological systems that influence self-control suggests that sleep should *actively* restore self-control performance. This proposition is further bolstered by evidence that particular kinds of sleep (slow wave sleep, REM sleep) seem vital to restoring particular functions needed for self-control. Thus, evidence suggests that sleep may both passively and actively restore self-control, and this study sought to provide the first direct test of whether sleep restores self-control by examining both overt self-control performance as well as the underlying mechanisms necessary for self-control (i.e., motivation, cognitive control).

Current Study

To test this possibility, the current study examined if the degree of overnight change in self-control is explained by the duration, continuity, or subjective sleep quality of the intervening period of sleep that night. Specifically, this study tested if overnight changes in the success of inhibiting the urge to blink are predicted by a period of intervening sleep that is of longer duration or better continuity. Moreover, whether concomitant overnight changes in core self-control mechanisms (i.e., inhibition, motivation, effort) mediate this relation will be tested. To capture how these dynamics occur in everyday life, daily diary methodology was employed to assess natural fluctuations in self-control and sleep over fourteen days.

While a variety of paradigms can be used to asses self-control (e.g., self-report, handgrip task), the eye blink task was used as the core measure of self-control (Schmeichel & Zell, 2007). During this task participants are instructed to inhibit the urge to blink for two minutes. Greater number of blinks over this time period is an index of worse self-control. The eye blink task was used because a.) it can easily be assessed via a mobile device outside of the lab, b.) it quickly captures an observable self-control conflict (task duration is less than two minutes) that involves both inhibition and persistence, c.) inhibiting desires is a critical form of self-control affected by sleep loss (Baumeister, Heatherton, & Tice, 1994; Barnes, Schaubroeck, Huth, & Ghumman, 2011; Perkinson-Gloor, Lemola, & Grob, 2013; Vohs, & Heatherton, 2000), and d.) a validated mobile measure exists for assessing a core cognitive mechanism that should underlie the eye-blink task (i.e., cognitive inhibition assessed by the Stroop task). Thus, while the current study does not assess the full breadth of ways that self-control can be affected by sleep, it directly assesses how sleep may impact inhibitory self-control and its underlying mechanisms.

In addition to the eye blink task, the State Self-control Capacity Scale was also used as an index of self-control. Though scale validity information is lacking on this instrument, this scale purportedly measures a person’s capacity or mental resources available to exert self-control. Given that this assessment of self-control is a self-report of current perceptions of self-control capacity, this scale is not a direct manifestation of self-control and measures a separate aspect of self-control (i.e., perception of self-control capacity vs. actual inhibition of bodily urge) than the eye blink task. However, if both the eye blink task and the State Self-control Capacity Scale measure self-control, findings with sleep should be similar. It is also important to consider that the vast majority of studies examining the influence of sleep on self-control outcomes have utilized this scale (e.g., Barnes, Miller, & Bostock, 2017; Christian & Ellis, 2011; Lanaj, Johnson, & Barnes, 2014). Thus, to more directly connect findings from this study to those of the past literature, this scale was also evaluated as an outcome. Moreover, including both the eye blink task and this scale allow for evaluating whether scores on this scale correlate with a behavioral index of self-control and provide an explicit test of its validity.

Advantages and Disadvantages of Using Daily Diary Methodology

The use of daily dairy methods confers important advantages for assessing relations between sleep and self-control. The foremost of these is the use of multilevel statistical procedures that estimate the relations among repeatedly assessed variables within a person first and then aggregate these effects across people (Raudenbush & Bryk, 2002). Importantly, this allows for separating variance into *between*-person (i.e., individual differences) and *within*-person (i.e., daily variation) sources. Because these two sources of variance can be specified and separated, between-person variance can be removed from the analyses. This allows for removal of individual differences that confound estimates of day-level effects of sleep on self-control, such as sleep need, habitual wake and rise times, timing of circadian rhythms, chronic dry eyes, and trait self-control.

An additional advantage of using a daily diary design is a focus on natural fluctuations in sleep. Much of the evidence reviewed earlier comes from studies manipulating sleep to extreme and rarely experienced levels (e.g., 75 hours of sleep deprivation, sleep restricted to 4 hours a night for a whole week). Comparing the effects of total sleep deprivation to the effects of smaller doses of sleep loss demonstrates that smaller fluctuations in sleep produce smaller effects than sleep deprivation or can produce different effects (Belenky et al., 2003; Reynolds & Banks, 2010; Van Dongen, et al., 2003). For instance, feelings of sleepiness linearly increase over time during sleep deprivation, but increases in sleepiness plateau after a couple days during sleep restriction (Reynolds & Banks, 2010; Van Dongen, et al., 2003). Thus, investigating sleep at naturally experienced levels over time is critical to understanding the day-to-day role of sleep in self-control and should produce findings that have more generalizable and applied implications.

A final strength involves collection of numerous sleep and self-control assessments which produce high statistical power and precision. A power analysis based upon 90 participants completing assessments over 14 days would results in a day-level sample size of 1,260, which affords .80 power to detect a day level correlation as small as .05 when alpha is set to .05 (estimated using PINT; Snijders & Bosker, 1993). These sample specifications were implemented in the current study because of their ability to detect such a small day level correlation. Based upon pilot data collected from three undergraduate research assistants over two weeks, it is likely that observed day level correlations would be larger than .05. However, it is important to note that it is unlikely that participants would complete all days of assessments, that this study seeks to simultaneously detect the presence of multiple day level effects, and hypothesized mediation effects will be the product of two day level effects and are therefore are likely to be small. Thus, to account for these factors, the power analysis was conducted based on conservative estimate.

While daily diary methodology does confer significant advantages, it is not without its drawbacks. The most pressing drawback is the lack of rigid experimental control over timing of assessments. As mentioned earlier, task performance at any given time is a function of not only homeostatic sleep pressure, but also the sleep-wake circadian rhythm and sleep inertia. Because this study seeks to isolate the effect of sleep itself, it will have to control for how these other processes differentially impact self-control when assessed during the evening or morning. One way to control for the influence of circadian rhythm on task performance is for participants to complete all assessments at the same time across study days. Accordingly, all morning and evening assessments in this study occurred at approximately the same time each day (between 9-10 am and 9-10 pm). Although circadian rhythms will be affecting self-control differently when assessed at 9 am and 9 pm, this time-of-day difference will be approximately the same across days within a person because time of assessment is held constant across days. Because time-of-assessment is held constant within a person, changes in self-control from evening to morning within a person across different days will minimally reflect time-of-day differences.

However, due to individual differences in circadian rhythms, there will be time-of-day differences in self-control across people (Randler, Diaz-Morales, Rahafar, & Vollmer, 2016). For instance, morning-oriented people should, on average, perform better at self-control at 9 am than evening-oriented people. Importantly, these between person differences can be removed by centering morning and evening self-control within participants. By both holding time of assessment constant across days and by removing between-person variance, variation in evening and morning self-control within a person should not be due to factors such as the time-of-day and timing of circadian rhythms.

Finally, to minimize the impact of sleep inertia, participants were instructed to complete assessments only after they have been awake for at least 30 minutes. Because participants completed the study outside of the lab and this awake time before task completion cannot be enforced by lab personnel, actigraphically recorded time of awakening was used as a covariate to statistically control for sleep inertia.

Study Hypotheses

Based upon evidence implicating that sleep passively and actively restores cognitive abilities and motivation needed for self-control, it was hypothesized that the change in self-control performance on the eye blink task from the evening to the next morning is due to the intervening period of sleep (i.e., its duration, continuity, subjective sleep quality; see Figure 1.2 below). Observed overnight changes in inhibitory ability (Stroop task), motivation (difficulty, temptation, and motivation), and effort (self-reported Eye blink task effort) should also be partially due to that night's sleep. Because inhibition, motivation, and effort are key mechanisms of self-control, overnight changes in inhibition, motivation, and effort should contribute to the effect of sleep on changes in Eye blink performance.

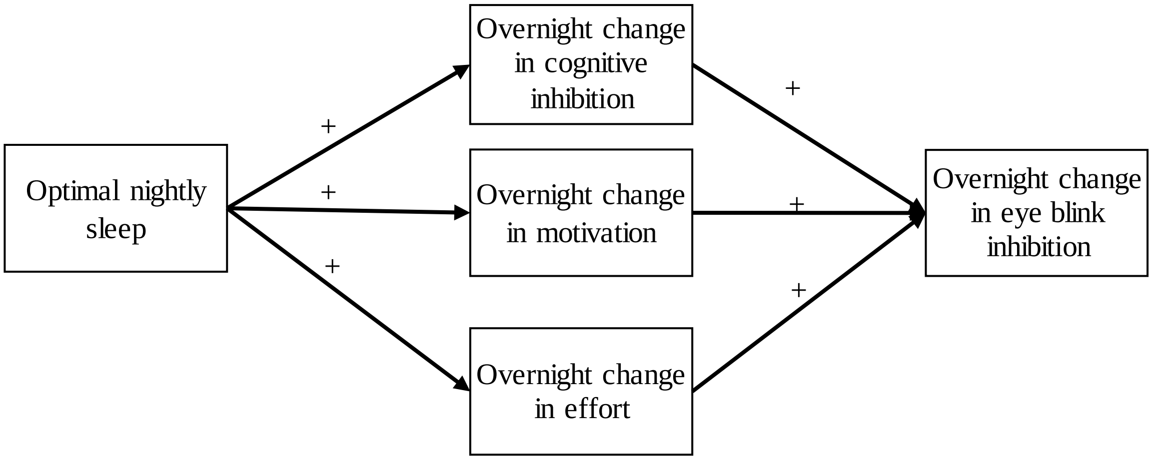

Figure 1.2. The influence of sleep on self-control and its underlying mechanisms.

CHAPTER 2. METHODS

Participants and Procedure

99 participants were recruited from the student participant pool at a large Midwestern university to participate in a two-week study on sleep and behavior. Participants first came to the lab where they provided informed consent, were screened for sleep, mental, and dry-eye disorders, and completed demographic and individual difference metrics. During this process, five participants indicated they had an ongoing sleep or mental disorder or had chronically dry eyes and were dismissed from the study. All remaining participants received study instructions and training for completing daily diary measures and using the actiwatch. Importantly, while receiving training on completing the eye-blink task, participants were informed that they can earn $50 if they are one of the ten participants who blinked the least during the Eye-blink task. To increase participants' trust that they could receive money based on their performance, all participants were shown $50 in cash. Afterwards, participants were dismissed and the two-week daily diary portion of the study began (Figure 2.1 presents an overview of the daily data collection timeline).

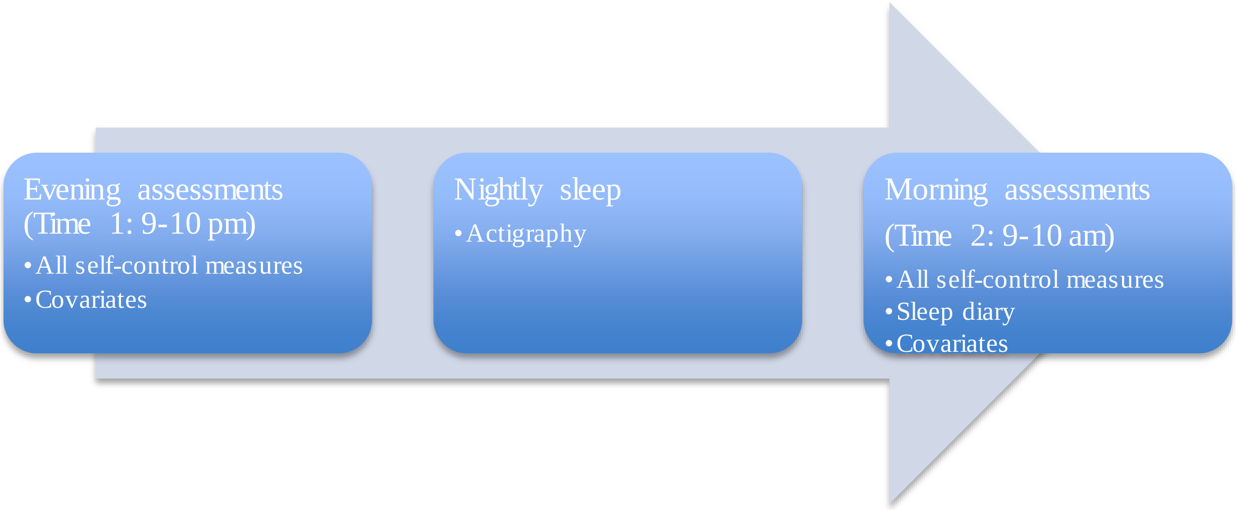

Figure 2.1. Overview of data collection timeline.

During the daily diary phase, all participants continuously wore an actiwatch, a wrist worn accelerometer that continuously measures movement to estimate sleep-wake state. At 9 pm each evening and 9 am each morning, participants were emailed a short self-report survey which included a prompt to complete the behavioral measures of self-control. While participants received emails at the same time each day, in order to compensate for variability in participants daily schedules (e.g., having conflicting morning obligations on some days and not others), participants were instructed to complete the surveys by 10 am and 10 pm for morning and evening surveys, respectively. In this survey, participants first completed measures of current affect, sleepiness, self-control capacity, and eye dryness. The morning survey also included questions regarding prior night sleep timing (to cross-validate actigraphic sleep onset and offset times) and subjective quality of prior night's sleep.

After completing these assessments, the survey then instructed participants to first complete the cognitive response inhibition task (i.e., Stroop task) and then the eye blink inhibition task before completing the rest of the survey. This fixed order was used because it was unclear whether participants would follow counterbalancing instructions for the tasks or whether particular people (e.g., more conscientiousness people) may follow such instructions better than others. To circumvent this possible noise within and across participants, the order was fixed in the hopes of setting a constant and habitual routine for participants. The limitations of this approach are addressed in the discussion.

Once these two tasks were completed, participants then reported their motivation, effort expenditure, and use of contacts or glasses during the eye-blink task. Finally, participants then reported on physical activity for the day and whether they had consumed caffeine, alcohol, or recreational drugs or smoked any cigarettes or similar substances in the past three hours. Both evening and morning assessments took approximately 10 minutes to complete. After completing these measures for 14 days, participants came back to the lab to return their actiwatch and were debriefed. This study was approved by the Iowa State University IRB (see Appendix B).

Participant Attrition and Exclusion

Of the 94 participants who passed initial screening and began the study, five participants dropped during the study (all within a day or two of study onset) and another 3 participants were excluded from analyses for not providing enough data (i.e., at least eight assessments on at least two other tasks or measures). One additional participant was excluded from the study for not following study instructions. This reduced the final sample size to 85 participants. This final sample had a mean age of 19.58 (SD = 2.70), was mostly female (65%), and predominately identified as European American (73%). Participants also indicated that on free days (i.e., days without work or school) they usually went to bed around 12:30 am (SD = 1.32 hours) and woke up at 9 am (SD = 1.26 hours). The corresponding midpoint of sleep from these free days was approximately 4:30 am (SD = 1.67 hours) and participants self-reported (i.e., “What is your chronotype?”) on average having an intermediate chronotype. These two metrics of chronotype converge on the conclusion that most participants tended to have an average or intermediate chronotype relative to their age group (i.e., neither morning nor evening oriented), though their chronotype would be more evening oriented relative to adolescents or middle aged adult populations (Reonneberg & Merrow, 2007). Finally, most participants did not screen positive for potential sleep disturbances via the Pittsburgh Sleep Quality Index using a cutoff score of 6 for a college population (M = 5.50, SD = 2.50; Dietch, et al., 2016).

Measures

Daily Self-control

Self-control assessments.

Eye blink inhibition. Participants were asked to complete the eye blink task in which they must refrain from blinking for two minutes (Schmeichel & Zell, 2007). During this task, participants must continuously override the visceral desire to blink, which requires both persistence (focus on keeping the eyes open, meeting study demands) and inhibition (suppressing sensations of impulse to blink, dryness, or boredom). Moreover, to ensure a sufficient desire-goal conflict necessary for the operation of self-control, participants were informed that the top 10 participants who blink the least during this task over the study period will receive cash rewards of $50. This reward for sustained long-term performance should create the goal-desire conflict necessary for self-control because participants will need to inhibit the desire to blink during the task in order to achieve the long-term goal of earning a sizeable portion of money (as well as comply with study requirements). Note that besides directly indexing a specific type of self-control (i.e., control over a bodily urge), people who are better able to inhibit eye blinks also persist longer at the handgrip task and score higher on trait self-control (Schmeichel & Zell, 2007; Tunze, 2012).

To complete this task, participants were asked to use their smartphone to video record themselves while attempting to stare into the camera lens for two minutes without blinking. Participants were instructed to continue with the task even if they blink before the two minutes are completed and to continue attempting to not blink for the remainder of the video. To complete the recording, participants were asked to place their phone on a flat surface, such as a table, where they can sit down and stare into the camera in a position that is physically comfortable. The number of blinks during the two minutes was used as a behavioral metric of self-control with greater blinks representing worse self-control. Once the task was completed, participants uploaded their video to the lab's secure cloud-based storage system where the number of blinks could be coded for number of eye blinks by lab personnel. Four members of the lab were trained on how to count the eye blinks and engaged in coding of these videos. Since having all coders code these videos would be highly impractical, all coders first coded a set of 30 eye blink videos from the first three participants. Interrater agreement was near perfection indicating that all coders were producing highly similar estimates of number of blinks (ICC = .99). Given the high agreement, only one coder counted any given participants eye blink videos for the remaining cases (the same coder counted for all of a particular participant's videos).

Self-reported self-control capacity. Self-reported self-control capacity was assessed with a shortened version of the State Self-control Capacity Scale, rating the extent to which they agree with four statements from 1 (*disagree very much*) to 7 (*agree very much*) (e.g. "Right now my mental energy is running low", "Right now my mind feels unfocused", ''Right now I am having a hard time controlling my urges'', "Right now if I were given a difficult task, I would give up easily"; Ciarocco, Twenge, Muraven, & Tice, 2004; DeHart, Peterson, Richeson, & Hamilton, 2014). Scores on this scale were reverse scored so that greater values reflect better self-control capacity. Individuals with worse scores on this scale are more likely to consume alcohol, verbally abuse others, and disengage from work (Barnes, Lucianetti, Bhave, & Christian, 2015; DeHart, Peterson, Richeson, & Hamilton, 2014). The within person reliability was .74 and .81 during evening and morning assessments, whereas the between person reliability was .92 and .90 for evening and morning assessments.

Self-control mechanisms.

Cognitive response (dis)inhibition. Participants completed a smartphone administered Stroop task to capture their current ability to inhibit competing behavioral responses, a cognitive ability critical for self-control (Carter, Kofler, Forster, & McCullough, 2015; Stroop, 1935). Better inhibition as assessed by the Stroop task is associated with better suppression of facial reactions to disgusting stimuli and reduced probability of giving in to desires (Hofmann, Adriaanse, Vohs, & Baumeister, 2014; von Hippel & Gonsalkorale, 2005). Additionally, meta-analysis demonstrates that performance on the Stroop task converges cognitive (executive function tasks), behavioral (delay of gratification tasks), and survey (both self- and informant-report) measures of self-control (Duckworth & Kern, 2011). It is worth noting that such correlations tend to be small (r's from .09 to .16) but are similar in magnitude to the correlations of other inhibition measures with cognitive, behavioral, and survey measures of self-control. Moreover, these estimates are based upon individual differences in Stroop performance rather than daily fluctuations within people because prior self-control research has not examined the effects of daily variations of Stroop performance on self-control. While it is unknown what the implications of daily Stroop performance are for self-control, having poorer inhibition at any particular moment should make restraining impulses more difficult.

The Stroop task was administered on participants' smartphones via EncephalApp, a freely downloadable application (Bajaj, et al., 2013). This app was originally designed as a quick and mobile tool to screen for minimal hepatic encephalopathy (i.e., brain dysfunction that is associated with liver disease). Initial validation demonstrated that worse Stroop performance on this app correlates with poorer performance on other inhibition, psychomotor speed, and attention tasks (Bajaj et al., 2013). Each completion of this task proceeded in two phases. In the first “off” phase, participants indicate as quickly as possible the presentation color of pound signs (i.e., ###) presented onscreen, which are a neutral stimulus (see Appendix A for layout of example trial). In the second “on” phase, participants again indicate the color of the stimulus presented onscreen, but now the stimulus is a color word (see Appendix A for layout of example trial). Importantly, for 90% of these trials the color-word is presented in an incongruent color, which creates a competing impulse for the participant to indicate the color-word that was read instead of the color of the word that was seen. For example, if presented with the color-word “blue” written in green text (i.e., not color-congruent), participants must respond with “green” while inhibiting the impulse to indicate “blue.” Both the off-phase and the on-phase consist of five runs. Within each run, participant must correctly complete ten stimulus presentation trials in a row, if not the run restarts. Participants completed three on phases and then three off phases during each assessment. Completion of this task required approximately three minutes.

The main measure of inhibition from this task is time needed time to complete the three on-phase runs minus time needed to complete the three off-phase runs. Off-phase runs are subtracted from on-phase runs to control for individual differences in processing speed. Increases on this metric reflect *worse* inhibition of a predominant cognitive response and the outcome variable is therefore referred to as *cognitive response disinhibition*.

Motivation, temptation, and effort. Motivation, temptation, and effort during the eye blink task were assessed with six questions assessing (1) the intensity of the temptation to blink, (2) intensity of motivation to avoid blinking during the eye blink task, (3) intensity of motivation to earn $50 based upon eye blink performance, (4) amount of effort put into not blinking, (5) difficulty of not blinking, and (6) how stressful it was to not blink, adapted from Hagger and colleagues (2016). All responses were made on a scale from not at all (1) to very much (5). State sleepiness was also assessed given that the desire to sleep may interfere with the motivation to exert effort on self-control. Sleepiness will be assessed with the Karolinska Sleepiness Scale which asks participants how sleepy they currently are from “Extremely alert” (1) to “Extremely sleepy” (9). This scale converges with objective measures of sleepiness (within individuals) and has been shown to be highly sensitive to changes in sleep pressure (Akerstedt, Anund, Axelsson, & Kecklund, 2014).

Theoretically, temptation, motivation, and effort are distinct constructs. However, the independence of these experiences in a daily diary study has not been evaluated. To determine the factor structure of these items and whether they measure three distinct constructs at the within-person level (i.e., daily changes), multilevel exploratory factor analysis was conducted on the items completed during the evening assessments. A final factor solution was determined with a confirmatory factor analysis conducted on the morning assessments. Geomin rotation was used in all factor analyses to allow for correlated factors. Although a three factor solution cannot be mathematically identified with only seven items, poor loading items in a two factor solution would suggest the presence of a third construct.

Raw means and standard deviations of these items as well as the day-level and person-level correlations are presented in Table 2.1. Factor analyses revealed that a two factor solution at both the within and between levels best fit the data (see Table 2.2). Temptation to blink, difficulty of not blink, and stress of not blink strongly loaded onto one factor, this factor is referred to as the *Temptation* factor. Motivation to avoid blinking, motivation to earn $50, and effort expenditure strongly loaded onto a separate factor, referred to as *Motivation*. These two factors were minimally correlated at both the within and between levels (r’s $< .16$), supporting the notion that the intensity of the urge individuals had to combat was independent from their motivation to do so. Subjective sleepiness loaded onto neither the temptation nor motivation factors. Altogether, factor analyses suggest that temptation, motivation, and sleepiness were independently measured at the within person level in this study and thus these constructs were used in study analyses. To simplify study analyses, temptation was measured by averaging the three temptation loading items (as opposed to extracting a latent factor) and motivation was measured by averaging the three motivation items. Multilevel reliability defined as multilevel Cronbach’s alpha from Geldhof, Preacher, and Zyphur (2014) was calculated for these (and all within person scale) items. The multilevel reliability of the motivation items was .80 during morning assessments and .78 during evening assessments at the within level and was .88 during morning assessments and .89 during evening assessments at the between level. The multilevel reliability of the temptation items was .85 during morning assessments and .84 during evening assessments at the within level and was .90 during morning assessments and .87 during evening assessments at the between level.

Table 2.1 Correlations among motivation and effort items (N = 1,107 at the day-level and N = 84 at the person-level).

	M (SD)	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1. How tempted were you to blink? (Eve)	3.56 (0.92)	--	.14	.06	.95*	.65*	.25*	.06	.94*	.14	.05	.90*	.62*	.23*	.09
2. How motivated were you to avoid blinking? (Eve)	3.86 (0.92)	.11*	--	.80*	.18†	.29*	.84*	-.30*	.16	.94*	.78*	.17	.30*	.81*	-.22*
3. How motivated were you to earn the $50 for your performance? (Eve)	3.69 (1.22)	.08*	.64*	--	.11	.26*	.66*	-.19†	.05	.74*	.99*	.06	.25*	.62*	-.24*
4. How difficult did you find it to not blink? (Eve)	3.55 (0.90)	.72*	.08*	.06*	--	.70*	.29*	.03	.88*	.16	.09	.92*	.64*	.25*	.07
5. How stressful did you find it to not blink? (Eve)	2.74 (1.09)	.56*	.17*	.18*	.66*	--	.36*	-.05	.58*	.25*	.23*	.62*	.97*	.30*	.10
6. How much effort did you put into Eye-blink task? (Eve)	3.91 (0.87)	.19*	.53*	.46*	.21*	.24*	--	-.22*	.21†	.80*	.65*	.24*	.32*	.96*	-.21†
7. How sleepy are you currently? (Eve)	4.63 (1.22)	.11*	-.03*	-.01	.12*	.14*	.00	--	.04	-.23*	-.16	-.03	-.06	-.20†	.45*
8. How tempted were you to blink? (Mor)	3.51 (0.84)	.15*	.15*	.13*	.14*	.12*	.11*	.03	--	.13	.03	.95*	.62*	.19†	.21†
9. How motivated were you to avoid blinking? (Mor)	3.85 (0.93)	.11*	.31*	.30*	.08*	.12*	.26*	-.02	.04	--	.77*	.11	.26*	.87*	-.36*
10. How motivated were you to earn the $50 for your performance? (Mor)	3.62 (1.26)	.10*	.36*	.54*	.07*	.18*	.30*	.00	.01	.61*	--	.03	.24*	.65*	-.31*
11. How difficult did you find it to not blink? (Mor)	3.50 (0.79)	.16*	.16*	.16*	.19*	.14*	.09*	.06*	.78*	.02	-.01	--	.64*	.19†	.19†
12. How stressful did you find it to not blink? (Mor)	2.65 (1.08)	.15*	.13*	.19*	.15*	.13*	.11*	-.02	.59*	.10*	.08*	.61*	--	.29*	.08*
13. How much effort did you put into Eye-blink task? (Mor)	3.94 (0.83)	.07*	.30*	.29*	.06*	.18*	.29*	.04	.14*	.60*	.50*	.13*	.13*	--	-.31*
14. How sleepy are you currently? (Mor)	4.57 (1.36)	.01	-.03	-.03	.04	-.03	.00	.05†	.01	-.15*	-.10*	.05†	-.01	-.10*	--

Note. *p<.05, †p < .10. Correlations *below* the diagonal are *within*-person and correlations above the diagonal are between person correlations.

Table 2.2 Factor loadings of motivation, temptation, and effort items

Scale items	Exploratory factor analysis		Confirmatory factor analysis	
	Factor loadings at within level		Factor loadings at within level	
	Temptation	*Motivation*	*Temptation*	*Motivation*
How tempted were you to blink?	***.78***	.01	***.87***	--
How motivated were you to avoid blinking?	.00	***.86***	--	***.85***
How motivated were you to earn the $50 for your performance?	.00	***.75***	--	***.71***
How difficult did you find it to not blink?	***.93***	-.04	***.89***	--
How stressful did you find it to not blink?	***.70***	.11	***.68***	--
How much effort did you put into Eye-blink task?	.17	***.59***	--	***.70***
How sleepy are you currently?	.15	-.05	--	--
	Factor loadings at the between level		Factor loadings at the between level	
	Temptation	*Motivation*	*Temptation*	*Motivation*
How tempted were you to blink?	***.95***	-.02	***.95***	--
How motivated were you to avoid blinking?	.00	***1.00***	--	***1.00***
How motivated were you to earn the $50 for your performance?	-.03	***.80***	--	***.76***
How difficult did you find it to not blink?	***1.00***	.01	***1.00***	--
How stressful did you find it to not blink?	***.66***	.18	***.64***	--
How much effort did you put into Eye-blink task?	.15	***.82***	--	***.86***
How sleepy are you currently?	.09	-.29	--	--
χ^2	10.09 (df = 16)		43.93 (df = 18)	
RMSEA	.01		.04	
CFI	1.00		.98	
TLI	1.00		.97	

Note. Factor loadings are standardized. Exploratory factor analysis was conducted on evening assessments and confirmatory factor analyses was conducted on morning assessments.

Daily Sleep Measures

Daily sleep was assessed through self-reported sleep diary and through actigraphy.

Sleep diary.

During each morning daily diary entry, participants reported what time he or she went to bed (with the intention of sleeping), how long it took to fall asleep, what time he or she woke up, and subjective perceptions of sleep quality (via the global sleep quality index from the Karolinska Sleep Diary). Items in this sleep quality index include ratings of overall sleep quality, calmness of sleep, ease of falling asleep, sleeping throughout the night, and feeling refreshed after sleep (Akerstedt, Hume, Minors, & Waterhouse, 1994). The multilevel reliability indicated that the reliability of these items at the within level was .83 and was .93 at the between level.

Actigraphic sleep.

During the study period, participants continuously wore the Actiwatch Spectrum Pro wrist on their non-dominant wrist. This device measures wrist movement and activity to evaluate sleep-wake state at every 30-second epoch and derive estimates of sleep. The main actigraphic sleep outcomes were nightly sleep duration and nightly sleep continuity. Sleep *duration* represents the number of minutes spent sleeping. Sleep *continuity* measures the ease of initiation and maintenance of sleep throughout the night. Sleep continuity was calculated by first standardizing and then averaging nightly sleep onset latency (number of minutes to fall asleep), number of wake episodes (scored based upon frequency and intensity of movements), and total duration of wake episodes, as suggested by Ohayon and colleagues (2017).

Convergent testing with polysomnography has demonstrated that the Actiwatch Spectrum Pro reliably estimates basic sleep indices (Marino, et al., 2013). To further increase reliability of actigraph sleep estimates, estimated sleep and wake times were cross-referenced with participant self-reported sleep and wake times from the sleep diary. For instance, times during the evening or morning in which participants are sedentary for sustained periods of time, such as when watching TV or reading a book, can incorrectly be classified as sleep latency or sleep by the actiwatch. To correct for these possibilities, actiwatch recorded sleep and wake times are checked against participant self-reported sleep and wake times. If sizeable discrepancies between actiwatch recorded and participant reported bed or wake time was present on a given day, the corresponding participant recorded bed or wake time was used. When making these decisions, the intensity and frequency of actiwatch recorded movement and light were used as additional sources of insight into whether the actiwatch incorrectly set a bed or wake time (similar to procedures used to clean and score actigraphy data in Krizan & Hisler, 2019).

Finally, it is important to note that participants were instructed to complete morning surveys and measures of self-control between 9 am and 10 am. Given the college student population, it is possible that participants could complete these measures and go back to sleep. Because this study is primarily interested in how sleep occurring between two assessments of self-control predicts the change in self-control, sleep after the completion of the morning survey was not used in calculating sleep variables.

Covariates

The following variables were also measured to control for potential confounds: use of glasses (no [0] /yes [1]) or contacts (no [0] /yes [1]), current eye dryness, caffeine (no [0]

/yes [1]) and alcohol use (no [0] /yes [1]) in the past three hours, and time of awakening. Wearing glasses or contacts may shield eyes from drying out and can take effort to put in, both of which may be impacted by poor sleep. Current eye dryness is likely to deteriorate eye blink task performance and may be amplified by sleep loss. Caffeine and alcohol use may boost and undermine self-control performance, respectively, and both are known to corrode sleep and are more likely to be used when unrested. Too late of a time of awakening may signal sleep inertia which undermines self-control performance, and should also be predicted by longer sleep duration.

An adapted form of the dry eye questionnaire was used to assess eye dryness (Chalmers, Begley, & Caffery, 2010). This questionnaire asked how often the participants experienced eye discomfort, how intense this discomfort was, how often their eyes felt dry, how intense this dryness was, and how often their eyes felt excessively watery. Responses were aggregated to form a composite measure of eye dryness. Reliability during the morning was .83 at the within and .95 at the between level and reliability during the morning was .86 at the within and .94 at the between level.

Daily Task Data Completion and Exclusions

One participant's stroop data was omitted from study analyses given an alarmingly high number of attempts on the stroop task (over 30 attempts every day). 70 eye blink videos were excluded from data analysis because participants were engaging in some kind of distracting activity during the recording (e.g., talking to friends, watching TV, attending class). An additional video was excluded because the participant erroneously uploaded a video of a cow licking a metal gate. To control for substantial time of day differences across survey days, all surveys, videos, and stroop task data that were not submitted between the 9 am to 10 am and 9 pm to 10 pm completion times were excluded from analyses. This excluded 236 eye blink videos, 207 surveys, and 181 stroop completions.

After these exclusions, participants completed 1,555 eye blink videos (65% of total possible eye blink videos), 1,872 surveys (79% of total possible surveys), and 1,532 instances of the stroop task out (64% of total possible stroop instances). Sleep was recorded on 1,079 out of the possible 1,190 possible nights (91% completion rate). Missing sleep data was due to watch recording errors or participants taking off the watch. On average, participants completed 22.02 surveys (SD = 6.35), 18.29 eye blink videos (SD = 7.86), and 18.02 stroop instances (SD = 10.04) out of the total possible of 28. Participants on average completed 13 days of sleep data (SD = 3.22).

Missing Data

To evaluate the potential influence of missing data within the study, correlations of key study variables with missingness on surveys, eye blink videos, stroop data, and sleep data were calculated. These analyses were performed after person-centering variables to evaluate the day specific associations of missingness with study variables. Correlations greater than .10 were deemed large enough to warrant discussion of potential relation with missing data. Morning surveys, videos, and stroop data were more likely to be missing on the weekend (r's = .10 to .14) and when participants woke up later in the day (r = .19 to .21). Completion of evening surveys, videos, and stroop data was not related to any sleep or self-control variable. Missing sleep data was associated with worse stroop performance in the morning (r = .22). Overall, missing data patterns suggest that sleeping in, which is likely to occur on the weekends, interfered with task completion. Missing data was handled using Full Information Maximum Likelihood estimation in MPLUS v7 (Muthen & Muthen , 2012).

Analytic Strategy

To examine study hypotheses, multilevel structural equation modeling was first used to test if nightly sleep predicts the degree of overnight change in self-control. To estimate this change, an autoregressive approach was used in which self-control in the morning was predicted by the intervening period of sleep, adjusting for prior evening self-control. All continuous variables were person-centered to disaggregate the person-level variance from the day-level variance and thereby remove the influence of correlations among individual differences from estimates of day-level (within-person) effects. Better sleep in the form of longer duration, more continuity, or better subjective quality was then tested as a predictor of overnight changes in self-control performance. Additionally, to examine if changes in self-control due to sleep occur because of parallel overnight change in cognitive inhibition, motivation, and effort, mediation models were examined (see Figure 1.2). Given the high power of study (correlations as small as .08 are significant at the .05 level) and the arbitrary nature of making decisions based upon significance thresholds, this study focuses on using both effect sizes and p-values to interpret statistical evidence (Funder & Ozer, 2019; McShane, et al., 2019).

CHAPTER 3. RESULTS

Table 3.1 presents the key descriptive statistics and correlations of study variables. Raw un-centered means appear in the second to leftmost column of Table 3.1. Day-level variability (presented in standard deviations) and correlations among all key variables after person-centering are presented in the rest of Table 3.1. The raw un-centered means depict the average daily sleep characteristics and illustrate the overnight change in self-control and covariates in the sample. On average, participants slept for seven hours prior to completing daily assessments, had fairly good subjective sleep quality, and woke around 8 am. Participants also blinked an average of 6 to 7 times during each eye blink assessment, which is lower than reported in prior research utilizing this task in lab, perhaps due to the fact that this study offered monetary incentive for performance (Schmeichel & Zell, 2007). During this task they were moderately tempted to blink ($M = 3.27/5.00$), but were very motivated to avoid blinking and do well on the task ($M = 3.88/5.00$). Participants also reported a moderate capacity for self-control ($M = 4.17/7.00$). Additionally, participants had a good amount of inhibitory control as response time to the “on” trials of the stroop task were only slightly longer than the “off trails of the stroop task ($M_{diff} = 4.40$ ms). These average sleep and self-control characteristics suggest that participants in the study sample tended to be relatively self-controlled and had healthy sleep.

In terms of overnight change in self-control, participants had worse self-reported self-control capacity in the evening than in the morning, in line with past research ($M_{diff} = -.34$, $p < .001$, 95% CI = .16 to .53). There were no mean differences between evening and morning assessments on all other self-control constructs (all d’s < |.05|, p’s > .54). Participants also reported greater eye dryness ($M_{diff} = .05$, $p = .03$, 95% CI = .01 to .10) and were slightly more likely to have recently consumed caffeine (M_{diff} = .06, p = .05, 95% CI = .001 to .11) in the evening than in the morning.

While it was assumed that self-control should improve overnight due to sleep, it is important to consider the influence of the circadian rhythm on these average differences between the evening and morning. College students tend to be more evening oriented than other age groups and may perform well later in the evening (e.g., 9 to 10 pm), but have more difficulties in the morning (e.g., 9 to 10 am) due to the delayed timing of their circadian rhythm. Thus, when comparing changes in average self-control from 9 pm to 9 am, the circadian rhythm of an evening oriented sample may reduce or cancel out the beneficial effect of sleep on the average overnight change. Indeed, when correlating chronotype (as indexed via the midpoint of sleep on freedays), participants who were more evening oriented tended to have greater overnight increases in number of eye blinks (r = .21) and sleepiness (r = .32), as well as parallel decreases in overnight improvements in self-reported self-control capacity (r = .18, all p's < .10). In other words, in comparison to morning people, more evening oriented participants tended to perform worse in the morning than the evening. Averaging these variables across diverse chronotypes may yield an average of no change.

Critically, this study was not interested in predicting these average sample differences, but rather the deviations from a person's average. These deviations are calculated by person-centering day-level variables, which removes the confounding influence of individual differences in circadian rhythms on day level associations. Importantly, the day-level variability estimates in Table 3.1 reveal that that all variables significantly varied across days within a person. Thus, although there may not be differences on *average* in most self-control assessments from one evening to the next morning, there was significant daily variability in the day-to-day deviations of these variables from their average. It is these daily deviations from the average which might be explained by sleep and which the remainder of this study focuses on.

Relations among Key Self-control Measures within Individuals

Overall, eye blink inhibition was unrelated to concurrent assessments of self-reported self-control capacity, though a small expected correlation emerged between having better self-reported self-control capacity and fewer number of eye blinks in morning assessments (*r* = -.07). These small correlations suggest that scores on the self-reported self-control capacity scale are at most only slightly associated with behavioral inhibition of blinking. Self-reported self-control capacity was highly correlated with reported sleepiness, however (*r*'s = -.54 and -.61 in the evening and morning, respectively). Together these correlations suggest that this pervasively used (yet non-validated measure) of self-control may tap more into feelings of tiredness than actual self-control performance (though tiredness should impact self-control).

Providing validity evidence for scores on the motivation and temptation measures, participants blinked slightly less on days in which they were more motivated to inhibit eye blinks (*r's* = -.08 and -.12 for motivation in the evening and morning, respectively) and blinked substantially more when they felt more tempted to blink (*r's* = .33 and .42 in the evening and morning, respectively). Thus, both motivation and temptation predicted performance on the eye-blink task, but temptation was substantially more important for than motivation.

The Influence of Covariates on Self-control

Eye blink inhibition was not correlated with use of contact lenses, glasses, caffeine, or alcohol (all *r*'s < .04, all p's > .10). As expected, participants did blink more when they

Table 3.1 Day-level variability and correlations among person-centered study variables (N = 1,049-1,144).

	rM	cSD	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1. Sleep duration (minutes)	421.16	76.79*	--																							
2. Sleep continuity	.00	0.58*	-.50*	--																						
3. Subjective sleep quality	3.64	0.67*	.15*	.11*	--																					
4. Time of awakening	7:56	1.07*	.52*	-.26*	.13*	--																				
5. Number of blinks eve.	6.47	5.37*	.03	.00	.00	.06	--																			
6. Temptation eve.	3.28	0.79*	.02	.03	-.01	-.03	.33*	--																		
7. Motivation eve.	3.89	0.60*	.03	-.04	.01	.00	-.08*	.18*	--																	
8. Sleepiness eve.	4.65	1.59*	.08*	-.03	-.04	-.10*	.02	.15*	.00	--																
9. Self-control capacity eve.	4.00	1.01*	-.06	-.01	.01	.09*	.00	-.13*	.03	-.54*	--															
10. Cognitive response disinhibition eve.	3.36	4.23*	.04	-.02	-.02	.01	.01	.07*	.04	.06	-.02	--														
11. Eye dryness eve.	1.34	0.43*	.04	.03	.09*	.04	.13*	.16*	.02	.21*	-.16*	.02	--													
12. Contact use eve.	18%	--	-.05	.00	.13*	-.01	-.01	-.01	.03	-.02	.01	.00	-.03	--												
13. Glasses use eve.	11%	--	.01	.01	.02	-.01	.04	.02	-.04	.01	-.02	.04	.04	-.16*	--											
14. Caffeine use eve.	18%	--	-.05	.00	-.06	.03	.01	-.01	.01	-.08*	.06	.04	-.01	.02	.03	--										
15. Alcohol use eve.	6%	--	-.03	.02	.02	.07	.02	.01	-.01	.00	-.03	-.01	.00	.02	.06	.17*	--									
16. Number of blinks mor.	6.74	5.31*	-.08*	.02	-.06	.05	.21*	.07	.03	-.01	.03	-.02	-.02	.00	.04	.06	.13*	--								
17. Temptation mor.	3.25	0.79*	-.10*	.06	-.08*	-.04	.03	.22*	.18*	.01	-.02	.06	.06	.02	.03	.04	.08*	.42*	--							
18. Motivation mor.	3.86	0.55*	.02	-.05	.14*	.00	-.04	.11*	.48*	-.01	.02	.05	.04	.01	.00	.02	.02	-.12*	.11*	--						
19. Sleepiness mor.	4.61	1.75*	-.03	.06	-.18*	.26*	.00	.02	-.04	.04	-.02	.01	-.02	-.01	.04	.04	.09*	.07	.01	-.13*	--					
20. Self-control capacity mor.	4.34	1.01*	.00	.01	.13*	-.17*	.01	-.01	.04	-.06	.08*	.06	-.02	.01	.00	-.01	-.05	-.07	-.02	.13*	-.61*	--				
21. Cognitive response disinhibition mor.	3.43	4.93*	-.01	.03	.02	.02	.01	.01	.01	.02	.00	-.10	-.01	.01	-.07	-.03	.01	-.03	.04	.01	-.04	.07	--			
22. Eye dryness mor.	1.29	0.36*	-.11*	.02	.08*	-.02	.01	.12*	.10*	.04	-.01	.04	.06	-.02	.18*	.08	.06	.14*	.14*	.06	.15*	-.07	-.01	--		
23. Contact use mor.	16%	--	-.01	-.01	-.01	.01	.01	.00	.01	-.01	.00	-.01	-.01	.85*	-.11*	-.03	-.02	.03	.02	.02	-.05	.06	-.01	.02	--	
24. Glasses use mor.	11%	--	-.05	.03	-.01	-.08*	-.01	-.01	.01	.02	-.03	-.03	.04	-.10*	.84*	.03	.01	-.03	-.03	-.01	.01	-.01	.02	-.01	-.14*	--
25. Caffeine use mor.	13%	--	-.18*	.07	-.05	-.27*	-.07	-.03	.03	.01	-.03	-.02	-.01	-04	.00	.16*	.10*	.03	.01	-.01	-.11*	.08*	-.02	.07*	-.01	-.01

Note. *p<.05, rM represents the raw mean prior to person-centering. cSD represents the day-level variability after person-centering.

experienced greater eye dryness (*r*'s = .14 and .13, in the evening and morning, respectively, all *p*'s < .05). Self-reported self-control capacity was also worse when participants experienced greater eye dryness (*r*'s = -.14 and -.07 in the evening and morning, respectively, all *p*'s < .10), but tended to be slightly better when participants had recently consumed caffeine (*r*'s = .06 and .08 in the evening and morning, respectively, all *p*'s < .10). Interestingly, waking up later in the day was associated with worse self-reported self-control capacity in the morning (likely as a result of sleep inertia; $r = -.17$, $p = .001$), but better self-reported self-control capacity in the evening (likely as a result of sleeping in and getting more sleep; $r = .09$, $p = .02$).

In sum, self-control tended to be worse when participant also reported having drier eyes or had recently woken up, and self-control was better after consuming caffeine.

Relations among Sleep Characteristics and Covariates within Individuals

Longer sleep durations were associated with less sleep continuity ($r = -.50$, $p < .001$). Longer sleep duration was also associated with better subjective sleep quality ($r = .15$, $p = .002$) and waking later in the day ($r =.52$, $p < .001$). More continuous sleep was also associated with better subjective sleep quality ($r = .11$, $p = .02$), but with earlier time of awakening ($r = -.26$, $p < .001$).

Participants likely experienced more continuous sleep when they awoke earlier in the day because they had to wake up early for morning class or work obligations. Given that most college students are more evening oriented and tend to naturally fall asleep later in the night than the typical adult, waking up earlier should then reduce sleep duration, but also avoid some sleep fragmentation. This reduction in sleep duration and early morning fragmentations due to waking up early would result in a strong negative correlation between sleep continuity and sleep duration observed here.

All sleep indices were generally unrelated to evening covariates (e.g., alcohol, caffeine, and eyewear use). However, worse sleep was associated with morning covariates. Shorter sleep or sleep of worse subjective sleep quality predicted slightly greater eye dryness in the morning (*r*'s= -.11 and .08, *p*'s < .05). Additionally, participants were more likely to consume caffeine after sleeping less than normal ($r = -.18$, $p < .001$) and if they woke up earlier than usual ($r = -.27$, $p < .001$), consistent with typical patterns of caffeine use.

Combining correlations of the covariates with sleep variables to those with self-control variables demonstrates that only eye dryness, time of awakening, and caffeine use were substantially related to both key sleep and self-control indices. Because these were the only covariates that had significant relations to both sleep and self-control, they may confound associations between sleep and change in self-control. Therefore, only eye dryness (both morning and evening), time of awakening, and caffeine use (both morning and evening) were used as covariates in the following analyses examining whether sleep predicted the overnight change in self-control. The results of key analyses are reported before and after covariates are regressed on all outcome variables.

Note that time of awakening is a particularly important variable to adjust for because it approximates sleep inertia, which is critical when examining the effects of sleep duration. Participants may sleep late, and thereby increase their sleep duration, but because morning assessments are fixed to occur between 9 to 10 am, this may reduce the time between awakening and completing morning assessments which require exerting effortful mental activity. This reduction in time between awakening and completion of morning assessments could lead to impaired performance in the morning because of sleep inertia. This could mask the effects of sleep duration because time of awakening and sleep duration are strongly confounded (r = .52) yet later time of awakening could harm morning self-control while sleep duration could boost it.

Did Sleep Predict Overnight Change in Self-control within Individuals?

Sleep and Change in Self-control Outcomes.

After adjusting for prior evening assessment and study covariates, longer sleep duration predicted better morning eye blink inhibition (β = -.10, p = .02, 95% CI = -.18 to -.02), but not self-reported self-control capacity (β = .02, p = .68). Sleep continuity had a small, though statistically marginal association with poorer eye blink inhibition (β = .06, p = .10, 95% CI = -.01 to .13), but not with self-reported self-control capacity (β = -.01, p = .85). Subjective sleep quality also had a small, but statistically marginal association with eye blink inhibition (β = -.06, p = .09, 95% CI = -.12 to .01), while it predicted better self-reported self-control capacity (β = .13, p = .001, 95% CI = .05 to .21).

Next, covariates (time of awakening, morning and evening eye dryness and caffeine use) were included in these models. After including study covariates, sleep duration predicted both eye blink performance (β = -.14, p = .007, 95% CI = -.23 to -.04) and self-reported self-control capacity more strongly (β = .12, p = .004, 95% CI =.04 to .21). The amplification of these effects was primarily due to removing the confounding effect of time of awakening which had an opposing effect to sleep duration for both eye blink inhibition (β = .11, p = .04, 95% CI =.01 to .23) and self-reported self-control capacity (β = -.24, p = .04, 95% CI = -.35 to -.13). Note that shorter sleep duration was both related to experiencing greater eye dryness and decreases in morning eye blink inhibition, yet even after controlling for eye dryness, shorter sleep duration still predicted worse eye blink inhibition. Thus, reductions in sleep duration amplified the urge to blink (via increased dryness), but also independently deteriorated the ability to restrain this urge, suggesting that sleep duration impacts controlling the impulse to blink beyond the simple amplification of the urge to blink.

The small and negligible effects of sleep continuity on eye blink inhibition and self-reported self-control capacity remained unchanged after including covariates. Subjective sleep quality still did not predicted morning eye blink inhibition, but remained a strong predictor of morning self-reported self-control capacity ($\beta = .15$, $p < .001$, 95% CI = .07 to .23).

What sleep characteristics uniquely predicted change in self-control outcomes? The small association of sleep continuity and subjective sleep quality with eye blink performance may be due to their overlap with sleep duration, which had an association with eye blink performance that was twice as strong in magnitude. In a follow-up analysis using sleep duration as a covariate (in addition to the inclusion of other study covariates), sleep continuity ($\beta = .02$, $p = .72$, 95% CI = -.07 to .10) and subjective sleep quality ($\beta = -.05$, $p = .14$, 95% CI = -.11 to .02) no longer predicted morning eye blink inhibition, but sleep duration did ($\beta = -.12$, $p = .02$, 95% CI = -.23 to -.02). Similarly, both sleep duration and subjective sleep quality predicted morning self-reported self-control capacity, yet were correlated with one another. After regressing morning self-reported self-control capacity on both sleep duration and subjective sleep quality (as well as all study covariates), both sleep duration ($\beta = .11$, $p = .009$, 95% CI = .03 to .19) and subjective sleep quality ($\beta = .15$, $p < .001$, 95% CI = .07 to .22) uniquely predicted self-reported self-control capacity.

Taken together, these results suggest that the core relation of sleep with overnight change in eye blink inhibition is through sleep duration, while how long someone slept and their perceived quality of sleep were important for overnight change in *self-reported* self-control capacity.

Sleep and Change in Self-control Factors.

After controlling for the prior evening assessment, shorter sleep duration predicted greater morning eye blink temptation ($\beta = -.10$, $p = .001$, 95% CI = -.18 to -.02), but not eye blink motivation ($\beta = .01$, $p = .68$, 95% CI = -.09 to .10) nor cognitive response disinhibition ($\beta = -.02$, $p = .67$, 95% CI = -.09 to .06). Shorter sleep duration also predicted more sleepiness, but this was a small and statistically marginal association ($\beta = -.06$, $p = .08$, 95% CI = -.13 to .01). More continuous sleep predicted greater morning sleepiness ($\beta = .08$, $p = .04$, 95% CI = .01 to .16), and had a small trend to predict greater morning temptation ($\beta = .06$, $p = .09$, 95% CI = -.01 to .14). After a night of better subjective sleep quality, participants reported less temptation ($\beta = -.08$, $p = .05$, 95% CI = -.15 to .00), more motivation ($\beta = .14$, $p = .001$, 95% CI = .06 to .22), and less sleepiness ($\beta = -.19$, $p < .001$, 95% CI = -.27 to -.12). Neither sleep continuity nor subjective sleep quality predicted cognitive response disinhibition (both β‘s < .03, both p‘s > .50).

Once again, these analyses were repeated after including study covariates. After accounting for time of awakening and morning and evening caffeine use and eye dryness, longer sleep duration still predicted less temptation, but not motivation and cognitive response disinhibition in a similar fashion. However, sleep duration now had an effect on morning sleepiness that was four times as strong ($\beta = -.23$, $p < .001$, 95% CI = -.31 to -.16). This large change was again due to controlling for time of awakening which had a strong opposing effect on morning sleepiness ($\beta = .39$, $p < .001$, 95% CI = .27 to .48). The effects of sleep continuity remained largely the same, but now had twice the effect on morning sleepiness ($\beta = .15$, $p < .001$, 95% CI = .07 to .23). Better subjective sleep quality also still predicted greater morning motivation and less sleepiness in similar fashions, but now had a statistically marginal association with less temptation ($\beta = -.07$, $p = .08$, 95% CI = -.14 to .01).

What sleep characteristics uniquely predicted change in self-control factors? Sleep duration, sleep continuity, and subjective sleep quality all predicted both morning sleepiness and temptation. To examine which sleep characteristics uniquely predicted change in sleepiness and temptation, all three sleep variables were simultaneously regressed upon sleepiness and temptation (in addition to all study covariates). Sleep duration ($\beta = -.17$, $p = .16$, 95% CI = -.18 to .03) and sleep continuity ($\beta = .04$, $p = .47$, 95% CI = -.06 to .14) no longer predicted morning temptation, and subjective sleep quality only had a marginal effect ($\beta = -.07$, $p = .09$, 95% CI = -.15 to .01). In contrast, duration ($\beta = -.15$, $p < .001$, 95% CI = -.23 to -.07), continuity ($\beta = .12$, $p = .001$, 95% CI = .05 to .19), and subjective sleep quality ($\beta = -.21$, $p < .001$, 95% CI = -.28 to -.14) all uniquely predicted morning sleepiness.

Altogether these analyses suggest that the length, continuity, and subjective quality all contribute to various motivational factors underlying self-control. No single characteristic was uniquely important for changes in temptation, but all three independently contributed to sleepiness. Subjective sleep quality was also related to motivation making it broadly related to all motivational factors.

Did Change in Underlying Self-control Factors Explain the Effect of Sleep on Change in Self-control?

Because sleep duration and subjective sleep quality predicted both self-control outcomes (i.e., eye blink inhibition and self-reported self-control capacity) and underlying self-control factors (i.e., temptation and sleepiness) only sleep duration and subjective sleep quality linkages were examined in mediational models. Note that bootstrapping in multilevel mediation models is not available in Mplus v7, thus tests of mediation may have reduced power (although the originally high study power should offset this limitation). Additionally, as neither sleep duration nor subjective sleep quality predicted change in cognitive response disinhibition, cognitive response disinhibition was not included in mediation models. Finally, because temptation, motivation, and sleepiness were minimally correlated (r's < |.18|), these mediators were simultaneously entered in the model. Time of awakening and morning and evening eye dryness were used as covariates. Caffeine use was not included due to the number of model parameters exceeding the number of participants in the study and causing model estimation to be unreliable. Caffeine use was selected because it was the least important of all study covariates in prior models. The results of these final mediation models are depicted in Figures 3.1, 3.2, and 3.3.

Eye blink inhibition. Recall that the overall effect (i.e., total effect) of sleep duration on morning eye blink inhibition after adjusting for evening eye blink inhibition and study covariates was -.14. After entering temptation, motivation, and sleepiness as mediators in the model, this total effect was almost halved to -.08 (p = .04, 95% CI = -.16 to -.003), demonstrating that these factors accounted for approximately 50% of the effect of sleep duration on eye blink inhibition. Further inspection of the mediation model shows that only the indirect effect though temptation was significant and therefore it was primarily temptation that was accounting for 50% of the effect of sleep duration ($_{\text{ind}}\beta = -.04$, $p = .02$, 95% CI = -.08 to -.01, all other $_{\text{ind}}\beta$ ‘s < |.002|, *p’s* > .79).

Self-reported self-control capacity. The overall effect of sleep duration on self-reported self-control capacity was -.12, which was essentially reduced to zero after entering the mediators in the model ($\beta = -.02$, $p = .61$, 95% CI = -.10 to .06). Thus, these mediators fully accounted for the effect of sleep duration on self-reported self-control capacity, which was solely due to sleepiness ($_{\text{ind}}\beta = .14$, $p < .001$, 95% CI = .10 to .19) as there was no evidence that temptation nor motivation were contributing mediators (both $_{\text{ind}}\beta$ ‘s < |.001|, *p’s* > .76).

Turning to subjective sleep quality, recall that the overall effect of subjective sleep quality on morning self-reported self-control capacity after adjusting for evening self-reported self-control capacity and study covariates was .15. After entering temptation, motivation, and sleepiness as mediators in the model, this effect was practically reduced to zero ($\beta = .02$, $p = .60$, 95% CI = -.07 to .04). Therefore, these mediators accounted for the effect of better subjective sleep quality on better self-reported self-control capacity. Of all three mediators, only sleepiness mediated this effect ($_{\text{ind}}\beta = .12$, $p < .001$, 95% CI = .08 to .16, all other $_{\text{ind}}\beta$ ‘s < |.008|, *p’s* > .12).

Since both better sleep duration and subjective sleep quality improved morning self-control capacity by reducing sleepiness, a final model examining the unique mediation effects of sleepiness for both sleep duration and subjective sleep quality was examined. Both sleep duration $_{\text{ind}}\beta = .12$, $p < .001$, 95% CI = .08 to .18) and subjective sleep quality $_{\text{ind}}\beta =$

.13, $p < .001$, 95% CI = .08 to .15) uniquely decreased morning sleepiness, which in turn increased self-reported self-control capacity.

Altogether these results reveal that a.) longer sleep duration improved eye blink inhibition mostly by reducing the temptation to blink (regardless of eye-dryness) and that b.) both increases in sleep duration and better subjective sleep quality each uniquely boosted self-reported self-control capacity by decreasing subjective sleepiness.

Alternative analyses using change scores. An alternative method for assessing change between two time points is to use change scores. While change scores are criticized for a number of statistical problems (e.g., reliability, Edwards, 2001), they provide an intuitive avenue for evaluating how a night of sleep predicts overnight change in self-control by explicitly modeling the evening to morning change. Using change scores as an outcome also provides an opportunity to evaluate if findings are robust across different analytic methods. Thus, to provide further evidence that sleep is related to the overnight change in self-control via the proposed self-control mechanisms, change scores models were also examined. In these final models it was examined whether the effect of sleep on overnight change scores in eye blink inhibition was explained by parallel overnight change scores in temptation, motivation, and sleepiness. Overnight change was quantified by subtracting evening scores from morning scores so that positive values indicate overnight increases. All change scores were then person-centered to remove the influence of individual differences on day-level estimates, same as in the autoregressive analyses.

The results of these models are presented in Figures 3.4, 3.5, and 3.6. Overall, the magnitude of the coefficients and interpretation of all results are largely similar to the autoregression results. Evidence from both the autoregressive models and change score models converge on notion that longer sleep duration increases overnight self-control performance (as indexed by eye blink inhibition) by reducing experiences of temptation and that both longer sleep duration and better subjective sleep quality uniquely reduced sleepiness and thereby increased self-reported self-control capacity overnight. Predicted overnight change in temptation, sleepiness, self-reported self-control capacity, and eye blink inhibition when a person sleeps for one hour longer than their average, their average, and one less than their average is presented in Figure 3.7. This figure depicts that as sleep duration increases, temptation and sleepiness decrease overnight while self-reported self-control capacity and eye blink inhibition increase over night.

Relations among Individual Differences in Sleep and Self-control

Although the key question of this study focused on the day-level relations among sleep and self-control variables, examining the relations among these variables at the individual difference level can provide further insight into sleep and self-control. To do, correlations among the aggregated assessments of sleep and self-control variables were calculated (see Table 3.2). Inspection of Table 3.2 provides several interesting patterns of relations among sleep and self-control variables at the individual difference level. First, subjective sleep quality is correlated with all morning and evening self-control measures except temptation ($|r| > .20$), suggesting that people with better subjective sleep quality were more motivated, less sleepy, had better cognitive response inhibition, greater self-reported self-control capacity, and blinked less. Second, although sleep continuity was relatively unrelated to self-control variables at the day-level, people with greater sleep continuity also had more motivation and temptation in the evening and morning.

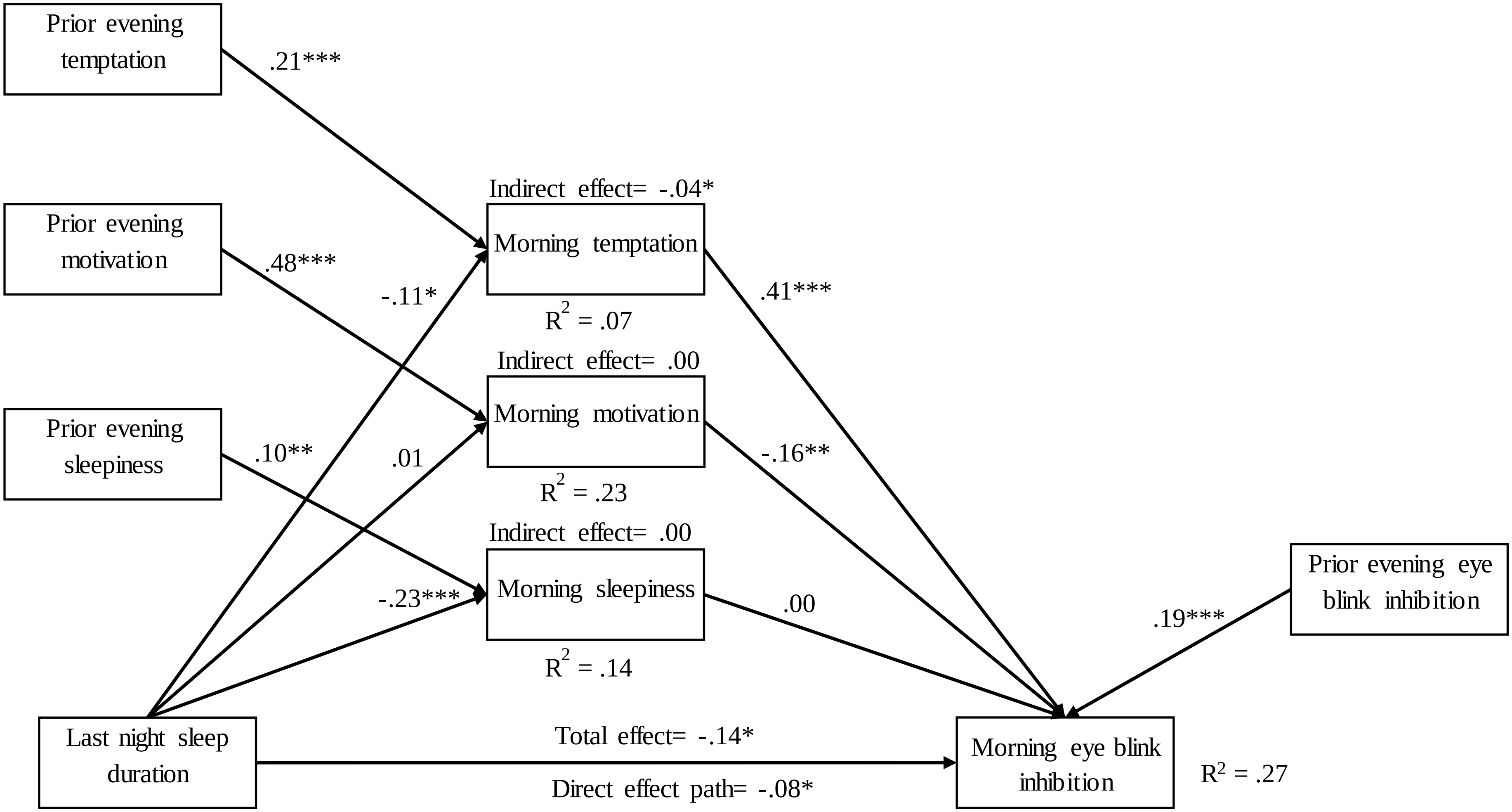

Figure 3.1. Mediation of the effect of sleep duration on next morning eye blink inhibition by temptation, motivation, and sleepiness (*Coefficients are standardized*). †p<.10, *p<.05, **p<.01, ***p<.001. Time of awakening and morning and evening eye dryness are regressed on all outcomes. $\chi^2 = 63.96$, CFI = .95, RMSEA = .03.

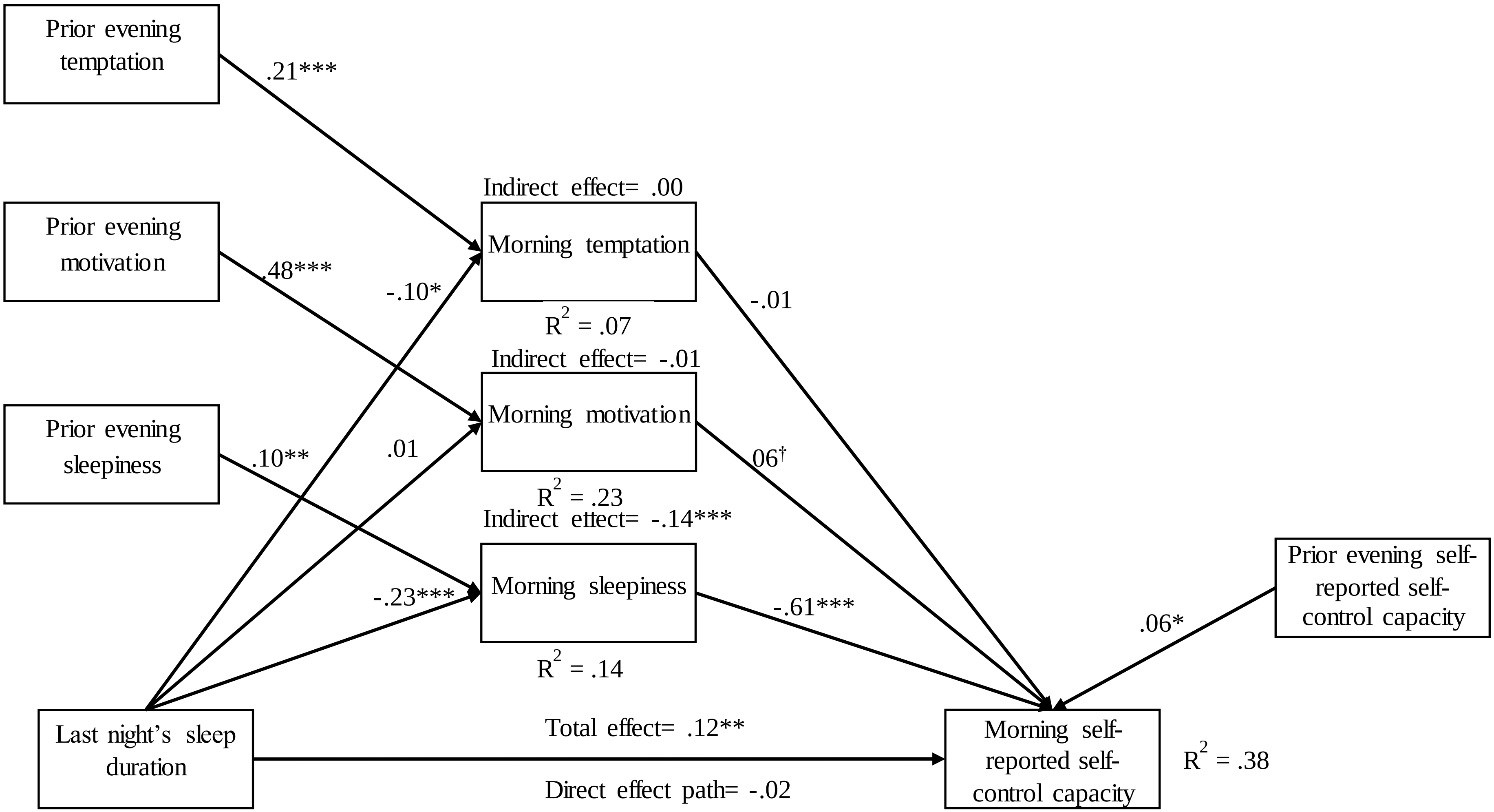

Figure 3.2. Mediation of the effect of sleep duration on next morning self-reported self-control capacity by temptation, motivation, and sleepiness (*Coefficients are standardized*). †p<.10, *p<.05, **p<.01, ***p<.001. Time of awakening and morning and evening eye dryness are regressed on all outcomes. $\chi^2 = 50.15$, CFI = .98, RMSEA = .03.

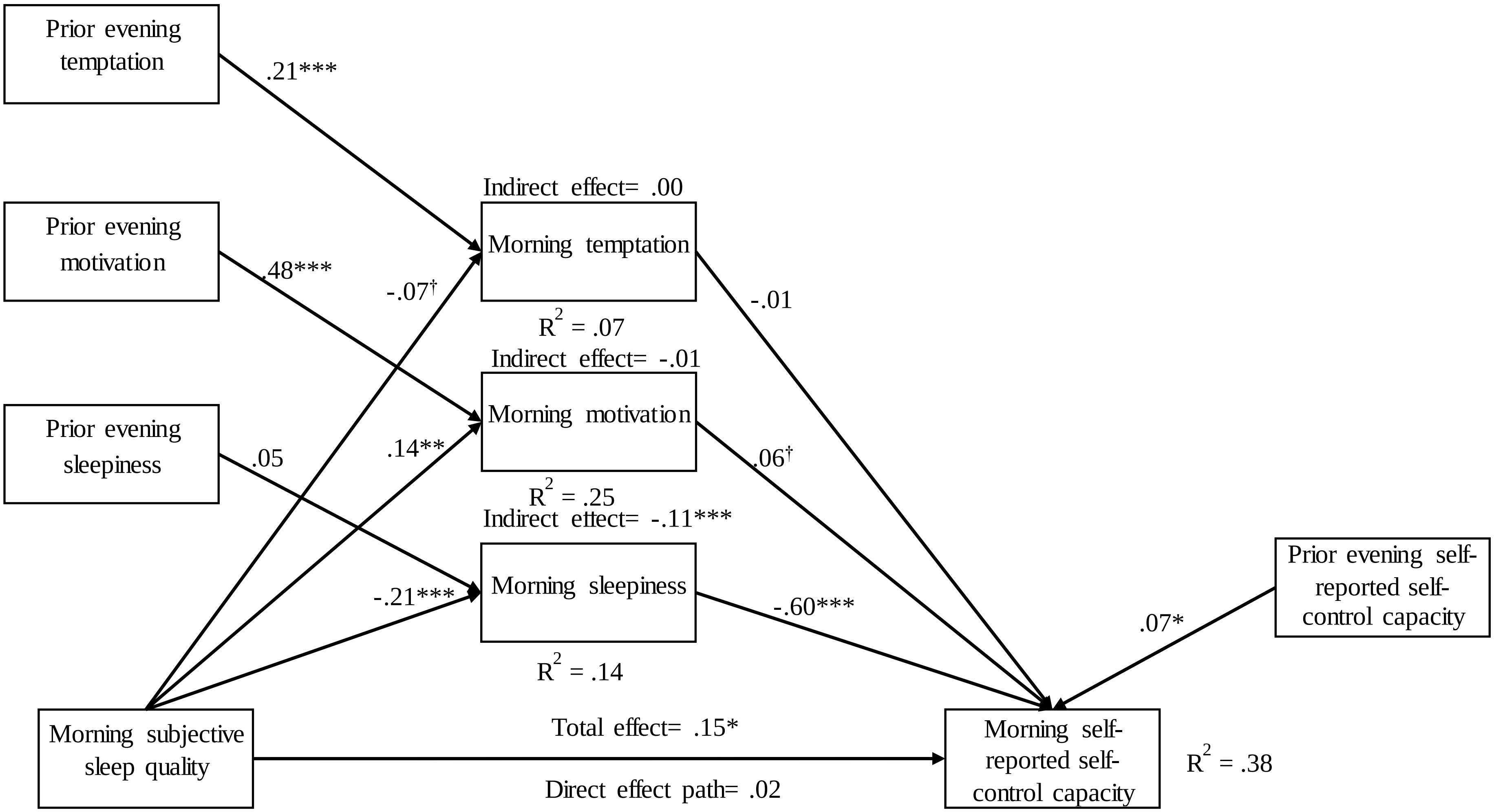

Figure 3.3. Mediation of the effect of subjective sleep quality on next morning self-reported self-control capacity by temptation, motivation, and sleepiness (*Coefficients are standardized*). †p<.10, *p<.05, **p<.01, ***p<.001. Time of awakening and morning and evening eye dryness are regressed on all outcomes. $\chi^2 = 42.61$, CFI = .98, RMSEA = .02.

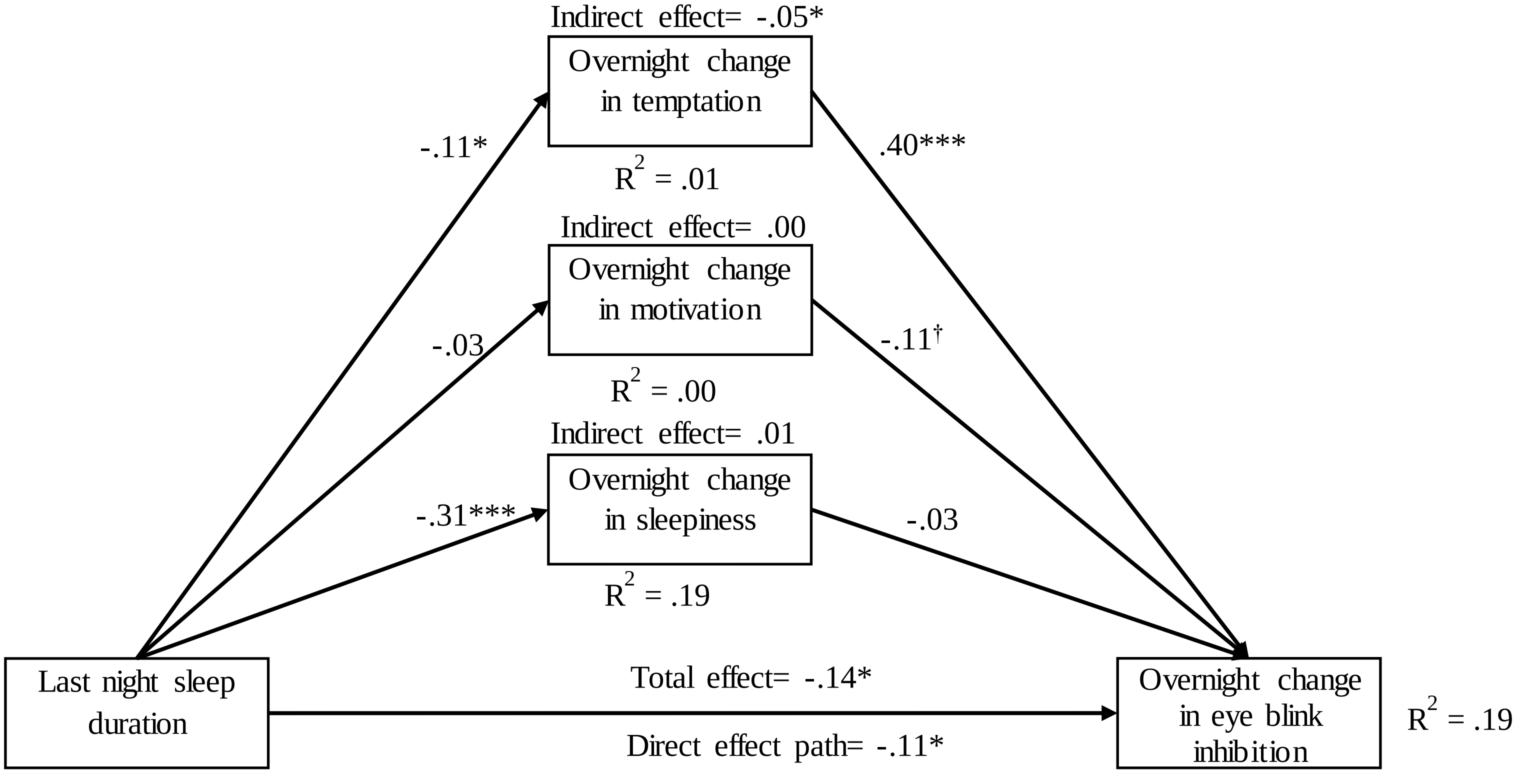

Figure 3.4. Mediation of the effect of sleep duration on overnight change in eye blink inhibition by overnight change in temptation, motivation, and sleepiness (*Coefficients are standardized*). †p<.10, *p<.05, **p<.01, ***p<.001. Time of awakening and morning and evening eye dryness are regressed on all outcomes.

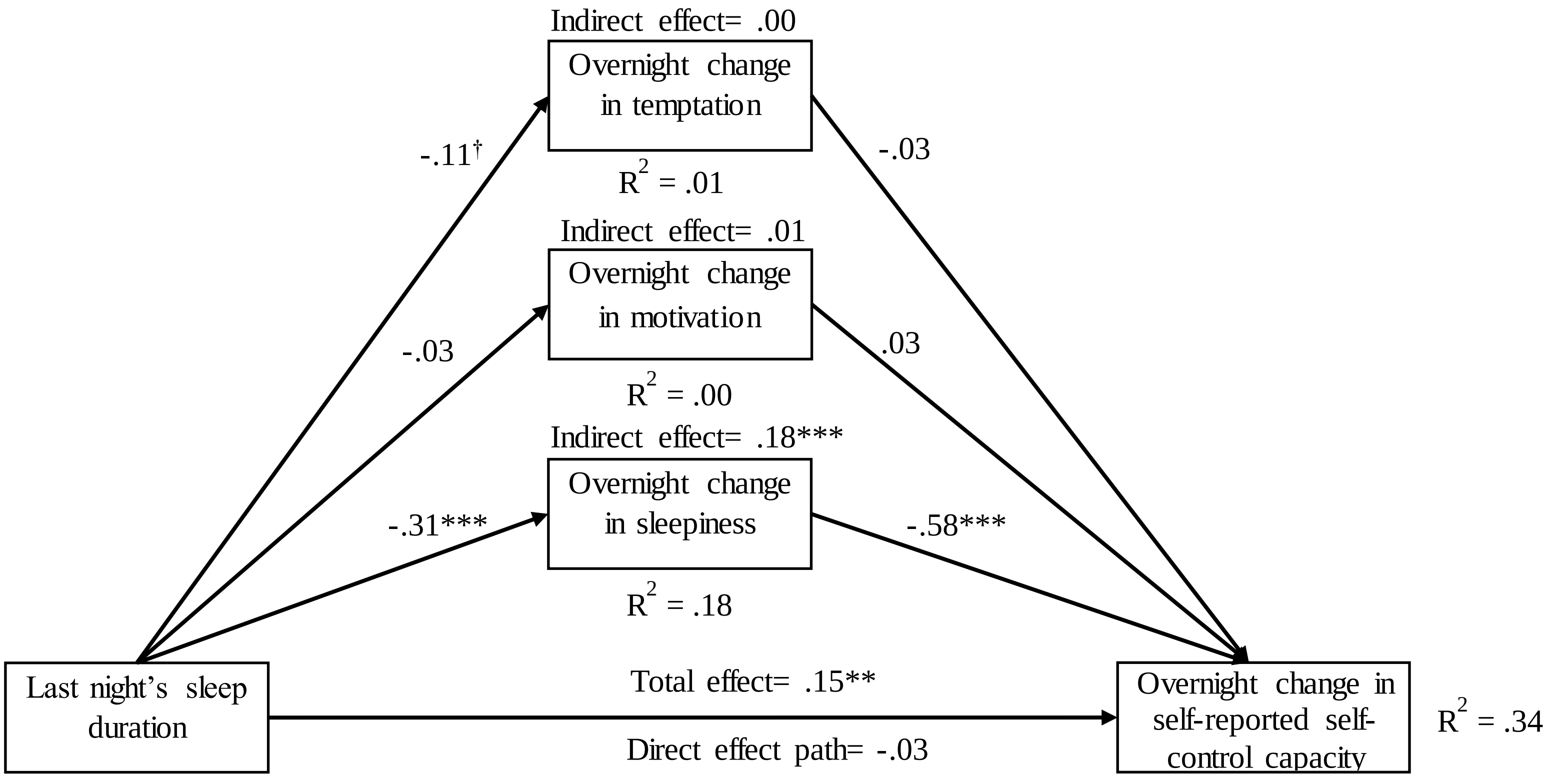

Figure 3.5. Mediation of the effect of sleep duration on overnight change in self-report self-control capacity by overnight change in temptation, motivation, and sleepiness (*Coefficients are standardized*). †p<.10, *p<.05, **p<.01, ***p<.00. Time of awakening and morning and evening eye dryness are regressed on all outcomes.

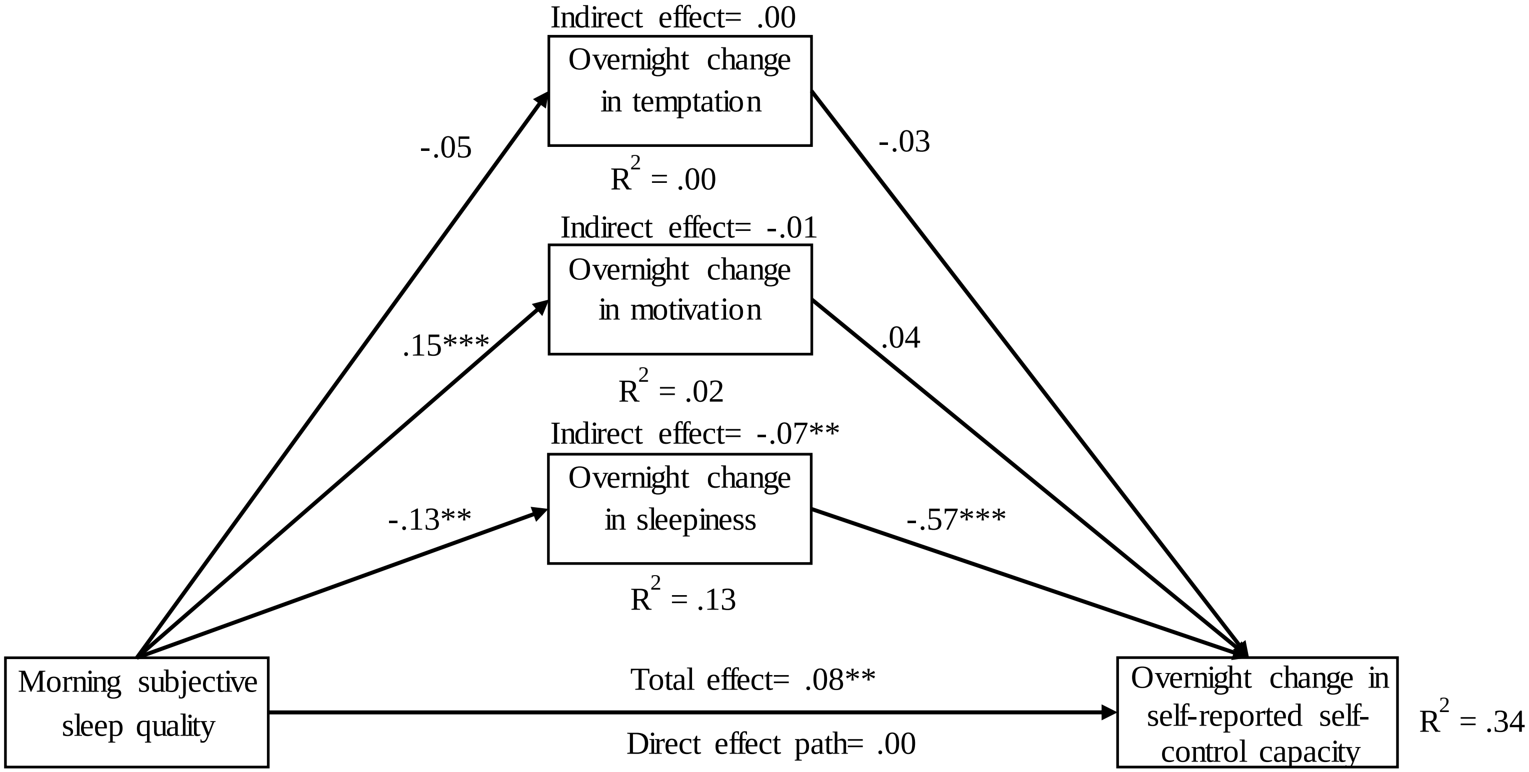

Figure 3.6. Mediation of the effect of subjective sleep quality on overnight change in self-reported self-control capacity by overnight change in temptation, motivation, and sleepiness (*Coefficients are standardized*). $^{\dagger}p<.10$, $*p<.05$, $**p<.01$, $***p<.00$. Time of awakening and morning and evening eye dryness are regressed on all outcomes.

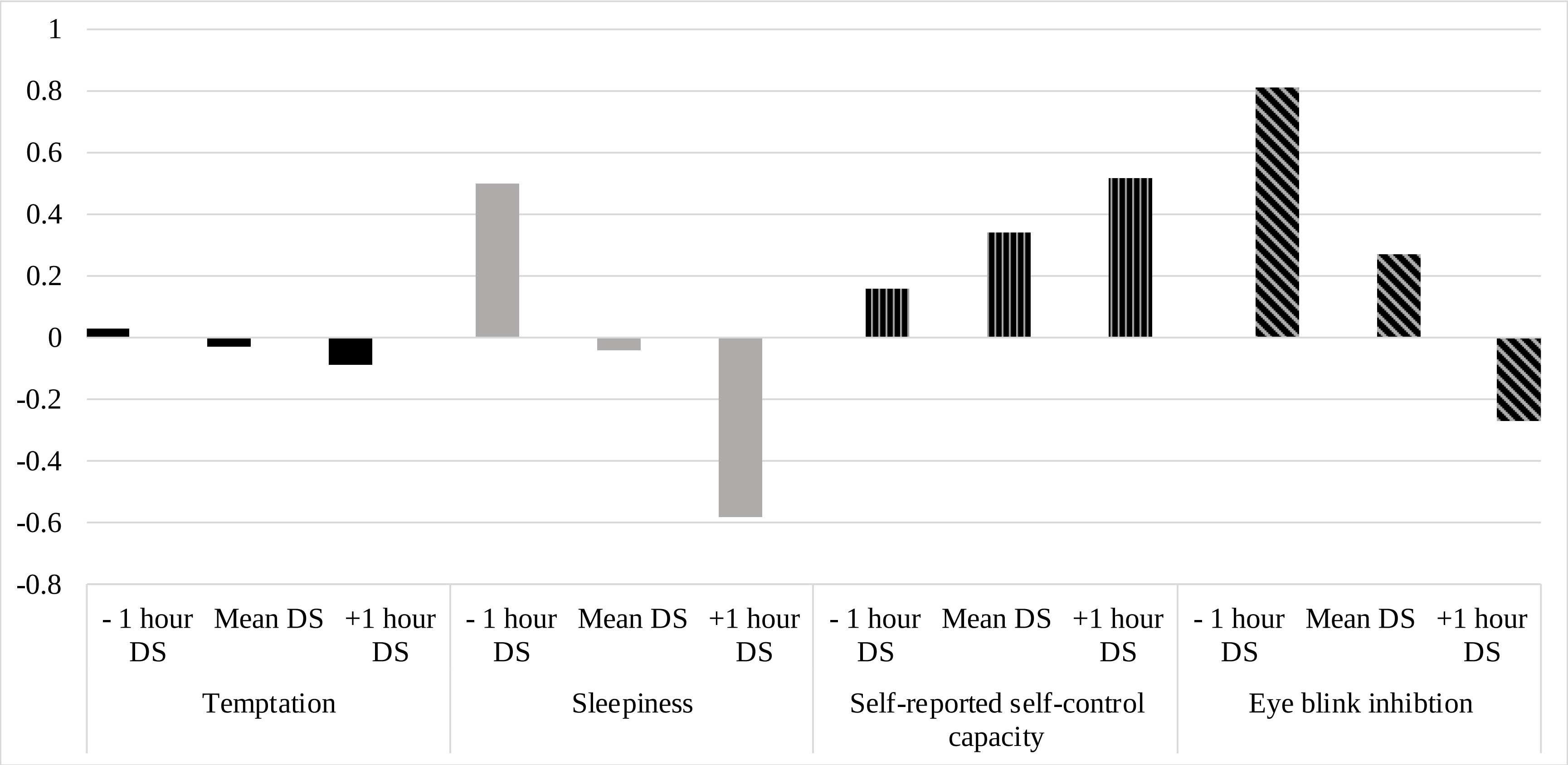

Figure 3.7 Predicted overnight change in self-control outcomes as a function of person's nightly duration of sleep. Positive values indicate increases in construct of interest. DS = Duration of Sleep.

Though these correlations are not statistically significant, this pattern of relations suggests that people with better cognitive response inhibition were better at inhibiting eye blinks in general. This supports that cognitive response inhibition is important for the inhibition of urges at the individual difference level, but not on a day-to-day basis. Altogether, these correlations reveal that different relations among sleep and self-control emerge at the individual difference level than at the day-level and demonstrate the need to keep in mind the differential relations among these variables at different levels of analysis when studying sleep and self-control.

Table 4.1. Correlations among individual differences in key study variables (N = 85).

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1. Sleep duration (minutes)	--														
2. Sleep continuity	-.12	--													
3. Subjective sleep quality	.08	.33*	--												
4. Time of awakening	-.13	-.26*	.02	--											
5. Number of blinks eve.	.25*	-.01	-.21*	-.26*	--										
6. Temptation eve.	-.02	.26*	.11	-.12	.31*	--									
7. Motivation eve.	.03	.36*	.29*	-.04	-.17	.24*	--								
8. Sleepiness eve.	.35*	.02	-.29*	-.24*	.22*	.00	-.27*	--							
9. Self-control capacity eve.	-.09	.12	-.33*	-.23*	.05	-.02	-.33*	.69*	--						
10. Cognitive response disinhibition eve.	-.22*	.17	-.25*	-.20†	.13	-.16	-.06	.18†	.35*	--					
11. Number of blinks mor.	-.05	-.01	-.34*	-.13	.87*	.27*	-.24*	.17	.12	.31*	--				
12. Temptation mor.	-.13	.18†	.08	.06	.23*	.92*	.22*	-.04	.01	-.20†	.27*	--			
13. Motivation mor.	.17	.27*	.29*	-.13	-.11	.21*	.96*	-.24*	-.36*	-.03	-.24*	.20†	--		
14. Sleepiness mor.	.18†	-.06	-.36*	.47*	.09	.07	-.29*	.44*	.37*	-.02	.24*	.15	-.40*	--	
15. Self-control capacity mor.	.25*	.01	-.50*	.22*	.02	.03	-.37*	.46*	.67*	.16	.11	.11	-.45*	.82*	--
16. Cognitive response disinhibition mor.	.01	-.26*	-.23*	-.15	.17	-.10	-.32*	.23*	.33*	.81*	.20†	-.18†	-.21†	-.05	.14

Note. *p<.05, †p<.10.

CHAPTER 4. DISCUSSION

Prior research has repeatedly linked short or poor sleep to breakdowns in self-control, theorizing that better sleep should predict better self-control because sleep restores the cognitive and motivational forces that are needed to exert self-control (e.g., Barnes, et al., 2015; Christian & Ellis, 2011; Kuhnel et al., 2017). Providing the first direct test of this possibility, this study demonstrated that sleep is indeed a factor in how self-control changes overnight. After a night of longer sleep then usual, participants performed better than usual on the eye blink inhibition task and reported greater self-reported self-control capacity than usual, after controlling for the prior evening self-control assessment. Similarly, better subjective sleep quality predicted greater morning self-reported self-control capacity, and did so independently of sleep duration.

Change score analyses also demonstrated these same effects and provided convergent evidence that longer sleep duration reduced overnight increases in the number of blinks during the eye blink task. Note that average eye blink performance did not differ between evening and next morning assessments (likely partially driven by the influence of circadian rhythms), demonstrating that eye blink performance tended to be stable, on average, over the night in this sample. Combining this on average overnight stability with the findings that longer sleep than average predicted smaller overnight increases in the number of eye blinks suggests that if a person slept for longer than usual, then eye blink inhibition would be better in the morning than in the evening. A similar pattern appeared with self-reported self-control capacity, though self-control was better in the morning than the evening, on average, similar to findings by Zhang and colleagues (2017). Thus, nights of longer sleep than usual or of better subjective quality than usual led to greater gains in self-reported self-control capacity.

These findings demonstrate that overnight improvements in self-control performance are predicted by the intervening period of sleep and implicate that sleep in restoring the self-control of visceral urges.

How did Sleep Restore Self-control?

While this study cannot speak to any physiological changes underlying restoration of self-control, it did provide evidence for psychological changes that account for some of the restoration effect of sleep on self-control. Changes in temptation, motivation, sleepiness, and cognitive response disinhibition were all evaluated as reasons for how better sleep predicted overnight improvements in self-control. Of these four factors, temptation was partially responsible for the link between sleep duration and overnight improvements in eye blink inhibition, and sleepiness was fully responsible for the effects of sleep duration and subjective sleep quality on overnight improvements in self-reported self-control capacity.

Sleep, Temptation, and Self-control

This effect of sleep duration on improvements in eye blink inhibition emerged even after accounting for eye dryness, a key sensation that would tempt someone to blink. Thus, longer sleep reduced experiences of temptation even after accounting for the main sensory source of the urge to blink. Perhaps sleep loss led to a general increases in the perception of temptation or impulse strength. This possibility would converge with findings that sleep loss amplifies the neural representation and processing of rewarding or pleasurable stimuli (Gujar, et al., 2011; Mullin, et al., 2013; Benedict, et al., 2012). For instance, activation of the anterior cingulate cortex, a key brain region involved in the evaluation of food, was increased in response to images of food after sleep deprivation and was positively correlated with subjective reports of the appeal of various food items (Benedict, et al., 2012). Nights with shorter sleep duration in the current study may have led to amplified experiences of temptation via similar changes in relevant neural structures. However, some caution about generalizing the findings from these neuroscience studies to the current study is warranted because a.) temptation in the current study consisted of relieving the discomfort of not blinking rather than obtaining a pleasurable state and b.) temptation is defined as the experience of a desire that is opposition of a goal, rather than just having a desire for something (Hofmann & Van Dillen, 2012). Further research on how sleep alters the brain networks which represent the experience of temptation, rather than desire, would be insightful.

Documenting that longer sleep improves self-control by reducing temptation is a novel finding. The strength of a temptation is a critical feature of self-control as it not only uniquely predicts self-control failure, but also modulates the probability of self-control success (DeYoung & Reuter, 2016; Hofmann, et al., 2012; Lopez, et al., 2014). Furthermore, experiencing temptation is a prerequisite for recognizing that a goal-desire temptation is occurring and that self-control may be needed. The enactment of self-control cued by experiencing a desire may then offset the increased probability of desire enactment caused by greater desire strength (Ozaki, Goto, Koboyashi, & Hofmann, 2016). Thus, temptation can directly undermine self-control and indirectly promote it, though the overall effect of temptation in this study was to decrease self-control. In general, people who experience less temptation or avoid it altogether are more successful at self-regulation and proper sleep may be key to reducing temptation (Gillebaart & de Ridder, 2015; Milyavskaya & Inzlicht, 2017).

It is also important to consider that prior theorizing largely focuses on how sleep can lead to a breakdown in processes that are needed to resist temptations, rather than focusing on how sleep loss may amplify the number or strength of temptations (Barnes, 2012; Krizan & Hisler, 2016; Pilcher, Morris, Donnelly, & Feigl, 2015). Indeed, even the conceptual basis of this study focused on cognitive abilities, motivation, and effort, all factors primarily theorized to influence how a person enacts self-control, rather than which urges are experienced and how strong they are. Findings from this study demonstrate that future research will need to evaluate how sleep influences both the characteristics and determinants of self-control (i.e., goals, desires, goal-desire conflicts), as well as the mechanisms needed for prioritizing goal-desire conflicts and exerting self-control (i.e., cognitive abilities, motivation, effort, see Kotabe & Hofmann, 2015). Since temptation did not fully account for the restorative effect of sleep duration on self-control, it is likely that additional self-control components not assessed in this study were playing a role in this association.

Identifying that longer sleep duration more fully restores self-control partially by reducing the experience of temptation has applied utility. First, interventions seeking to increase self-control or intervene on a behavior that requires self-control (e.g., exercise, quitting smoking) could include a sleep intervention targeted to increase sleep duration. Second, focusing on ways to avoid temptation, especially after a night of insufficient sleep, could also increase the effectiveness of such interventions given that the experience of temptation played the largest role in self-control performance and in the restoration of self-control by sleep. Altogether, this suggests that a two pronged approach in which sleep duration is maximized and temptation is minimized could bolster self-control interventions.

Sleep, Sleepiness, and Self-reported Self-control Capacity

While only temptation accounted for the effect of prior night's sleep duration on the overnight change in eye blink inhibition, sleepiness was fully responsible for the overnight improvements in self-reported self-control capacity associated with prior nights' sleep duration and subjective quality. Linking sleep to self-reported self-control capacity is expected as multiple other studies have linked worse sleep to worse self-reported self-control capacity (Barnes, Lucianetti, Bhave, & Christian, 2015; Barnes, Miller, & Bostock, 2017; Christian & Ellis, 2011; Hisler, Krizan, & DeHart, 2018; Lanaj, Johnson, & Barnes, 2014; Welsh, Ellis, Christian, & Mai, 2014; Welsh, Mai, Ellis, & Christian, 2018). What is particularly interesting about the current findings is that subjective sleepiness fully accounted for the relation between sleep and self-reported self-control capacity.

To measure self-control capacity, the current study (and virtually all prior studies) used the State Self-control Capacity Scale (though the exact questions from this scale differ a little across studies). However, the actual validation of scores on this scale has never been published and while it has been linked with various self-control outcomes, it remains unclear exactly what it measures. Item content of the scale typically selected for use in research (e.g., “I feel drained”, “My mental energy is running low”, “My mind feels focused”, “It took a lot of effort to concentrate on something”) focuses on whether someone feels like they have the mental resources/capacities available for self-control. These items thus reflect tiredness and mental fatigue rather actual current ability to restrain urges and impulses. The lack of relation with scores on this scale with eye blink performance (r = -.07 in the morning & .00 in the evening) and exorbitant correlations of the scale with sleepiness in the current study (r = -.54 in the morning & -.61 in the evening) further bolster the idea that this scale is tapping into fatigue and sleepiness (rather than a distinct construct of self-control “capacity”). If the State Self-Control Capacity Scale is largely measuring subjective sleepiness, then it should hardly be surprising that longer sleep duration and better subjective sleep quality were associated with overnight improvements in this scale and that these improvements were completely explained by co-occurring improvements in reported sleepiness.

Regardless of what the State Self-control Capacity Scale is measuring, it is important to note that scores on this scale have been found to consistently account for some of the effects of poor or insufficient sleep on self-control failures (Barnes, Miller, & Bostock, 2017; Christian & Ellis, 2011; Lanaj, Johnson, & Barnes, 2014; Welsh, et al., 2018; Welsh, et al., 2014). Thus, collective evidence support that the State Self-control Capacity Scale measures part of the reason why sleep loss undermines self-control, but it is unclear exactly what it is. Prior studies purport that this scale captures self-control capacity and conclude that sleep loss reduces self-control resources and thereby undermines self-control. However, the current findings suggest a more parsimonious explanation is that sleep loss impairs self-control by making people feel sleepy. In order to better understand findings utilizing this scale, future research will need to tease apart what this scale is actually measuring and hopefully both validate and standardize the item content. Sleep research that is unwittingly utilizing a measure assessing whether a person is feeling tired is likely to obtain a different understanding of the dynamics between sleep and self-control than sleep research using a measure assessing whether a person is *able* to effectively exert self-control.

What about Motivation, Effort, and Cognitive Response Disinhibition?

It is just as important to consider what self-control factors did *not mediate* the effects of sleep as those that did mediate these effects in the current study. Both motivation and cognitive response disinhibition were hypothesized to be important mediators, yet both tended to have small or negligible associations with sleep and self-control assessments. Two explanations are readily apparent for these surprising small relations; 1.) the motivation and cognitive response disinhibition measures did not capture the motivation and cognitive abilities theoretically important for self-control, and 2.) motivation and cognitive response disinhibition were measured properly, but were not important predictors of eye blink inhibition and self-reported self-control capacity. While the small or null day-level effects could support either of these interpretations, examining the mean level correlations provides some evidence against both of these possibilities.

Correlations of mean level (i.e., individual) differences in motivation and cognitive response disinhibition with sleep and self-control variables were much larger than their corresponding day-level correlations (which are calculated after removing these individual differences). While the sample size is relatively small at the level of the person (making power low and correlations potentially imprecise), the overall pattern of these correlations supports the conclusion that motivation and cognitive response disinhibition as assessed in this were related to sleep and self-control, just not in day-to-day fluctuations. For instance, the person-level correlations of cognitive response disinhibition with eye blink inhibition were -.13 in the evening and -.17 in the morning. This suggests that people with better cognitive response inhibition were better at inhibiting eye blinks in general. It may be that the average absolute levels of motivation and cognitive response disinhibition across people are the most important for tying sleep to self-control, rather than the likely smaller day-to-day deviations from a person's general level.

Additionally, participants, on average, were highly motivated (3.88/5.00) and had good cognitive response inhibition (4.40 ms). It may be that day-to-day deviations at these fairly high levels of motivation and cognitive response disinhibition may not meaningfully impact or be impacted by sleep. For instance, the standard deviations for motivation and cognitive response disinhibition in the motivation were .60 and 4.23, respectively. Thus, on a moderately bad day, a participant's motivation may decline to 3.36 and cognitive response disinhibition increase to 7.59 milliseconds. Perhaps these seemingly small changes at high ends of motivation and cognitive response disinhibition do not produce any discernable relations with sleep and self-control within a person, though further research is needed on this possibility. For instance, future research could examine these relations in sample that may have greater daily fluctuations, such as clinical sleep populations with chronic sleep disturbances or forensic populations with poor impulse control.

Finally, it is important to note that effort put into self-control and motivation to exert self-control are theoretically different constructs (Kotabe & Hofmann, 2015). However, multilevel factor analysis revealed that the effort and motivation strongly items loaded onto the same factor (which was labelled as the motivation factor) both at the person and day level. While theoretically effort and motivation should be different constructs, these findings implicate that there might not be a substantial difference between how motivated a person is for self-control and how much effort they put into self-control. Intuitively this makes sense since having more motivation should translate into investing more effort. While important findings, more research is needed before concluding effort and motivation are not different constructs. In the current study, participants were extrinsically motivated by money to perform well on the eye blink task and there were only two items assessing motivation and one item assessing effort. A study utilizing a more assessment of different types of motivation (e.g., intrinsic vs. extrinsic) and with more items assessing both motivation and effort is needed. Perhaps motivation and effort can be teased apart with different motivations or when adding more items into the factor analysis.

Sleep Continuity and Subjective Sleep Quality

While sleep duration predicted overnight improvements in self-control, it was intriguing that sleep continuity and subjective sleep quality did not. In fact, sleep continuity had very slight associations with overnight improvements in eye blink inhibition, self-reported self-control capacity, and their theoretically underlying self-control components. This is surprising because decreases in sleep continuity should mark greater disruptions to the sleep cycle and its associated physiological processes that maintain and restore the mind and body. For instance, experimentally induced sleep continuity disruptions fragment the sleep cycle, resulting in less slow wave sleep than even participants restricted of sleep (Finan, Quartana, & Smith, 2015; Finan, et al., 2017). The reductions in slow wave sleep in turn may account for subsequent declines in positive affect. Based upon these it is surprising that better sleep continuity did not predict better self-control outcomes.

However, such findings from tightly controlled and scheduled sleep disruption paradigms are meant to mirror the sleep of people with sleep apnea or insomnia and may not necessarily extend to sleep in the daily lives of college students. In these lab studies, disruption to sleep continuity results in reduced sleep duration, but in the current study sleep continuity was highly negatively correlated with sleep duration (r = -.50) and moderately negatively correlated with time of awakening (r = -.26) Thus, on nights during which participants had more continuous sleep than usual, they also had shorter sleep and woke up earlier than usual. This reveals that sleep continuity was associated with a curtailment of sleep during the later morning hours, likely as a result of an evening oriented sample having to wake up earlier than desired for class or work obligations. Given that sleep duration was especially important for self-control in this study, perhaps the associated sleep curtailment counteracted any benefits of better sleep continuity (i.e., suppressed the contribution of sleep continuity in analyses). These co-occurring reductions in sleep duration may also be why better sleep continuity was paradoxically associated with a slight overnight deterioration in eye blink inhibition and increases in sleepiness and temptation. While an interesting possibility, future research should keep these day-level relations in mind and examine if they replicate, and if so, try to further understand them.

While sleep continuity was mostly unrelated to self-control, better subjective sleep quality broadly predicted self-reported self-control outcomes (i.e., less temptation, more motivation, less sleepiness, and greater self-control capacity) and had a small marginal relation with eye blink inhibition (which was independent of sleep duration). One reason that subjective sleep quality was so broadly related to self-reported self-control could be common method bias (MacKenzie & Podsakoff, 2012). The self-reported nature of all these assessments could artificially drive their associations; however, it is important to note that sources of common method biases that systematically vary across people (e.g., negative response style, lack of conscientiousness) would be removed by the person-centering procedures which remove individual differences from day-level estimates (though sources of common method bias that vary across days would remain).

Besides common method bias, subjective sleep quality could have broadly predicted self-reported self-control because of its item content. The assessment of subjective sleep quality not only contained items which directly assessed how a person feels (e.g., “How refreshed do you feel after your sleep?”) but also contained items which indirectly assessed psychological states that can disrupt sleep and self-control (e.g., “How easy was it to fall asleep?”, “How calm was your sleep?”). How a person actually feels after sleeping should be more closely related than sleep duration or sleep continuity to perceptions of psychological states, such as self-control capacity, temptations, motivation, and sleepiness. It likely that assessing these feelings and perceptions are why subjective sleep quality is a sleep characteristic that uniquely predicts behavior and health (Buysee, 2014). If a person does not feel refreshed after sleeping, it is unlikely that they are also going to feel alert and motivated to restrain impulses and desires. Thus, asking someone how refreshed they feel upon awakening should provide an important and unique source of information about sleep pertinent to understanding other psychological phenomena.

In contrast, subjective sleep quality items which ask people to rate how easy it was to fall asleep and how calm their sleep was could indirectly reflect other psychological states, such as stress. Experiencing stress is known to delay and disrupt sleep as well as impair self-control (Akerstedt, 2006; Arnsten, 2009; Hall, et al., 2004; Hisler et al., 2018; Park, et al., 2016). Fluctuations in stress could potentially account for the relations between subjective sleep quality and self-control assessments. Theoretically, current feelings of refreshment and stress should in turn influence actual self-control behavior (e.g., eye blink inhibition). Nevertheless, psychological states and actual behavior are still separated by the process of expression, which may be why subjective sleep quality is more strongly related to self-reported self-control than behaviorally assessed self-control in this context.

Altogether, common method bias, the evaluative nature of subjective sleep quality items, and the potential confounding by broader distress make it difficult to discern exactly why subjective sleep quality is related to self-reported self-control outcomes. Teasing apart these different possibilities should be an important avenue for future research.

Limitations

Effect Size

One of the first limitations that a reader may note is that while sleep is positioned as a vital source of restoration for self-control, the effect size seems to be small. For instance, squaring the effect of sleep duration on overnight improvements in eye blink inhibition (β = -.14) reveals that duration of sleep explained a "measly two percent" of the variance in these overnight changes. Furthermore, changes in temptation in turn explained only approximately 50% of this effect. Putting all of this together reveals that the ultimate conclusion of this intrusive and intensive study was that sleep duration explained 1% of the variability in overnight improvements in eye blink inhibition because longer sleep duration decreased the intensity of temptation. In response to this seemingly small effect size, a critic may ask, "So what?" and conclude that sleep ultimately has little importance for self-control. However, there are three considerations every reader should note when interpreting this effect size.

First, recall that centering daily variables at that individual's mean removed the (sizeable) influence of individual differences from all analyses. This would inherently reduce the effect size by removing effects at the individual-difference level from influencing the estimation of the day-level effects. Inspection of table 4.1 shows that the individual difference associations regarding sleep and self-control tended to be larger than the day-level effects. Including individual differences with these day-level effects would likely result in even larger effects. Along these lines, the importance of sleep for self-control can vary across people. Increases or decreases in typical sleep may be much more important for someone who is chronically restricted of sleep than for someone who typically receives sufficient sleep. Indeed, prior research had found that less sleep had a greater effect on self-control in people who chronically slept less (Hisler, Krizan, & DeHart, 2018).

Second, self-control is critical for many different health and well-being factors across the lifespan, including diet, substance use, exercise, happiness, adjustment, and educational attainment (Bogg & Roberts, 2004; De Ridder, et al., 2012; Hofmann, et al., 2012; Stitzman & Ely, 2011). Understanding and accounting for even a small amount of variance in such important outcomes is ultimately more important than accounting for a large amount of variance in inconsequential outcomes.

Third and most importantly, it is critical to consider the frequency with which outcomes occur (Funder & Ozer, 2019). Abselson (1985) uses data from professional baseball players to drive this point home. A baseball player's batting skill (indexed by their average ability to hit the ball when batting) only explains one third of a percent (a seemingly insignificant .33%) of the variance in the performance of any single time a player attempts to bat. Despite this miniscule effect on any given performance, batting skill is hugely important and is strongly influential on which baseball teams will go to the playoffs. Why? Because while average batting skill only explains .003% in any single batting attempt, each player has about 550 attempts a season. Couple this with the fact that there are multiple players on a team, the consequences on small change in average batting skill begins to add up over the course of the season to have major consequence for the success of the team.

This same line of reasoning extends (if not even more so) to sleep and self-control. In one experience sampling study, 205 participants reported experiencing 6,972 different goal-conflicting temptations over the course of a week. This translates to approximately 5 temptations (or "batting attempts") a day per person (Hofmann, Vohs, & Baumeister, 2012). Each day a person will have slept once and findings from this study and many others support that how a person has slept on any given day will influence, to a small degree, whether they are able to resist each of these five problematic desires. Zooming out to the course of a year, how a person slept over the 364 days will predict whether and how they resisted the 1,820 desires over the course of the year. Considering that most people live approximately 70 to 80 years, the day-today effects of sleep on self-control surely accumulate and have meaningful and profound consequences over the lifespan.

Causality

Beyond issues surrounding the interpretation of the effect sizes in this study, a second limitation is the study's inability to infer causality. At most the study can conclude that sleep predicts overnight improvements in self-control, but not that sleep causes these improvements. While the study design and statistical approach substantially limit the influence of many critical confounds (e.g., time of day, circadian rhythm), other uncontrolled factors may confound and obscure results. For instance, all assessments occurred sometime between 9-10 pm and between 9-10 am, yet it is likely that most participants remained awake after 10 pm and unassessed events occurring after this time may influence both stress and self-control, such as encountering late night stressors. The only way to rule out or control many of these confounds would be to conduct a costly and intensive experimental in-lab study in which various aspects of sleep are manipulated and all participants are constantly monitored and contained within the same artificial environment.

However, such a study would not capture "life as it is lived" (Bolger, Davis, & Rafaeli, 2003) and could not speak to how sleep influences self-control as people go about their day-to-day lives. For instance, an important predictor in how sleep affects functioning is whether participants have control over the task or their environment (Engle-Friedman, et al., 2003; Hockey, Wastell, & Sauer, 1998). When given control over the task or the environment, sleep deprived people can maintain task performance by choosing easier tasks or reducing performance on other less important tasks. Participants would largely be prevented from taking such compensatory actions within an artificial and controlled lab setting, but daily life abounds with various opportunities for compensation (Hisler & Krizan, 2019). By sacrificing greater causal certainty, the findings in this study better reflect life as it is lived, rather than life as constrained to the lab.

Other Limitations

Another important limitation of the findings is their generalizability. First, this study was conducted on a sample of college students who are emerging adults and were mostly Caucasian American. Because of this limited sample, findings may not readily generalize to other populations. Sleep characteristics and timing of the circadian rhythm can vastly differ across the lifespan, ethnicities, and culture and particular sleep characteristics may be more or less important (or not important at all) for self-control across different populations. Future research on this topic should utilize more diverse samples.

Additionally, longer sleep duration predicted improvements in eye blink inhibition, yet it is unclear whether these findings may generalize to other self-control scenarios. The eye blink task has been infrequently used in the self-control literature, which has resulted in a limited understanding of its nomological network. Self-control can take the shape of many different types of behaviors, such as planning for the future, inhibiting impulses, persisting on unpleasant tasks, and disengaging on pleasant tasks. It is unclear whether findings from the eye blink inhibition task will uniformly extend to these many different domains (most likely they will not). One study assessing both handgrip persistence (i.e., time clenching down on a spring-loaded exercise handgrip) and eye blink inhibition found that individuals who were better at inhibiting eye blinks also persisted longer at the handgrip task (r = .30; Tunze, 2012). Thus, findings may extend to instances of persistence in face of physical discomfort, but this should be empirically tested. Future research should seek to replicate current findings as well as extend them to other types of self-control (e.g., emotional impulses), though creating behavioral self-control paradigms that can be assessed quickly on a daily basis is challenging.

A last important limitation to consider is the fixed order of the stroop task and the eye blink task. Participants first completed the stroop task and then completed the eye blink task for all assessments. The back-to-back assessment of two inhibition tasks mirrors the dual-task paradigm used to study ego-depletion effects. Regardless of any controversy surrounding this effect, two recent multi-lab pre-registered replication projects have found that appropriately designed dual-task paradigms can induce a small ego depletion effect in which performance on a second self-control task deteriorates after completing a difficult initial self-control task (Dang, et al., 2019; Vohs & Schmeichel, 2018). These findings suggest that performance on the eye blink task could have been made slightly worse by first completing the stroop task. While this may be true, it should be equally true for all days and all participants since all participants were instructed each day to complete the stroop task before the eye blink inhibition task. Because this should be equally true for all days, day-to-day fluctuations should not be due to this order effect.

However, the ordering of these two tasks may still confound the observed results. Evidence from Vohs & Schmeichel (2018) suggests that the ego depletion effect is more pronounced in participants who are more fatigued. Moreover, sleep reduces feelings of fatigue (Akerstedt, et al., 2014). If ego depletion is stronger when a person is fatigued and better sleep reduces fatigue, perhaps the ordering of the stroop task and the eye blink task may have boosted the association between longer sleep duration and improvements in eye blink inhibition. In other words, on days in which participants slept longer, they had less fatigue in the morning (than in the evening) during the stroop task and eye blink assessments and because they had felt less fatigued in the morning, completing the stroop task did not impair subsequent performance on the eye blink task.

This possibility seems unlikely, however. Fatigue is correlated with both sleepiness and motivation, yet both sleepiness and motivation had small or negligible concurrent associations with eye blink inhibition and neither were associated with overnight changes in eye blink inhibition (Akerstedt, et al., 2014; Hockey, 2013). Despite its improbability, future research should be aware of this possibility and account for it or even empirically examine it. It is also worth noting full control over all elements of a study is impossible in a daily diary study and that even if the ordering of the stroop and eye blink task is driving the observed effects, this order still models the environment in which people frequently encounter self-control dilemmas. People often need to exert self-control after completing other demanding tasks and in exhausted states, such as a tired adult having to choose whether to exercise vs. watch TV and whether to cook a healthy meal vs. order a pizza after getting home for work.

Conclusion

These findings are the first to show better sleep leads to overnight improvements in both behavioral and self-reported self-control, implicating sleep duration as a particularly important component of sleep for these improvements. The dampening of temptation, rather than the improvement of motivation or cognitive response inhibition, partially explained how sleep restored behavioral self-control (i.e., eye blink inhibition). In addition, while it remains unclear exactly what self-reported self-control capacity scale measures, the offloading of sleepiness fully explained why longer sleep duration and better subjective sleep quality improved self-reported self-control capacity. Altogether these findings suggest that sleep is a restorative factor for self-control performance and that alleviating temptation and sleepiness are two key psychological mechanism by which this restoration occurs.

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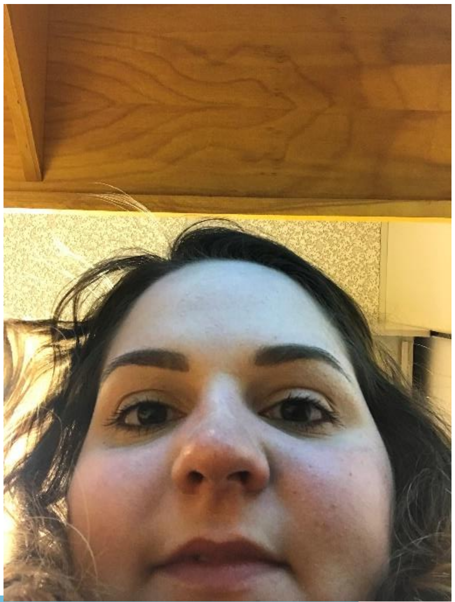
APPENDIX A. LIST OF MEASURES

Stroop task via EnchepalApp (Bajaj et al., 2013).

“Off” phase trial example (circled color indicates expected correct response):

“On” phase trial example (circled color indicates expected correct response):

Eye-blink task example from iPhone camera.



State self-control difficulty scale (Ciarocco, Twenge, Muraven, & Tice, 2004)

How true are the following statements for you?

1. Right now my mind feels unfocused
2. Right now my mental energy is running low
3. Right now I am having a hard time controlling my urges
4. Right now if I were given a difficult task, I would give up easily

From disagree very much (1) to agree very much (7).

Motivation/Effort/Difficulty for Blink task

1. How tempted were you to blink during the don't-blink task? [not at all (1) to very much (7)].
2. How motivated were you to avoid blinking during the don't-blink task? [not at all (1) to very motivated (7)].
3. How motivated were you to earn the $50 based during completion of the don't-blink task? [not at all (1) to very motivated (7)].
4. How much effort did you put into not blinking? (no effort (1) to a lot of effort (7)].
5. How difficult did you find it not to blink? [not at all difficult (1) to very difficult (7)].
6. How stressful did you find it not to blink? [not at all stressful (1) to very stressful (7)].
7. Please indicate your current sleepiness: [extremely alert (1) to very sleepy, great effort to keep awake, fighting sleep (9)]

Daily consumption and activity measures

1. In the last three hours have you:
    a. Consumed caffeine? (yes/no)
    b. Consumed alcohol? (yes/no)
    c. Smoked cigarettes or other similar substances? (yes/no)
    d. Consumed any recreational drugs? (yes/no)
2. How many minutes of moderate to vigorous physical activity have you engaged in today?
3. Are you wearing contacts currently?
4. Are you wearing glasses currenty?

Karolinska sleep diary questions (Akerstedt, Hume, Minors, & Waterhouse, 1994)

Please rate your sleep last night in terms of:

1. Overall sleep quality [very poorly (1) to very well (5)]
2. Calmness of sleep [very restless (1) to very calm (5)]
3. Ease of falling asleep [very difficult (1) to very calm (5)]
4. Sleeping throughout the night [woke up much too early (1) to yes (5)]
5. Feeling refreshed after sleep [not at all (1) to completely (5)]

Actigraphic sleep variables

1. Sleep duration = total minutes scored as "asleep"
2. Sleep continuity = average of wake after sleep onset, number of fragmentations, and sleep onset latency after each variable has been standardized.
   a. Wake after sleep onset = number of minutes scored as "awake" between sleep onset and offset.
   b. Number of fragmentations = number of times scored as "awake" between sleep onset and offset.
   c. Sleep onset latency = number of minutes scored as "at rest" prior to sleep period.

Daily state affect via PANAS-X (Watson & Clark, 1999).

PANAS-X

This scale consists of a number of words and phrases that describe different feelings and emotions. Read each item and then mark the appropriate answer in the space next to that word. Indicate to what extent you feel this way *right now*. Use the following scale to record your answers:

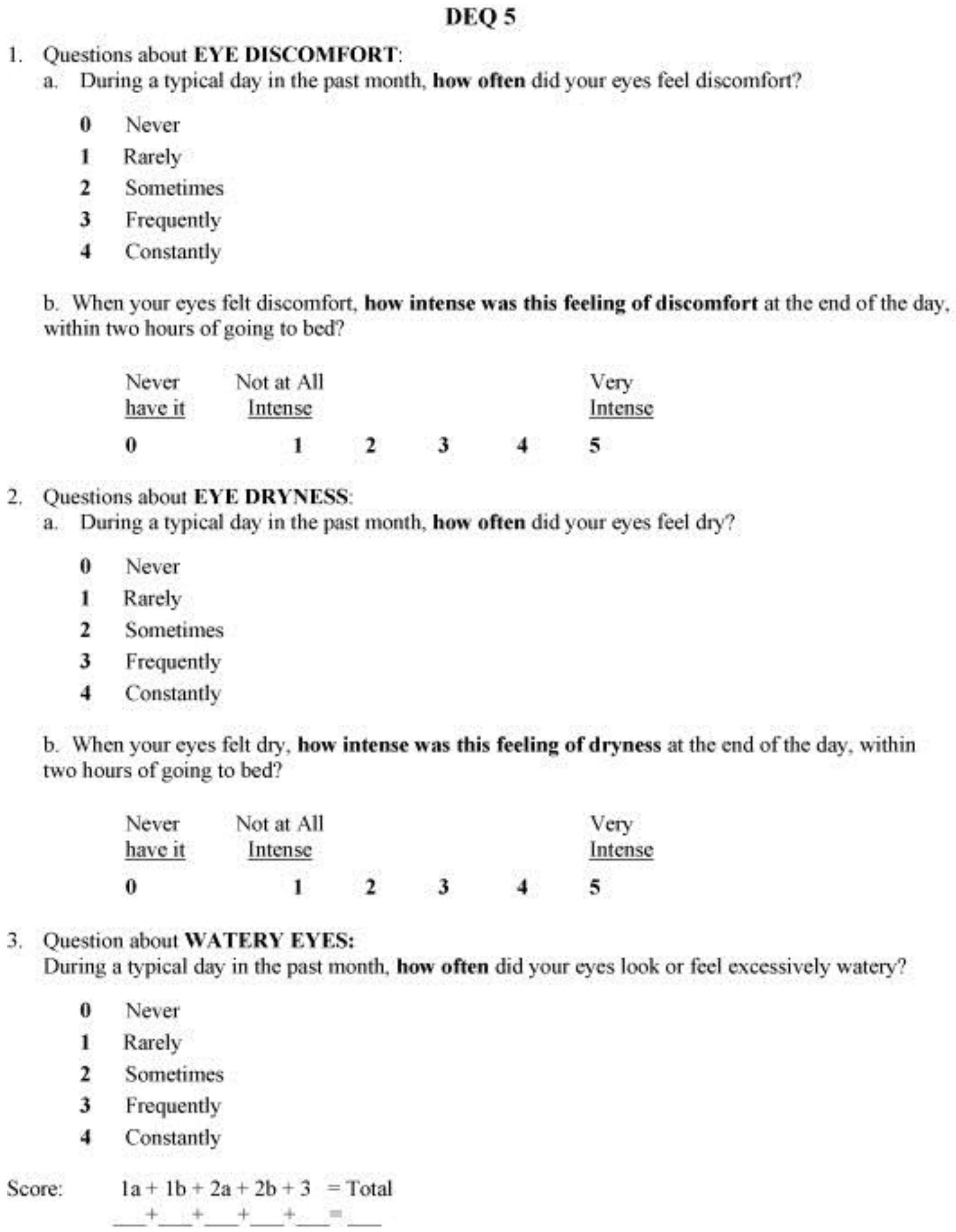
1	**2**	**3**	**4**	**5**
very slightly or not at all	a little	moderately	quite a bit	extremely

1. _______ Happy
2. _______ Cheerful
3. _______ Excited
4. _______ Concentrating
5. _______ Attentive
6. _______ Determined
7. _______ Angry
8. _______ Irritable
9. _______ Hostile
10. _______ Sad
11. _______ Blue
12. _______ Downhearted
13. _______ Distressed
14. ______ Calm
15. ______ Jittery

Sleep and mental disorder screening questions.

1. Are you 18 years of age or older? (IF YES, CONTINUE)
2. Do you sleep at least 6 hours a night on average? (IF YES, CONTINUE)
3. Do you have a third shift or nighttime job? (IF NO, CONTINUE)
4. Do you have an ongoing diagnosis of a sleep or mental disorder? (IF NO, CONTINUE)

Dry eye questionnaire (Chalmers, Begley, & Caffrey, 2010).



DEQ 5

1. Questions about **EYE DISCOMFORT**:

a. During a typical day in the past month, **how often** did your eyes feel discomfort?

0 Never
1 Rarely
2 Sometimes
3 Frequently
4 Constantly

b. When your eyes felt discomfort, **how intense was this feeling of discomfort** at the end of the day, within two hours of going to bed?

Never have it	Not at All Intense				Very Intense
0	**1**	**2**	**3**	**4**	**5**

2. Questions about **EYE DRYNESS**:

a. During a typical day in the past month, **how often** did your eyes feel dry?

0 Never
1 Rarely
2 Sometimes
3 Frequently
4 Constantly

b. When your eyes felt dry, **how intense was this feeling of dryness** at the end of the day, within two hours of going to bed?

Never have it	Not at All Intense				Very Intense
0	**1**	**2**	**3**	**4**	**5**

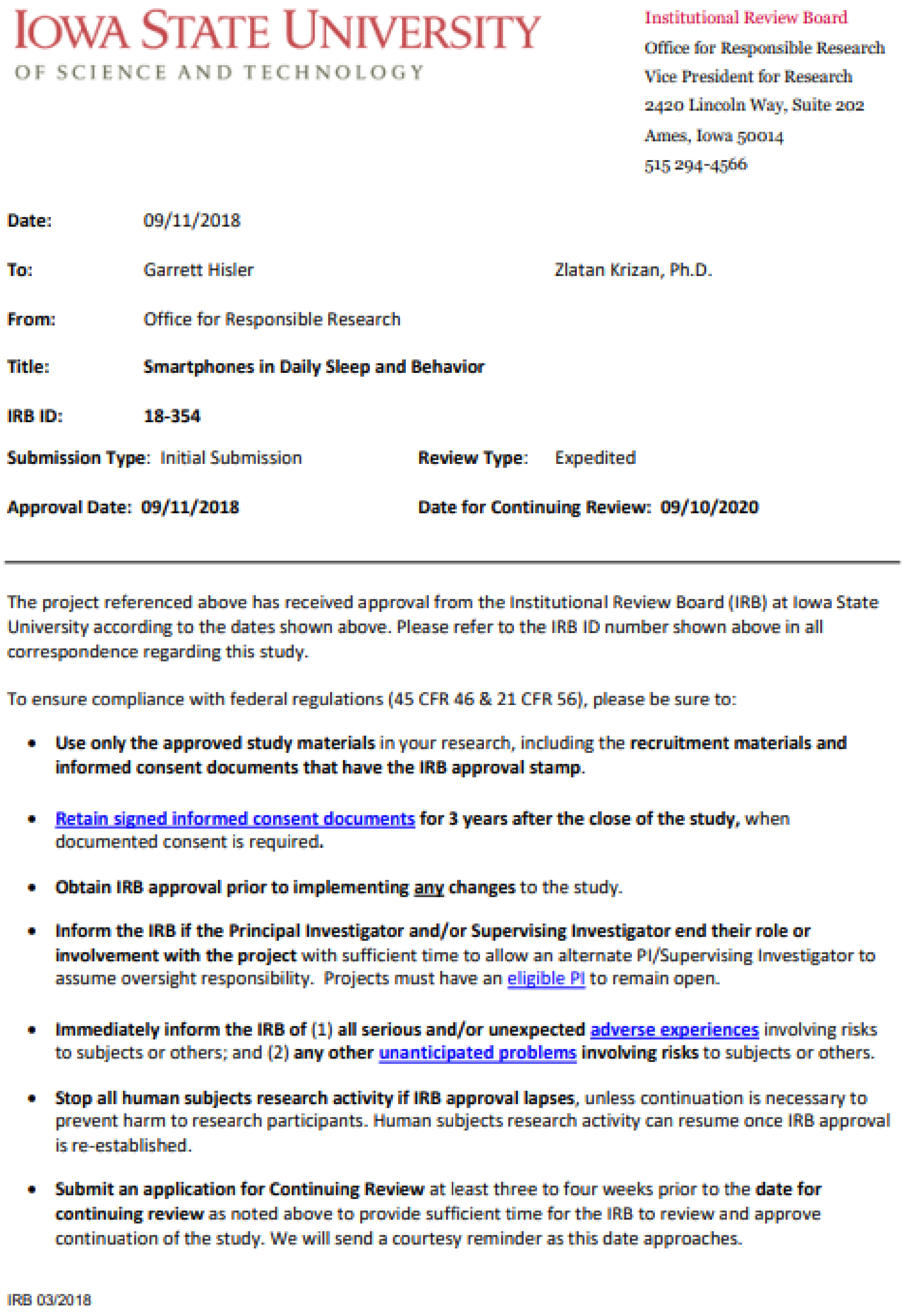
3. Question about **WATERY EYES:**

During a typical day in the past month, **how often** did your eyes look or feel excessively watery?

0 Never
1 Rarely
2 Sometimes
3 Frequently
4 Constantly

Score: 1a + 1b + 2a + 2b + 3 = Total
___+___+___+___+___= ___

APPENDIX B. IRB APPROVAL



IOWA STATE UNIVERSITY
OF SCIENCE AND TECHNOLOGY

Institutional Review Board
Office for Responsible Research
Vice President for Research
2420 Lincoln Way, Suite 202
Ames, Iowa 50014
515 294-4566

Date: 09/11/2018

To: Garrett Hisler   Zlatan Krizan, Ph.D.

From: Office for Responsible Research

Title: **Smartphones in Daily Sleep and Behavior**

IRB ID: **18-354**

Submission Type: Initial Submission   **Review Type**: Expedited

Approval Date: 09/11/2018   **Date for Continuing Review: 09/10/2020**

The project referenced above has received approval from the Institutional Review Board (IRB) at Iowa State University according to the dates shown above. Please refer to the IRB ID number shown above in all correspondence regarding this study.

To ensure compliance with federal regulations (45 CFR 46 & 21 CFR 56), please be sure to:

- **Use only the approved study materials** in your research, including the **recruitment materials and informed consent documents that have the IRB approval stamp**.
- Retain signed informed consent documents **for 3 years after the close of the study,** when documented consent is required.
- **Obtain IRB approval prior to implementing any changes** to the study.
- **Inform the IRB if the Principal Investigator and/or Supervising Investigator end their role or involvement with the project** with sufficient time to allow an alternate PI/Supervising Investigator to assume oversight responsibility. Projects must have an eligible PI to remain open.
- **Immediately inform the IRB of** (1) **all serious and/or unexpected** adverse experiences involving risks to subjects or others; and (2) **any other** unanticipated problems **involving risks** to subjects or others.
- **Stop all human subjects research activity if IRB approval lapses**, unless continuation is necessary to prevent harm to research participants. Human subjects research activity can resume once IRB approval is re-established.
- **Submit an application for Continuing Review** at least three to four weeks prior to the **date for continuing review** as noted above to provide sufficient time for the IRB to review and approve continuation of the study. We will send a courtesy reminder as this date approaches.

IRB 03/2018