Fall 2013

The Effect of Sleep Restriction on Executive Function and Emotion Regulation in Early Childhood

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Senior Honors Thesis

October 14, 2013

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Abstract

Sleep loss is experienced universally, and significantly impacts cognition and emotion in adults. However, little to no research has investigated this relationship in the preschool-aged years. This is an essential time period in which executive function and emotion regulation undergo extensive development. As sleep patterns also mature in children during this time, pronounced effects of sleep on developmental domains may be apparent. We experimentally manipulated sleep restriction in 4-6 year-old children, to test its effects on executive function and emotion regulation, aspects of cognition and emotion, respectively. We conducted a 10-day study, where executive function and emotion regulation were assessed twice in children, following a strict sleep schedule for five days prior. Children received either a sufficient amount of sleep or a restricted amount of sleep (3 hour sleep loss) the night prior to assessments. Sleep restriction impaired children's overall performance on tasks and affected physiological responses to affective stimuli, but did not seem to specifically affect executive function or emotion regulation. This study has implications for future work on the development of executive functions, emotion regulation, and on the potential mediational nature of executive function between sleep and emotion regulation.

INTRODUCTION

Early childhood is characterized by dramatic shifts in development, particularly in sleep. By ages 4-5, children have reduced their sleep duration from infancy by 4-6 hours, by eliminating daytime naps and sleeping primarily only at night (Crosby, LeBourgeois, & Harsh, 2005; Weissbluth, 1995). These sleep pattern alterations may arise naturally, atypically through sleep problems or disorders, or externally through lack of opportunities to sleep (Crosby, et al., 2005). If these maturational changes in sleep do not arise naturally, children may or may not be obtaining adequate amounts of sleep. This could prove consequential because sleep loss significantly impacts cognition and emotion in adults (Durmer, & Dinges, 2005; Nilsson et al., 2005; Killgore, 2010; Gujar, Yoo, Hu, & Walker, 2011; Franzen, Buysse, Dahl, Thompson, & Siegle, 2009), and may in children as well.

Children develop both cognitively and emotionally across childhood. Cognitively, children begin to think flexibly, overcome perseverative habits, and demonstrate self-directed control in difficult situations (Munakata, Synder, & Chatham, 2012). Similarly, they are increasingly able to understand, process, express emotion, and control emotion expression through regulation (Ashiabi, 2000). For example, children can understand happiness and express it in socially acceptable situations. However, they also learn to regulate their expression of happiness in socially unacceptable situations, such as at a funeral. While cognition and emotion are markedly developing in children, little is known about the effects of sleep on these domains in children (Sadeh, 2007).

To our knowledge, only one experimental study has investigated the relationship between sleep and emotion regulation in toddlers. Following a nap-deprivation paradigm, children displayed more negative emotions (e.g. shame, frustration) to negative stimuli,

and fewer positive emotions (e.g. joy, pride) to positive stimuli (Berger, Miller, Seifer, Cares, & LeBourgeois, 2012), indicating that sleep restriction negatively impacted toddler's emotional processing and expression.

In adults, insufficient sleep negatively impacts executive function and emotion regulation, aspects of cognition and emotion. Executive functions refer to a set of cognitive processes that guide and control attention and behavior to appropriately respond to and interact with the environment. This includes, but is not limited to, flexibly shifting between information, inhibiting irrelevant responses, and actively maintaining and updating information in working memory (Miyake, Friedman, Emerson, Witzki, Howerter, & Wager, 2000). Following sleep impairment, individuals demonstrate impaired executive functioning relative to when a sufficient amount of sleep has been obtained (Durmer, & Dinges, 2005; Nilsson et al., 2005). Namely, individuals demonstrate reduced response inhibition performance (Killgore, 2010), impaired accuracy and reaction times on working memory tasks, and increased perseveration on tasks by reverting to ineffective solutions to achieve a goal (Durmer, & Dinges, 2005).

Likewise, insufficient sleep in adults results in substantial differences in emotion expression and regulation when compared to sufficient sleep. Adults who have been sleep deprived demonstrate exaggerated responses to affective stimuli. Responses to negative and positive stimuli are amplified, as ratings of mood decrease substantially (Pilcher, & Huffcutt, 1996), stimuli are perceived as more negative or more positive (Gujar, et al., 2011), and physiological and neurological patterns differ from baseline observations (Franzen, et al., 2009; Gujar, et al., 2011). Pupillary dilation, indicating affective processing and cognitive effort, changes significantly in sleep-deprived individuals; however, whether

this exaggeration occurs only in response to negative stimuli or both positive and negative stimuli is unclear as studies have indicated opposing results (Franzen, et al., 2009; Partala, & Surakka, 2003).

Sleep deprivation has resulted in amplification and reduction in activation for various brain regions. The amygdala and other mesolimbic brain regions show amplified activity in sleep-deprived individuals, especially in response to negative stimuli (van der Helm, Yao, Dutt, Rao, Saletin, & Walker, 2011; Yoo, Gujar, Hu, Jolesz, & Walker, 2007). In addition, reduced functional connectivity between the amygdala and the prefrontal cortex is observed in sleep-deprived individuals (Gujar et al., 2011). It is hypothesized that, under such circumstances, the prefrontal lobe lacks the ability to inhibit the over-activated amygdala (van der Helm, & Walker, 2009). These brain regions, namely the amygdala and prefrontal cortex, are viewed as supporting emotion regulation and executive function, respectively (Gallagher, & Chiba, 1996; Arons, Robbins, & Poldrack, 2004).

Rather than sleep impacting executive function and emotion regulation independently, it may only impact one domain which, in turn, impacts the other. This connection is demonstrated behaviorally as both executive function and emotion regulation rely on one another to accomplish certain goals. For example, controlling emotion involves inhibiting the automatic response to express internal states. Therefore, the development of inhibitory control, a component of executive function, may partially drive the development of a more mature emotion regulation.

Although the above findings with adults are relatively conclusive regarding the general detrimental nature of sleep reduction, inconsistencies remain. How individuals react to positive and negative stimuli both behaviorally and physiologically is ambiguous,

as is the specific mechanism underlying the effects of sleep on executive function and emotion regulation. The specific pathway by which sleep affects cognition and emotion may be most clearly understood during the development of these two areas as it may be easier to tease them apart before full maturation is achieved. However, the above findings may not necessarily generalize to preschool- and elementary-aged children. This population of children is undergoing extensive changes developmentally and neurologically. It is necessary to investigate the effects of sleep and sleep restriction in this population, as they may be placed at increased risk as their brains have not fully developed. However, little research has been done to investigate these risks. To address these issues, we will investigate how sleep affects executive function and emotion regulation in preschool- and elementary-aged children.

Drawing from adult research, we hypothesize that overall, children will display more impaired executive function and amplified emotion expression, and thus decreased emotion regulation, when sleep restricted. We will investigate physiological responses to affective stimuli by investigating how pupil diameter changes, measured through a sound listening task. We are interested in pupil diameter changes in response to positive, negative, or neutral stimuli. Additionally, we will measure behavioral responses to affective stimuli by investigating whether negative stimuli (e.g. frustration-eliciting tasks) will cause sleep-restricted children to demonstrate heightened negative emotion expression and decreased positive emotion expression as found in the nap-deprivation study with toddlers (Berger, et al., 2012).

Finally, drawing from the neurological findings in adults, we propose that the reduced functional connectivity between the prefrontal cortex and the amygdala, and

amplified activity in the amygdala following sleep restriction, signifies a mediating relationship between executive function, emotion regulation, and sleep. Specifically, we propose that sleep restriction will detrimentally impact executive function, which in turn will negatively impact emotion regulation. That is, individuals who experience sleep restriction will demonstrate more impaired executive functioning; and as a result of impaired executive function, emotion regulation will be impaired as well. If this connection does in fact exist, it may be most apparent in early childhood, as this is a key period during the development of mature executive functions and emotion regulation.

We will utilize an experimental within-subjects design as this design is particularly powerful, with effects apparent with as few as ten subjects (Berger, et al., 2012; Pollatsek, & Well, 1995). By comparing children's responses on cognitive and emotional tasks following a sufficient night of sleep and a night of sleep restriction, we will examine how sleep affects executive functioning, and emotion regulation. It is our hope that by exploring these two areas of development we will be able to run a future meditation analysis to examine whether executive function plays a mediating role between sleep and emotion regulation.

METHODS

Participants

Ten participants (5 females) ages 4.0-5.9 years (*M*: 62 months, *SD*: 7.4) completed the approximately ten day study. Participants were excluded from specific task analyses due to fussiness: three from set-shifting, two from working memory, and one from inhibition, and sound-listening.

Prior to study entry, parents completed various screeners to assess children's eligibility as well as answer questionnaires regarding their child's sleep habits, behavioral temperament, and medication use, described in detail below. Parents also completed a sleep-wake diary that documented children's sleep schedules and daily activities. Researchers contacted parents daily over-the-phone or through email to ensure this was completed.

Participants were excluded based on the following criteria, gathered from a prescreening questionnaire: sleep problems (e.g., night terrors, sleep walking, enuresis, sleep onset association disorder); napping; traveling across time zones within two weeks of assessments; variable sleep schedule as reported by parents; medication use that affected the sleep/wake cycle, daytime sleepiness/alertness, or the circadian system; illness at time of assessments, physical handicap that interfered with testing (e.g., blindness, deafness); developmental disabilities; neurological disorders; chronic medical conditions; head injuries; family history of sleep, mood, and/or psychotic disorders; behavioral or emotional problems; and migraines or frequent headaches.

Testing Procedure

Prior to study enrollment parents completed a prescreening questionnaire. Once participants were enrolled in the study, parents also filled out questionnaires assessing their child's sleep habits, emotion regulation and behaviors, and family background and history. After these were completed, participants came into the laboratory for the consenting process. At this time, parents were debriefed on all testing procedures including sleep schedules, lab visits, experimental tasks the child would complete, actigraph

guidelines, and home visits. Parents signed IRB-approved consent forms and children were given the actigraph and taught how to wear it. Following study completion, families received $50 and were reimbursed $0.51 per mile for travel.

Children were tested twice on a series of executive function and emotion regulation tasks after following a strict sleep-wake schedule. For the first four consecutive days prior to the testing session, children were placed on a set sleep schedule that provided them with an average amount of sleep preschool and elementary-aged children receive (~11 hours). On the night before the first testing session, children either remained on the same set sleep schedule, receiving a sufficient amount of sleep, or were sleep restricted for three hours past their bedtime. The next morning, children completed a series of experimental tasks at the laboratory (see below). Children completed this schedule design twice so they would be tested on the tasks both following a sleep condition and a sleep restricted condition.

Parents were instructed to avoid allowing their children to have caffeine, including chocolate, and naps throughout the course of the project. Children were also to keep a consistent sleep-wake pattern and sleep duration for all days prior to the testing session except the night of sleep restriction (e.g. ~11 hours of sleep per night, morning rise time: 7:30am, evening bedtime: 8:30pm; night of sleep restriction: evening bedtime: 11:30pm, rise time following morning: 7:30am). During the entire study, children wore an actigraph wristwatch movement sensor which confirmed wake and sleep states. Children were required to wear the actigraph at all times except when it could get damaged or wet.

Sleep Schedule Measures

In order to ensure sleep schedules were adhered to, parents completed a 26-item sleep diary recording children's daily events, namely, rise times and bed times, caffeine or medication consumption, accidental naps, child's mood, child's stress level, and activities before bedtime (Appendix A). In addition, children wore an actigraph on their non-dominant hand (Model AW Spectrum, Philips/Respironics, Pittsburg, PA, USA), which provided recordings of sleep-wake states through wrist activity. Sleep and wake periods were determined from 1-min actigraph epochs processed by Actiware-Sleep V5.02 software. Using this software and daily reports by parents, markers of 'lights-on' and 'lights-out' were identified. For each sleep period, actigraphy indicated time in bed (sleep opportunity): lights-out to lights-on, and sleep period (duration): minutes from sleep start (sleep start scored as the first of three consecutive minutes after lights-out) to sleep end (sleep end scored as the last of five consecutive minutes before lights-on). Actigraphy was used to confirm sleep schedules, and to assess children's sleep duration and opportunity for five days prior to testing sessions.

Sleep Schedule Protocol and Home Visits

Following the orientation visit, children began the sleep schedule. Participants wore the actigraph consistently throughout the study and parents were called daily to ensure that they consistently followed the sleep schedule. If participants had caffeine, naps, or deviated from the sleep schedule by more than 15 minutes, the sleep schedule was re-stabilized and the testing session rescheduled 3-5 days out; if this was not possible, children were excluded from the study. On the night of sleep restriction, which was counterbalanced across participants to be before the first or second testing session,

researchers visited the child's home. During this time, researchers played with the child, keeping them up three hours past their bedtime, and downloaded actigraph data to confirm that the set sleep schedule had been followed. Similarly, actigraph data were also collected on the morning of the testing session following the night of sufficient sleep.

Lab Visits

At each lab visit, participants completed a series of tasks that assessed executive function and emotion regulation between 2-3 hours after their morning rise time. Each task was no longer than 5-10 minutes and completion of all tasks took less than one hour. Children completed three age-appropriate, computerized executive function tasks that measured response inhibition, task-switching, and working memory. In addition, children completed three emotion tasks including a computerized frustration task, a puzzle box task, and a computerized sound-listening task that examined children's physiological responsiveness to emotional stimuli through pupil measurements. All tasks are described below, but because the computerized frustration task and the puzzle box task are still being analyzed, only the executive function tasks and the sound-listening task results will be presented.

Executive Function Tasks

Children's executive function was measured through three different computer games, using E-Prime software (Psychology Software Tools, Pittsburgh, PA). Response inhibition was measured through a computerized version of a Simon task. In this game, either a frog or a shoe (stimulus) appeared on the left or right sides of the screen. A

response pad indicated which button was the frog button (left button) and which was the shoe button (right button). When the picture appeared on the screen, children were told to press the button that matched the stimulus identity. On half of the trials, the stimulus was presented on the same side as the response pad button (congruent trials), whereas it was presented on the opposite side on the other half of the trials (incongruent trials). Incongruent trials were more difficult as the nature of the response required children to inhibit the tendency to respond to stimulus location. Response inhibition was indexed by contrasting response times and accuracy on congruent and incongruent trials.

Switching between task sets was measured through a task-switching paradigm. In this computerized task, children had to switch between color- and shape-matching tasks. The stimulus was either blue or red and either a square or a circle which had to be matched with one of the four response options (e.g., blue, circle, red, square) displayed on a response pad. The relevant matching task (i.e., color or shape) was signaled by both an auditory cue (the word “color” or “shape”) and a visual cue (a rainbow or a palette of geometric shapes above the stimulus). Children first practiced responding to only shape and then only color (simple trials). Mixed practice and test trials were then played. During these trials, the matching task could either repeat (no-switch trials) or change (switch trials). Task switching performance was indexed by contrasting accuracy and RTs on switch and no-switch trials, while task mixing was indexed by contrasting simple trials and no-switch trials.

Working memory was assessed through a forward and backward-span task. In this age-appropriate adaptation of Corsi blocks, children viewed a frog jumping from lily pad to lily pad. After the frog finished jumping, children used a pointer to press the lily pads on the

screen where the frog had jumped. Children started with a forward version in which they pressed lily pads in the same order the frog jumped on them. They then moved on to a backward version in which they had to recall which lily pads were jumped on in the backwards order. Once the child was unsuccessful in three attempts on a given sequence length (e.g. four lily pads jumped on), the game was terminated. Following Handley et al. (2004), short-term and working memory scores were calculated as the maximum span length that children successfully recalled twice plus 0.5 points for any additional correct trials in the forward and backward versions, respectively.

Emotion Regulation Tasks

Children's emotion expression and emotion regulation was measured through two different frustration tasks, each of which had two variations. One version was a computerized task and the other consisted of opening an unsolvable puzzle box.

Two different computerized variants of the Delay Frustration task were utilized. In one version, children were asked to press a button indicating the larger character on the computer screen. In the other version, children were asked to indicate which animal was the ocean animal versus a land animal. The size version was always given at the participant's first session, and the animal version at the second session. Children were warned that the computer might not work well for this task. Both of these cover tasks were designed so that children had to wait for feedback on their accuracy. Feedback was immediate on most trials, while other feedback was delayed by a given amount of time (i.e. 2-20 seconds). While waiting for feedback and for the game to continue, children were told, "sometimes this computer game freezes. When this happens, there's nothing to do but

wait." The experimenter did not interact with the child at this time, to minimize interference with children's emotion expression and regulation. Children's emotion expression and the amount of frustration was indexed by the number and latency of button presses during delays, as well as facial expression, verbal behaviors, fidgeting, and other frustration-related behaviors coded from session videotapes.

In the puzzle task, which also measured emotion expression and regulation, children had to open a transparent box with prizes inside. Two versions of the puzzle box were utilized. Both boxes were unsolvable, that is, they were specifically designed not to open. The first puzzle box, given at every participant's first session, was kept closed by a stick that had to be maneuvered through a maze in order to open it. To further keep the box closed, in case some children were able to remove the stick by maneuvering it through the maze, the box was taped shut with clear packaging tape. The second box, given at every participant's second session, was locked with a padlock. Children were given a set of keys, none of which was the right one. During this task, children were video recorded and monitored through a camera in a nearby room. Parents were asked to leave the room to allow the child to open the box without outside help or regulating their emotions through others. The researcher did not engage in the task unless the child specifically directed comments or questions to the researcher. If the child asked, "could you help me open this?" or commented, "this is too hard", the researcher responded with "you need to open the box to receive your prize." After five minutes had elapsed, the child had given up, or the child became too frustrated to continue (i.e. began to cry), the researcher discontinued the task. Children were then given a different maze box that was openable or were given the correct set of keys to open the locked box. In both cases, children were given the prize inside of the

box despite their unsuccessful attempts to open the box. A coding scheme was also developed for this task to assess emotion and facial expression in children as well as utilization of strategies to open the boxes.

Finally, children completed a computerized task examining physiological responsiveness to affective stimuli. This task measured affective processing and cognitive load through pupil dilation in response to positive, negative or neutral sounds (e.g. a baby laughing, a baby crying, and a fan) taken from the International Auditory Digitized Sounds stimuli set (Bradley, & Lang, 2007). The auditory stimuli were age appropriate and were chosen based on valence and arousal levels rated by adults. Children sat 60cm away from the monitor and completed a 5-point calibration procedure prior to playing the game. Pupil dilation was recorded by a Tobii eye-tracker (Tobii, Model X50, Stockholm, Sweden) while children listened to each sound (and meanwhile looked at a fixation star on the screen). Children were asked to name what sound they heard to ensure understanding as well as limit the potential passive nature of the task by engaging in questions, not just sound-listening.

Analysis

An analysis of variance for repeated measures (ANOVA) was utilized for all cognition tasks. Reaction time (RT) was calculated for both the inhibition and set-shifting tasks and accuracy was calculated for all three cognition tasks. The emotional responsiveness to affective stimuli (IADS) task was also analyzed with a repeated measures ANOVA. The other two emotion regulation tasks are still being coded through video recording and therefore will not be presented here.

RESULTS

Inhibition

The effect of sleep restriction on inhibition was examined by a 2 (Condition: Sleep, Restricted) × 2 (Congruency: Congruent, Incongruent) repeated-measure ANOVA on accuracy and reaction times (RTs) in the Simon task (N=9). For both accuracy and RTs, there were significant effects of congruency ($F(1,8) = 6.49$, $p = 0.034$, $\eta^2_p = 0.448$, Figure 1; $F(1,8) = 5.84$, $p = 0.042$, $\eta^2_p = 0.422$, Figure 2). As expected, children performed more accurately and were faster in their response on congruent (M = 78.1%, SD = 4.6%; M = 753ms, SD = 48) compared to incongruent trials (M = 69.2%, SD = 6.1%; M = 823ms, SD = 72). Although the condition had no effect on RTs ($p = 0.847$), children in the sleep condition tended to be more accurate overall (M = 76.9%, SD = 4.4%), relative to the restricted condition (M = 70.3%, SD = 6.3%; $F(1,8) = 3.71$, p=0.09, $\eta^2_p = 0.317$). No significant interaction was observed between condition and trial type for either accuracy ($p = 0.169$) or RT ($p = 0.723$).

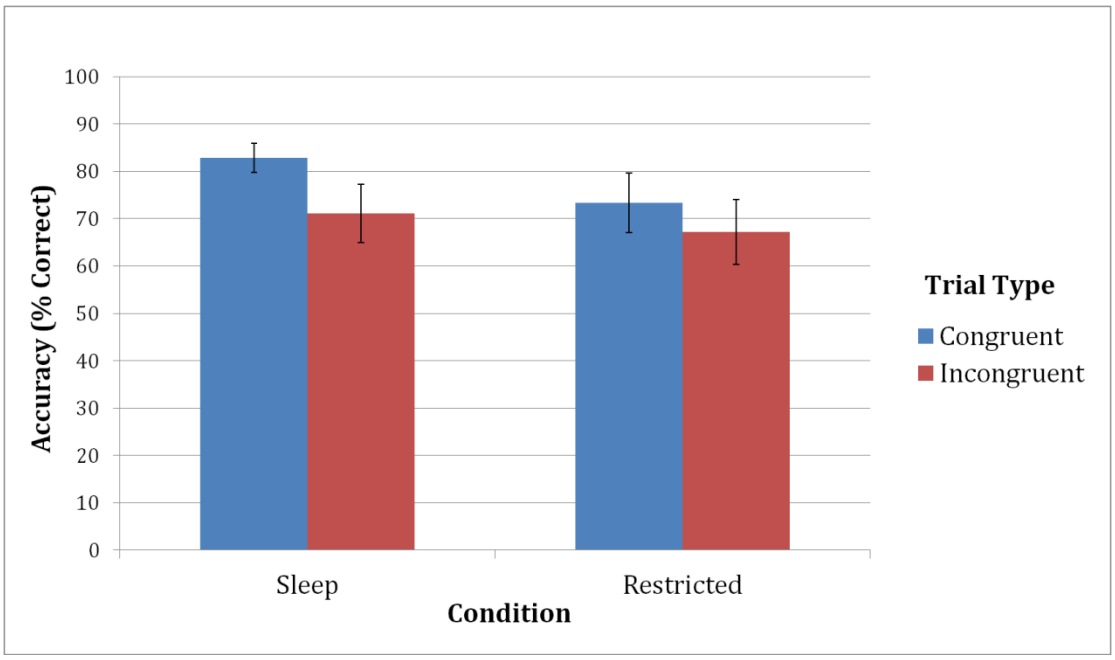

Figure 1. Inhibition accuracy: Participants performed better on congruent trials than incongruent, and overall performed better in the sleep sufficient than sleep restricted condition. No significant interaction was observed. Error bars represent standard error.

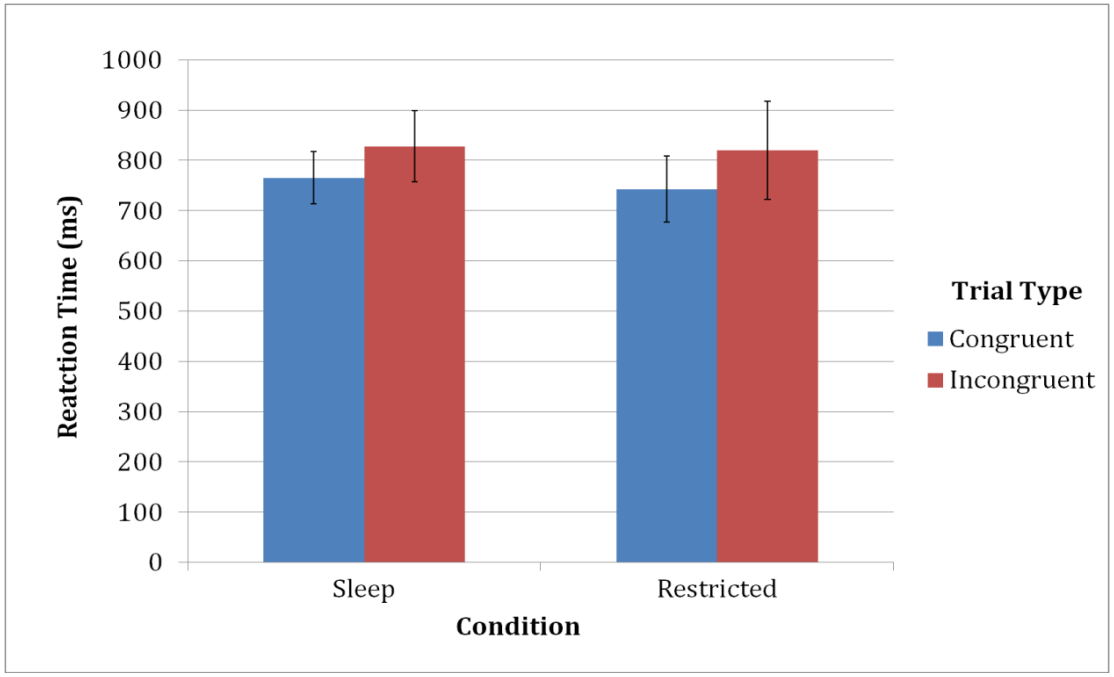

Figure 2. Inhibition reaction time: Participants responded faster to congruent trials than to incongruent trials. No effect of condition or interaction was observed. Error bars represent standard error.

Working Memory

The effect of sleep restriction on working memory was examined by a 2 (Condition: Sleep, Restricted) × 2 (Span Type: Forward, Backward) repeated-measure ANOVA on accuracy in the working memory game (N=8). A significant effect of span type was observed ($F(1,7) = 15.75$, $p = 0.005$, $\eta^2_p = 0.692$, Figure 3), with greater performance in the forward span task ($M = 3.43$, $SD = 0.36$) than the backward span task ($M = 2.69$, $SD = 0.39$). No significant effect of sleep condition on working memory was observed ($p = 0.461$) and neither was an interaction between condition and span type observed ($p = 1.0$).

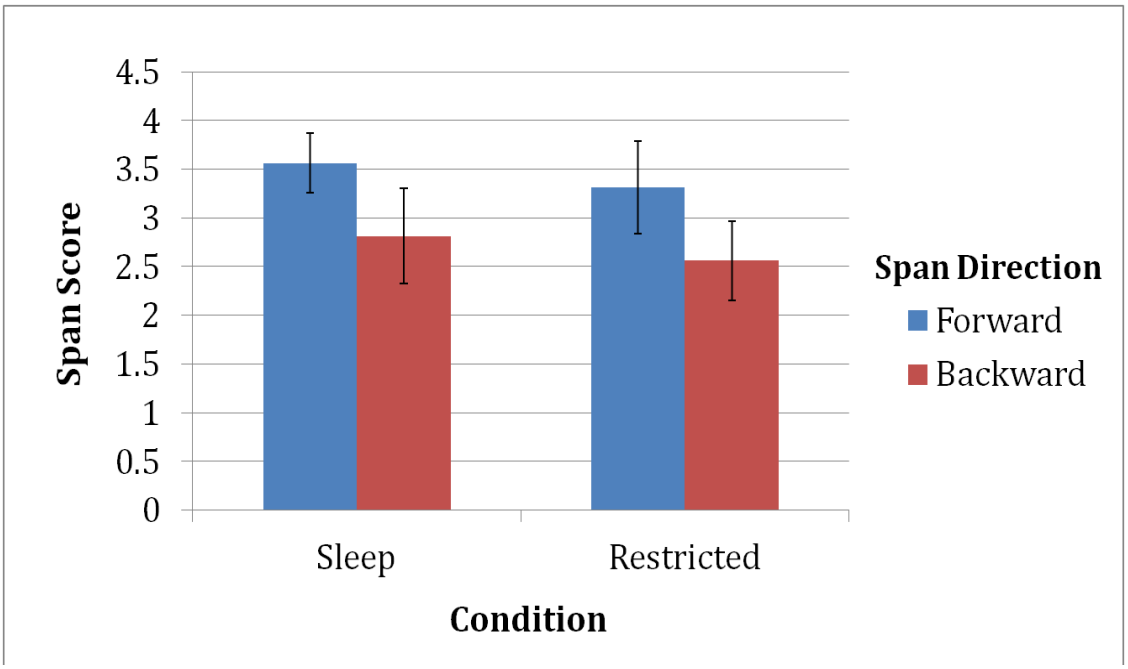

Figure 3. Working memory span scores: Participants performed better on the forward span task relative to the backward span task. No main effect of condition or interaction was observed. Error bars represent standard error.

Set-Shifting

The impact of sleep restriction on set-shifting was investigated by performing a 2 (Condition: Sleep, Restricted) × 3 (Trial Type: Simple, No-Switch, Switch) repeated-measure ANOVA on accuracy and RTs in the Task-Switching game (N=7). A significant effect of trial type was observed both for accuracy, ($F(2,12) = 4.465$, $p = 0.036$, $\eta^2_p = 0.427$, Figure 4), and RT, ($F(2,12) = 64.57$, $p < 0.0001$, $\eta^2_p = 0.915$, Figure 5). Simple trials yielded greater accuracy ($M = 92.1\%$, $SD = 2.1\%$) and shorter RTs ($M = 1246$ms, $SD = 131$) than no-switch trials ($M = 87.4\%$, $SD = 2.0\%$; $M = 1738$ms, $SD = 107$; all $ps < 0.043$), thereby showing significant mixing costs. In turn, no-switch trials yielded shorter RTs than switch trials ($M = 1738$ms, $SD = 107$; $M = 2116$ms, $SD = 129$; respectively; $p = 0.005$), showing significant switch costs. No-switch and switch trials did not differ from one another in terms of accuracy, generating no switch costs ($p = 0.363$). Importantly, the ANOVA revealed a significant effect of condition on RTs ($F(1,6) = 5.98$, $p = 0.05$, $\eta^2_p = 0.5$, Figure 5), due to faster RTs in the sleep condition ($M = 1625$ms, $SD = 133$) relative to the restricted condition ($M = 1775$ms, $SD = 102$). In contrast, condition had no effect on accuracy ($p = 0.908$) and no significant interaction was observed for either accuracy ($p = 0.727$) or RT ($p = 0.503$).

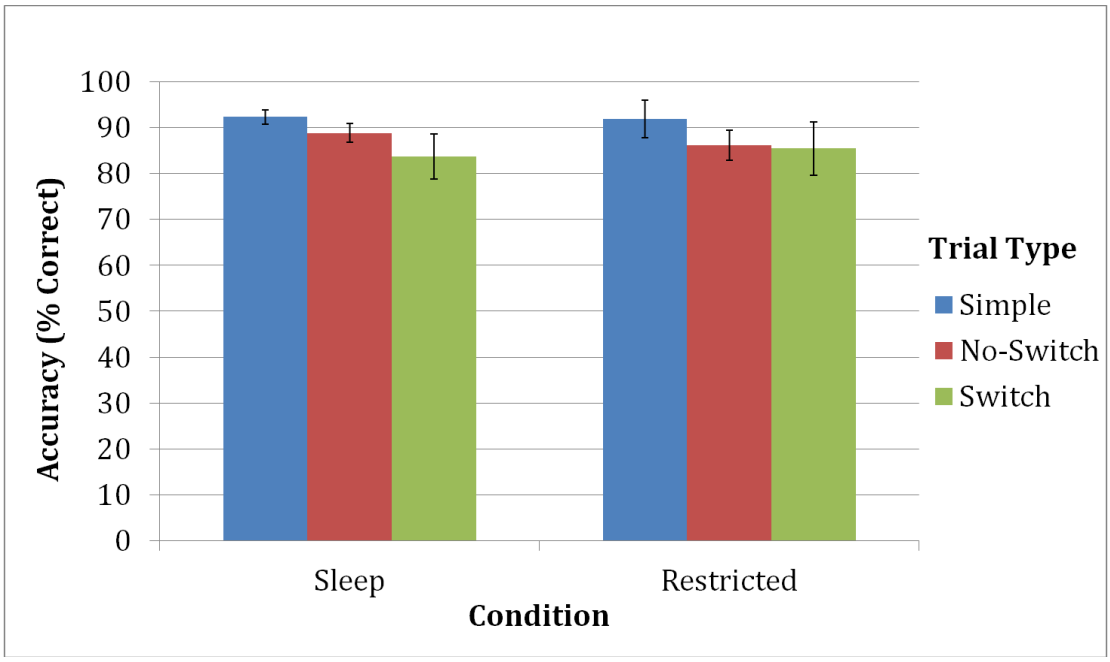

Figure 4. Set-shifting accuracy: Participants performed better on simple trials relative to no-switch and switch trials. No difference between switch and no-switch trials was observed. There was no main effect of condition or interaction between condition and trial type. Error bars represent standard error.

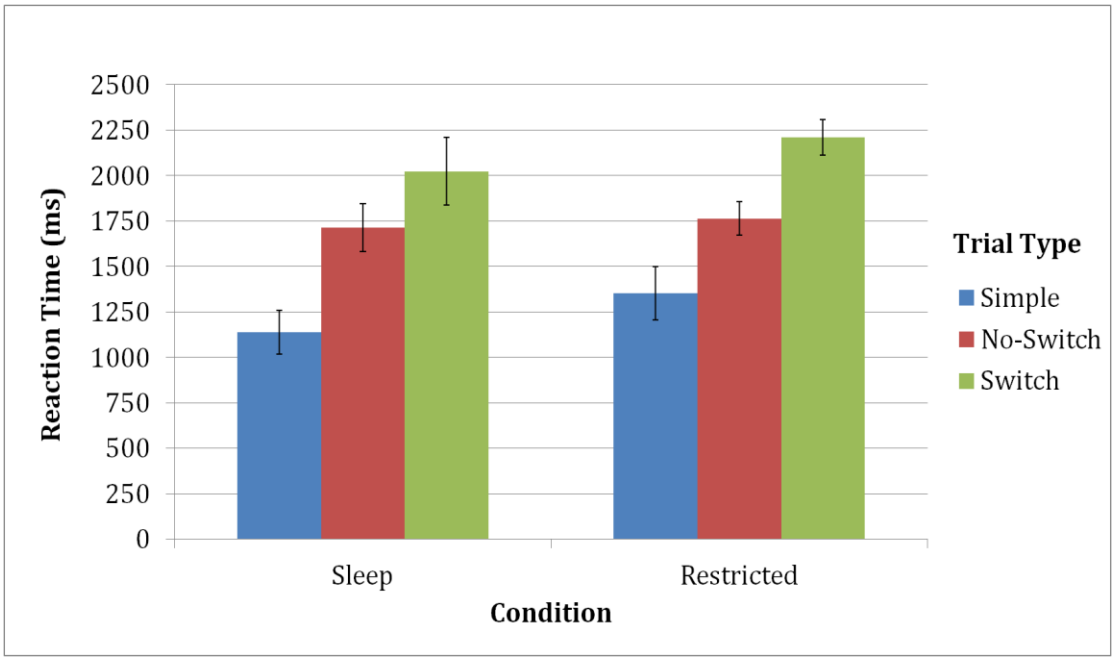

Figure 5. Set-shifting reaction time: Participants responded more quickly to simple trials relative to no-switch and switch trials; and also responded more quickly on no-switch trials relative to switch trials. Overall, children responded more quickly when in the sleep sufficient condition relative to the restricted condition. No interaction was observed. Error bars represent standard error.

Physiological Response to Affective Stimuli

The impact of sleep restriction on physiological responses to affective stimuli was analyzed by a 2 (Condition: Sleep, Restricted) × 3 (Valence: Positive, Negative, Neutral) repeated-measure ANOVA on the average percent change in pupil dilation relative to baseline measures (N=9). Stimuli valence did not have any significant effect on pupil diameter change from baseline levels (p = 0.966, Figure 6). There was no significant effect of condition on pupil diameter response (p = 0.247), or interaction between stimulus valence and condition (p = 0.25). Although not significant, we ran a paired T-test to compare the sleep sufficient and sleep restricted conditions on positive stimuli where effects have been observed behaviorally (Berger, et al., 2012). We did not observe a significant interaction between sleep sufficient and sleep restriction condition responses to positive stimuli; however, it trended towards significance ($t(8)$ = 1.907, p = 0.093; Figure 6).

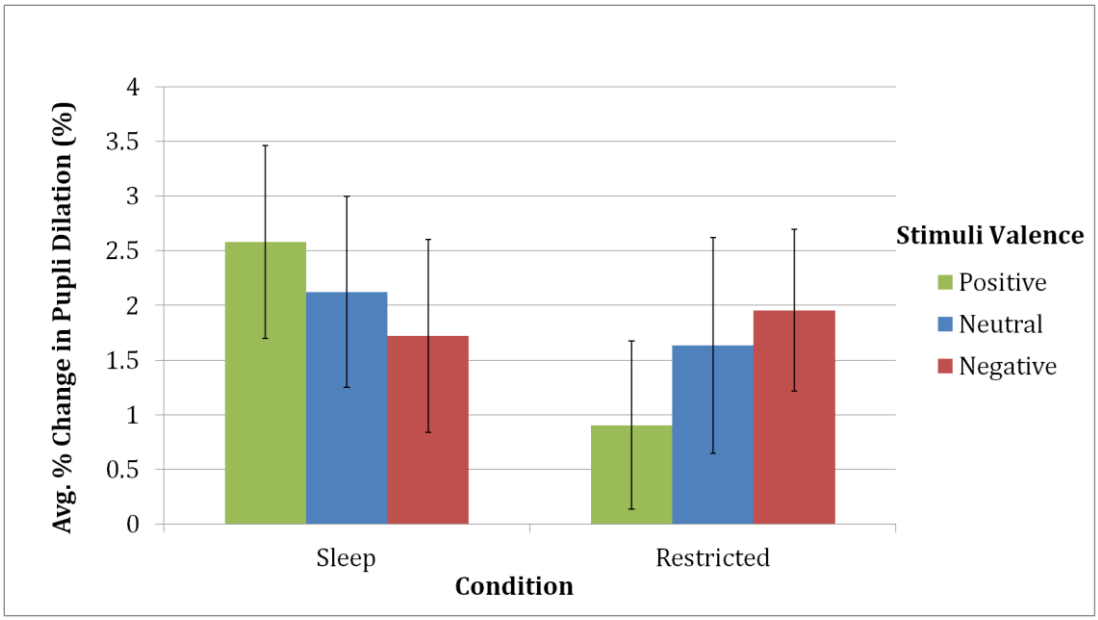

Figure 6. Average percent change in pupil dilation: No main effect of condition or stimuli valence, and no interaction was observed on pupil diameter response. Error bars represent standard error.

DISCUSSION

Our study experimentally explored the effect of sleep restriction on young children's executive function and emotion regulation. Overall, we observed general trends suggesting sleep restriction negatively impacted accuracy and reaction time on executive function tasks. In addition, sleep restriction decreased physiological responses to positive stimuli.

Sleep Restriction Affects Executive Function

We investigated the effects of three hour sleep restriction on executive function through measures of inhibition, visuospatial working memory, and task-switching. Given our small sample size and the exclusion of participants from our analyses, it is difficult to draw strong conclusions regarding sleep and executive function. Our preliminary results suggest the effects of sleep restriction on children's executive functioning may be more general than the specific effects observed in adults. Specifically, children's accuracy on a response inhibition task was impaired by sleep restriction. However, this impairment was seen across trial types, not just the ones designed to be demanding on executive function. Research has suggested trial types designed to be less challenging could still prove demanding on children's executive function, thereby explaining our broader findings (Cepeda, Blackwell, & Munakata, 2013). Thus, we cannot definitively conclude sleep restriction impacts inhibition exclusively.

We did not find working memory to be significantly impacted by sleep restriction. While adult literature has indicated working memory is detrimentally impacted, it has been suggested that the executive aspects of working memory, such as scanning efficiency, are not taxed by sleep restriction; rather, non-executive components such as performing the

task through sustained attention and executing motor responses are (Tucker, Whitney, Belenky, Hinson, & Van Dongen, 2010). Thus, it is possible that the executive component of working memory is not significantly affected by sleep restriction, consistent with our null finding. Follow-up work is needed to support the above hypothesis.

Performance on the set-shifting task was significantly affected by sleep restriction. Children showed significantly slower response times in the sleep restricted condition relative to the sleep sufficient condition, suggesting children had more difficulty rapidly responding to information from the environment in general. However, there was no significant interaction of condition with trial type, suggesting sleep restriction may not necessarily affect set-shifting. In general, however, slowed responses to the environment, at home or school, could impact children's ability to perform various tasks. While we cannot definitively conclude sleep restriction directly impacts various components of executive function, it is clear that sleep restriction limits the ability to maintain attention, execute, and perform well on various tasks.

Sleep Restriction Affects Emotion Responses

We also investigated the effect of three hour sleep restriction on physiological responses to emotional stimuli through our sound-listening (IADS) task and on emotion regulation and expression through our Delay Frustration and Puzzle Box tasks.

While the effects of sleep restriction on physiological pupil diameter responses were not significant, we observed a marginally significant interaction between positive stimuli and condition. Overall, children tended to respond less to positive stimuli following sleep restriction, as was also found in the only other experimental study in toddlers investigating

nap deprivation (Berger, et al., 2012). Together, these findings obtained through different methodologies (observed behavioral responses and physiological responses through pupillometry) converge to the conclusion that sleep restriction limits the ability to process and respond to positive stimuli.

Our ongoing analyses of emotion regulation and expression might further our understanding of how sleep restriction affects behavioral responses to frustration-eliciting stimuli, which children come across daily. While the tasks themselves were specific to laboratory settings, the eliciting stimuli were similar to what children may encounter in their environment. By furthering our understanding of how children respond to following sleep restriction, we may be able to modify the environment and recognize children's responses.

Implications

While our tasks were performed in a laboratory setting, children could encounter similar situations at home or in school where inhibition is a necessary skill. For example, in a school setting, children learn when to raise their hand and refrain from glancing at a peer's test answers. As executive function predicts subsequent academic performance (Blair, & Razza, 2007), consistently impaired executive function, stemming from sleep restriction, could detrimentally impact academic performance and learning. Simply targeting the sleep schedule may provide a promising and inexpensive route to improve executive function in children who are at risk for academic achievement. Furthermore, intervening in the preschool years may prove more beneficial to society and the economy than intervening in later years (Heckman, 2006).

In addition, consistently taxed emotion response and expression, influenced by sleep restriction, could negatively impact children's development over time. We observed limited ability to process and respond to positive emotional stimuli, which children often come across, such as when they do well on an assignment, or have a play-date with friends. Children may not process or react to such positive stimuli as they usually would. Likewise, their non-adaptive emotion processing could lead to future dysregulation in emotion. Dysregulation in emotion in childhood could put children at risk for developing mental health disorders or behavioral problems later in life (Cole, Michel, & Teti, 1994).

Limitations and Future Directions

Our study utilized a within-subjects experimental. However, with the four tasks that were analyzed, only one showed a significant effect of condition on performance. What must be taken into account, however, is our sample size. Due to the time-intensive nature of these 10-day testing-sessions, with strict criteria for maintaining the testing schedule versus starting the sleep schedule again, only ten subjects have participated in our study thus far. While these study designs are powerful enough to detect effects of sleep reduction in as few as ten subjects (Berger, et al., 2012), our sample of ten is nonetheless underpowered. Of those ten, up to three subjects were eliminated from specific task analyses due to incomplete data (fuss out), thus effects and interactions may become significant with more subjects.

Additionally, our experimental manipulation was not completely successful. Families adhered to the lights-out, rise-time sleep-wake schedule as confirmed by actigraphy data; however, we observed significant differences in sleep parameters 24

hours before the sleep sufficient condition testing session. Although all children were in bed at their scheduled bedtime, half of our participants experienced shorter sleep periods than expected as a result of either falling asleep later or spontaneously waking up earlier than scheduled times. Thus, when children completed our tasks in the sleep sufficient condition, half of our participants had actually experienced some level of sleep loss. The specific tasks were analyzed prior to this finding, which could explain our null results.

Our executive function tasks did reveal significant effects of trial type indicating they were appropriately designed. However, we only had one task per domain: one for inhibition, one for working memory, and one for set-shifting. Due to task impurity (i.e., a specific task taps both executive and non-executive processes, thereby introducing measurement error), this could have limited generalizability, as children may have been more or less vulnerable to the nature of our tasks versus other executive function tasks. Future studies should include multiple tasks assessing a specific domain to increase reliability across tasks.

Our emotion tapping tasks may have also been limited in nature. The sound-listening task with IADS stimuli had not previously been used with children of this age range. Valence and arousal ratings were done so by adults, thus children may differ in what they found positive, negative, and neutral. For example, a rooster was rated as neutral by adults, but could have been interpreted as a more positive sound by children.

Our sample was extremely selective and so the children in this project may not generalize to the larger population. Inclusion criteria required children to be fairly scheduled in that they had a regular wake-sleep schedule that was consistent throughout the week. Children oftentimes vary their sleep schedule (Owens, Spirito, & McGuinn, 2000),

thereby limiting the generalizability of our sample to the general population. If children vary their schedules dramatically day-to-day they may be more (or less) susceptible to sleep restriction and the negative consequences that follow it. Indeed, children with more variable sleep schedules may come from low socioeconomic status (SES) neighborhoods. Lower SES children demonstrate more impaired cognitive performance compared to higher SES children following sleep disruption (Buckhalt, El-Sheikh, & Keller, 2007). Future directions should aim to include this population of children, as our results may not be as robust or necessarily generalize to these children.

Although this study was limited due to time constraints, I plan to test 15 additional subjects during the next few months, and analyze our two emotion tasks to further understand sleep restriction and its effect on emotion regulation. If sleep restriction is found to impair executive function and emotion regulation, I will include mediational analyses to examine whether executive function explains the relationship between sleep and emotion regulation suggested by adult literature through neurological findings. Nonetheless, our results indicate that sleep restriction negatively impacts overall performance and impacts physiological responses to affective stimuli.

ACKNOWLEDGEMENTS

This research was supported by grants from the National Institute of Child Health and Human Development and the National Institute of Mental Health. Yuko Munakata, PhD, Monique LeBourgeois, PhD, Nic Chevalier, PhD, Peter Franzen, PhD, and Sarah Watamura, PhD, were invaluable in conducting the research and designing the study. We are grateful to both the Cognitive Development Center, the Sleep and Development Lab, and the research assistants who aided in this project. We are extremely appreciative of the families and children that made this study possible.

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