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A One-Hour Sleep Restriction Impacts Brain Processing in Young Children Across Tasks: Evidence From Event-related Potentials

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Abstract

The effect of mild sleep restriction on cognitive functioning in young children is unclear, yet sleep loss may impact children's abilities to attend to tasks with high processing demands. In a preliminary investigation, six children (6.6 - 8.3 years of age) with normal sleep patterns performed three tasks: attention (“Oddball”), speech perception (conconant-vowel syllables) and executive function (Directional Stroop). Event-related potentials (ERP) responses were recorded before (Control) and following one-week of 1-hour per day of sleep restriction. Brain activity across all tasks following Sleep Restriction differed from activity during Control Sleep, indicating that minor sleep restriction impacts children's neurocognitive functioning.

Keywords

Children; Sleep; ERP; Stroop; Speech Perception; Attention

Children frequently experience mild sleep loss (restrictions) for a variety of reasons - demands of school and family activities, homework, peer interactions, and/or poor sleep hygiene. Sleep restriction refers to the reduced number of hours of sleep that children experience from day-to-day or week-to-week. In such cases, sleep restrictions usually occurs at the front end of the sleep period by delaying the time that the child goes to bed and

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subsequently to sleep. These restrictions in sleep duration have been found to impact the ability of elementary school aged children to attend to tasks with heavy processing demands (Sadeh, Gruber and Raviv, 2002). Sleep restriction was also found to increase irritability, acting-out, and restlessness. These relations between sleep and behaviors are characterized by the International Classification of Sleep Disorders (2001) as “the performance of daily living activities that are inconsistent with the maintenance of good quality sleep and full daytime alertness” (p. 73). However, compared to adult studies, much less is known about the impact on cognitive skills from even relatively small decreases in sleep commonly experienced by the majority of American school-aged children.

Studies of human performance after sleep restriction are not new and have been considered as a classic approach to advance our understanding of the value of sleep and the effects of sleep on performance. Meta-analyses and reviews of these studies report remarkably consistent results, namely that sleep restriction leads to decreased reaction times, reduced levels of alertness and memory consolidation, along with increases in perceptual and cognitive distortions, and changes in the regulation of affect (Kopasz et al., 2010; Koslowsky and Babkoff, 1992; Pilcher & Huffcutt, 1996; Philibert, 2005; Lim & Dinges, 2010). However, the mechanisms that underlie these negative effects are not clearly understood. For example, one explanation sugggests that sleep restriction influences “bottom-up” attention and arousal processes on a global level, mediated by wake-state instability (Doran, Van Dongen, & Dinges, 2001). These disruptions lead to performance decline on attention and vigilance tasks (Dinges, 1992; Kjellberg, 1977; Martella, Casagrande, & Lupiáñez, 2011). Other theories posit that sleep restriction has domain-specific effects that target specific “top-down” brain areas, notably the prefrontal cortex (PFC). Functional neuroimaging (using positron emission tomography scans or nuclear magnetic resonance spectroscopy) and neuropsychological testing indicate that short-term sleep restriction in healthy young adults greatly affects PFC functions, such as flexible thinking, verbal fluency, inhibition, and memory (Beebe, DiFrancesco, Tlustos, McNally, & Holland, 2009; Braun et al., 1997; Chee & Chuah, 2007; Cote, Milner, Osip, Baker, Cuthbert, 2008; Dorsey et al., 2000; Drummond & Brown, 2001; Szelenberger, Piotrowski, & Dabrowska, 2005; Thomas et al., 1998). A more integrative approach encompassing these different theoretical accounts suggests that sleep restriction primarily negatively impacts PFC functions, which influence both top-down and bottom-up processes (Boonstra, Stins, Daffertshofer, and Beek, 2007).

Developmental sleep research suggests an important role for sleep during early brain development. From birth, and through preschool and early school age, children spend more time asleep than awake, and the amount of sleep they require exceeds the physiological sleep requirements of young adults. Links between insuffient sleep and behavior problems in children have been reported. For example, sleep-restricted children exhibit behavioral and cognitive symptoms that resemble those observed in attention deficit hyperactivity disorder (Dahl, Pelham, & Wierson, 1991; Picchietti & Walters, 1994) or exhibit significant manifestations suggestive of “executive dysfunction”, resulting in maladaptive daytime behavior and reduced academic performance (Beebe & Gozal, 2002; O'Brien et al., 2003). It is possible that brain maturation processes enhance the vulnerability of the PFC to the effects of sleep restriction in young children. Indeed, the PFC matures later than other

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cortical regions with some functional components extending their maturational process into adolescence or even adulthood (Gozal, Row, Schurr, & Gozal, 2001; Miller & Cohen, 2001). Thus, the early childhood years may constitute a unique period of particular susceptibility to both intrinsic and extrinsic disruptions in PFC development.

To address the need for more information on the impact of sleep restriction in children, this preliminary investigation used brain imaging techniques to study how sleep restriction impacts neurocognitive skills by comparing brain activity after a control period of the children's typical sleep duration and after one week of experimental mild (1 hour) sleep restriction. In this study, event-related potentials (ERPs) were recorded using a geodesic 128 electrode net during children's performace on three commonly used tasks to assess potential cognitive changes due to mild sleep restriction. Task 1 utilized the standard “oddball” paradigm known to measure attention-related neurocognitive components (Sangal & Sangal, 1997). Task 2 involved a simple speech perception task as a measure of auditory discrimination (Molfese, 1978). Task 3 utilized a Directional Stroop paradigm to measure working memory and inhibitory control (Davidson, Cruess, Diamond, O'Craven, & Savoy, 1999).

Hypothesis 1

Two hypotheses were proposed. The first hypothesis was that ERPs elicited during the Control Sleep condition would differ from those elicited from the same children during the Sleep Restriction condition. Specific predictions are outlined in the next three paragraphs.

For Task 1 (Hypothesis 1a), it was hypothesized that ERP responses during the classic P300 oddball task following one-week of their typical sleep routine (Control Sleep Condition) would differ from those recorded from the same children after one week of 1 hour less sleep per night (Sleep Restriction Condition). More specifically, it was anticipated that while overall amplitudes in the ERP responses (e.g. P300) associated with the “odd-ball” task would show the typical increase in ERP amplitude while children attended to the infrequent occurring tones, the restricted sleep condition would elicit markedly smaller P300 amplitudes than during the control condition.

For Task 2 (Hypothesis 1b), differences in amplitude at specific latencies were expected to occur during the speech perception task between the Control and Restricted Sleep conditions. ERP studies of speech perception have shown consistency across studies in the peak latencies at which speech discrimination was reported in children (e.g., Molfese & Molfese, 1988; Molfese, Maguire, Dove & Molfese, 2005). It was expected that Restricted Sleep would result in decreased amplitudes at specific latencies.

In the third task (Hypothesis 1c), the Directional Stroop task, it was expected that amplitude changes would be associated with the Restricted Sleep condition. However, since we are aware of no published ERP studies investigating young children's performance on the age-appropriate version of the Stroop task, we were not able to make specific predictions.

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Hypothesis 2

A second hypothesis addressed more specific aspects of ERP processing between different scalp regions for the three different tasks. The three tasks are thought to tap different types of cognitive processes subserved at some level by different brain structures. Consequently, we hypothesized that topographic patterns of ERP brain activity would differ between the Control and Restricted Sleep conditions for each of the three tasks.

Methods

Participants

Six typically developing, male children (mean age = 7.66 years, range 6.6-8.3 years) participated in this preliminary study. A same-sex sample was selected to reduce variability in the sample that could result from known brain-gender differences.

Initial screening—All children were right handed (Laterality Quotient = .74; Oldfield, 1971), and had IQ and neuropsychological test scores in the normal range. Information on sleep habits was obtained before baseline and experimental tests were conducted. Any child already diagnosed with medical, neurological, attention, behavioral and/or learning disorders excluded using a screening questionnaire on health history, a psychological interview and/or by the Child Behavioral Checklist (CBCL; Achenbach & Edelbrock, 1983; Achenback, 1991). Pre-existing sleep disorders were screened using a Sleep Behavior Questionnaire (Montgomery-Downs, O'Brien, Holbrook & Gozal, 2004). Parents complete all questionnaires. Parents were compensated for their time and transportation expenses.

Sleep screening—All children who passed the initial screening underwent an overnight polysomnographic recording prior to their inclusion in the study, with testing performed at the the Pediatric Sleep Research Center within Kosair Children's Hospital, Louisville, KY. No sleep deprivation or sedation was used during the polysomnography. Children were studied for at least 8 hours in a quiet, darkened room with an ambient temperature of 24°C in the company of one parent. The following parameters were measured: chest and abdominal wall movement by respiratory impedance or inductance plethysmography, heart rate by ECG, air flow was monitored with a sidestream end-tidal capnograph which also provides breath-by-breath assessment of end-tidal carbon dioxide levels ($PETCO_2$; Pryon SC-300, Menomonee Falls, WI), as well as a nasal pressure transducer (Braebon Medical Corporation, NY) and/or a thermistor. Arterial oxygen saturation (SaO_2) was assessed by pulse oximetry (Nellcor N 100; Nellcor Inc., Hayward, CA), with simultaneous recording of the pulse waveform. The bilateral electro-oculogram (EOG), 8 channels of electroencephalogram (EEG: F3, F4, C3, C4, O1, O2, A1, A2, using A2 as the online reference), chin and bilateral anterior tibia and forearm electromyograms (EMG), and analog output from a body position sensor (Braebon Medical Corporation, NY) were also monitored. All measures were digitized using a commercially available polysomnography system (Medcare, Buffalo, NY). Tracheal sound was monitored with a microphone sensor and a digital time-synchronized video recording was performed. Sleep architecture was assessed by standard techniques (Rechtschaffen & Kales, 1968). The apnea index (AI) was defined as the number of apneas per hour of total sleep time (TST). Central, obstructive, and

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mixed apneic events were counted. Obstructive apnea was defined as the absence of airflow with continued chest wall and abdominal movement for a duration of at least two breaths. Hypopneas were defined as a decrease in nasal flow of ≥50% with a corresponding decrease in SpO_2 of ≥4% and/or arousal. The apnea/hypopnea index (AHI) was defined as the number of apneas and hypopneas per hour of TST, and considered abnormal if greater than 2/hr TST. The mean oxygen saturation, as measured by pulse oximetry (SpO2), together with SpO2 nadir, were determined, and considered abnormal if <95% and <92%, respectively. The mean and peak end-tidal carbon dioxide tension ($P_{ET}CO2$) were determined, and defined as abnormal if >48 and >53 mmHg, respectively. While criteria for arousal have not yet been developed for children, arousals were defined for other ages (e.g. Bonnet et al., 1992) and include respiratory-related (occurring immediately following an apnea, hypopnea or snore), technician-induced and spontaneous arousals. Arousals were expressed as the total number of arousals per hour of sleep time (Arousal Index). Periodic leg movements (PLM) during sleep were scored if there were at least 4 movements of 0.5 to 5 seconds duration, and between 5 and 90 seconds apart. A PLM index of ≥5 per hour of sleep is generally considered as exceeding the normal range in children. Any of the above abnormal findings on polysomnography led to exclusion from the study.

ERP Measures. Recordings of brain electrical activity (stimulus or task relevant event-related potentials – ERPs) were used to investigate the brain's role in cognitive processing preceeding and following sleep restriction. Although the ERP is a portion of the ongoing brain's electroencephalography (EEG) activity, it is distinct from the EEG because it is repeatedly time-locked to the onset of a stimulus (e.g., sound, picture) presentation. The notion of time-locking refers to recording only the part of an EEG wave that immediately follows the onset of the stimulus in time. Repetition refers to recording and combining ERPs to multiple repetitions of the same stimulus in order to average out random and non-stimulus related background electrical activity that is inherent in the ongoing EEG. ERPs have advantages over other sleep assessments because they reflect subtle physiological and behavioral changes that otherwise go unnoticed. ERPs also can be obtained more easily and faster than some other sleep-related measures. Furthermore, ERPs can be useful in documenting neural dysfunction associated with sleep problems, evaluating treatment efficiency, and possibly determining causes of daytime sleepiness in patients with sleep problems.

Throughout the ERP studies described below, results focus on sleep and stimulus related effects. Effects related only to ERP differences between various scalp regions are not described except to allow comparisons with previous child based ERP studies so that the comparability of brain processing to prior research can be assessed.

Procedures

Following all the screening phases, a two-week block was identified for testing all participants. During the first week, participants were requested to align their sleep/wake times to a 9:00 pm bedtime and 7:00 am wake-up time (Control) schedule, while avoiding naps, medications, caffeine, or any other psychoactive substances. This specific schedule was chosen because it represented the most commonly reported sleep/wake times for this

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age group. Parents were instructed to maintain daily sleep log and report any changes in the child's sleep/wake schedule. At end of the week (Saturday), children came to the laboratory in the morning between 9:30 am and Noon for the ERP and cognitive performance tests. For the following week, children underwent sleep restriction by delaying their scheduled bedtime by 1 hour (i.e., 10:00 pm). At the end of the sleep restriction week (Saturday), children returned to the laboratory for the second ERP and behavioral tasks session. Testing on this day was scheduled at the same time in the morning as during the first week. As described below, each week each child was tested on three tasks, with a different test order employed each week for each child. Rest periods of approximately 5 to 10 minutes occurred between tasks.

Sleep schedule verification (Actigraphy)

During the two consecutive weeks when the baseline control and sleep reduction protocols occurred, children wore a wrist actigraph on their non-dominant hand to measure their activity levels. The Actiwatch (MiniMitter Actiwatch® -64 Co, Inc, 1998– 2003, version 3.4) is a 28 × 27 × 10 mm device weighing 17.5 g. The watch-size device provided continuous activity data with little interference imposed on the child. Epoch registration of activity counts by the actigraph are determined by comparison, ie, counts for the epoch in question and those immediately surrounding that epoch are weighted with a threshold sensitivity value (activity count) that was originally set at 40 (activity 40, default, being medium sensitivity). The score = E - 2*(1/25) + E − 1*(1/5) + E0 + E + 1*(1/5) + E + 2*(1/25), with En being activity counts for the epoch and E0 being the scored epoch. Activity counts that were equal to or below the threshold sensitivity value were scored as “sleep”, whereas they were considered as “awake” when exceeding the threshold sensitivity value. The activity-sleep interval was manually marked for each record, based on sleep log bedtime and risetime. The activity parameter of interest was total sleep time by activity, representing the amount of time between sleep start and sleep end, scored as “sleep”. Sleep start and sleep end were determined automatically as the first 10-minute period in which no more than one epoch (one minute) was scored as mobile, and likewise for the last 10-minute period, respectively. The activity algorithm enabled summation of the number of epochs that did not exceed the threshold sensitivity value, and therefore provided individual total sleep time for each night of recording. Thoughout the two week period of the study, parents maintained a sleep log for their child that recorded the time that their child was put to bed and the time that the parents woke the child in the morning. In addition, parents were instructed to mark on the sleep log when the device was taken off and why (for example “went swimming from 6 pm to 7 pm”), and parents were instructed to have their children wear the device continuously during the day except when at risk of getting wet. Validation studies indicate high agreement rates (above 90 percent) between actigraph-based and polysomnographic-based sleep/wake scoring (Dayyat, Spruyt, Molfese, & Gozal, 2011). Actigraph data were downloaded during the two weekly laboratory visits.

Experiment 1 - Odd-Ball task

The “oddball” or “P300” task is frequently used in tests of sleep restriction, deprivation and sleep apnea (e.g. Cote, et al., 2008; Gosselin, de Koninck, & Campbell, 2005; Lee et al.,

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2004). The inclusion of this task in the present investigation provided an important link to prior ERP-sleep studies that employed this paradigm. In general, the task engages attention and generates changes in brain activity across the scalp, especially at central and parietal sites.

Stimuli

Two pure tones (1000 and 1500 Hz) served as stimuli. Tone duration was 300 ms. Tone frequency (i.e., high vs. low) was used to denote the infrequent and frequent stimuli. Tone frequency and its assignment to the infrequent condition were counterbalanced across children and test days. Rise and decay times were the same across stimuli. Auditory stimuli were matched in loudness levels, 75 dB SPL(A) as measured at the ear, and presented through a speaker centered 1 meter over the center (Cz) of the child's head and equidistant from each ear.

Procedures

Each child was instructed that they would hear a series of tones. One tone occurred on 70% of the trials and was intermixed randomly with a second tone that occurred on 30% of the trials. Children were instructed to press one key when the frequent tone occurred and a second key to the infrequently occurring tone. Behavioral responses to both tones were sought in order to lower the likelihood of muscle artifacts differentially affecting the ERPs if the child responded to only one stimulus type. While the entire paradgim included 100 trials with more frequent than infrequest tone presentations, data analyses compared ERPs to an equal number of frequent and infrequent tones using the rule that ERPs to the infrequent tones were selected for analysis if they immediately occurred after a frequent tone. In contrast, ERPs to the frequent tones were selected for analysis if they immediately occurred before an infrequent tone. Thus, the two tones occurred closely in time as a further attempt to limit differential extra-experimental effects that might occur across the testing period. Responses of the children were recorded on-line using Net Station software. Analyses indicated a high level of accuracy for both groups of children (>90%) for both days of testing. On average, mean task duration was 9.5 ± 2.3 minutes across children.

Experiment 2 - Speech Perception Task

ERPs to speech sounds change across development and relate to the acquisition of later cognitive skills such as reading (Molfese, 2000). The speech perception task was selected because it employed stimuli known to produce reliable and specific changes in the ERP waveforms of children over temporal and parietal scalp location, and contain elements that were predictive of concurrent and later performance on language and reading tasks (Molfese & Molfese, 1985; Molfese & Molfese, 1997). Based on our earlier published studies, it was expected that peak latencies occurring around 200 ms, 330 ms, 450 ms would be identified and these peak latencies would vary based on differences in sleep duration.

Stimuli

Six computer generated synthetic consonant-vowel (CV) syllables (ba, da, ga, bu, du, gu) were presented in a blocked random order with 25 repetitions of each, separated by an inter-

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stimulus interval that varied randomly from 2.0 to 4.0 seconds. The varied ISI and stimulus orders were used to reduce or eliminate habituation and expectation effects. Stimulus duration (300 ms), formant number (3), rise and decay times all were identical across stimuli. Auditory stimuli were matched in loudness levels (75 dB SPL(A) as measured at the ear) and presented through a speaker positioned 1 meter over the midline of the child's head (Cz) and equidistant from each ear.

Procedure

Children were instructed to listen to the speech syllables and report the names of the different syllables at the end of the testing session. Average task duration was 10.5 ± 2.4 minutes.

Experiment 3 - Directional Stroop Task

The Stroop Color Naming Test (Stroop, 1935) has been used extensively to examine the relationship between cognitive performance and brain measures. There is substantial literature on the use of this task to investigate frontal lobe functions in adults and children (Diamond, 2002; Duncan-Johnson & Kopell, 1981). In contrast to the odd-ball/P300 task that requires individuals to attend to infrequent stimuli, the Stroop task places increased demands on participants, requiring them both to attend and inhibit intrusive responses. Thus, when presented with a color name – “RED” – that is printed in another color such as green - participants must inhibit reading the word while naming the color of the print. Although prior work suggested that adult performance on Stroop-like tasks is not affected by sleep restriction (Binks, Waters, & Hurry, 1999; Sagaspe et al., 2006), it is not known whether children maintain their performance on this task following sleep restriction. A recent innovation, the Directional Stroop Task is a variation of the classic task and is designed for young children with few reading skills. Importantly, this task controls for task difficulty, posing the same level of difficulty for children between 4 and 11 years of age. Diamond and her colleagues successfully used the Directional Stroop Task with 4-year olds (Davidson et al., 1999). She hypothesized that the Directional Stroop Task allows demands on holding information and on inhibition to be independently varied. The task has 3 conditions. In the Congruent condition the child must press a button on the same side of the display that a stimulus appears (e.g., a gray circle presented on the right side of the screen requires pressing the right button) while in the Incongruent condition they must press a button on the opposite side of the display when they view a different stimulus (e.g., a striped circle on the right side of the screen requires pressing a button on the left). The Mixed condition involves randomly ordered presentations of Congruent and Incongruent trials. Diamond argues that the Mixed condition is more difficult than the other two conditions because it requires the child to change their response strategy from trial to trial instead of choosing one consistent response type within the block of trials. In fact Diamond found that children from 4 through 11 years made more errors in the Mixed condition than on the Incongruent or Congruent conditions. However, even though errors differed across conditions, error rates and reaction times remained relatively constant across ages, with errors varying 18% to 30% between 4 and 11 years and latency of responding varying less than 100 ms. These findings support Diamond's model that the task is equally difficult across preschool and elementary school

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ages. Because there are no published ERP studies with children involving the Directional Stroop task, no specific amplitude or latency effects could be hypothesized.

Stimuli

A solid gray circle and a white circle containing vertical black stripes presented on the white background to the left or right of the fixation point.

Procedure

Each child was seated in front of a 17” computer screen at a distance of 1 meter, and then viewed a series of gray or striped circles on the computer screen. The child was instructed to press a key every time a stimulus was presented on the screen. The gray circles required a button press on the same side (Congruent Task, 30 trials). The striped circles required a button press on the opposite side (Incongruent Task, 30 trials). The order of these tasks was counterbalanced across children and testing sessions. Following Diamond's procedures, the Mixed block (60 trials) was always presented last. The Mixed block included both gray and striped circles presented in random order and required a switch button presses (same or opposite side) depending on the stimulus presented. For all trial blocks, each trial began with a 1000-ms presentation of a plus sign that serves as a fixation point followed by a gray or striped circle presented for 2000 ms to the left or right of the fixation point. All stimuli were presented on each side an equal number of times. The intertrial interval varied randomly between 1800 ms and 2800 ms to prevent habituation. Trial blocks were separated by 20-second breaks during which block-specific instructions were repeated. Average task duration was 15.4 ± 2.7 minutes.

Across all three tasks, a researcher was seated in the test room to the side of the screen to assess the child's gaze at the monitor and redirect their attention, if necessary, to the center of the screen. Prior to the test, children completed a practice session to familiarize them with each task. The practice trials were terminated after each child demonstrated full understanding of the procedures (as indicated by exceeding the threshold of 80% correct responses).

Results

All 6 participants had normal polysomnographic characteristics with no somnography evidence of snoring, periodic leg movements, or disrupted sleep architecture. Actigraphic recordings revealed that the mean duration of daily sleep during the Control condition was 9.3 ± 0.6 hours and 8.4 ± 0.5 hours during the Restriction condition. The mean daily reduction in average sleep duration during the restriction week was 43.6 ± 2.8 min.

Experiment 1 – Odd-Ball Task

Following artifact rejection, the single trial data were re-referenced to a calculated average reference and then averaged separately for each of the 128 electrode sites, each of the two sleep conditions (Control, Restricted), and each of the two tones (frequent, infrequent). In this manner, 512 averages were obtained for each child resulting in a total of 3,072 averaged ERPs collected from the six children.

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The data were next submitted to a two-step analysis procedure that first involved the use of a principal components analysis (PCA) followed by an overall MANOVA and then a set of univariate ANOVAs conducted separately on the component scores calculated for each principal component. Although there are a variety of different analysis procedures that could be used to analyze ERPs data (Coles, Cratton, Kramer, & Miller, 1986, pp. 196-198), a decision was made to utilize a multivariate approach that produced consistent results in programmatic research across a number of laboratories (Brown, Marsh, & Smith, 1979; Chapman, McGrary, Bragdon, & Chapman, 1979; Donchin, Tueting, Ritter, Kutas, & Heffley, 1975; Molfese, Molfese, & Pratt, 2007). For example, Molfese, in a series of articles investigating speech perception cues such as voice onset time and place of articulation, noted consistent systematic effects across studies for each cue (Molfese, 1978; Molfese, 1980; Molfese & Schmidt, 1983). Moreover these effects were independently replicated using comparable analysis procedures (Gelfer, 1987; Segalowitz & Cohen, 1989). The rationale for the use of the PCA procedure is that it has proven successful in identifying temporal intervals of the ERPs where most of the variability occurred across subjects and ERPs. In this way the procedure offers a more parsimonious description of the data, by reducing the original set of measures (ERPs time points) to a limited set of more "meaningful" and informative principal components. The PCA procedure itself is blind to experimental conditions and generates the same solutions regardless of the order in which the ERPs are entered. The option of a correlation matrix was selected for the PCA routine. With this method centroid amplitude values for each time-point were first subtracted from the corresponding values of each average ERPs. These deviation scores were then normalized by dividing by their respective standard deviation. Thus, variability due to differences among the time-points with respect to the grand-mean, as well as standard deviation, were first extracted before the application of the PCA (Donchin & Heffley, 1978). Once the PCA identified where within the ERPs most of the variability occurred, the MANOVA was used to identify the overall sources of this variability. The MANOVA accomplished this task by determining whether the variability reflected in the component scores assigned across factors for each component differed as a function of changes in manipulated variables. Subsequently, separate ANOVAs determined whether the variability reflected in the component scores assigned for each component to each averaged ERPs differed as a function of changes in the auditory and visual stimuli. This procedure directly addressed the question of whether the ERPs waveshapes in the region characterized by the most variability for any one component changed systematically in response to sleep conditions or stimulus/task conditions recorded from the different electrode sites over each hemisphere.

Experiment 1 – P300 Task Analysis

This analysis design involved a Sleep Condition (2: Control, Restricted) × Stimulus Frequency (2: Frequent, Infrequent) × Electrode Regions (5: Frontal, Central, Temporal, Parietal, Occipital) × Hemisphere (2: Left, Right). Analyses of the P300 region (Fig. 1, peak latency = 284 ms; 23.19% of the total variance) yielded a Sleep × Electrode × Hemisphere interaction, $F(4,20) = 5.45$, $p<.0004$ [observed power = .931]. A two-tailed test of the interaction indicated that the left temporal-parietal electrode sites responded differentially

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between the Control and Sleep Restriction conditions, t(5) = 2.6, p<.05, where ERPs following sleep restriction had smaller amplitudes compared to those recorded after the baseline sleep period. This effect is illustrated in the plot of the group averaged ERPs presented in Figs. 1 and 2 that were elicited to the “frequent” (black line) and “infrequent” (blue line) tones presented during the “Odd-Ball” Task from children in the Control condition at the end of week 1 when they slept 10 hours on average each night. For Figs 1 and 2, the ERPs recorded from the frontal electrode scalp regions are represented at the top of the figure, the ERPs recorded from temporal regions on the sides, and ERPs recorded from the occipital area displayed at the bottom of the figure. Left hemisphere electrode sites are displayed on the left of each topographic representation. An examination of the topographic maps (Fig. 3) illustrates that compared to Control condition, the Restricted condition (that is displayed to the right of the calibration bar) was characterized by lower activity levels over posterior and frontal sites.

Experiment 2 - Speech Perception Task Analysis

This analysis approach was modeled after that used for Experiment 1. The analysis design included a Sleep Condition (2: Control, Restricted) × Consonant (3: /b, d, g/) × Vowel (2: /a, u/) × Electrode Region (5: Frontal, Central, Temporal, Temporal/Parietal, Occipital) × Hemisphere (2: Left, Right) analysis of variance. Following artifact rejection and re-referencing, ERPs were averaged separately for each of the 128 electrode sites and each of the six stimulus speech sounds. In this manner, 768 averages were obtained for each child resulting in a total of 4,608 averaged ERPs from the six children.

Three distinct tempral variations in the ERP waveforms occurred as a function of sleep restriction at different latencies. For the temporal region of the ERPs between 164 and 300 ms (peak latency = 208 ms), a main effect for Sleep Condition, F(1,5) = 29.046, p<.003, and a Sleep × Electrode interaction, F(4,20) = 12.83, p<.001, [observed power = 1.0] accounted for 12.5% of the total variance. An examination of the Sleep × Electrode interaction indicated that marked differences occurred between the Control and Restricted conditions at Central, t(5) = −16.4, p<.00001, Temporal, t(5) = 3.98, p<.011, Parietal, t(5) = 3.35, p<.02, and Occipital, t(5) = 8.98, p<.001, electrode sites (2-tailed tests). These effects are illustrated in the topographic display of Fig. 4a. A greater amplitude and larger area positive voltage occurred over the central scalp area while a more negative voltage was noted over temporal regions during the Restricted condition (displayed to the right of the calibration bar). In contrast, more positivity was noted at parietal and occipital sites (posterior or bottom portions of the topomap displayed to the left of the calibration bar) during the Control condition.

Analyses of ERPs at 324 ms (range: 268 to 436 ms), identified a Main effect for Sleep, F(1,5) = 29.77, p<.003, and a Sleep × Electrode interaction, F(4,20) = 17.08, p<.001 [observed power = 1.0]. The Sleep × Electrode interaction (accounting for 14.4% of the total variance) resulted from differences in this temporal window between the Control and Restricted conditions at Frontal, t(5)= −4.75, p<.005, Temporal, t(5)=8.61, p<.001, Parietal, t(5)=3.49, p<.017, and Occipital electrode sites, t(5)=3.28, p<.022 (2-tailed tests). This effect is evidenced in Fig. 4b by the increased negativity at frontal (top) sites for the Control

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condition while the Restricted condition displayed less negative amplituds as illustrated to the right of the calibration bar. The temporal, parietal, and occipital areas all generate more positive voltages (red/yellow) for the Control condition while these responses appear to be reduced to baseline levels (indicated by the purple color) for the Restricted condition.

A third region of the ERPs also differed as a function of variations in the Sleep Condition. Peaking at 452 ms (range: 412 – 484 ms), a Sleep × Electrode interaction, $F(4,20)=5.03$, $p<.006$, [Observed Power = .91] accounted for 4.5% of the total variance, reflected marked differences between Control and Restricted conditions at Parietal, $t(5)= -3.078$, $p<.028$, and Occipital electrode sites, $t(5)= -2.952$, $p<.023$ (2-tailed tests). As illustrated in Fig. 4c, the parietal sites for the Control condition (left side of the calibration bar) appear to generate more positive voltages (yellow) in contrast to the lower positive levels noted for the Restricted condition. During the Control condition the occipital sites decreased to baseline voltages (purple) over occipital sites at this latency while voltages appear more positive during the Restricted condition. Similar to the ERP effects at 324 ms illustrated in Fig. 4b, voltage levels are more clearly demarcated for the Control condition than for the Restricted condition.

Experiment 3 - Directional Stroop Task

As was the case in Experiment 2, the analysis approach was modeled after that used for Experiment 1. The analysis design employed was based upon a Sleep Condition (2: Control, Restricted) × Response Type (2: Congruent, Incongruent) × Trials Blocks (2: Single vs. Mixed Condition) × Electrode Region (5: Frontal, Central, Temporal, Temporal/Parietal, Occipital) × Hemisphere (2: Left, Right) analysis of variance. Following artifact rejection and re-referencing, ERPs were averaged separately for each of the 128 electrode sites. In this manner, 10,240 averages were obtained for each child resulting in a total of 61,440 averaged ERPs obtained from the six children.

A portion of the ERP that characterized the late slow positive wave between 524 and 700 ms (peak = 668 ms) varied as a function of Sleep condition. A Sleep × Trial Block × Electrode Region × Hemisphere interaction, $F(4,20) = 4.16$, $p<.013$, [observed power = .84] resulted from reduction in activity over the right hemisphere parietal sites from the Control to Restricted conditions during the Congruent trials, $t(5) = 3.23$, $p<.023$. The effect was also noted between left and right hemisphere occipital sites, $t(5) = 3.24$, $p<.018$. A Sleep × Response Type × Electrode × Hemisphere interaction, $F(4,20) = 5.39$, $p<.004$, [observed power = .93] was also noted that resulted from differences in the ERPs elicited during the Control vs. the Restricted conditions over left temporal, $t(5) = 3.12$, $p<.026$, left parietal, $t(5) = 5.1$, $p<.004$, and right parietal, $t(5) = 4.31$, $p<.008$, electrode sites when stimuli were presented in the Incongruent trials (2-tailed tests). As indicated in Fig. 5, these effects can be seen as increased negativity (as indicated by dark blue) at left temporal, parietal and occipital sites (all at the bottom of the Fig. 5, to the left of the calibration bar) for the Control in contrast to the Restricted condition that is displayed to the right of the calibration bar. During this time period, nearly all of the electrical activity elicited during the Restricted condition appears to be at baseline levels (as characterized by the purple color).

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Discussion

The purpose of this preliminary study was to investigate the effects of a one hour sleep restriction for the same young children on different cognitive tasks. Changes in brain responses recorded during the performance on three cognitive tasks – “odd-ball”, speech perception and Directional Stroop - were analyzed by comparing the children's ERP responses following one-week with 9:00 pm bedtime and 7:00 am wake-up time (Control) compared to a one-week restricted sleep condition where bedtime schedules were delayed by 1 hour (i.e., 10:00 pm). Overall, the pattern of ERP activation showed responsivity across temporal, parietal and occipital electrode sites that were distinctly different for all tasks when recorded following the Control Sleep week compared to the ERPs recorded following the week of Sleep Restriction.

The major effect noted for the “odd-ball” task corresponded to changes in the third positive peak in the ERP waveform. Consistent with prior studies on sleep deprivation in adults (Rumbach et al., 1991, Kingshott et al., 2000), the P300 amplitude was markedly reduced following the Restricted Sleep condition compared to that recorded after the Control condition.

For the speech perception task similar differences between the Control and Restricted Sleep conditions were noted but at three different peak latencies (208 ms, 324 ms, 452 ms). The ERPs recorded following the Restricted condition was characterized by more baseline activity levels at all scalp locations while the Control condition elicited larger amplitude positive and negative ERP peak responses at all scalp locations.

Although the speech perception task has not been used previously to assess the impact of sleep reduction or sleep disturbances in children or adults, our present findings are consistent with those from a recent study of children with preclinical levels of sleep-disordered breating (Key, Molfse, O'Brien, & Gozal, 2009), where an increase in the amplitude of the N1/P2 responses to speech sounds were associated with more interrupted sleep due to an increase in the number of apnea episodes. This finding is also in line with a report by O'Brien et al (2003) that 1st grade children characterized with sleep-disordered breathing, which is known to distrupt the quantity and quality of sleep, performed more poorly than children without sleep-disordered breathing on a test of phonological processing. Phonological processing is an important skill known to be related to both language acquisition as well as to the acquisition of reading skills. That even short-term sleep restriction can impact a simple speech perception task is an important finding with implications for the acquisition of critical cognitive and academic skills.

The pattern of sleep-related changes in activation present in the “odd-ball” and speech perception tasks also characterizes brain activation observed during the Directional Stroop Task. Differences between Control and Restricted Sleep conditions occurred when children performed the Mixed condition of the Diretional Stroop task. This is the most difficult condition and the one identified by Diamond as tapping attention and inhibition mechanisms. Areas of activation varied across temporal, parietal and occipital scalp locations during the Control Sleep condition. However, following the Restriction condition

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the scalp locations displayed baseline levels of activity, with little positive or negative voltage shifts. The time interval of observed sleep-related differences is consistent with the P600 response reflecting memory processes (e.g., Curran & Cleary, 2003), suggesting that after Restricted sleep, children had more difficulty recalling two task response rules (relating side of response to the color of the stimulus), despite the overall greater familiarity with the task.

Across all three tasks, the most marked changes were the noticeable reductions in ERP amplitudes found for the Restricted condition. This finding can be interpreted to indicate that a marked decrease in brain processing is related to sleep restriction and is particularly identifiable on tasks with high processing demands .

Major portions of the scalp displayed little variation from baseline at any point in time or for any scalp location following the Restricted condition in contrast to the noted variability across time over temporal, parietal and occipital sites during the Control sleep condition. Such findings suggest that brain processing is less than optimal during periods of even minor sleep reduction. Mild sleep restriction procedures employed in the prsent study may mimic conditions frequently occurring in real life and appear to impose substantial alterations in brain responses on a variety of cognitive tasks. The long-term implications of sleep restriction on synaptic organization and function during critical periods of brain development are currently unknown. However, the present findings provide initial insights and a major impetus to investigate this important topic further.

There are several notable limitations for the present study. First, all children experienced the two different sleep conditions in the same order. A baseline sleep time of 10 hours per night was first established for all children and the ERPs recorded across the three tasks one week later. This condition was always followed by a one week periood of sleep restriction which were then followed by ERP recordings during task performace. It is possible, therefore, that the present results could be influenced by our failure to counterbalance condition order across the participants. Nevertheless, as noted above, the findings are consistent with other published reports of ERP and behavioral changes that accompany reductions in sleep time, at least for those tasks on which ERP studies involving children have been reported. A second concern involves the number of participants. The sample is a small one with only six children and all participants were males. Only male participants were included in this preliminary study as a control for gender differences that are reliably noted in ERP studies. A replication involving a larger sample with both genders would increase one's confidence in the study outcomes and the findings would better generalize to a larger population. Nevertheless, as indicated, there was sufficient statistical power to provide a reasonable level of confidence in the reported results for this population.

In spite of these limitations, the current study findings fit well with earlier studies suggestive the association between sleep quantity and quality and “executive dysfunction”, resulting in maladaptive daytime behavior, and reduced academic performance (Beebe & Gozal, 2002; Gozal & Pope, 2001; O'Brien et al., 2003). Clearly the pattern of brain processing across tasks was significantly altered and altered in similar ways across tasks. The overall reduction in processing and processing organization suggest that the brain was not operating as

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efficiently in children with even 1-hour of reduced sleep over a period of one week. Given that these data were collected from children at the beginning of the formal educational process, one wonders about the effects that both brain maturation processes and episodes of sleep restriction may play in impacting the PFC and the impact of sleep loss on this important brain region and cognitive performance in school. Children with even slightly reduced sleep time may have less than optimal brain resources available to master classroom instructional material, thereby reducing their chances of achievement and advancement.

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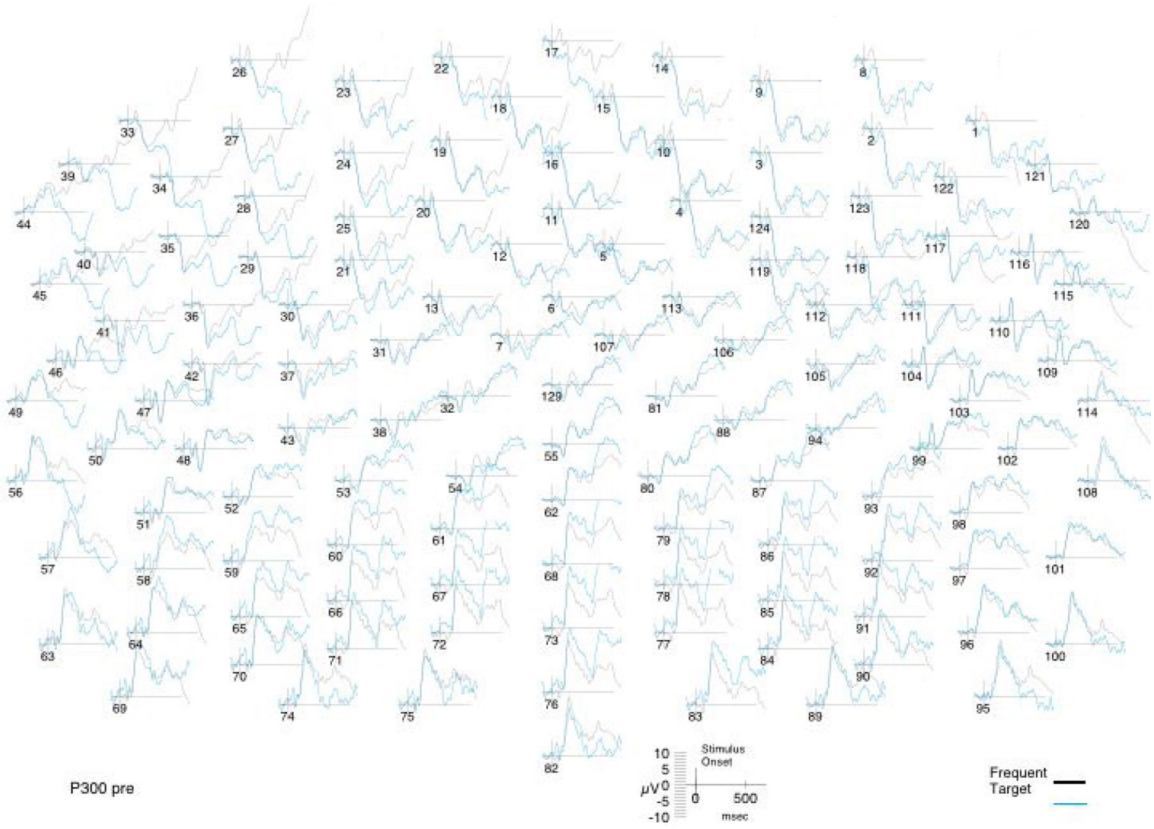

Figure 1.

ERP waveforms elicited to the “frequent” (black line) and “infrequent” (blue line) tones presented during the “Odd-Ball” Task from children in the Control condition at the end of a week with night sleep times beginning at 9 PM and ending at 7 AM. Note the larger third peak (“P300”) responses over midline central and central-parietal scalp locations. The calibration bar is +/−10 μV. ERP duration is 800 ms that includes a 100 ms pre-stimulus period and the 700 ms post stimulus onset period.

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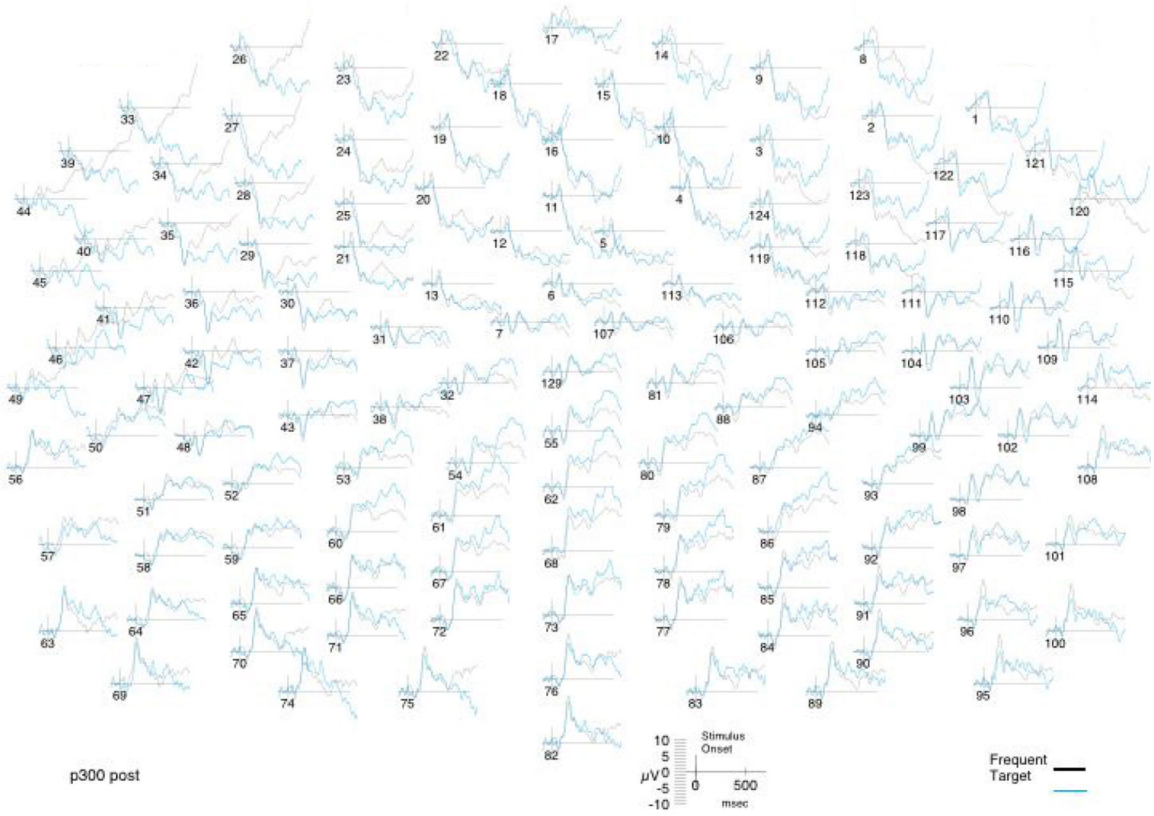

Figure 2.

ERP waveforms elicited to the “frequent” (black line) and “infrequent” (blue line) tones presented during the “Odd-Ball” Task from children in the 1-hour Restriction condition at the end of a week where sleep times began at 10 PM and ended at 7 AM. Calibration bar is +/−10 μV. ERP duration is 800 ms that includes a 100 ms pre-stimulus period and the 700 ms post stimulus onset period.

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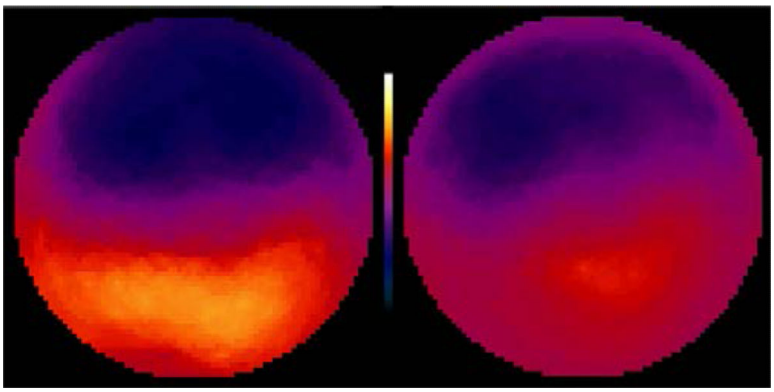

Figure 3.

The figure depicts the scalp topography exactly 284 ms following stimulus onset for children during the “Odd-Ball” Task before (left picture) and after (right) implementation of the 1-hour Sleep Restriction week. For this and the following figures. The top of each oval depicts scalp currents recorded over frontal regions, the left side of the oval reflects activity recorded over the left temporal area, and the bottom of the oval depicts activity levels recorded over occipital electrode sites. The Color variations reflect amplitude variations in the ERP waveforms. As ERP amplitude increases above baseline (purple), colors change from red to yellow to white. Negative going waves below baseline change from blue to black. The x-y plot of the ERP waveform to the right of the topographic displays illustrates the relation between positive-negative amplitude variations in the ERP waveform and the color patterns used in the topographic displays. Note more baseline activity (purple) and less focused negativity over frontal-central areas for reduced sleep condition. The calibration bar positioned between the Control and Reduced scalp topographies is 28 μV.

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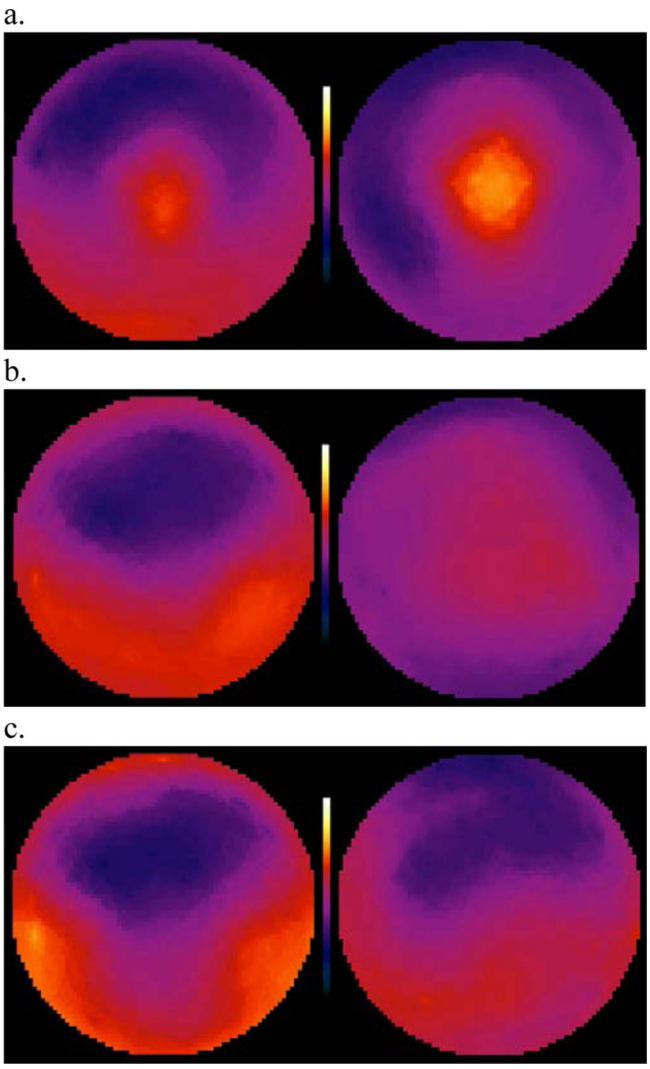

Figure 4.

Scalp topographic displays for children during the Speech Perception Task before (left picture) and after (right) 1 week of Sleep Restriction. The vertical color calibration bar is 21 μV for all figures.

(a) At 208 ms note the increase in positive amplitudes over central scalp, the larger extent of baseline activity (purple) across the scalp and asymmetrical negativity greater over left hemisphere frontal areas for the reduced sleep condition relative to the Control.

(b) At 324 ms note that there is evidence of more baseline activity (purple) and less clearly defined positivity over central regions for children during the reduced sleep condition relative to the Control. Calibration bar is 21 μV.

(c) At 452 note that during the Control Sleep condition (left picture) there was clear bilateral positivity at lateral temporal-parietal areas and negativity over central frontal areas with somewhat decreased negativity extending back to occipital areas. In contrast, during the reduced sleep condition (right), there was less clearly demarcated front negativity and less localized positivity occur over parietal areas.

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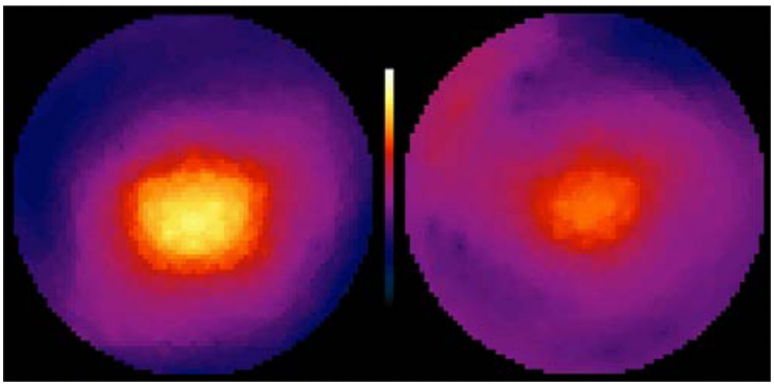

Figure 5.

Scalp topographies at 668 ms for children during Directional Stroop Task before (left picture) and after (right) 1 week of Sleep Restriction. Note more baseline activity (purple) and less focused negativity across the scalp during the reduced sleep condition. Calibration bar is 32 μV.