The Association Between Sleep and Dual-Task Performance in Preterm and Full-Term Children: An Exploratory Study

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Abstract

Objectives: The present study explored associations between sleep and children's dual-task performance using cognitive-motor dual tasks (e.g., walking and talking). Previous research with older adults indicated correlations between higher gait variability and unfavorable sleep continuity variables. Based on this research, as a first aim, we investigated similar correlations in a sample of children. Second, we explored correlations between dual-task performance and dimensions of sleep architecture. Third, we tested moderating effects of prematurity on these associations.

Methods: Seven- to 12-year-old children were tested within dual-task situations; of those, 39 were formerly very preterm and 59 were full-term born children. They were asked to simultaneously walk and perform different cognitive tasks. Gait was measured using an electronic walkway system. Sleep was measured using in-home sleep-electroencephalography.

Results: After accounting for age and cognition, regression analyses revealed correlations between a higher number of awakenings after sleep onset and lower dual-task performance. With respect to sleep architecture, analyses yielded correlations between a higher amount of rapid-eye-movement (REM) sleep and lower gait variability. Furthermore, associations between a higher amount of slow wave sleep (SWS) and children's higher cognitive performance were found. Moderation analyses indicated no effects of prematurity.

Conclusions: Our exploratory study suggests that a more disrupted sleep was related to children's poorer dual-task performance. Importantly, our findings support claims that REM sleep seems more related to performance in procedural tasks whereas SWS seems more related to performance in declarative tasks, indicating that different sleep stages may support the processing of different performance types.

Keywords: sleep, polysomnography, gait, dual task, prematurity

Highlights

- Correlations between children’s sleep and dual-task performance were investigated.
- A higher amount of REM sleep was correlated to children’s lower gait variability.
- A higher amount of SWS was associated with children’s higher cognitive performance.
- Prematurity did not moderate these associations.

The Association Between Sleep and Dual-Task Performance in Preterm and Full-Term Children: An Exploratory Study

1. Introduction

Decades of research investigating the functions of sleep have shown that sleep is fundamental for children's well-being, psychological functioning, and cognitive abilities (Astill, Van der Heijden, Van Ijzendoorn, & Van Someren, 2012; Brand et al., 2015; Dewald, Meijer, Oort, Kerkhof, & Bogels, 2010). One set of skills that is particularly affected by short and poor sleep is children's attention skills and executive functioning (Astill et al., 2012; Dahl, 1996; Keshavarzi et al., 2014; Paavonen et al., 2010). This association between sleep and executive functioning has been shown using a wide range of methodological approaches. For example, using an experimental approach, it was found that sleep restriction resulted in higher rates of behavioral inattention in 8- to 15-year-olds (Fallone, Acebo, Arnedt, Seifer, & Carskadon, 2001). Correlational evidence came for instance from studies indicating that more awakenings after sleep onset and wake-after-sleep-onset (WASO) time were related to decreased executive functioning in children (Kuula et al., 2015; Sadeh, Gruber, & Raviv, 2002). Overall, based on 19 studies, a meta-analysis from Astill et al. (2012) showed that sleep duration was substantially related to executive functioning while no correlations were found with sleep efficiency.

Executive functioning is critical for children's social, cognitive, and psychological development in general (Diamond, 2013) and for motor functions such as gait in particular (Woollacott & Shumway-Cook, 2002). This influence of executive functioning on gait has been assessed using dual-task paradigms (Schneider & Chein, 2003). In such a paradigm, participants are asked to simultaneously walk and perform a cognitive task. Such dual-task situations are an integral part of children's daily life when, for example, they walk and pay attention to a busy traffic intersection or when they walk and already think about their homework. Given that the pool of cognitive resources is limited (Kahneman, 1973;

Wickens, 1991), such situations result in performance reductions when both tasks are challenging and compete for resources. In line with this conclusion, developmental research has shown that children’s gait is affected by concurrent tasks in that children walked more slowly and with higher gait variability (Abbruzzese et al., 2014; Hagmann-von Arx, Manicolo, Lemola, & Grob, 2016).

Given that lower executive functioning seems related to poor sleep and to impaired motor skills such as gait, it seems likely that poor sleep may also be associated with children’s gait impairments in dual-task situations. The few studies that have examined this link so far found evidence for such an association in older adults. Using a dual-task paradigm in which older adults were asked to simultaneously walk and subtract numbers, it was found that poor sleep was related to higher gait variability (Agmon, Shochat, & Kizony, 2016) and thus, to a higher risk to fall (Lundin-Olsson, Nyberg, & Gustafson, 1997). In particular, adults’ lower sleep efficiency (SE, i.e., the proportion of time spent in bed asleep relative to the total time spent in bed) and longer sleep onset latency (SOL, i.e., the time from going to bed until falling asleep) were related to higher stride-length variability in the dual-task situation. In line with these findings, other studies indicated that lower SE and shorter total sleep time (TST) were risk factors for falling in a sample of older women (Stone, Ensrud, & Ancoli-Israel, 2008). Furthermore, treatments of sleep apnea improved older adults’ gait regularity (Allali et al., 2014).

In sum, these studies indicated that sleep was related to older adults’ gait performance in dual-task situations. However, the question remains whether similar associations between sleep and dual-task performance also exist earlier in development. As sleep characteristics in children are inherently different from those in adults (Ohayon, Carskadon, Guilleminault, & Vitiello, 2004), it is difficult to generalize these findings from older adults to children. Furthermore, even though children face several dual-task situations in their daily life, influencing factors such as sleep on their ability to cope with these situations remain poorly understood. The present study aimed to fill this gap by examining whether children's sleep was associated with their gait and cognitive performance under dual-task conditions. To this end, we assessed children's gait and sleep objectively using an electronic walkway system and in-home sleep-electroencephalography (EEG).

A different line of research investigated effects of developmental risks such as prematurity for children's sleep, executive functioning, and their motor skills. These studies have indicated that children born very preterm (i.e., being born before 32 weeks of gestation) are at risk for suffering from poor sleep (Hagmann-von Arx et al., 2014; Perkinson-Gloor et al., 2015b) and decreased executive functioning (for a meta-analysis, cf. Aarnoudse-Moens, Weisglas-Kuperus, van Goudoever, & Oosterlaan, 2009). Furthermore, being born very preterm has been associated with a number of motor impairments (for an overview, see de Kieviet, Piek, Aarnoudse-Moens, & Oosterlaan, 2009), ranging from later onsets of independent walking (Jeng et al., 2008; Nuysink et al., 2013), to higher variability in children's gait (Hagmann-von Arx et al., 2015), to more motor coordination problems (Goyen & Lui, 2009). In addition, it was found that correlations between sleep and cognitive skills seemed to be stronger in very preterm children as opposed to typically developing children (Hagmann-von Arx et al., 2014), indicating that prematurity is an important moderating factor. Considering these latter findings, it is possible that associations between sleep and gait impairments in dual tasks are similarly moderated by prematurity; however, no study has investigated this question to date.

Based on this theoretical background, the aims of the current study were three-fold. First, we investigated correlations between children's indicators of their sleep continuity and their dual-task performance. In accordance to previous literature (Agmon et al., 2016; Stone et al., 2008), we hypothesized that unfavorable sleep continuity variables such as shorter TST, lower SE, and longer SOL are associated with children's higher gait variability in the dual task. Second, we explored correlations that have – to our knowledge - never been investigated so far. That is, we tested associations between dual tasking and other sleep continuity variables such as the number of awakenings after sleep onset or WASO given that these variables seemed to play a critical role for children's executive functioning (Kuula et al., 2015; Sadeh et al., 2002). Another set of exploratory analyses focused on associations between gait and indicators of children's sleep architecture such as the percentage of light sleep (LS), slow wave sleep (SWS), and rapid-eye-movement (REM) sleep. As a third aim, we investigated differences between very preterm and full-term children based on studies indicating that prematurity is a risk factor for deficits in cognitive and motor functioning (Aarnoudse-Moens et al., 2009; de Kieviet et al., 2009). We expected that very preterm children showed stronger associations between sleep and dual-task performance as compared to full-term children, based on the notion that very preterm children were shown to be more vulnerable to poor sleep (Emancipator et al., 2006; Hagmann-von Arx et al., 2014).

2. Methods

2.1 Participants

Data from the second wave (May 2013 – September 2014) of the Basel Study of Preterm Children were used for the current study (for recruitment procedures, cf. Hagmann-von Arx et al., 2015; Maurer et al., 2016). Children born very preterm (*n* = 39) and full-term (*n* = 59) aged 7 to 12 years served as participants (for demographics, see Table 1). All of them attended primary schools. The Ethics Committee of Basel approved the current study (Nr. 122/11 and 386/11), which was performed in accordance with the rules laid down in the 1964 Declaration of Helsinki and its later amendments. Parents gave written informed consent for children's participation, and children provided verbal assent.

2.2 Procedure and Measures

Children visited the laboratory at the University of Basel for assessing their gait performance at one assessment session and underwent one night of in-home sleep-EEG. Prior to the sleep assessment, children's intelligence was measured by trained experimenters at their homes. Children were either tested with the gait or sleep assessment first[1]. The mean temporal lag between the sleep and gait assessment was 117.96 days (*SD* = 108.51); however, this temporal lag did not affect the association between sleep and dual tasking (cf. footnote 2). Furthermore, given that several sleep parameters (such as TST, SE, SWS, or REM) show a moderate to high stability over periods of 7 days (Hatzinger et al., 2010; Hatzinger et al., 2014) and 12-18 months in early-to-middle childhood (Hatzinger et al., 2013, 2014; Jenni, Molinari, Caflisch, & Largo, 2007; Perkinson-Gloor et al., 2015a), the relation between sleep and dual-task performance seems less affected by variations over time.

2.2.1 Sleep and Intelligence Assessment

Sleep was assessed using a portable sleep-monitoring device (Somté PSG, Compumedics, Singen, Germany) during a single night before a regular school day at children's homes. Sleep-EEG signals C3/A2 and C4/A1, right and left electrooculogram, and bipolar submental electromyogram were assessed. Sleep-EEG reports were visually analyzed by two experienced observers in accordance to a standardized procedure (Rechtschaffen & Kales, 1968) similarly to several recent studies (Brand et al., 2015; Perkinson-Gloor et al., 2015a; Urfer-Maurer et al., 2017). The following sleep indicators were measured: TST (the

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[1] Children who were tested first with the gait assessment did not differ significantly in their sleep behavior or dual-task performance from children who were tested with the sleep assessment first, as indicated by a multivariate analysis of variance (MANOVA) with all sleep and dual-task parameters as dependent variables and order as a between-participants variable (all *F*s < 1.99, all *p*s > .16).

time in bed minus time spent awake, in hours), SE (TST/time in bed × 100, in %), SOL (time between switching off the lights and onset of stage 2 sleep, in min), the frequency of awakenings after sleep onset (# awake) and WASO (in min), LS (percentage of sleep in stages 1 and 2), SWS (percentage of sleep in stages 3 and 4), and REM sleep (percentage of REM sleep).

As a control variable, children's intelligence was assessed prior to the sleep assessment using the Wechsler Intelligence Scale for Children (WISC-IV, Petermann & Petermann, 2011). The WISC-IV provides a measure for general cognitive ability and consists of four index scores (verbal comprehension, perceptual reasoning, working memory, and processing speed).

To assess whether the associations between sleep and dual-task performance were affected by children's sleep-disordered breathing, we asked parents to fill out the Children's Sleep Habits Questionnaire (CSHQ, Owens, Spirito, & McGuinn, 2000) which includes a scale about breathing disturbances. This questionnaire is a common measure in previous research and by the clinical community and shows an acceptable internal consistency (0.78 and 0.68 for clinical and community samples respectively, Owens et al., 2000) and test-retest reliability (ranging from 0.62-0.79) (cf. Johnson, Turner, Foldes, Malow, & Wiggs, 2012; Owens et al., 2000; but see Markovich, Gendron, & Corkum, 2014). Following the approach from Markovich et al. (2014), we considered scores as clinically relevant when these scores were higher than 1 *SD* above the mean score of the norm values provided by Owens et al. (2000; i.e., when they were higher than 3.87 in case of the Sleep Disordered Breathing scores). By doing so, it was found that the majority of the sample (83.7%) did not show any signs of sleep-disordered breathing (and the associations under investigation did not change when excluding children with sleep-disordered breathing from the sample, cf. footnote 2).

2.2.2 Gait Assessment

Gait parameters were measured in single- and dual-task situations using an electronic walkway system (GAITRite, CIR Systems, Sparta, New Jersey). This 7.01 m long mat consisted of 23’040 sensors which enabled to measure participants’ gait characteristics and is regarded a reliable and valid instrument for gait assessments (Dusing & Thorpe, 2007). To reduce effects of acceleration and deceleration, inactive sections (1.25 m) were added to the beginning and end of this mat. Coherent to previous research (Agmon et al., 2016; Hagmann-von Arx et al., 2015), we assessed the coefficients of variation (CV) of stride length, stride time, and stride velocity as indices of children’s rhythmicity and regularity of walking (i.e., gait variability; standard deviation / mean * 100).

2.2.3 Dual-Task Performance

Prior to the dual-task assessment, children’s body metrics were measured (weight, height, shoe size, leg length). Then, children’s single-task performance was assessed. To this end, children were asked to perform six cognitive tasks while standing (cognitive single-task performance). Afterwards, their motor single-task performance was measured. Children were asked to walk at a self-chosen velocity for four times over the walkway without a concurrent task. Finally, children’s dual-task behavior was assessed by asking children to walk at their preferred pace over the walkway while solving the identical, cognitive tasks.

In these cognitive tasks, children were asked to name animals, to count backwards, and to listen to and recall digits. Children performed two trials of increasing complexity in each type of task, amounting to six cognitive tasks. These tasks have typically been used in previous research investigating cognitive-motor dual tasking (e.g., Agmon et al, 2016; Woollacott & Shumway-Cook). For the naming-animals task, children were asked to name as many animals as possible (easy version) and animals with two legs (hard version) within 10 seconds. For the counting-backwards task, children were asked to count backwards by one (easy) and by two or three (hard) from different initial numbers within 10 seconds. For the hard version of this latter task, children solved both versions (i.e., counted back by two and three) in the single tasks and based on children's performance, it was decided which version was used in the dual tasks (e.g., if the child failed to count back by three, the other version was chosen). In the recalling-digits task, children heard a sequence of spoken digits (easy) and a sequence of digits and objects (hard) and were asked to recall the digits within 10 seconds. The number of correct answers served as the dependent variable.

2.3 Statistical Analyses

First, gait parameters were scanned for outliers (± 3 *SD* from the group mean, amounting to a total of 2.74%) as these values may severely bias the statistical procedures. If such extreme values were detected, they were truncated to ± 3 *SD* (for a similar procedure, see Manicolo, Grob, Lemola, & Hagmann-von Arx, 2016). To investigate differences in socio-demographic variables, anthropometric dimensions, intelligence, dual-task performance, and sleep parameters between very preterm and full-term children, a multivariate analysis of variance (MANOVA) with these variables and prematurity status as a between-participants variable was computed.

To analyze associations between sleep variables and dual-task performance, we calculated correlations and separate hierarchical regression analyses for children's motor and cognitive performance. To assess main effects of the sleep variables, we computed hierarchical regression analyses with the control variables (age, sex, height, weight, full-scale IQ, and prematurity status) and each sleep variable (e.g., TST) in one single step. Moderation analyses were calculated in accordance to the procedure suggested by Aiken and West (1991). Therefore, we ran identical hierarchical regression analyses as indicated above (e.g., control variables and TST) together with the respective interaction term (e.g., prematurity status × TST). Significant interaction terms were followed by separate hierarchical regression analyses for very preterm and full-term children.

3. Results

3.1 Socio-Demographic, Anthropometric Dimensions, Intelligence, Dual-Task Variables, and Sleep Parameters in Very Preterm and Full-term Children

The MANOVA revealed a significant difference regarding full-scale IQ, $F(1, 77) = 7.83$, $p < .01$, $\eta_P^2 = .09$, with very preterm children showing on average lower scores than full-term children (for means and *SD*s, see Table 1). Furthermore, there was an effect of cognitive performance in the dual tasks, $F(1, 77) = 8.29$, $p < .01$, $\eta_P^2 = .10$, with very preterm children producing less correct answers as compared to full-term children (for a detailed overview of means and *SD*s, see Appendix). There were no further effects (all *F*s < 1.57, *p*s > .21), indicating that children with different prematurity status did not differ with respect to socio-demographic, anthropometric, gait, and sleep parameters.

3.2 Associations between Sleep Variables and Gait Variability

Correlations between gait variability and sleep parameters indicated significant associations between higher gait variability and a higher number of awakenings after sleep onset, a higher amount of SWS, and a lower amount of REM sleep, but no other significant results (see Table 2). Given that there were no correlations for the sleep parameters TST, SE, SOL, WASO, and LS, these variables were not considered in the following regression analyses.

Using children's indicators of gait variability as dependent variables, hierarchical regression analyses were computed for the single task and the six dual tasks. After accounting for the control variables, sleep variables were not related to children's gait variability in the single-task condition (all βs < -.111, *p*s > .310), nor were there any significant interactions with prematurity status in this condition (all βs < -.233, *p*s > .172). However, sleep variables were significantly associated with children's gait variability in the dual-task conditions even after accounting for effects of age, sex, height, weight, full-scale IQ, and prematurity status (see Table 3). When using Bonferroni corrections for *p*-values, it was found that children with lower proportional amounts of REM sleep walked with higher stride-length, stride-time, and stride-velocity variability. Furthermore, results indicated that children who showed more awakenings after sleep onset walked with significantly higher stride length variability. The moderated hierarchical regression analyses yielded no significant prematurity × sleep variables interactions at Bonferroni-corrected significance level.

3.3 Associations between Sleep Variables and Cognitive Performance

Correlations between cognitive performance and sleep parameters indicated significant associations between higher cognitive performance and higher TST, a lower number of awakenings after sleep onset, and a higher amount of SWS, but no other significant results (see Table 2). Given that there were no correlations for the sleep parameters SE, SOL, WASO, LS, and REM sleep, these variables were not considered in the following regression analyses.

Hierarchical regression analyses were calculated for the single and dual tasks with children's cognitive performance as the dependent variable. After accounting for the control variables and applying Bonferroni corrections, it was found that a lower number of awakenings after sleep onset was significantly related to children's higher cognitive performance (see Table 4). With respect to sleep architecture variables, SWS was related to children's cognitive performance with higher amounts of SWS being associated with higher cognitive performance. The moderated hierarchical regression analyses yielded no significant prematurity × sleep variables interactions at Bonferroni-corrected significance level[2].

4. Discussion

The present study explored links between children's sleep and their dual-task performance. We found that the number of awakenings after sleep onset was associated with children's gait variability and their cognitive performance. However, none of the other sleep continuity variables such as TST, SE, or SOL were related to gait variability, which is in contrast to a previous study with older adults (Agmon et al., 2016). Furthermore, we found that sleep architecture variables were differently related to dual-task performance, with a higher amount of REM sleep being associated with lower gait variability and a higher amount of SWS being related to higher cognitive performance.

This finding is coherent with the dual process hypothesis according to which different sleep stages support the processing of different types of memory (Diekelmann, Wilhelm, & Born, 2009; Gais & Born, 2004; Maquet, 2001; Rasch & Born, 2013; Rauchs, Desgranges, Foret, & Eustache, 2005; Wilhelm, Prehn-Kristensen, & Born, 2012). In particular, this hypothesis assumes that REM sleep seems to relate to memory processing of tasks involving procedural content whereas SWS serves the consolidation of tasks with declarative material (Diekelmann et al., 2009; Smith, 2001; Smith, Aubrey, & Peters, 2004).

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[2] Results remained widely similar when a) temporal lag was added as a control variable in the regression analyses, and b) when children with signs of sleep-disordered breathing ($n = 16$) were excluded from the sample and c) when the sample of very preterm children was matched for age and sex ($n = 36$, $M_{\text{age}} = 9.64$ years, 13 girls) with the sample of full-term children ($n = 36$, $M_{\text{age}} = 9.66$ years, 13 girls). Using these matched samples, it was found that the number of awakenings after sleep onset ($\beta = .303$, $p < .05$) and REM sleep ($\beta = -.289$, $p < .05$) were significantly related to children's gait variability in the dual task. Furthermore, SWS was related to children's cognitive performance ($\beta = .386$, $p < .01$).

Whereas procedural knowledge is usually implicitly learned and is described as "knowing how", declarative knowledge describes the memory of events and facts and is described as "knowing what" (Smith et al., 2004). Typical examples for procedural tasks are riding a bike, tying the shoes, and walking. Examples for declarative tasks are recalling general knowledge such as recalling numbers or naming animals.

The importance of REM sleep for procedural learning was proposed based on studies demonstrating that adults showed increased REM sleep after learning a novel motor coordination behaviour such as trampolining (Buchegger, Fritsch, Meier-Koll, & Riehle, 1991). Moreover, using a sequential finger motor task, those adults with higher amounts of REM sleep after learning, showed the greatest performance gains (Fischer, Hallschmid, Elsner, & Born, 2002). Corroborative evidence comes from sleep deprivation experiments indicating that tasks with procedural memory content seemed more strongly affected from a REM-sleep deprivation than tasks with declarative memory content (Smith, 1995).

Analogous evidence on the importance of REM sleep for *children*'s procedural knowledge is mixed. Several studies failed to find similar results for children as compared to adults (Fischer, Wilhelm, & Born, 2007; Prehn-Kristensen et al., 2009; Wilhelm, Diekelmann, & Born, 2008). For example, Wilhelm and colleagues (2008) showed that nocturnal sleep as opposed to daytime wakefulness enhanced consolidation of declarative memory (i.e., learning word-pair associates) but not of procedural memories (i.e., finger sequence tapping). Importantly, these non-significant findings were qualified by a recent study indicating that the pre-sleep level of performance is an essential influencing variable. That is, only after children received an extensive training in the procedural task (i.e., a motor sequence learning task) before going to bed, children benefitted significantly from sleeping in the same procedural task (Wilhelm, Metzkow-Meszaros, Knapp, & Born, 2012). This result brought the authors to the conclusion that "the lack of benefit from sleep for motor skill memories that was consistently found in children resulted from children's slower and less automatized pre-sleep task performance" (p. 512).

Interestingly, our findings indicated that a higher amount of REM sleep was related to children's lower gait variability and thus, to the successful completion of a complex motor task that children have practiced for several years already. Children in our study were on average 9 to 10 years old and thus, can be described as experienced walkers given that children typically show a mature gait pattern at 7 years of age (Adolph, Vereijken, & Shrout, 2003). However, another study has indicated that children's gait variability shows considerable developmental progression until adolescence (Hausdorff, Zemany, Peng, & Goldberger, 1999). Therefore, it seems that even though children were experienced walkers, their gait variability showed sufficient individual variance in order to detect shared variance with other variables such as sleep. Importantly, the associations between REM sleep and gait variability were only found in dual-task situations, indicating specific correlations for gait performance under attention-taxing, challenging conditions. We also found associations between children's SWS and their cognitive performance, which is in line with studies indicating positive effects of SWS-rich sleep on declarative memory (Diekelmann et al., 2009). However, given that our approach was rather explorative, more corroborative evidence about links between children's REM sleep, SWS, and dual-task performance is needed.

Contrary to our expectation, the moderation analyses revealed no differences between very preterm and full-term children. Therefore, it seems that correlations between sleep and dual-task performance did not differ between very preterm and full-term children. However, on average we found lower intelligence scores and lower cognitive performance in very preterm children, which is in line with evidence indicating that very preterm children are at higher risk for deficits in cognitive functioning (Aarnoudse-Moens et al., 2009; Lemola, 2015). In contrast to several other studies (Emancipator et al., 2006; Hagmann-von

Arx et al., 2015; Hagmann-von Arx et al., 2014), our study did not find differences with respect to sleep or gait variability, which may indicate that variables such as critical birth weight are important additional variables. Future studies with larger samples of very preterm children may investigate effects of prematurity and additional influencing variables (such as birth weight) on children's sleep and gait variability.

The current study has strengths and weaknesses. A major strength was that gait and sleep were measured objectively. Additionally, using *in-home* sleep-EEG increased the likelihood that this assessment reflected children's typical sleep behavior as they were in their familiar surrounding as opposed to a laboratory-based assessment. Furthermore, several indicators of sleep continuity but also sleep architecture were measured, making it possible to reveal a more detailed picture of potential correlations between sleep and dual-task performance. Limitations include that the sample size was not large enough to facilitate adequate statistical power for multiple analyses of associations between sleep parameters and gait variables with Bonferroni corrected significance levels[3]. Furthermore, the order of the single and dual tasks was not counterbalanced (similarly to Abbruzzese et al., 2014; Hagmann-von Arx et al., 2015; Manicolo, Grob, & Hagmann-von Arx, 2017; Springer et al., 2006) in order to keep conditions similar for all participants. Since we intended to calculate *correlations* between participants' sleep and effects of dual tasking rather than *comparing* absolute performance levels, we prioritized to keep conditions constant in order to ensure comparability between participants. However, this decision precludes investigations of potential order effects and future studies may investigate effects of dual tasking using a counterbalanced research design.

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[3] Power analyses, using G-Power 3.1, yielded a statistical power of .86 to reveal moderate associations of $r = 0.30$, with a sample size of $N = 98$, and a P-level of $p < 0.05$. When using Bonferroni corrections ($p < .0056$), this statistical power decreased to .60 to reveal the same correlations.

Moreover, sleep-EEG was only measured within a single night (and not during the night before gait assessment) as opposed to measurements across multiple nights. Thus, it is not possible to assess the influence of a potential first-night effect or the night-to-night variability. However, with regards to possible first-night effects, it appears that among pediatric samples, results of previous studies are mixed: While among pediatric samples with sleep-disordered breathing, first-night effects have been observed (Scholle et al., 2003; Verhulst, Schrauwen, De Backer, & Desager, 2006), this was not the case for children with autism spectrum disorder (Buckley et al., 2013). Therefore, even though the present data do not allow to fully rule out the possibility of a first-night effect, based on previous studies, we think that this effect may be of minor concern. Future studies may investigate a potential first-night effect in samples of preterm children by measuring children's sleep across several nights.

5. Conclusions

In conclusion, our findings provided evidence for associations between a higher number of awakenings and lower dual-task performance in a sample of children. Furthermore, our exploratory analyses revealed links between REM sleep and gait performance in dual-task conditions as well as between SWS and cognitive performance. These results provide support for the dual process theory at an early developmental stage. Overall, our findings offer first evidence that sleep seems not only important for children's cognitive functioning (Rasch & Born, 2013), but also when coping with cognitive-motor dual-task situations and thus, situations that children are faced with repeatedly in their daily life.

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Table 1. Socio-demographic characteristics, anthropometric dimensions, intelligence, and indicators of sleep and dual-task performance of very preterm and full-term children. Standard deviations are presented in parentheses.

	Very preterm children ($n = 39$)	Full-term children ($n = 59$)	Comparisons p
Socio-demographic and anthropometric characteristics			
Age (in years)	9.66 (1.48)	9.80 (1.32)	.746
% female	33.3	39.0	.670
Gestational weeks	30.43 (1.59)	39.30 (1.71)	.000***
Birth weight (in g)	1447 (409)	3273 (508)	.000***
Weight (in kg)	34.02 (8.80)	34.12 (7.21)	.984
Height (in cm)	140.95 (11.17)	140.49 (9.09)	.588
Intelligence			
Full-IQ scores	99.49 (13.54)	106.31 (11.49)	.006**
Sleep variables			
Total sleep time (h)	9.06 (0.80)	8.86 (0.68)	.388
Sleep efficiency (in %)	93.41 (2.87)	93.91 (2.48)	.700
Sleep onset latency (in min)	18.79 (8.95)	17.07 (7.27)	.446
Awakenings after sleep onset (in min)	19.03 (15.40)	16.88 (12.37)	.788
Awakenings after sleep onset (#)	17.08 (7.41)	14.42 (6.57)	.344
Stage 1 and 2 sleep (%)	50.69 (4.52)	50.92 (5.24)	.831
Slow wave sleep (%)	21.20 (5.58)	21.97 (4.72)	.502
Rapid-eye-movement sleep (%)	25.62 (3.78)	24.56 (3.66)	.215
Dual-task parameters			
Stride-length variability	3.10 (1.07)	3.08 (1.15)	.730
Stride-time variability	3.51 (1.60)	3.39 (1.76)	.708
Stride-velocity variability	4.88 (1.73)	4.72 (2.27)	.644
Cognitive performance	4.70 (0.99)	5.44 (1.35)	.005**

Note. Data are presented as means (*SD*) or relative frequencies (%).
P-values are reported from an MANOVA or a χ^2 test in case of categorical variables such as sex.
* $p < .05$, ** $p < .01$, *** $p < .001$.

Table 2. Correlation coefficients between sleep variables and gait parameters as well as cognitive performance in very preterm and full-term children.

		Sleep parameters							
		TST	SE	SOL	WASO	# awake	LS	SWS	REM
ST walking	Stride-length variability	-0.086	-0.055	0.186	-0.073	0.028	-0.087	0.091	-0.01
	Stride-time variability	-0.002	-0.064	-0.007	0.082	0.074	0.063	-0.033	-0.049
	Stride-velocity variability	0.013	-0.091	0.193	-0.01	0.104	-0.048	0.002	0.039
Naming-animals/easy	Stride-length variability	0.076	-0.106	-0.067	0.179	0.321***	0.025	0.178	-0.271**
	Stride-time variability	0.058	0.028	-0.159	0.057	0.068	-0.012	0.148	-0.19
	Stride-velocity variability	0.079	-0.011	-0.121	0.099	0.187	0.007	0.133	-0.187
Naming-animals/hard	Stride-length variability	0.179	0.071	0.128	-0.113	0.067	-0.05	0.045	0.03
	Stride-time variability	0.012	0.109	-0.075	-0.079	-0.019	0.002	0.082	-0.104
	Stride-velocity variability	0.053	0.08	0.013	-0.088	-0.018	-0.063	0.121	-0.063
Counting/easy	Stride-length variability	0.094	0.081	-0.092	-0.033	0.049	-0.044	0.07	-0.047
	Stride-time variability	0.174	0.076	-0.049	-0.033	0.003	0.006	-0.022	0
	Stride-velocity variability	0.158	0.017	-0.047	0.035	0.071	-0.041	0.017	0.021
Counting/hard	Stride-length variability	0.063	0.028	-0.15	0.063	0.116	-0.123	0.237*	-0.159
	Stride-time variability	-0.147	0.068	-0.002	-0.107	-0.13	-0.035	0.246*	-0.297**
	Stride-velocity variability	-0.079	0.061	-0.056	-0.062	-0.085	-0.026	0.209*	-0.242*

	Stride-velocity variability	0.096	0.067	-0.097	0.001	0.054	-0.145	0.178	-0.037
Recalling-digits/hard	Stride-length variability	0.188	-0.031	0.008	0.054	0.11	0.036	0.15	-0.242*
	Stride-time variability	0.114	0.057	0.039	-0.088	0.114	-0.081	0.205*	-0.151
	Stride-velocity variability	0.136	0.02	0.005	0.005	0.153	0.001	0.213*	-0.274**
Naming-animals/easy	Cognitive performance - ST	0.332**	-0.085	0.059	0.045	-0.059	-0.043	0.065	-0.046
	Cognitive performance - DT	-0.001	0.159	-0.039	-0.155	0.018	-0.131	0.097	0.033
Naming-animals/hard	Cognitive performance - ST	0.056	0.16	-0.109	-0.095	0.011	0.02	0.045	-0.079
	Cognitive performance - DT	-0.041	0	-0.021	0.027	0.052	-0.006	-0.073	0.109
Counting/easy	Cognitive performance - ST	-0.064	-0.016	-0.077	0.049	0.102	0.035	-0.036	-0.013
	Cognitive performance - DT	-0.058	-0.047	0.095	-0.006	0.159	-0.053	0.124	-0.116
Counting/hard	Cognitive performance - ST	-0.131	0.096	-0.064	-0.106	-0.106	-0.027	0.132	-0.174
	Cognitive performance - DT	-0.009	0.098	-0.054	-0.083	0.041	-0.09	0.093	-0.028
Recalling-digits/easy	Cognitive performance - ST	-0.132	0.046	0.113	-0.142	-0.042	-0.151	0.239*	-0.121
	Cognitive performance - DT	-0.133	-0.081	0.073	0.059	0.107	0.008	-0.06	0.081
Recalling-digits/hard	Cognitive performance - ST	-0.042	-0.098	0.097	0.103	0.299**	-0.17	0.135	0.024
	Cognitive performance - DT	-0.167	0.021	0.076	-0.1	0.036	0.003	0.005	-0.01

Note. ST = single task, DT = dual task, TST = total sleep time, SE = sleep efficiency, SOL = sleep onset latency, WASO = awakening after sleep onset, # awake = number of awakenings after sleep onset, LS = light sleep (stage 1 and 2 sleep together), SWS = slow wave sleep, REM = rapid eye movement sleep.

* $p < .05$, ** $p < .01$, *** $p < .001$.

Table 3. Sleep and gait variability in very preterm and full-term children: Hierarchical regression analyses. Bonferroni-corrected *p*-values are presented in bold.

	Stride-length variability			Stride-time variability			Stride-velocity variability		
	β	*t*	*p*	β	*t*	*p*	β	*t*	*p*
Naming animals/easy									
# awake[1]	**.364****	**3.401**	**.001**	.126	1.159	.250	.220*	2.028	.046
SWS[1]	.111	.934	.353	.190	1.686	.096	.204	1.788	.078
REM[1]	-.261*	-2.300	.024	-.221*	-2.015	.047	-.247*	-2.234	.028
# awake × prematurity[2]	.095	.872	.386	.036	.322	.748	-.032	-.293	.770
SWS × prematurity[2]	.239	1.391	.168	.266	1.639	.105	.390*,[a]	2.425	.018
REM × prematurity[2]	-.114	-.994	.324	-.191	-1.745	.085	-.244*,[b]	-2.247	.028
Naming animals/hard									
# awake[1]	.062	.553	.582	.028	.256	.799	-.027	-.243	.808
SWS[1]	-.141	-1.213	.229	-.066	-.580	.564	-.048	-.416	.679
REM[1]	.024	.207	.837	-.162	-1.468	.146	-.079	-.703	.484
# awake × prematurity[2]	-.169	-1.493	.140	.020	.179	.859	-.053	-.464	.644
SWS × prematurity[2]	.269	1.606	.112	.198	1.196	.235	.305	1.837	.070
REM × prematurity[2]	-.226	-1.981	.051	-.109	-.974	.333	-.122	-1.072	.287
Counting/easy									
# awake[1]	.021	.191	.849	-.047	-.411	.682	.004	.038	.970
SWS[1]	-.070	-.607	.545	-.083	-.694	.490	-.038	-.323	.747
REM[1]	.059	.530	.597	.044	.373	.710	.099	.863	.391
# awake × prematurity[2]	-.042	-.373	.710	-.098	-.841	.403	-.051	-.440	.661
SWS × prematurity[2]	.009	.052	.958	-.176	-1.016	.313	-.029	-.169	.866
REM × prematurity[2]	-.013	-.111	.912	-.045	-.381	.704	-.151	-1.304	.196

Counting/hard									
# awake[1]	.154	1.420	.160	-.068	-.592	.556	-.051	-.454	.651
SWS[1]	.034	.298	.766	.258*	2.211	.030	.207	1.809	.074
REM[1]	-.207	-1.867	.066	**-.335****	**-2.967**	**.004**	**-.342****	**-3.134**	**.002**
# awake × prematurity[2]	-.125	-1.128	.263	.182	1.558	.124	.142	1.244	.218
SWS × prematurity[2]	.064	.388	.699	.017	.100	.920	.134	.819	.415
REM × prematurity[2]	.031	.278	.782	.078	.686	.495	.047	.427	.671
Recalling digits/easy									
# awake[1]	.084	.731	.467	-.106	-.921	.360	.070	.614	.541
SWS[1]	.136	1.154	.252	.066	.553	.582	.028	.235	.815
REM[1]	-.018	-.157	.875	-.089	-.765	.446	-.004	-.033	.974
# awake × prematurity[2]	.024	.208	.836	.092	.804	.424	.035	.310	.757
SWS × prematurity[2]	.210	1.214	.229	.007	.038	.970	.412*[,c]	2.471	.016
REM × prematurity[2]	.041	.343	.732	-.078	-.659	.512	-.034	-.291	.772
Recalling digits/hard									
# awake[1]	.106	.932	.354	.085	.754	.453	.138	1.232	.222
SWS[1]	.250*	2.171	.033	.263*	2.337	.022	.266*	2.344	.022
REM[1]	**-.328****	**-2.982**	**.004**	-.185	-1.645	.104	**-.364****	**-3.384**	**.001**
# awake × prematurity[2]	-.051	-.443	.659	.069	.605	.547	-.024	-.210	.834
SWS × prematurity[2]	.317	1.901	.061	.036	.216	.830	.321	1.958	.054
REM × prematurity[2]	-.082	-.730	.468	-.114	-1.002	.320	-.144	-1.329	.188

Note. # awake = number of awakenings after sleep onset, SWS = slow wave sleep, REM = rapid eye movement sleep.
Sex was coded: -1 = females, 1 = males; prematurity status was coded: -1 = full-term, 1 = preterm.
* $p < .05$, ** $p < .01$, † $p < .0056$ (Bonferroni-corrected p-value).
Model 1: Regression models analyzing sleep variables separately and controlling for age, sex, height, weight, prematurity, and full-scale IQ.

[1] Standardized regression coefficient β without interaction terms in the model.

[2] Standardized regression coefficient β from hierarchical regression analyses according to the procedure of Aiken and West (1991).

[a] Separate follow-up regressions for very preterm children ($\beta = .500$, $p = .012$) and full-term children ($\beta = -.054$, $p = .706$)

[b] Separate follow-up regressions for very preterm children ($\beta = -.469$, $p = .016$) and full-term children ($\beta = .007$, $p = .959$)

[c] Separate follow-up regressions for very preterm children ($\beta = .273$, $p = .171$) and full-term children ($\beta = -.226$, $p = .143$)

Table 4. Sleep and cognitive performance in very preterm and full-term children: Hierarchical regression analyses. Bonferroni-corrected *p*-values are presented in bold.

	Cognitive Performance - ST			Cognitive Performance – DT		
	β	*t*	*p*	*β*	*t*	*p*
Naming animals/easy						
TST[1]	-.156	-1.453	.151	.228*	2.101	.039
# awake[1]	.059	.630	.530	.107	1.120	.267
SWS[1]	.035	.361	.719	.034	.337	.737
TST × prematurity[2]	.252	1.879	.064	.268	1.984	.051
# awake × prematurity[2]	.061	.643	.522	.035	.354	.725
SWS × prematurity[2]	-.116	-.816	.417	.012	.079	.937
Naming animals/hard						
TST[1]	.062	.489	.626	.002	.018	.986
# awake[1]	.109	1.009	.316	.066	.602	.549
SWS[1]	.071	.625	.534	.022	.195	.846
TST × prematurity[2]	.216	1.353	.180	.105	.644	.521
# awake × prematurity[2]	.197	1.813	.074	.225*[,a]	2.062	.043
SWS × prematurity[2]	.316	1.950	.055	.169	1.015	.314
Counting/easy						
TST[1]	.240*	2.158	.034	.111	.905	.369
# awake[1]	.141	1.447	.152	.187	1.804	.075
SWS[1]	-.156	-1.536	.129	.059	.530	.598
TST × prematurity[2]	.032	.224	.824	.099	.632	.530
# awake × prematurity[2]	.056	.564	.575	-.137	-1.299	.198
SWS × prematurity[2]	-.042	-.280	.780	-.185	-1.156	.252
Counting/hard						

TST[1]	.077	.645	.521	.190	1.633	.107
# awake[1]	-.033	-.318	.752	.114	1.123	.265
SWS[1]	.055	.513	.609	.082	.770	.444
TST × prematurity[2]	.207	1.381	.171	.062	.418	.677
# awake × prematurity[2]	.034	.320	.750	-.091	-.883	.380
SWS × prematurity[2]	.173	1.115	.269	.300	1.981	.051
Recalling digits/easy						
TST[1]	.012	.095	.925	.126	1.149	.254
# awake[1]	-.043	-.400	.691	.143	1.528	.131
SWS[1]	**.341**	**3.237**	**.002**	-.108	-1.088	.280
TST × prematurity[2]	.264	1.682	.097	.065	.463	.645
# awake × prematurity[2]	.071	.647	.519	.017	.180	.857
SWS × prematurity[2]	-.120	-.784	.436	-.001	-.006	.995
Recalling digits/hard						
TST[1]	.071	.567	.572	-.013	-.115	.909
# awake[1]	**.315**	**3.087**	**.003**	.090	.936	.352
SWS[1]	.055	.485	.629	.036	.358	.722
TST × prematurity[2]	-.015	-.091	.927	.263	1.873	.065
# awake × prematurity[2]	.079	.756	.452	.168	1.730	.088
SWS × prematurity[2]	.172	1.049	.298	-.070	-.472	.638

Note. ST = single task, DT = dual task, TST = total sleep time, # awake = number of awakenings after sleep onset, SWS = slow wave sleep.
Sex was coded: -1 = females, 1 = males; prematurity status was coded: -1 = full-term, 1 = preterm.
* $p < .05$, ** $p < .01$, † $p < .0056$ (Bonferroni-corrected *p*-value).
Model 1: Regression models analyzing sleep variables separately and controlling for age, sex, height, weight, prematurity, and full-scale IQ.

[1] Standardized regression coefficient β without interaction terms in the model.

[2] Standardized regression coefficient β from hierarchical regression analyses according to the procedure of Aiken and West (1991).

[a] Separate regressions for very preterm children ($\beta = .338$, $p = .063$) and full-term children ($\beta = -.075$, $p = .593$)

Appendix

Gait parameters and cognitive performance under single- and dual-task conditions in very preterm and full-term children. Standard deviations are presented in parentheses.

	Very preterm children				Full-term children			
	Gait variability			Cognitive performance	Gait variability			Cognitive performance
	Stride-length variability	Stride-time variability	Stride-velocity variability		Stride-length variability	Stride-time variability	Stride-velocity variability	
Naming-animals task								
Easy – ST	2.21 (0.70)	2.03 (0.73)	2.90 (1.09)	5.95 (1.66)	1.99 (0.61)	1.82 (0.59)	2.56 (0.84)	7.11 (1.88)
Easy - DT	4.50 (2.92)	5.01 (4.61)	7.27 (5.03)	6.03 (1.76)	3.85 (2.66)	4.32 (3.49)	6.13 (4.73)	6.38 (1.85)
Hard - ST	2.21 (0.70)	2.03 (0.73)	2.90 (1.09)	1.18 (1.25)	1.99 (0.61)	1.82 (0.59)	2.56 (0.84)	1.30 (1.13)
Hard - DT	3.61 (2.10)	3.51 (2.04)	5.13 (2.80)	1.53 (1.27)	3.65 (3.15)	4.11 (4.05)	5.92 (5.92)	1.62 (1.32)
Counting task								
Easy - ST	2.21 (0.70)	2.03 (0.73)	2.90 (1.09)	9.84 (3.38)	1.99 (0.61)	1.82 (0.59)	2.56 (0.84)	11.86 (4.33)
Easy - DT	3.28 (2.16)	4.69 (5.13)	5.90 (4.06)	7.92 (3.46)	3.34 (2.66)	3.58 (3.06)	5.09 (4.87)	10.38 (4.85)
Hard - ST	2.21 (0.70)	2.03 (0.73)	2.90 (1.09)	3.97 (2.51)	1.99 (0.61)	1.82 (0.59)	2.56 (0.84)	5.21 (2.97)
Hard - DT	3.10 (2.00)	4.00 (2.84)	4.89 (2.68)	3.92 (2.93)	3.98 (2.78)	5.15 (6.55)	6.48 (5.41)	5.38 (2.90)
Recalling-digits task								
Easy – ST	2.21 (0.70)	2.03 (0.73)	2.90 (1.09)	4.63 (0.54)	1.99 (0.61)	1.82 (0.59)	2.56 (0.84)	4.55 (0.57)
Easy - DT	2.70 (1.66)	2.47 (1.33)	3.91 (2.16)	4.47 (0.65)	2.47 (1.43)	2.53 (1.27)	3.56 (1.67)	4.34 (0.96)
Hard - ST	2.21 (0.70)	2.03 (0.73)	2.90 (1.09)	3.47 (1.22)	1.99 (0.61)	1.82 (0.59)	2.56 (0.84)	3.39 (1.42)
Hard - DT	2.27 (1.11)	2.77 (1.29)	4.10 (1.95)	3.50 (1.03)	2.22 (1.10)	2.18 (0.93)	3.20 (1.49)	3.79 (1.12)

Note. ST = single task, DT = dual task.