THE JOURNAL OF CHILD PSYCHOLOGY AND PSYCHIATRY
ACAMH THE ASSOCIATION FOR CHILD AND ADOLESCENT MENTAL HEALTH

Journal of Child Psychology and Psychiatry 56:2 (2015), pp 171–182 doi:10.1111/jcpp.12296

Cognitive benefits of last night's sleep: daily variations in children's sleep behavior are related to working memory fluctuations

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Background: Recent studies have suggested substantial fluctuations of cognitive performance in adults both across and within days, but very little is known about such fluctuations in children. Children's sleep behavior might have an important influence on their daily cognitive resources, but so far this has not been investigated in terms of naturally occurring within-person variations in children's everyday lives. **Methods:** In an ambulatory assessment study, 110 elementary school children (8–11 years old) completed sleep items and working memory tasks on smartphones several times per day in school and at home for 4 weeks. Parents provided general information about the children and their sleep habits. **Results:** We identified substantial fluctuations in the children's daily cognitive performance, self-reported nightly sleep quality, time in bed, and daytime tiredness. All three facets were predictive of performance fluctuations in children's school and daily life. Sleep quality and time in bed were predictive of performance in the morning, and afternoon performance was related to current tiredness. The children with a lower average performance level showed a higher within-person coupling between morning performance and sleep quality. **Conclusions:** Our findings contribute important insights regarding a potential source of performance fluctuations in children. The effect of varying cognitive resources should be investigated further because it might impact children's daily social, emotional, and learning-related functioning. Theories about children's cognitive and educational development should consider fluctuations on micro-longitudinal scales (e.g., day-to-day) to identify possible mechanisms behind long-term changes. **Keywords:** Working memory, sleep, school children, structural equation modeling, longitudinal studies.

Introduction

Cognitive performance fluctuations are largely known as the phenomenon of having good or bad days or moments. Poor results on tests or shortcomings in the cognitive demands of everyday life are often attributed to such bad days or moments. Furthermore, the experience of having a particularly good or bad night's sleep is common in daily life. Astonishingly, however, empirical research on both of these everyday phenomena is scarce. Therefore, our aim was to relate nightly variations in children's sleep to their cognitive performance the following day to gain knowledge about a potential source of cognitive performance fluctuations in children.

Some studies with adult samples suggest that cognitive performance fluctuations can be identified in a number of cognitive tasks and that these fluctuations vary according to age (Nesselroade & Salthouse, 2004; Schmiedek, Lövdén, & Lindenberger, 2013; Sliwinski, Smyth, Hofer, & Stawski, 2006). However, to the best of our knowledge, adolescents are the youngest age group that has been investigated in this area of research (Riediger, Wrzus, Schmiedek, Wagner, & Lindenberger, 2011). Hence, there is a serious lack of research on this issue concerning children. Performance fluctuations in young school children might be of major importance because these children are in a crucial learning phase in which they acquire the fundamentals for later knowledge acquisition. Therefore, varying cognitive resources in elementary school might have an impact on children's later cognitive and educational development. However, the fluctuations *per se* and their antecedents and consequences are not yet understood. We considered sleep to have an important influence on performance fluctuations, which has not been investigated with regard to the natural variations in children's sleep in their daily lives and especially not in the school context so far.

The existing literature provides numerous studies on the role of sleep behavior for children's cognitive performance in general. A recent meta-analysis that included mostly cross-sectional and some experimental studies revealed that sleep duration is positively related to cognitive performance in 5- to 12-year-old children (Astill, Van Der Heijden, Van Ijzendoorn, & Van Someren, 2012). Reviews have summarized the influence of daytime sleepiness and sleep quality on children's and adolescents' cognitive functioning (Araújo & Almondes, 2014; Curcio, Ferrara, & De Gennaro, 2006; Kopasz et al., 2010), and longitudinal studies have supported these conclusions. For example, poor sleep in 8-year-olds was

Conflict of interest statement: No conflicts declared.

related to lower performance in broad cognitive abilities at the age of 10 (Buckhalt, El-Sheikh, Keller, & Kelly, 2009), and children's sleep problems between 4 and 16 years of age had predictive value for inhibition and working memory at the age of 17 (Friedman, Corley, Hewitt, & Wright, 2009). Overall, the importance of sleep for children's cognitive performance is widely accepted. However, it is crucial to note that this belief is largely based on *between-person* findings. Such findings provide evidence that children who generally sleep better or longer tend to score higher on measures of cognitive performance than children who sleep less well or for less time. However, between-person findings do not need to provide information regarding the *within-person* level (Molenaar, 2004; Schmitz, 2006). Within-person findings reveal whether children's cognitive performance fluctuates as a function of variations in sleep behavior. Some experimental studies have provided important insights, indicating that even a 1-hr reduction of sleep impaired children's working memory performance (Sadeh, Gruber, & Raviv, 2003; Vriend et al., 2013). In addition to experimental manipulations, micro-longitudinal studies (i.e., studies with a high frequency of measurement occasions) on a day-to-day basis can contribute uniquely to the within-person perspective. Such studies can capture the nature and degree of naturally occurring variations in sleep behavior and cognitive performance and thus can provide information about children's everyday lives. Furthermore, such studies can provide information about potential between-person differences in the strength of within-person associations. However, these studies are largely lacking. Therefore, theoretical and applied questions remain unanswered. Does children's momentary cognitive performance depend on their naturally occurring sleep behavior? If so, do children differ in the strength of this association, and how can such individual differences be explained? These questions are of major practical concern for parents and teachers because they affect children's daily functioning at home and school.

Micro-longitudinal approaches to the coupling (i.e., within-person relationship) of sleep and cognition are scarce even with adult samples (Fuentes, Hunter, Strauss, & Hultsch, 2001; Gamaldo, Allaire, & Whitfield, 2010). For example, Gamaldo et al. (2010) found a within-person coupling of sleep duration, but not sleep quality, with cognitive performance across eight occasions. The relationship demonstrated an inverted-U shape with an optimum at the average sleep duration. Although this is an important finding, it is not advisable to rely on adult samples to build hypotheses about this type of coupling within children. The proportion of sleep stages in nocturnal sleep (e.g., the percentage of (non-)rapid eye movement sleep) changes over an individual's life span (Hill, Hogan, & Karmiloff-Smith, 2007 for a review), especially in adolescence (Campbell & Feinberg, 2009 for a longitudinal study; Gaudreau, Carrier, & Montplaisir, 2001 for a cross-sectional study; Kurth et al., 2010 for an experimental study). Changes in adolescents' sleep-EEG measures are even discussed as indicators of adolescent brain maturation (Campbell & Feinberg, 2009; Feinberg & Campbell, 2013). Because adolescent brain maturation includes significant changes in the connectivity of the hippocampus and the prefrontal cortex, the mechanisms that underlie the sleep-cognition relationship in children might differ from those of adults. This can work in two ways: children cannot yet fully benefit from some aspects of sleep, and they do not yet fully suffer from others (cf. Astill et al., 2012 for a detailed discussion). Hence, the findings from adults provide little, if any, information on children. Thus, our research objective was to investigate whether sleep behavior predicts daily cognitive performance fluctuations in children.

First, we had to test whether children's sleep behavior varies systematically across nights (by the term 'systematic variability', we refer to fluctuations across occasions that cannot be explained by measurement error because they manifest in a tendency toward low or high responses for all items of a scale or for performance to be low or high for all tasks of a construct on a measurement occasion). In principle, only systematic within-person variability can predict daily cognitive performance. Therefore, we investigated the variation of sleep behavior in 110 third- and fourth-graders who provided daily information about their previous night's sleep and daytime tiredness for 31 consecutive days. Ideally, children should be well rested to meet their daily demands in school and at home. However, studies often report that healthy elementary school children experience sleep problems, sleep deprivation, or daytime tiredness (Friedman et al., 2009; Owens, Spirito, McGuinn, & Nobile, 2000; Spilsbury et al., 2004). Children usually stop their regular napping at 5–6 years of age. In grades three and four, children have a single nighttime sleep period per day (Hill et al., 2007; Iglowstein, Jenni, Molinari, & Largo, 2003). Therefore, recovery and the other functions of sleep are provided by nightly sleep and are no longer considerably supported by naps. For the age range of our sample, the average nightly sleep duration is commonly found to be between 9 and 10.5 hr, involving substantial inter-individual differences and a typical decline in the mean with age (Galland, Taylor, Elder, & Herbison, 2012; Iglowstein et al., 2003; Spilsbury et al., 2004). To measure the variability of nightly sleep behavior in our study, we focused on three commonly differentiated aspects: time in bed as a measure of sleep quantity, sleep quality, and daytime tiredness (of course, daytime tiredness is not only related to sleep but also influenced by daily experiences; however, we list it as a sleep variable to simplify reading). These are dependent but distinct dimensions with qualitative differences. In this study, 'tiredness' refers to a rating of a current state, 'sleep quality' refers to a subjective evaluation of a past period of sleep, and 'time in bed' refers to the duration between going to bed and waking up (which is usually slightly longer than the actual amount of time asleep; cf. Meijer, Reitz, Dekovic, Van Den Wittenboer, & Stoel, 2010). The between-person relationships of the three dimensions are often nonsignificant or low in children (e.g., Liu, Liu, Owens, & Kaplan, 2005; Meijer, Habekothé, & Van Den Wittenboer, 2000; Meijer et al., 2010).

Research with adult samples suggests systematic within-person variability in the three dimensions (Åkerstedt et al., 2012; Knutson, Rathouz, Yan, Liu, & Lauderdale, 2007; McCrae et al., 2008). For example, Gamaldo et al. (2010) showed substantial within-person variability of self-reported sleep duration and sleep quality in adults over eight measurement points (within 3 weeks). The respective intra-class correlations suggest that the participants differed from themselves over time as much as they differed from others, on average. Elementary school children might show systematic within-person variability in their sleep behavior as well, but this issue has rarely been tested. Most studies have aggregated sleep data (e.g. a week's actigraphy) to capture children's typical sleep behavior (Lemola et al., 2011; Vriend et al., 2012). However, Spilsbury et al. (2005) found substantial variations in 8- to 11-year-olds' sleep duration across 1 week. Parents also regularly report inconsistent sleep schedules of their children, such as more than 70 min of bedtime variability during the school week (Biggs, Lushington, Van den Heuvel, Martin, & Kennedy, 2011). We assumed that sleep quality, time in bed, and daytime tiredness would vary systematically within children because many situational factors in the school, family, or peer-group context might evoke daily variability. Therefore, our first goal was to identify these fluctuations.

Next, we associated children's sleep behavior with their daily cognitive performance. Our second goal was to test whether one aspect of sleep behavior predicts daily cognitive performance fluctuations within children. We hypothesized that the previous night's sleep quality and time in bed would be positively related and that tiredness would be negatively related to cognitive performance. To test these assumptions, we had to measure performance with a task that was sensitive to daily fluctuations. Only a measure of the *actual* performance level that captures the currently available cognitive resources and varies systematically across days can be predicted on a day-to-day basis. We focused on working memory because it has the three following features: (a) it exhibits systematic fluctuations, (b) it has a strong theoretical background, and (c) it is practically important for children in school. First, from an empirical perspective, research on cognitive performance fluctuations in adults is largely based on working memory and has identified substantial fluctuations in the laboratory (Schmiedek et al., 2013) and everyday life (Riediger et al., 2011). These fluctuations co-vary on a within-person level with other cognitive processes, such as attention switching and processing speed (Stawski, Sliwinski, & Hofer, 2013), and with daily experiences, such as affect, motivation (Brose, Schmiedek, Lövdén, & Lindenberger, 2012), and stress (Sliwinski et al., 2006). Second, working memory is embedded in a remarkably elaborate theoretical background. It can be defined as the ability to simultaneously maintain and process information in a controlled manner (Baddeley & Hitch, 1994) and as the cognitive mechanism that allows for the building, maintaining, and updating of structural representations via dynamic bindings (Oberauer, 2009; Wilhelm, Hildebrandt, & Oberauer, 2013). Such bindings temporarily organize input as words, objects, numbers, or events by connecting them to places in a cognitive coordinate system (Oberauer, 2009). They can be used to organize and represent diverse problems and situations and thus qualify working memory as a basic cognitive resource. Third, from a practical perspective, working memory is of central importance for children's cognitive resources as they are needed in school. It is related to school achievement in various domains (e.g. Friso-van den Bos, Van der Ven, Kroesbergen, & Van Luit, 2013; for a meta-analysis on mathematics; Loosli, Buschkuehl, Perrig, & Jaeggi, 2012; for a controlled training study on reading; Swanson, 2011; for a longitudinal study on mathematical problem solving) and to children's general and fluid intelligence (Giofrè, Mammarella, & Cornoldi, 2013; Hornung, Brunner, Reuter, & Martin, 2011).

We wanted to capture children's cognitive resources directly at the time and place in which they are naturally required. Therefore, we measured performance in children's everyday life in school and at home by means of ambulatory assessment on smartphones. We chose working memory updating (WMU) tasks because they have proven to be (a) valid operationalizations of working memory (Schmiedek, Hildebrandt, Lövdén, Wilhelm, & Lindenberger, 2009; Wilhelm et al., 2013), (b) reliable measures of cognitive performance fluctuations (Schmiedek et al., 2013), (c) feasible for ambulatory assessment on mobile phones in everyday life (Riediger et al., 2011), and (d) suitable for elementary school children (Carretti, Cornoldi, De Beni, & Romanò, 2005; Göthe, Esser, Gendt, & Kliegl, 2012).

Typically, children's quantitative working memory performance increases with age (Gaillard, Barrouillet, Jarrold, & Camos, 2011). For the age range of our sample, we did not expect any qualitative differences in performance because important developmental stages have been shown to occur earlier (e.g. children usually begin to actively refresh memory traces at approximately 7 years of age; Camos & Barrouillet, 2011).

In summary, our research goals were to (a) identify fluctuations in nightly sleep quality, time in bed, and daytime tiredness, and (b) test whether these fluctuations are coupled with fluctuations in working memory in elementary school children's everyday lives.

Method

Participants

The sample consisted of 110 third- and fourth-graders (65 boys) of an elementary school in an average urban neighborhood in Frankfurt am Main, Germany. The participants were 8–11 years old (M = 9.88, SD = 0.61), and their IQ was in an average range with M = 108.40 and SD = 15.52 (CFT 20-R; Jacobs, Petermann, & Weiß, 2007). German was the native language of 77% of the children, which is a common contingent for a German city. All of the children were familiar with classes taught in German. The education level of the children's parents was ordinarily distributed across the sample (the percentages for the mothers/fathers were as follows: *no graduation*: 0.9/0.9; *basic school graduation*: 32.7/27.3; *high school graduation*: 25.5/18.2; *college degree*: 31.8/36.4; *Ph.D.*: 2.7/5.5; *no information*: 6.4/11.8). The children received money or a gift certificate for their participation.

Procedure

This study was part of the FLUX project ('Assessment of Cognitive Performance FLUctuations in the School ConteXt'), which aims to quantify the magnitude of cognitive performance fluctuations and identify their antecedents and consequences in elementary school children. Because children differ in their cognitive preconditions and their daily life experiences, recent findings from samples with mostly adults and some adolescents provide little information on children. Cognitive performance fluctuations *per se* and especially their relationships to other variables might differ substantially in children. The present article focuses on the role of sleep behavior as a possible antecedent of such fluctuations.

The study included 4.5 hr (six lessons) of training and pretesting. We distributed smartphones (*Dell Streak 5, Android 2.2*) that were specifically chosen, bought, and programmed for the FLUX project. Our application was the only available function of the phones (internet, calls, games, and even the regular system menu were blocked) and was programmed by the Technology Based Assessment Group at the DIPF (for details, see Dalir, Rölke, & Buchal, 2012). During its development, the application was regularly pretested with children, and the final version was pretested with 12 third-graders on 15 occasions.

The children received the smartphones for the duration of the study to perform WMU tasks and self-report questionnaires for 31 consecutive days in the middle of the term. The smartphones rang on several occasions each day in school and at home. Occasion 1 occurred at 8:50 am (which was at the beginning of the second lesson on school days), Occasion 2 occurred at 11:25 am (which was at the end of the fourth lesson on school days), and Occasion 3 occurred at around 3:00 pm (which was always after school). Test sessions were available for up to 60 min and lasted approximately 15 min. A fixed design was necessary in school so that teachers could schedule their instruction accordingly. Teachers and trained research assistants supervised the sessions in school to ensure that the participating children were not distracted by other children (who received coloring books to work on). Individually adapted timing of occasions (i.e., a window of ±2 hr) was realized out of school. The children's teachers and parents kept minutes of the children's participation. The reasons for missing data were manifold in such an intensive study design and included illness, exams, other obligations, technical problems such as a dead battery, and the smartphone being left at home or in school. At any time, the children could refuse to answer the self-report items and press a 'no idea' button. Taken together, 73% of the previous night's sleep data were available, 60% of the daytime tiredness data were available, and 67% of the WMU data were available (for details, see Table S1, Supporting information). The parents, children, and teachers were informed about the study in detail and in appropriate wording. The parents and children provided written informed consent. The FLUX project was approved by the ethics committee of the faculty for psychology and sport sciences at Goethe University, Frankfurt am Main, Germany.

Measures

Sleep. The children reported their current tiredness on all occasions and their previous night's sleep on the first occasion of each day. Due to the close temporal proximity, we expected negligible or no memory biases. All daily items (Table 1) were answered before WMU was tested. Children in the age range of our sample are often asked to report their sleep behavior (e.g., Meijer, 2008; Spilsbury et al., 2005). They tend to identify more sleep problems than their parents, especially problems with falling asleep and restless sleep (Owens et al., 2000; Wiater et al., 2005). Our items were pretested in a study with 75 elementary school children (five occasions) and had to be brief and easy for children. For example, instead of directly reporting their time in bed, the children reported the times of going to bed and awakening. Related studies have used similar items to capture sleep quality (cf. the sleep quality index by Åkerstedt et al., 2012). All items were explained in detail and practiced with trained research assistants until the children were confident about answering them. In a pretest, children reported how all sleep items apply to them 'usually' on days with or without school to capture the trait aspect (e.g., 'When do you usually wake up on schooldays?'). In addition, parents reported the habitual sleep behavior of their children.

Working memory updating. We presented a numerical and a spatial WMU task with two memory loads each at Occasions 1–3. The tasks were adapted versions of updating tasks that have been used previously with adolescents and children (Göthe et al., 2012; Riediger et al., 2011). They were specifically designed for children and embedded in a child-appropriate story. The tasks were pretested in a study with 75 elementary school children (10 occasions), explained in detail, and practiced by the children with trained research assistants. We presented both tasks with a memory load of two and three, which means that the children saw either two or three objects simultaneously at the beginning of a block. In the numerical task, the children saw icons depicting two or three types of sweets and a number representing their quantity (e.g., four chocolate bars, three candies). Then, they saw updating operations that implied that the quantity had changed (e.g. +1 chocolate bar). They had to memorize and track the quantity of the various sweets and enter the final quantity. The updating operations were additions and subtractions within a range of −2 to +2. The total was never negative or above nine. In the spatial task, the children saw two or three cartoon creatures in a 4 × 4 grid. The creatures disappeared, and the children saw arrows that corresponded to a specific creature (via color and a small picture of the creature in the middle of the arrow) and pointed in various directions, which indicated shifts of the

Table 1 Descriptive statistics of all daily measures

Variable	Scale	Occ	M (SD)	ICC	Deff	Mean ISD (SD)
Sleep quality						
How well did you sleep last night?	0–1 (five point)	1	.73 (0.31)	.30	6.16	.24 (0.11)
How restlessly did you sleep last night?[a]	0–1 (five point)	1	.23 (0.31)	.26	5.51	.24 (0.13)
How easily did you fall asleep yesterday evening?[a]	0–1 (five point)	1	.69 (0.34)	.33	6.65	.25 (0.11)
Mean sleep quality		1	.73 (0.25)	.40	8.17	.18 (0.08)
Time in bed						
When did you go to bed yesterday?	Time (list box, every 10 min.)	1	21:42 (1:27)	.17	4.45	1:12 (0:30)
When did you wake up today?[b]	Time (list box, every 10 min.)	1	7:23 (1:21)	.14	3.91	1:05 (0:33)
Arithmetic difference		1	9.67 (1.83)	.16	4.31	1.45 (0.78)
Daytime tiredness						
How tired do you feel right now?	0–1 (five point)	1	.24 (0.33)	.25	5.38	.26 (0.12)
		2	.15 (0.28)	.31	6.27	.20 (0.15)
		3	.15 (0.27)	.24	4.67	.19 (0.15)
Working memory updating						
Mean working memory updating	0–1 (accuracy)	1	.67 (0.28)	.54	11.41	.17 (0.08)
		2	.59 (0.30)	.54	11.63	.19 (0.08)
		3	.63 (0.29)	.50	9.42	.19 (0.08)

The items and tasks were presented in German.
ICC, Intraclass correlation (the portion of between-person variance to total variance); Occ, Occasion; Mean ISD, mean intraindividual standard deviation; Deff, design effect suggested by Muthén and Satorra (1995): deff = 1 + $(c-1)$ * ICC, with c = average cluster size (in our study, the average number of occasions per child). As a rule of thumb, with deff ≥ 2, both levels should be considered in the analyses. The estimated design effects are approximations because the cluster sizes were not constant.
[a]Both items were slightly adapted after the pre-study (the parts 'last night' and 'yesterday evening' were added).
[b]The children were explicitly instructed on the difference between 'getting up' and 'waking up.'

position of the corresponding (and now invisible) creature. The children had to memorize and track the positions of the cartoon creatures in the 4 × 4 grid and enter their final locations. The updating operations were shifts to an adjacent field (horizontal, vertical, or diagonal); positions were never doubly assigned to the cartoon creatures. In both tasks, the children completed four blocks of updating operations with two and three objects, which resulted in a total of 40 responses on each occasion. The children collected points for their performance and received a short feedback at the end of each session.

Data analyses

Our data were multilevel data because repeated measures (Level 1) were nested within persons (Level 2). Therefore, both levels were considered in all analyses. We used robust maximum likelihood estimation (MLR; Mplus 7, Muthén & Muthén, 1998–2012) and managed missing data with a full information approach (FIML). FIML (besides multiple imputation) is the current state of the art and requires weaker assumptions on the cause of missing data than do traditional approaches (Enders, 2010). We considered all p-values below .05 to be significant. Our main analyses consisted of three steps. First, we tested for all occasions whether daily WMU performance was correlated with sleep quality, time in bed or tiredness within children (Level 1). Then, we tested if the dimensions could predict performance fluctuations over and above one another as well as over and above individual daily trends (at Level 1). With this, we separated long-term trends and short-time variability and controlled for expectable long-term influences within children (e.g., practice-related gains or decreasing motivation). We tested for significant fixed (mean) effects within the children and the corresponding random effects. Random effects capture between-person differences (Level 2) in within-person couplings and imply that effect sizes or possibly the direction of effects vary between children. All Level-1 predictors were centered at the person-mean. Finally, we predicted significant random effects with the between-person variables (Level 2) that might explain the children's variations in the within-person couplings.

Results

Descriptive statistics and pre-analyses

Table 1 shows the descriptive statistics for the daily sleep measures and the mean of all WMU tasks. The mean accuracies in the single WMU tasks ranged from .47 to .77 (i.e., they were clearly above the chance level and showed no ceiling effects). The intraclass correlations (ICC, the portion of between-person variance over the total variance) of the WMU tasks and sleep variables indicated that overall variance was dominated by within-person fluctuations, but the ICCs of the aggregates were somewhat higher and close to equity. All measures showed a substantial average intraindividual standard deviation.

The between-person differences in sex and grade were tested with two-level multiple-group models. The boys and girls did not differ in their sleep variables or WMU performance (ps > .31). The third- and fourth-graders did not differ in tiredness or sleep quality (ps > .16), but the fourth-graders showed higher WMU performance (M_4 = .70, M_3 = .50; z = 5.51, p < .05) and spent less time in bed (M_4 = 9.47, M_3 = 9.91; z = −2.81, p < .05).

Plausibility, reliability, and validity

Mean bedtimes and awakening were plausible for the age range of our sample and corresponded to parents' reports. Children's reported mean bedtimes/awakenings correlated with their parents' reports at .59/.56 in general, at .47/.41 on schooldays and at .64/.65 on days without school.

As sleep quality and WMU were both represented by multiple indicators, we tested for systematic within-person and between-person factors (see Figure 1 for an example). All factors were well-defined at all occasions with significant factor loadings within and between, implying systematic common variance on both levels. These two-level factor models allowed assessing reliability separately on the within- and between-person level by relating the proportion of latent variation to total variation on each level (Wilhelm & Schoebi, 2007). Internal consistencies of WMU on the between/within-person level were overall .97/.78 and did not vary substantially due to daily measurement occasion (Occasion 1: .96/.79; Occasion 2: .98/.79; Occasion 3: .97/.77) or measurement context (school context: .97/.79; out of school: .97/.78). Internal consistencies of nightly sleep quality were somewhat lower with .92/.66 and also did not vary substantially due to measurement context (school context: .90/.64; out of school: .93/.65). Thereby, it is crucial to note that between-person reliabilities are naturally higher as they are based on aggregates of up to 31 days. Overall, the pattern suggested that disturbances based on the ambulatory assessment in daily life were probably not specifically related to one measurement occasion or the school context.

Finally, as a validity check, the two-level sleep quality factor was related to the children's trait reports on sleep quality from the beginning of the study. An aggregate of up to 31 ordinary nights should, at least in part, correspond to the trait report. Indeed, the between-person sleep quality factor and the trait factor correlated at .71 in general, at .88 on schooldays, and at .61 on days without school.

Predicting daily working memory performance

For our main analysis, we used the mean of all WMU tasks and load conditions as a performance score. Sleep quality was aggregated across three items; time in bed and tiredness were single items. All correlations between the sleep variables and cognitive performance at the within- and between-person level are shown in Table S2. In summary, sleep quality and tiredness were always negatively related within children, but time in bed was distinct to both within children. The previous night's sleep quality was positively related to performance within children at the morning and noon measurements. Daytime tiredness was negatively related to performance fluctuations at noon and in the afternoon. Time in bed was not correlated with performance fluctuations. This unexpected finding led us to also test a quadratic relationship in the further analyses.

Table 2 shows the prediction of daily WMU performance on all three occasions. In the morning, all the dimensions of sleep behavior accounted for 8% of the children's daily performance fluctuations. Time in bed and sleep quality reliably predicted performance over and above daily trends. Time in bed had a significant positive linear and a negative quadratic fixed effect, which indicates an asymmetric inverted-U shaped relationship (Figure 2). Performance after too little and after too much sleep was lowered. This relationship was robust regarding outliers (e.g., in the context of special events or sickness) because it did not change substantially when tested within the 2.5 and 97.5 percentiles of the time in bed data. Sleep quality showed a fixed positive and a random effect on performance fluctuations. All of the effects were further supported by likelihood ratio tests. No significant effects were found at noon (even when the predictors were tested separately). In the afternoon, 5% of the children's daily performance fluctuations could be explained. Only tiredness predicted performance fluctuations over and above daily trends. Although the fixed negative effect of tiredness was further supported by a likelihood ratio test, its random effect was not, indicating that there were no reliable differences between children in this coupling.

The findings were further investigated in potentially relevant sub-samples. All effects were also valid for (a) only healthy children according to their parents' report (e.g., no diagnosed asthma), (b) only days on which the children reported feeling absolutely healthy (e.g. no current cold), and (c) only school days. On school days, sleep accounted for 8% of the children's performance fluctuations in the morning and even 9% in the afternoon. Not all the effects remained reliable if the analyses were

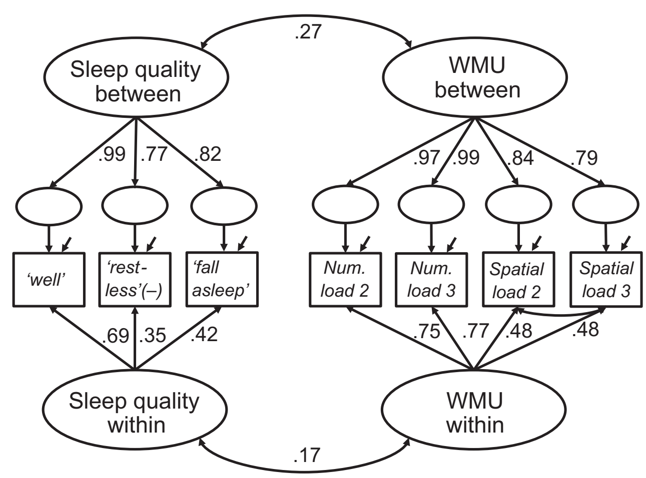

Figure 1 Mean within- and between-person relationships of WMU performance and last night's sleep quality in the morning. WMU = working memory updating. The factor loadings are standardized. The squares represent observed variables, and the circles represent latent variables. All the factor loadings and correlations were significant at $p < .05$. The fit of the model to the data was good [$\chi^2(25) = 40.73$, $p = .02$; CFI = .99; RMSEA = .02; SRMR within = .01; SRMR between = .07]

restricted to days without school (13 during the study due to two long weekends); sleep quality in the morning and tiredness in the afternoon were not significant here. However, sleep still accounted for 8% of the children's performance fluctuations in the morning, with time in bed as a significant predictor.

Finally, we aimed to identify between-person variables that were related to the random effect of sleep quality in the morning. The children's age (in months), mean time in bed, mean evening bedtime, mean morning wake time, mean perceived ease of getting up, and mean difference in time in bed on days with or without school ('propensity for sleep debt') were not predictive (*p*s > .23). However, mean performance accounted for 31% of the random effect variance ($b = -.29$, $SE = 0.14$), which indicates that the effect of sleep quality was particularly pronounced for children with lower average performance levels. It is crucial to note that there were no ceiling effects in WMU performance that might have caused this finding (Table 1). The children with high performance levels still showed substantial daily fluctuations in their morning performances (e.g., upper performance third: $M_{ISD} = .10$ ($SD = 0.05$; Scale 0–1), with M_{ISD} = mean intraindividual standard deviation) and did not show any specifics in their variations of sleep quality [e.g., upper performance third: $M_{ISD} = .18$ (SD = 0.08; Scale 0–1)].

Discussion

We identified substantial fluctuations in elementary school children's nightly sleep quality, time in bed, and daytime tiredness. The children differed from themselves over time more than they differed from other children in general. The previous night's sleep quality was positively related to performance fluctuations in the morning, but the children differed in the size of this effect. These differences were related to the children's performance level: children with lower

Table 2 Predictions of daily WMU from sleep quality, time in bed, and tiredness

	Morning (Occ. 1)		Noon (Occ. 2)		Afternoon (Occ. 3)	
	Estimate	SE	Estimate	SE	Estimate	SE
Fixed effects						
Intercept	0.669*	0.029	0.576*	0.021	0.595*	0.018
Trend day	−0.006*	0.001	−0.009*	0.001	−0.008*	0.001
Sleep quality	**0.071***	0.030	0.046	0.027	0.020	0.037
Tiredness	0.004	0.016	−0.036	0.035	**−0.060***	0.020
Time in bed linear	**0.053***	0.012	0.013	0.015	−0.021	0.020
Time in bed quadratic	**−0.003***	0.001	−0.001	0.001	0.001	0.001
Random effects						
Intercept	0.044*	0.005	0.048*	0.005	0.041*	0.004
Trend day	<0.001*	<0.001	<0.001*	<0.001	<0.001*	<0.001
Sleep quality	**0.034***	0.016	0.012	0.009	0.023	0.024
Tiredness	0.003	0.002	0.003	0.003	**0.005***	0.001
COV slope/WMU_B						
Trend day	0.001*	<0.001	0.001*	<0.001	0.001*	<0.001
Sleep quality	−0.014*	0.006	0.003	0.002	−0.006	0.006
Tiredness	−0.002	0.001	0.006	0.005	0.009*	0.003
Variance WMU_W	0.026*	0.002	0.029*	0.002	0.032*	0.003
Pseudo-R^2 model	28.05%				22.44%	
Δ Pseudo-R^2 sleep	7.75%				4.90%	
Log-likelihood	−14830.63		−14513.46		−14718.02	
Deviance differences (*df*)						
TIB lin. and quadr. = 0	28.78*(2)					
SLQ random = 0	12.82*(2)					
SLQ fix and random = 0	19.05*(3)					
Tired random = 0					4.55 (2)	
Tired fix & random = 0					14.11*(3)	

The models tested fixed and random effects of sleep quality and daytime tiredness as well as fixed linear and quadratic effects of time in bed. The random effects of time in bed approached zero and were therefore not included. Bold values indicate significant effects of the sleep-related predictors. Level 1 is represented by the model equation $WMU_{ij} = \beta_{0i} + \beta_{1i}$ (Trend day_{ij}) + β_{2i} (Time in bed_{ij}) + β_{3i} (Time in bed^2_{ij}) + β_{4i} (Sleep $quality_{ij}$) + β_{5i} ($Tiredness_{ij}$) + r_{ij} (with subscripts *i* denoting persons and *j* denoting days; r_{ij} = residual term). Level 2 is represented by the equations $\beta_{0i} = \gamma_{00} + u_{0i}$, $\beta_{1i} = \gamma_{10} + u_{1i}$, $\beta_{2i} = \gamma_{20}$, $\beta_{3i} = \gamma_{30}$, $\beta_{4i} = \gamma_{40} + u_{4i}$ and $\beta_{5i} = \gamma_{50} + u_{5i}$, with γ being the fixed effects and u being the random effects. Pseudo-R^2 was calculated as the reduction of unexplained variance WMU_W through (a) the inclusion of all predictors ('Pseudo-R^2 Model') or (b) the inclusion of all sleep-related predictors after controlling for individual daily trends ('Δ Pseudo-R^2 Sleep'). All significant effects of sleep behavior were additionally checked with likelihood ratio tests (LRTs). Therefore, the deviance difference to a model in which the respective parameters were fixed to zero was tested for significance based on the χ^2 distribution (the findings were comparable when using Satorra-Bentler scaled LRTs (Satorra & Bentler, 2001)). All effects were also valid when the standard errors were corrected for the grouping on the classroom level (with the Mplus complex twolevel random option).

TIB, Time in bed; SLQ, sleep quality; WMU, working memory updating; COV, covariance; *W*, within-person; *B*, between-person.
*$p < .05$, $N = 110$, average number of occasions per child: 21.74 (Occasion 1), 24.03 (Occasion 2), and 24.09 (Occasion 3).

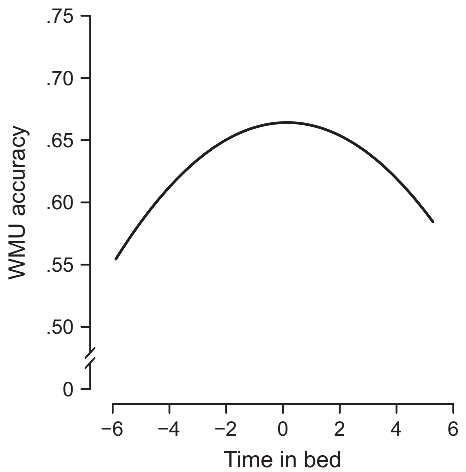

Figure 2 Working memory updating (WMU) accuracy (scaled from 0 to 1) in the morning as a function of the previous night's time in bed (in hours; centered at the person mean). Because many children tend to have a high average time in bed, numerically large departures from these averages are possible in nights with little sleep. To strengthen a valid interpretation, the predicted scores are plotted within only the 1st and 99th percentiles of the observed data distribution

average performance in general showed stronger couplings, which indicates that they might benefit more from a good night's sleep. Time in bed showed an asymmetric inverted-U shaped relationship to performance fluctuations in the morning. The children's average time in bed was optimal. Less time in bed than usual was related to lower performance, and performance after too much time in bed was also somewhat lower. Tiredness was negatively related to performance in the afternoon. Further analyses revealed differential effects for days with and without school.

With these findings, we can (a) demonstrate daily couplings between naturally varying sleep behavior and cognitive resources within children, and (b) identify which aspect of sleep behavior is relevant at which time of the day. Sleep quality and time in bed were predictive of performance in the morning, and tiredness was predictive of performance in the afternoon. The effects of last night's sleep were not stable across the day. In fact, working memory performance fluctuated during the day. Therefore, a good night's sleep might provide a comparatively good start to the day, but the later course of cognitive performance during the day might depend more strongly on other factors (e.g. events). Accordingly, tiredness was predictive of afternoon performance. Tiredness is, at least in part, a consequence of a more or less exhausting day. In addition, it is influenced by the homeostatic sleep pressure, which increases steadily during wakefulness (Achermann, 2004; Schmidt, Collette, Cajochen, & Peigneux, 2007). In the afternoon, children have been awake and active for a long time. Elementary school children usually do not nap anymore (Hill et al., 2007; Iglowstein et al., 2003), so tiredness becomes more evident in the afternoon. These ideas are also in line with the differential effects between days with and without school. Tiredness was highly important on presumably exhausting school days, but it was not predictive on days without school. Time in bed was the only significant predictor on days without school, possibly because children could more freely decide on it and were more rested.

On school days and on other days, the effect of time in bed had an asymmetric inverted-U shaped function on cognitive performance in the morning. The children's average time in bed was optimal, most likely indicating their individual need for sleep. There are substantial individual differences in the optimal amount of sleep, even in children of the same age (Buckhalt, 2012). Although the average time in bed varies considerably, deviations from this average seem to be generally unfavorable. A possible reason for the disadvantageous effect of 'too much' time in bed is that it may bring children out of their rhythmicity and, thus, negatively influence their sleep. Although this effect was found under the control of self-perceived sleep quality, there are mechanisms that are hardly accessible outside the laboratory. A desynchronization of the sleep–wake schedule and circadian rhythmicity has been found to influence sleep structure (because the propensity for sleep stages depends on circadian influences; Czeisler, Buxton, & Khalsa, 2005), sleep consolidation (because short nightly awakenings are a function of the circadian phase; e.g. Dijk & Franken, 2005; Dijk & von Schantz, 2005), and sleep-related biological functions (e.g. because some hormones are sensitive to sleep or are even suppressed during sleep; Czeisler et al., 2005). These laboratory findings provide some insight into why too much time in bed could be disadvantageous over and above self-perceived sleep quality. Our data simply suggest observing how much time in bed an individual child needs and keeping this as steady as possible.

We found that children with lower average performance showed stronger couplings between daily performance and sleep quality. This finding suggests that low-performing children were particularly vulnerable to the influence of the previous night's sleep quality, but high-performing children were also capable of good performance under unfavorable circumstances. Average performance was a strong predictor of this coupling, but other predictors, such as the children's age or average time in bed, were not significant. This might be due to a lack of statistical power at Level 2 ($N = 110$). Therefore, further evidence is needed, such as evidence about the potential moderating effect of children's average time in bed.

At first glance, all daily effects seem to be moderate in size. However, recent findings suggest that even well-established predictors of cognitive performance show numerically small effects within persons. For example, positive and negative affect together explained approximately 5% of adults' working memory fluctuations (Riediger et al., 2011), and negative affect, attention control, and motivation together explained approximately 10% (Brose et al., 2012). Bearing this in mind, the effect sizes found in this study might be considerable. Because sleep and tiredness were self-reported and cognition was measured by accuracy in updating tasks, common method effects can be ruled out. We attempted to increase the ecological validity of the study by assessing the children directly in their life context and not in an artificial test environment. The children slept in their natural environment, unaffected by the assessment. Cognitive resources were also measured in school, where they are naturally required.

However, there are some limitations that should be noted. First, our goal of measuring naturally occurring processes in children's daily lives comes at the cost of reduced experimental control and, therefore, reduced causal inference. Our findings are couplings (i.e., within-person co-variations), and our interpretation of the direction of effects is based only on the temporal order of the measures (daily cognitive performance after the previous night's sleep) and the existing literature, which suggests that experimental sleep reduction impairs children's working memory performance (Sadeh et al., 2003; Vriend et al., 2013). Second, our measures of sleep behavior are subjective self-report items. Children's self-reports should be supported by daily actigraphy and daily parental reports to provide a more complete perspective. All of these measures could offer unique insights: Whereas only the children can report how tired they feel, parents can rate how easily children get up in the morning, and actigraphy can measure the actual sleep minutes and short awakenings that children cannot remember and that parents do not observe in school-aged children anymore (Holley, Hill, & Stevenson, 2010). Third, we conducted three daily assessments of cognitive performance, which is only a rough account for a day. More occasions could provide a better picture of individual performance trajectories across the day with peaks and valleys. However, this would also increase the participant burden, which is already quite high in such an intensive study design.

Our findings have direct practical implications and allow for further research perspectives. From a practical point of view, the results are highly informative for parents and other caregivers. Previous research has only been able to inform caregivers that children's memory and learning generally benefit from good sleep (Kopasz et al., 2010). Our findings now contribute that not only the average sleeping behavior counts but also the fluctuations within children. Accordingly, children might benefit from a regular sleep schedule to produce their best cognitive performance in the morning. This finding challenges ideas such as 'single nights do not make such a difference'. If single bad nights are associated with lower cognitive resources in school, then every night counts.

Cognitive resources play an important role in the social, emotional, and learning-related functioning of children. Elementary school children rely on working memory resources to solve basic arithmetic tasks, and they perform significantly worse under additional working memory load (Busch, Oranu, Schmidt, & Grube, 2013; Imbo & Vandierendonck, 2007). Young adults with higher working memory capacity were found to focus more on challenging everyday activities and to maintain task-related thoughts better (Kane et al., 2007). They were also more effective in everyday self-regulation because their behavior was more guided by goals and attitudes and was less automatic or impulsive (Hofmann, Gschwendner, Friese, Wiers, & Schmitt, 2008). Furthermore, working memory resources are believed to allow more flexible and strategic emotional responses (Barrett, Tugade, & Engle, 2004) and to facilitate emotional regulation after negative feedback (Schmeichel & Demaree, 2010). Recently, working memory has been related to peer acceptance and overall social competence in healthy elementary school children (McQuade, Murray-Close, Shoulberg, & Hoza, 2013). Overall, a broad range of research suggests that available cognitive resources might influence children's behavior in and perception of their momentary social and educational environment. However, micro-longitudinal studies that capture these possible outcomes in children's daily life are lacking and highly needed.

Sleep behavior itself also requires further investigation. Generally, poor sleep has been related to internalizing and externalizing behavioral problems (Astill et al., 2012; Meijer et al., 2010) as well as negative affect (Baum et al., 2014; Ota, Ota, & Kitae, 2007) and emotional regulation (Vriend et al., 2013) in children and adolescents. We found systematic fluctuations in sleep behavior, which might have a direct influence on children's daily social and emotional functioning. Our findings also suggest a need to question what causes poor sleep in children. In a diary study, Åkerstedt et al. (2012) found that poor sleep quality in adults was associated with worry and anticipation of problems in the upcoming day. Sleep quality was quite sensitive to modest variations in stress. Such relationships might occur in elementary school children as well. The fact that we found sleep quality to predict performance fluctuations only on school days, which are naturally more demanding and stressful, highlights the potential of investigating the role of these additional factors.

Furthermore, our findings must be embedded in a broader research perspective. We found significant effects of sleep quality and time in bed in the morning at the beginning of the second lesson (Occasion 1), but not at noon or in the afternoon. Because the main school subjects are typically taught in the first school hours before major breaks (Klein, 2004), this finding might be particularly informative about children's further cognitive and educational development. Varying sleep behavior might foster performance fluctuations at a time of day in school in which children learn the fundamentals for later knowledge acquisition. In particular, children with a low average cognitive performance level showed higher couplings between sleep quality and performance. Taken together, these findings might yield a negative long-term perspective for low-performing children with occasional sleep problems. This finding also highlights a possible mechanism behind the well-known cross-sectional and macro-longitudinal findings indicating that sleep behavior is related to cognition and school achievement (Astill et al., 2012 for a meta-analysis on cognition; Buckhalt et al., 2009 for a longitudinal study on cognition; Dewald, Meijer, Oort, Kerkhof, and Bögels (2010) for a meta-analysis on school achievement; Meijer, 2008 for a longitudinal study on school achievement). Therefore, a developmental perspective could benefit from a micro-longitudinal approach that identifies couplings that directly occur in children's daily lives.

Acknowledgements

This research was part of the FLUX project at the IDeA-Center in Frankfurt am Main, Germany, which is funded by the Hessian Initiative for the Development of Scientific and Economic Excellence (LOEWE). We thank Heiko Rölke and the Technology Based Assessment Group at the DIPF for developing and providing the software we used to assess the children's performance and experiences via smartphones. We owe special thanks to Verena Diel, Jan Kühnhausen, Anja Leonhardt, Philipp Wiesemann, and a team of highly committed student assistants for their important roles in conducting the FLUX project. The authors have declared that they have no competing or potential conflicts of interest.

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Key points

- Substantial fluctuations of adults' daily cognitive resources are known; we found such fluctuations in elementary school children's everyday lives.
- Cognitive performance in the morning was related to nightly sleep quality and time in bed; afternoon performance was related to children's current tiredness.
- Low-performing children might be particularly influenced by the previous night's sleep quality.
- The findings provide another strong argument for consistent sleep routines because even single bad nights were associated with lower cognitive resources in school the following day.
- Cognitive resources play an important role in the social, emotional, and learning-related functioning of children.

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Accepted for publication: 3 June 2014
Published online: 23 July 2014