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The role of sleep timing in children's observational learning

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ABSTRACT

Acquisition of information can be facilitated through different learning strategies, classically associated with either declarative or procedural memory modalities. The consolidation of the acquired information has been positively associated with sleep. In addition, subsequent performance was better when acquisition was quickly followed by sleep, rather than daytime wakefulness. Prior studies with adults have indicated the viability of the alternative learning strategy of observational learning for motor skill acquisition, as well as the importance of sleep and sleep timing. However, relatively little research has been dedicated to studying the importance of sleep for the consolidation of procedural memory in children. Therefore, this study investigated whether children could encode procedural information through observational learning, and whether sleep timing could affect subsequent consolidation and performance. School-aged children aged 9–12 years ($N = 86$, 43% male, $M_{age} = 10.64$ years, $SD = .85$) were trained on a procedural fingertapping task through observation, either in the morning or evening; creating immediate wake and immediate sleep groups, respectively. Performance was evaluated the subsequent evening or morning on either a congruent or incongruent task version. Observation and task execution was conducted using an online interface, allowing for remote participation. Performance of the immediate wake group was lower for a congruent version, expressed by a higher error rate, opposed to an incongruent version; an effect not observed in the immediate sleep group. This finding showed that observational learning did not improve performance in children. Yet, immediate sleep prevented performance reduction on the previously observed task. These results support a benefit of sleep in observational learning in children, but in a way different from that seen in adults, where sleep enhanced performance after learning by observation.

1. Introduction

The acquisition and consolidation of information can be allocated to two memory modalities: the first dedicated to events and facts (declarative memory) and the second to procedural skills (procedural memory; Cohen, Eichenbaum, & Deacedo, 1985; Rajaram & Roediger, 1993; Roediger, 1990; Squire, 1992). The consolidation of newly acquired information has been positively associated with sleep. Following training, sleep can positively affect subsequent motor task performance (Hill, Tononi, & Ghilardi, 2008; Walker, Brakefield, Morgan, Hobson, & Stickgold, 2002) and recollection (Gais, Lucas, & Born, 2006; Stickgold & Walker, 2007). Improvements of performance following sleep can be stronger compared to an identical wake period (Gais et al., 2006; Hu, Stylos-Allan, & Walker, 2006; Walker et al., 2002; Wilhelm, Diekelmann, & Born, 2008). In addition, the timing of sleep relative to acquisition can affect memory consolidation and subsequent performance. When acquisition was followed by a period of sleep rather than daytime wakefulness, subsequent performance was found to be higher for both declarative (Gais et al., 2006; Talamini, Nieuwenhuis, Takashima, & Jensen, 2008) and procedural memory tasks (Van der Werf, Van der Helm, Schoonheim, Ridderikhoff, & Van Someren, 2009). These studies implemented similar durations of wakefulness and sleep, the only differences being the timing of sleep relative to acquisition. In addition, it has been suggested that the different memory modalities benefit from different sleep stages. While declarative memory has been

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positively associated with slow-wave sleep (SWS), procedural memory has been positively associated with rapid-eye movement (REM) sleep (reviewed by Marshall and Born (2007) and Plihal and Born (1999)). The time spent in these sleep stages, as well as total sleep time, has been observed to change over the life-span. Compared to adults, children spend more time in SWS and have a longer sleep duration, while adults spend relatively more time in REM sleep and have a shorter sleep duration (Ohayon, Carskadon, Guilleminault, & Vitiello, 2004). Thus, it is possible that the two memory modalities benefit differently from sleep for children and adults. Consolidation through declarative memory appears to be similar between children and adults (Prehn-Kristensen et al., 2009; Wilhelm et al., 2008), while procedural memory was found to not benefit as strongly from sleep in children as in adults (Fischer, Wilhelm, & Born, 2007; Prehn-Kristensen et al., 2009; Wilhelm et al., 2008). These changes in time dedicated to different sleep stages could potentially affect memory consolidation processes, and consequently lead to differences in performance between children and adults for declarative and procedural tasks. In addition to changes in the sleep architecture, another important aspect is that learning mechanisms and trajectories undergo marked changes from childhood to adulthood (Casey, Tottenham, Liston, & Durston, 2005). A major difference between children and young adults that might lead to differences in (observational) learning, is that children's working memory and executive functions that are prerequisites for learning, such as cognitive control, integrative processes, and speed of information processing, are still developing (e.g., Friedman, Nessler, Cycowicz, & Horton, 2009; Gathercole, 2005; Gathercole, Pickering, Ambridge, & Wearing, 2004; Kail, 2000). Consequently, children are less efficient in processes such as strategy use/development, rehearsal, chunking, encoding, and error monitoring/correction, which are imperative for the acquisition of motor skills (Thomas, 1980).

A study by Wilhelm et al. (2008) investigated the benefits of sleep for the declarative and procedural memory modalities in children and adults by training them on word pairs and a fingertapping task (Walker et al., 2002), respectively. Following acquisition, participants were either awake or asleep during the retention period. At recollection, performance was evaluated on the number of recollected word pairs and on fingertapping performance on a version that was similar (congruent) or different (incongruent) to the trained version. Performance on the declarative memory task following sleep improved for children and adults alike. Participants from the sleep groups showed higher performance opposed to the wake groups. Differences in performance and differential effects of sleep between children and adults were found on the procedural task. Adults belonging to the sleep group showed higher performance on a congruent task version as opposed to the wake group. No difference in performance was found between the two adult groups on an incongruent version. In contrast, children from the wake group had a significant increase in performance on a congruent task version opposed to the sleep group. Additionally, the wake group showed significantly higher performance on an incongruent version opposed to the sleep group. These results indicated that children and adults could benefit from sleep in a similar fashion for declarative memory consolidation, yet showed different effects of sleep on procedural memory consolidation. Adults only benefitted from a period of nocturnal sleep, whereas children's performance was positively affected by a similar period of wakefulness, rather than sleep. These observations showed the relevance of sleep for memory consolidation and subsequent performance, which can be different for children and adults depending on the memory modality.

The majority of studies that investigated the benefits of sleep on memory consolidation explicitly trained adult participants through practice, whereas little research has been done on alternative learning strategies such as observational learning. Observational learning can be an effective strategy during initial skill acquisition (Bandura, 1986; van Gog & Rummel, 2010) and can be used by children as a stepping stone to acquire new strategies and improve performance (Crowley & Siegler, 1999). Studies that focused on learning by observation have generally evaluated performance on procedural motor tasks directly following observation in adults (Bird & Heyes, 2005; Heyes & Foster, 2002). Specifically, a study by Van der Werf et al. (2009) trained adult participants on a fingertapping task through observational learning. Participants were shown a demonstration video of an experimenter novel to the task; observation took place either in the morning or evening. Observation was either followed by a period of daytime wakefulness or nocturnal sleep, thus assigning participants to either a delayed or immediate sleep group, respectively. Performance was evaluated the following morning or evening on either a congruent or incongruent fingertapping task. For the immediate sleep group, performance on a congruent task was significantly higher as opposed to an incongruent task. Interestingly, no difference in performance due to congruence was found for the immediate wake group. These results indicated the importance of sleep timing relative to acquisition for subsequent consolidation and performance. In addition, performance from the immediate sleep group indicated that performance on a procedural motor task could be improved through observational learning, with subsequent consolidation during sleep. Trempe, Sabourin, Rohbanfard, and Proteau (2011) evaluated the effects of observational learning and offline consolidation on a motor sequence task in adults. Following observation, performance was evaluated either 5 min or 24 h later. In addition, performance was also evaluated for a control group without prior observation of the task (exp. 1). Performance was improved relative to a control group due to observational learning, yet no differences in performance were observed between the 5 min and 24 h retention groups. Interestingly, Trempe et al. (2011) showed in exp. 2 that motor skill information acquired through observational learning can be consolidated and stabilized within an 8 h time period, demonstrated by a low variability in performance and no apparent negative effects of observation of a secondary sequence 8 h later. They suggested that observational learning led to consolidation processes that stabilized the acquired information of the motor skill. While this study demonstrated the possible benefit of observational learning on performance, no close investigations were executed regarding timing of subsequent sleep on consolidation and subsequent performance. The effectiveness of observational learning for procedural information should be further evaluated in light of the possible benefits of nocturnal sleep and sleep timing for subsequent consolidation, especially in children. Therefore, the present study investigated (1) whether school-aged children could learn a procedural motor task through observation, and (2) whether sleep timing relative to acquisition affected memory consolidation and subsequent performance.

The present study investigated whether school-aged children were able to encode a procedural motor task through observational learning, and whether timing of sleep relative to acquisition affected memory consolidation and subsequent performance. Eighty-six school-aged children were shown a demonstration video of a task-naïve model executing the fingertapping task. Observation took place either in the early morning or late evening; effectively creating immediate wake and immediate sleep groups, respectively. The observation took place in the children's home environment by streaming the videos through an online connection. Performance was evaluated in the early morning or late evening on either a congruent or incongruent fingertapping task, relative to the demonstration video, in order to correct for time of day effects on memory retrieval. Integration of the two memory modalities during observational learning was expected to result in better performance on a congruent task relative to an incongruent task. Sleep timing relative to memory acquisition was expected to affect performance. Observation quickly followed by sleep was expected to be associated with higher performance as opposed to acquisition being separated from sleep by a period of daytime wakefulness.

2. Materials and methods

2.1. Participants

Participants were recruited by contacting parents in collaboration with elementary schools and through social networks of colleagues from the Erasmus University Rotterdam and the Netherlands Institute for Neuroscience. Consent was obtained from parents and children prior to protocol onset. A total of 165 candidates indicated to be interested in participation. Before the start of the protocol 22 participants withdrew from the study. A total of 28 participants dropped out before the end of the study due to internet connection issues or incompatible daily schedules. Prior to analyses several participants were removed due to faulty measurements and noncompliance to instructions (e.g. typed only one sequence per trial; $N = 9$), or due to exclusion criteria (left hand preference, $N = 13$; Attention Deficit (Hyperactive) Disorder (AD(H)D), $N = 3$; and autism, $N = 4$). The final sample consisted of 86 right-handed school-aged children aged 9–12 years (43% male, $M_{\text{age}} = 10.64$ years, $SD = .85$).

2.2. Experimental design

The study was conducted over the course of seven days, starting on a Saturday. Throughout the week participants' parents were required to keep a daily sleep diary concerning the sleeping behavior of their child(ren). On two occasions participants were scheduled to either observe a demonstration video of a fingertapping task, or to execute a fingertapping task, which was either similar (congruent) or different (incongruent) to the demonstration video. The specific timing of these sessions depended on randomized group assignments, determining whether sessions would take place during the morning (between 06:30 and 10:00) or evening (between 18:30 and 22:00). Thus participants were randomly assigned to one of four groups (morning–morning, morning–evening, evening–morning, and evening–evening). Consequently, the two sessions took place either on the same day, or on two consecutive days (Fig. 1). These assignments were counterbalanced between and within groups in order to correct for possible effects of time on learning abilities. Congruency of the fingertapping task relative to the demonstration video further divided the groups, which resulted in a total of 8 subgroups. However, post-hoc analyses allowed for the merger of groups based on whether acquisition was followed by daytime wakefulness (morning–morning & morning–evening groups) or immediate sleep (evening–morning & evening–evening groups). These merged groups were thus categorized as 'immediate wake' and 'immediate sleep', respectively. It should be noted that execution of the paradigm took place either at the start of the week (Monday–Tuesday) or at the end (Thursday–Friday), which served as a control and was counterbalanced between participants. Upon completion of the paradigm participants received a voucher for an online web store.

2.3. Instruments

The present study used an online interface which allowed participants to fill in a daily sleep diary and questionnaires, as well as observation and execution of a fingertapping task.

2.3.1. Online interface

Considering that the present paradigm applied specific time windows during the morning and evening, a requirement to conduct the paradigm in a laboratory setting would have heavily interfered with participants' everyday schedules and sleeping patterns. To minimize this problem, the present study used an online interface, which allowed participation from home using participants' own computers. This online interface was a cloned and adapted version of an already functioning online interface (Netherlands Sleep Registry: http://www.slaapregister.nl/; Benjamins et al., 2013), that allowed for a high degree of control for timing sessions and registering participants' behavioral activities while using the online interface. Demonstration videos and fingertapping tasks were created and controlled using JavaScript. The questionnaires and diaries were defined by using default question types of LimeSurvey (v1.86; www.limesurvey.org). Everything was presented to the participants through the Drupal front-end of the online interface. Participants were able to log in to the online interface using pre-created usernames and passwords. On all occasions, participants' parents were able to fill in a daily sleep diary. Depending on the time and date, participants were either able to continue with the paradigm, or were shown a message indicating the date and time window for when the paradigm would continue.

2.3.2. Sleep diary

In order to gain insight into participants' sleep durations, participants' parents were required to keep a daily sleep diary concern-

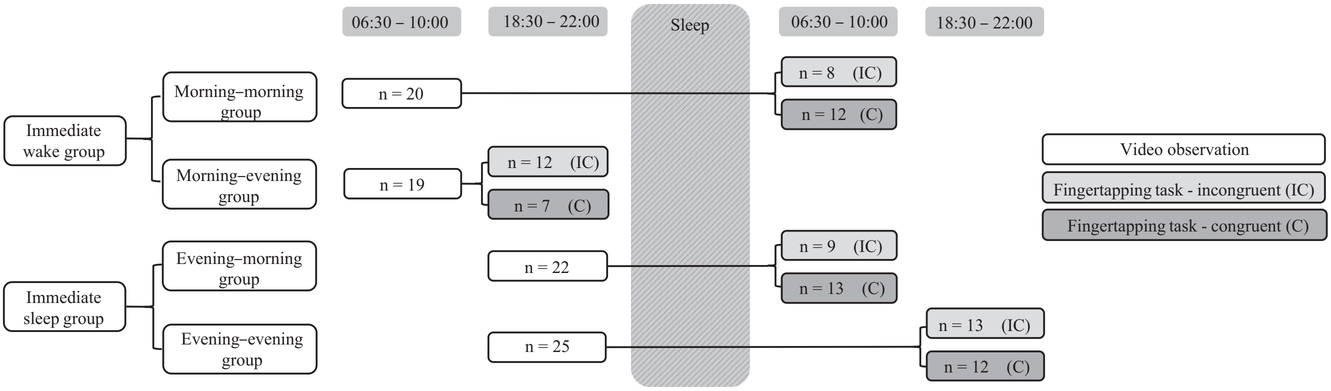

Fig. 1. Overview of group distribution. Participants were divided into four main groups which determined the timing of observation and task execution. Within these groups performance on the fingertapping task was evaluated for versions that were either incongruent (IC) or congruent (C) to the demonstration video. For analyses, groups were pooled based on the time between observation and subsequent sleep, creating immediate wake and immediate sleep groups.

ing the sleeping behavior of their child or children throughout the paradigm. This sleep diary was a Dutch translation of the Consensus Sleep Diary (Carney et al., 2012), and made inquiries regarding bedtimes, time until sleep onset, nocturnal awakenings, wake-up and get-up times, as well as subjective evaluations of sleep quality. These diaries allowed for estimations regarding time spent in bed and sleeping. The diary was converted into a digital version that participants' parents were able to fill in on a daily basis using the online interface.

2.3.3. Fingertapping demonstration video

The observation paradigm was similar to Van der Werf et al. (2009). During acquisition participants observed a demonstration video of six trials from a fingertapping task, executed by a task-naïve subject who was novel to the task using her non-dominant left hand. Hand movements were fully visible in order to maximize observation. The relevant sequence was continuously displayed both on the filmed laptop screen and additionally displayed in the center of the video (Fig. 2). Three different fingertapping sequences were used, each consisting of five elements of the numbers one to four (41324, 23142, and 32413). Sequences for the demonstration video and fingertapping task were randomized between participants. In order to prevent simultaneous practice during observation, participants were required to press and hold two keys on the keyboard (keys 'a' and 'c') using two fingers of their non-dominant left hand (ring and index finger, respectively). The demonstration video started or resumed playing whenever the two keys were continuously pressed. Upon release video playback was paused. As shown by Van der Werf et al. (2009), this requirement prevented subliminal muscle activation, preventing (un)conscious finger movements and parallel practice. This requirement also allowed for registration of the number of playback interruptions; interpreted as a measure of inattention and consequently used as a possible exclusion criterion. No participants were removed based on this criterion.

2.3.4. Fingertapping task

This task applied a similar fingertapping protocol to Walker et al. (2002). The session started with an initial countdown (10 s), which disappeared 3 s prior to trial onset. Following the initial countdown, a block design of 12 trials (23 s) and 12 inter-trial-intervals (ITI; 20 s) followed. Blocks belonging to the ITI were indicated by a red background and showed a countdown of 20 s, which disappeared 3 s prior to trial onset. Each trial was indicated by a green background (Fig. 3). Participants were instructed to repeatedly type the desired sequence as fast and accurately as possible. The desired sequence was continuously displayed in the top center of the screen and was either congruent or incongruent to the sequence shown in the demonstration video. Participants were instructed to use their non-dominant left hand to type the desired sequence and to let their right hand rest next to the keyboard. Sequences had to be typed by pressing the number keys 1–4 on a keyboard using the little finger to index finger, respectively. Typed input was displayed and masked in a text field that prevented online evaluation of performance. The text field was cleared when the amount of input characters reached a maximum, giving participants the sense of progression.

2.4. Analyses

Performance was evaluated per trial on fingertapping score, defined as the total number of correct sequences per trial, and error rate, defined as the percentage of correct input elements relative to the total number of elements per trial. Initial inspection of the data found no ceiling effects for fingertapping score or error rate, which allowed for analyses that included all 12 trials. Performance differences on fingertapping score and error rate due to congruence and group was evaluated using repeated measures ANOVA. Initial within-subjects effects were investigated using repeated measures ANOVA to determine whether participants improved their performance during the fingertapping session. Differences in performance between the four groups due to congruency were investigated. Post-hoc repeated measures ANOVA analyses showed no differences in performance between the subgroups based on sleep timing, which allowed for pooling of groups similar to the prior study by Van der Werf et al. (2009). Hence pooling created two main groups based on the timing of sleep relative to observation, creating an immediate wake group (morning–morning & morning–evening groups) and immediate sleep group (evening–morning & evening–evening groups). Again, performance differences due to congruency and group on fingertapping score and error rate were evaluated for the merged groups using repeated-measures ANOVAs with group (2 levels) and congruency (2 levels) as between-subject factors, and trial (12 levels) as within-subject factor, investigating the importance of sleep timing relative to acquisition. Data processing was done using MATLAB 7.1 (R2012b; Natick, MA, USA), with subsequent statistical analyses conducted using IBM SPSS statistics 21 (Armonk NY, USA).

3. Results

Performance was evaluated on fingertapping score (number of correct sequences) and error rate (percentage of correct input elements relative to the total number of elements). Given that no ceiling effects were observed, analyses were conducted on all 12 trials using repeated measures ANOVAs. Where appropriate, Greenhouse–Geisser corrections were used to accommodate for non-sphericity in the data as ascertained by Mauchly's test ($p < 0.05$).

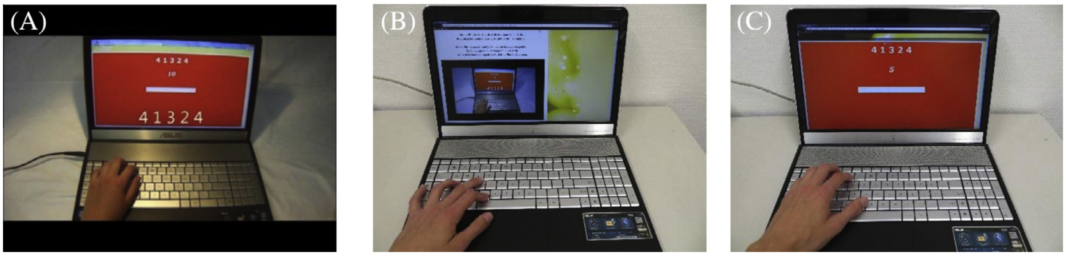

Fig. 2. Fingertapping observational paradigm. A visualization of the instruction video paradigm. (A) Screen capture of the instruction video. The instruction video started with an initial countdown of 10 s, followed by a block design of six trials and inter-trial-intervals (ITI). Each trial was indicated by a green background and lasted 23 s, during which the model typed as many sequences as possible. During ITI, the model rested her non-dominant left hand on the keyboard, with her four fingers (little finger to index finger) resting on the appropriate keys (1–4, respectively). (B) Video observation. Participants were required to press and hold two keys on the keyboard for video playback. (C) Participant executing the fingertapping task, waiting for trial onset during ITI countdown. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

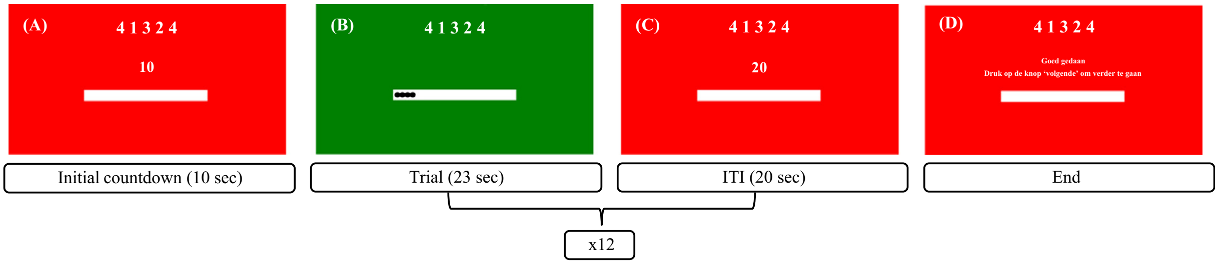

Fig. 3. Illustration of the fingertapping task. The present figure visualizes the fingertapping task protocol. (A) Initial countdown prior to onset of the first trial (B) A trial block was indicated by a green background, allowing the participant to type masked input in the text field. (C) ITI followed each trial block, indicated by a red background and a 20 s countdown that disappeared 3 s prior to trial onset. (D) At the end of the fingertapping session participants were shown instructions to continue within the online interface. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Initial analyses investigated differences in performance due to congruence and possible differences between the four groups due to timing of acquisition and recollection relative to sleep (morning–morning, morning–evening, evening–morning, and evening–evening groups). Significant within-subjects effects were found across trials for fingertapping score, $F(6.11, 476.29) = 35.75$, $p < .001$, $\eta_p^2 = .31$, and error rate, $F(8.83, 688.91) = 2.38$, $p = .013$, $\eta_p^2 = .03$. No differences in performance were found for fingertapping score between groups, $F(3,78) = .82$, $p = .49$, congruence, $F(1,78) = 1.94$, $p = .17$, nor an interaction between groups and congruence, $F(3,78) = 1.46$, $p = .23$. Similar results were found for error rate, which showed no difference in performance between groups, $F(3,78) = 1.44$, $p = .24$, congruence, $F(1,78) = 2.73$, $p = .10$, nor was there an interaction between groups and congruence, $F(3,78) = 2.46$, $p = .07$.

In line with a previous study with adults (Van der Werf et al., 2009), post-hoc repeated measures ANOVA analyses were conducted to determine whether groups could be pooled based on timing of sleep relative to acquisition. No differences were found between the morning–morning and morning–evening groups for fingertapping score, $F(1,35) = .02$, $p = .88$, as well as error rate, $F(1,35) = 1.37$, $p = .25$. In addition, no differences were found between the evening–morning and evening–evening groups for fingertapping score, $F(1,43) = .81$, $p = .37$, or error rate, $F(1,43) = 2.23$, $p = .14$. Based on these findings, the subgroups were merged as in Van der Werf et al. (2009), creating immediate wake and immediate sleep groups. Using these merged groups, similar comparisons were conducted to determine possible differences due to timing of sleep and the effect of sleep on consolidation. For fingertapping score, there were no effects of group, $F(1,82) = 1.85$, $p = .18$, or congruence, $F(1,82) = 2.37$, $p = .13$, nor an interaction between group and congruence, $F(1,82) = 2.02$, $p = .16$ (Fig. 4A and B). For error rate, no significant effect was found due to group, $F(1,82) = .82$, $p = .37$. However, significant effects were found for congruence, $F(1,82) = 4.17$, $p = .04$, $\eta_p^2 = .05$, indicating a higher error rate on congruent fingertapping versions relative to incongruent fingertapping versions, as well as an interaction between group and congruence, $F(1,82) = 7.55$, $p = .007$, $\eta_p^2 = .08$. This interaction effect indicated that the difference in error rate due to congruence was different between the two groups; the immediate wake group showed a higher error rate for the congruent fingertapping tasks relative to the incongruent tasks. No such difference was observed for the immediate sleep group (Fig. 4C and D). Importantly, no differences were observed between the two groups regarding estimated sleep time, $F(1,71) = .60$, $p = .44$, and time in bed, $F(1,60) = .46$, $p = .50$.

The previously discussed effects are further illustrated in Fig. 5, which shows the averaged performance over all 12 trials per group and congruence on both fingertapping score and error rate. Performance on a congruent version was lower for the immediate wake group, whereas no differences were observed in the immediate sleep group. Mean performance differed significantly for error rate.

4. Discussion

The present study investigated whether school-aged children were able to improve their performance on a procedural motor task when trained solely by observing a demonstration video of a fingertapping task. The effect of sleep timing on memory consolidation was investigated. The present study found that observation followed by daytime wakefulness resulted in increased errors on congruent task versions, opposed to incongruent task versions; a difference not observed when observation was followed by sleep.

The present results show that sleep timing is important for children's subsequent performance, but in an unexpected way: performance on a congruent task was lower compared to performance on an incongruent task when observation was followed by a period of daytime wakefulness. When observation was followed by nocturnal sleep, no differences in performance due to congruence were found. As we did not have a pre-sleep testing session, we cannot be certain the effects observed are really an effect of sleep on the learning process or an effect at baseline. Yet, in our previous study (Van der Werf et al., 2009), such baseline performance differences were ruled out. Therefore, we argue that performance on a task after observing a different task (i.e. incongruent) equals the performance on a novel task without any prior observation. Performance on the incongruent task is thus a proxy of baseline performance. Yet, in the absence of true baseline measurements, we can only conclude speculatively that children may benefit from sleep after observational learning, in the sense that immediate sleep prevents performance reduction. Astill et al. (2014) investigated the effects of sleep on consolidation of procedural information by explicitly training school-aged children on a fingertapping task. They found fingertapping score improved independent of sleep. However, acquisition followed by sleep was found to positively affect accuracy. As suggested by Trempe et al. (2011), consolidation processes following observational learning might result in performance stabilization, rather than improved performance. In our study, immediate sleep thus 'stabilizes' performance on the congruent task, keeping error rate and performance at the same level as that of the incongruent task, while immediate wake results in worse performance on the congruent task. Interestingly, the largest differences due to congruence on error rate for the immediate wake group can be observed during the first seven trials (Fig. 4C). We can only speculate regarding the cause of this difference in performance. It is possible that the uncontrolled testing situations induced a large variability in performance. In addition, participants could have attempted to match the observed performance from the demonstration video for congruent task versions, potentially

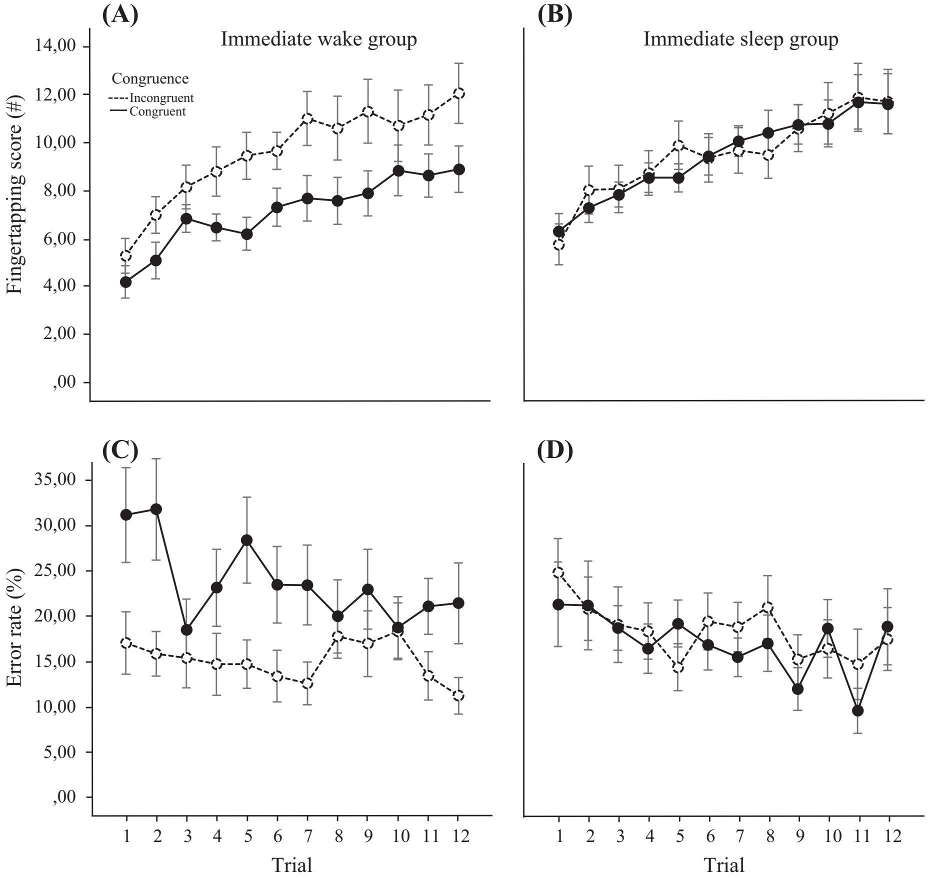

Fig. 4. Fingertapping performance. The above figure shows task performance expressed in mean fingertapping score and error rate (±SEM) for the immediate wake and immediate sleep groups, with separate lines for incongruent and congruent sessions. (A) Fingertapping scores for the immediate wake group were higher for the incongruent task as compared to the congruent task, although this failed to reach significance. (B) Fingertapping score showed no difference between the congruent and the incongruent task versions for the immediate sleep group. (C) Performance expressed by error rate was significantly different due to congruence for the immediate wake group. (D) Performance expressed by error rate showed no difference due to congruence in the immediate sleep group, but the interaction showed this to be different from the immediate wake group (C).

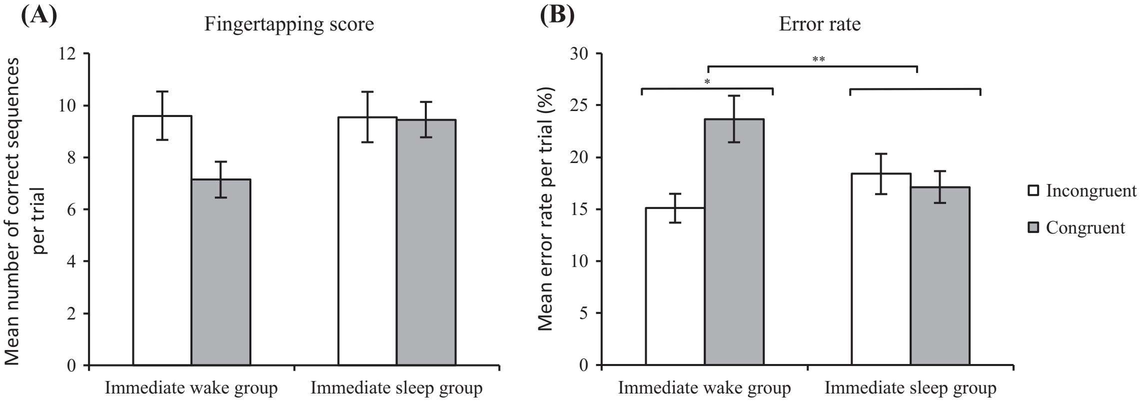

Fig. 5. Mean fingertapping performance. Mean performance on all twelve trials (±SEM). (A) Mean differences in performance due to group and congruence, expressed as fingertapping score, was found to be similar. (B) Significant differences were found for error rate due to congruence within the immediate wake group ($^{*}p < 0.05$). This effect of congruence was significantly different from the performance observed in the immediate sleep group ($^{**}p < 0.01$).

resulting in a higher error rate compared to developing their own strategy.

The present results are different from the findings with adults, for whom immediate sleep improved observational learning. The present study used the same paradigm as Van der Werf et al. (2009), who showed the importance of sleep timing relative to acquisition, expressed by improved performance on congruent fingertapping task versions in the immediate sleep group. They found no differences in performance due to congruence in the immediate wake group. The present study also found a benefit of immediate sleep, but in a different way: performance on congruent tasks was impaired when acquisition was followed by a period of daytime wakefulness. These results are unexpected considering that consolidation during wakefulness can occur, and can be stronger for children compared to adults, expressed by a positive association between consolidation during wakefulness and fingertapping score (Adi-Japha, Badir, Dorfberger, & Karni, 2014; Ashtamker & Karni, 2013). It is possible that, in order to benefit from observation of a demonstration video, the subsequent processing of the observed information depends more on declarative than procedural memory, which is still in development in children compared to adults (Ofen et al., 2007).

In addition, the study by Wilhelm et al. (2008) showed consolidation differences between children and adults. They found that adult performance was better following a period of sleep, whereas children's performance benefitted from a period of wakefulness. The present results indicate that observation of a fingertapping sequence can lead to reduced performance on a congruent task when observation and task execution are separated by a period of daytime wakefulness. Importantly, this negative effect of prior observation disappeared when observation was shortly followed by a period of sleep. Possibly, given that earlier studies found no positive effects of sleep on procedural memory consolidation in children (Prehn-Kristensen et al., 2009; Wilhelm et al., 2008), children may have encoded the demonstration video using a procedural strategy rather than using a declarative strategy, and were therefore hampered by the errors the model made. Given that the model shown in the demonstration video was naïve to the task, mistakes were made in the demonstration video. This choice was deliberate, considering a coping model has been shown to result in better performance opposed to a mastery model (Kitsantas, Zimmerman, & Cleary, 2000; Schunk & Zimmerman, 1997). However, Bandura (1986) stated that "people cannot learn much by observation unless they attend to, and accurately perceive, the relevant aspects of the modeled activities" (p. 51). So when children in our study did not see the mistakes made by the model as such, it is possible that they would learn more by doing, that is, by making and correcting their own errors. This way they would form their own internal model for the fingertapping task, rather than adapt a model observed in the demonstration video. Sleep timing would then appear to be a crucial factor to protect against this negative effect of prior observation.

This study has several potential limitations. First, a between subjects rather than a within subjects design was applied in order to evaluate the effects of observation and congruence. Following observation of the demonstration video, participants executed the fingertapping task once, which was either congruent or incongruent to the task shown in the demonstration video. Such a design showed the effects of observational learning as well as sleep timing, yet made possible changes in performance harder to determine due to the lack of evaluation of baseline performance during acquisition. Second, the study was executed by means of an online interface. While this had many advantages, as it allowed school-aged children to participate from their own home, as well as simultaneous testing of multiple participants at different locations, it also posed a limitation. Technical issues regarding participants' computer hardware or software occasionally resulted in dropout (3.5%). Furthermore, remote testing limited the amount of control on a participant's behavior and environment throughout the paradigm. While this can be considered a limitation, it also reflects a more ecologically valid way of learning and performance, both taking place in familiar environments for the participants. Third, the requirement to log in during certain time windows proved to be difficult to implement in the daily schedules of participants even though they were allowed a 3.5-h margin. In addition, the long duration of the time window could have resulted in increased variability regarding the timing of observation relative to subsequent sleep, which in turn could have affected the strength of consolidation processes during sleep, as well as overnight performance changes. Fourth, estimations of sleep duration and time in bed using diaries were suboptimal to more objective measures which could have been recorded using actigraphy. However, estimates of assumed sleep in children have been found to be comparable with sleep diaries and actigraphy (Werner, Molinari, Guyer, & Jenni, 2008). Despite these drawbacks, the present study showed the possibilities and advantages of using online paradigms and questionnaires.

Interesting directions for future studies would be to directly compare effects of sleep on observational learning of motor tasks in school-aged children, adolescents, and adults, given the changes in sleep characteristics that occur in these different age ranges (Ohayon et al., 2004). With an online testing paradigm such as the one used in the present study, this would seem feasible. It would also be interesting for education purposes to compare performance following either learning-by-doing or learning-by-observation of a fingertapping sequence as a function of sleep, and to extend this research to observational learning of cognitive tasks, such as learning to solve math problems (for a review of observational learning in cognitive domains, see van Gog & Rummel, 2010). Additionally it would be interesting for future research to obtain both subjective and objective measurements of nocturnal sleep using both sleep diaries and actigraphy.

The present study, using an online paradigm, found sleep timing to be important for subsequent performance on a fingertapping task by reducing consolidation of erroneous skill memory. Studies focusing on the importance of sleep are encouraged to take into account the importance of sleep timing on consolidation and subsequent performance.

Author contributorship

J.S.B. and F.M. created the online interface. F.J.V.S., J.S.B., and F.M. created the demonstration videos and fingertapping tasks. J.A.D.N., T.V.G, Y.D.V.D.W., and F.J.V.S. recruited the participants. F.J.V.S. and J.S.B. collected and cleaned the data. F.J.V.S. and Y.D.V.D.W. conducted statistical analyses. Y.D.V.D.W. and T.V.G. conceived and supervised the project. F.J.V.S. drafted the manuscript. All authors commented on and edited the manuscript drafts.

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