Infant Behavior and Development 65 (2021) 101652

Contents lists available at ScienceDirect

Infant Behavior and Development

journal homepage: www.elsevier.com/locate/inbede

Nap timing makes a difference: Sleeping sooner rather than later after learning improves infants' locomotor problem solving

Aaron DeMasi[a,*], Melissa N. Horger[a], Angelina M. Allia[b,c], Anat Scher[d], Sarah E. Berger[a,b]

[a] *Department of Psychology, The Graduate Center, The City University of New York, 365 Fifth Ave, New York, NY, 10016, United States*
[b] *The College of Staten Island, City University of New York, United States*
[c] *Macaulay Honors College, City University of New York, United States*
[d] *Department of Counseling and Human Development, University of Haifa, Haifa, Israel*

ARTICLE INFO

Keywords:
Infancy
Sleep
Napping
Problem solving
Learning
Walking

ABSTRACT

Twenty-nine newly-walking infants who had recently given up crawling trained to navigate a shoulder-height, nylon tunnel to reach a caregiver waiting at the other end. Infants in the *Nap First* group napped within 30 min of initial training. Infants in the *Delay First* group napped four hours after training. All infants were retested six hours after training on the same locomotor problem. Learning was measured by the number of training prompts required to solve the task, exploration, and time to solve the problem. *Nap First* infants benefited the most from a nap; they required fewer training prompts, used fewer posture shifts from training to test, and solved the task faster compared to *Delay First* infants, suggesting that optimally timed sleep does not merely protect against interference, but actively contributes to memory consolidation. This study highlights the importance of nap timing as a design feature and was a first step towards limit-testing the boundaries of the relation between sleep and learning. Infants' fragile memories require regular consolidation with intermittent periods of sleep to prevent interference or forgetting.

1. Introduction

Sleep changes significantly during infancy and toddlerhood, but one consistent feature until well into the preschool years is the presence of daytime sleep (Ednick et al., 2009; Mindell et al., 2016). Two recent reviews summarized the impact of napping on learning in infancy and early childhood (see Horváth & Plunkett, 2018; Mason, Lokhandwala, Riggins, & Spencer, 2021). In the context of declarative memory, napping positively influenced 3-month-olds' visual memory and 6- and 12-month-olds' ability to recall and imitate actions (Horváth, Hannon, Ujma, Gombos, & Plunkett, 2018; Seehagen, Konrad, Herbert, & Schneider, 2015). In addition to declarative memory, napping also helps infants remember how to perform actions that require high-order executive functions like inhibitory control and planning. Newly walking infants who napped remembered how to solve a locomotor problem involving inhibition more efficiently than infants who did not nap (Berger & Scher, 2017). Napping also facilitates infants' statistical language learning, the generalization of imitated actions to a new context, and the generalization of a grammatical rule of an artificial language (Friedrich, Wilhelm, Born, & Friederici, 2015; Horváth & Plunkett, 2018; Konrad, Herbert, Schneider, & Seehagen, 2016). Moreover, infants selectively discard irrelevant information only if they nap in between learning action sequences and imitating them (Konrad

* Corresponding author.
E-mail address: ademasi@gradcenter.cuny.edu (A. DeMasi).

https://doi.org/10.1016/j.infbeh.2021.101652
Received 21 May 2021; Received in revised form 14 September 2021; Accepted 3 October 2021
Available online 13 October 2021

et al., 2019).

Clearly naps aid learning and memory, but the processes underlying this relationship have yet to be fully explained. Within the past couple of years, researchers have made a concerted effort to begin addressing the mechanisms by which napping supports learning. For example, while 14- to 17-month-olds who did not nap remembered some visual information about previously presented objects, only infants who napped showed any neural evidence of episodic memory retention after a delay (Friedrich, Mölle, Friederici, & Born, 2020). Features of young children's daytime napping, such as greater spindle activity during NREM and proportion of time spent in slow wave sleep were related to better memory consolidation and performance on a visuospatial task, but sleep spindle activity was unrelated to memory for object pairs (Friedrich et al., 2020; Lokhandwala & Spencer, 2020). Different features of a nap make unique contributions to different tasks in infancy.

A mathematical model of neural repair and reorganization suggested that the function of sleep shifts from neural reorganization during infancy to neural repair at around 2.5 years (Cao, Herman, West, Poe, & Savage, 2020). In infancy, sleep spindles may facilitate moving short-term memories from limited hippocampal stores to long-term neocortical stores (Horváth, Myers, Foster, & Plunkett, 2015). Because changes in infants' performance from pre- to post-nap were not associated with the duration of the nap, but were associated with sleep spindle density, it is unlikely that napping merely serves to protect declarative memories from interference (Kurdziel, Duclos, & Spencer, 2013). Efforts must continue to clarify these kinds of nuances in the link between napping and learning early in development (Berger & Scher, 2021).

Understanding the temporal relationship between learning and napping is important because the more time that passes between learning and test, regardless of whether that delay includes a nap, the more opportunities there are for interference and forgetting (Muzzio & Rovee-Collier, 1996). However, it is often difficult to distinguish between sleep's role as a protective mechanism against interference versus its role in enhancing the learning that occurred prior to sleep (Cai & Rickard, 2009; Rickard, Cai, Rieth, Jones, & Ard, 2008; see Spencer, 2021). An experimental manipulation of the timing of sleep relative to learning could be useful for further understanding of infants' memory consolidation. For adults, when a delay contains a nap soon after training, memory at test benefits more than if the nap comes much later after training (Diekelmann & Born, 2010). This may be especially true for infants because their memories decay rapidly (e.g., Karaman & Hay, 2018), leaving them less equipped to store memories without an intervening period of sleep. The fragility of infantile memory may be due to the way infants' encoding differs from that of adults' who can more readily relate new experiences to prior information. Infants are not initially capable of generalization and must learn to extend their newly learned knowledge adaptively (Rovee-Collier, 1999).

Several studies have shown that infants who napped within 4 h of learning performed better at test than infants who did not nap, even when testing occurred after a 24 -h delay that included night sleep. That is, night sleep did not help the infants who did not have a nap soon after learning catch up to the infants who did nap soon after learning. This pattern was found across a variety of contexts, such as memory for action sequences and abstraction of grammatical patterns for an artificial language (Hupbach, Gomez, Bootzin, & Nadel, 2009; Konrad et al., 2019; Seehagen et al., 2015). Thus, all infants received two sleep periods between learning and test: either a nap, then night sleep or night sleep, then a nap. The key difference was whether the first sleep came within 4 h of learning. This pattern suggests that a sleep period occurring sooner rather than later after learning is optimal for infants' memory consolidation. However, because the later sleep in these studies was night sleep, the impact of recovery sleep on learning cannot be generalized to daytime sleep.

1.1. Aim

Thus, the aim of the current study was to test the effects of the timing of a daytime nap on infants' motor problem solving. Learning was assessed using a locomotor problem solving task in which newly walking infants had to crawl through a shoulder-height, nylon tunnel to reach a caregiver at the other side (Berger & Scher, 2017; Berger, 2010; Horger & Berger, 2019; Horger, DeMasi, Allia, Scher, & Berger, 2021). The postural shift to crawling is particularly challenging for newly walking infants because, when mastering a new posture, infants struggle to allocate attentional resources to inhibition, planning, and strategy maintenance (Berger, 2010; Berger, Harbourne, Arman, & Sonsini, 2019; Berger, Harbourne, & Guallpa Lliguichuzhca, 2019; Horger et al., 2021; for a review, see Berger, Harbourne, & Horger, 2018). The tunnel task provides a valuable context for studying problem solving in infancy because most infants can learn to solve it and the task elicits observable whole-body motor behaviors (Horger & Berger, 2019). Additionally, performance on the tunnel task may be more susceptible to sleep-dependent improvements than other tasks because it requires a complex sequence of motor behaviors (e.g., Brawn, Fenn, Nusbaum, & Margoliash, 2008; Kuriyama, Stickgold, & Walker, 2004). In past work, new walkers who napped between training and test solved the tunnel problem more efficiently at test than new walkers who did not nap; they approached the tunnel more quickly, used fewer prompts, had faster solution times, and made fewer errors than infants who did not nap (Berger & Scher, 2017). In the current study, as in previous work, infants were taught to navigate the tunnel and tested with the same tunnel again after a delay. To test the effects of the timing of a nap on motor problem solving, one group of infants napped right after training while the other group napped a few hours after training. We hypothesized that sleep would be most effective when it occurred soon after learning, without longer periods of intervening wakefulness.

2. Method

2.1. Participants

Criteria for participation was the ability to walk at least 10 feet across a room without falling or stopping to rest and being within a week of having given up crawling (Berger & Scher, 2017; Horger et al., 2021). Thirty-six infants were recruited and participated. Seven infants were excluded due to excess fussiness ($n = 2$), experimenter error ($n = 3$), and nap timing that was not in accordance with the study design ($n = 2$). The final sample included data from 29 infants (12 female; mean age = 13.84 months, $SD = 1.44$, range = 10.88–18.48). Infants had an average of 23.41 days of walking experience ($SD = 20.78$) and an average of 5.57 days since giving up crawling ($SD = 2.55$). Twelve infants had prior tunnel experience, 15 had no prior tunnel experience, and the parents of two infants did not know whether the infants had prior tunnel experience. Most infants were tested in the home (25 infants; 86.2 % of sample) while four were tested in the lab (4 infants; 13.8 % of sample).

Families were recruited through word of mouth and via a collaboration with branches of the local public library. Informed consent was obtained from parents on enrollment. The sample was 48.3 % White, 10.3 % Asian, 10.3 % Hispanic, 17.2 % multi-ethnic/racial, and 13.8 % chose not to answer. Most parents had a graduate degree (51.7 % of mothers and 34.5 % of fathers) or a college degree (20.7 % of mothers and 27.6 % of fathers). Ten percent of mothers and 20.7 % of fathers had at most a high school degree. Seventeen percent of mothers and 17.2 % of fathers did not report highest degree.

2.2. Procedure

Infants were assigned to one of two groups that differed depending on the timing of a nap relative to training and test. In both groups, the total delay between training and test was six hours (±30 min). Infants in the *Nap First* group ($n = 15$) napped immediately after the tunnel training for two hours (±30 min) and then had a four-hour delay of wakefulness before the tunnel test session. Infants in the *Delay First* group ($n = 14$) began their approximately two-hour nap (±30 min) four hours after the tunnel training. Naps had to last for at least 30 min during the delay to meet criteria for napping. Parents recorded when infants were put down for their naps and when they woke up, to ensure that sleep timing was consistent with group assignment. Infants tested at home slept at home while infants tested in the lab slept in the lab. Fig. 1 depicts a sample procedure. Training and test sessions were scheduled around infants' regular naps to keep their sleep schedule as natural as possible; parents were not asked to skip or delay their infants' regular naps.

2.2.1. Tunnel task

Infants were tested using the tunnel task procedure (Berger & Scher, 2017; Horger & Berger, 2019; Horger et al., 2021). At the start of the task, infants were placed, standing upright on two feet, at the entrance of a round, tricolor, nylon tunnel (18.5 in. diameter, 71 in. length). The roof of the tunnel was at infants' shoulder height, requiring infants to switch postures to crawling to fit inside of the entrance. Infants were encouraged (e.g., via verbal encouragement, snacks, toys) to navigate the tunnel to reach the caregiver at the other end. Caregivers were asked not to provide any instructions to infants for how to navigate the tunnel.

If infants did not solve the task immediately (by crawling all the way through the tunnel to the other end), a strict 15-step protocol was implemented (e.g., Berger & Scher, 2017). The protocol guided when and how experimenters highlighted task-relevant details. Three phases of five steps each were implemented in order. In the first phase, infants were reset to a standing posture at the entrance each time they attempted to detour the tunnel by walking or crawling around it. If infants still had not entered the tunnel after five standing prompts, the protocol proceeded to the second phase, wherein infants were placed on hands-and-knees at the entrance to the tunnel. If infants still had not entered the tunnel after five hands-and-knees prompts, the protocol proceeded to the third phase. In this final phase of the training protocol, the experimenter rolled five balls through the tunnel to draw attention to the route. See Fig. 2 for an example of the procedure. The session ended either when the infants crawled through the tunnel and touched the floor outside of the tunnel on the caregiver-side with both hands or when they exhausted all 15 prompts without going through. The tunnel task was administered twice: once prior to any napping, and a second time six hours after the first session.

2.2.2. Data coding

All sessions were digitally recorded. Using Datavyu (http://datavyu.org), a computerized coding system used to record frequencies and durations of behaviors, videos were coded for number of *prompts* (0–15) of the training protocol infants needed to solve the tunnel problem; number of exploratory *postural shifts* (changing postures before entering the tunnel, e.g., from standing to hands-knees or from hands-knees to sitting); *latency* to enter the tunnel (time from when infants were free to move until they entered the tunnel); *time in tunnel* (time from when infants entered the tunnel with two hands on the tunnel floor until they exited with two hands outside the tunnel); and *tunnel shifts* (postural changes inside the tunnel). Infants who used all 15 prompts and never solved the task did not have durations or latencies. A trial ended after 10 min if the infant used all 15 prompts, but still had not entered the tunnel.

***Nap First* Group**

Tunnel Training	Nap (2 hours +/- 30 minutes)		Delay (4 hours +/- 30 minutes)				Tunnel Test
8:45 – 9:00	9:00 – 10:00	10:00 – 11:00	11:00 – 12:00	12:00 – 13:00	13:00 – 14:00	14:00 – 15:00	15:00 – 15:15

***Delay First* Group**

Tunnel Training	Delay (4 hours +/- 30 minutes)				Nap (2 hours +/- 30 minutes)		Tunnel Test
8:45 – 9:00	9:00 – 10:00	10:00 – 11:00	11:00 – 12:00	12:00 – 13:00	13:00 – 14:00	14:00 – 15:00	15:00 – 15:15

Fig. 1. Sample of different nap timing groups.

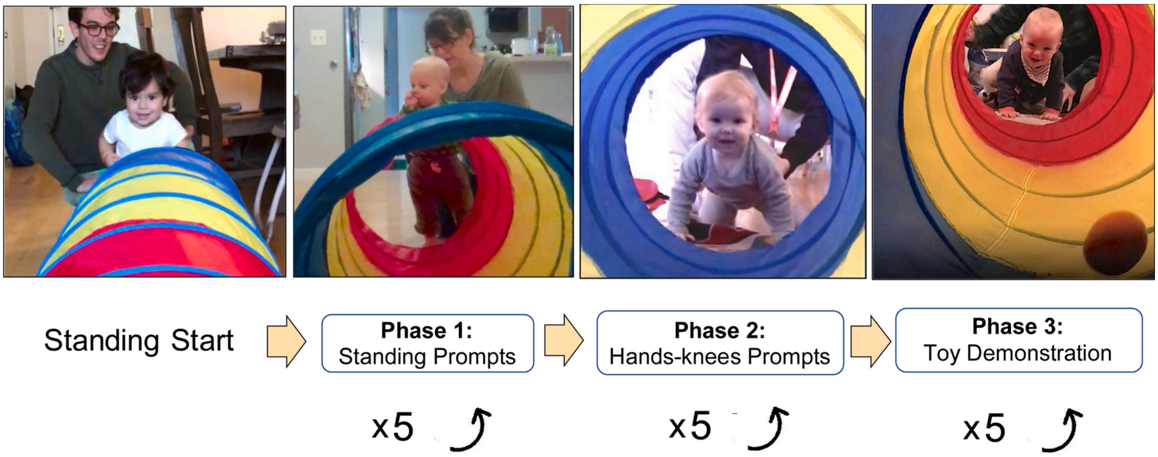

Fig. 2. Schematic diagram of the three phases of the tunnel task training protocol. Infants could receive up to 15 total prompts to solve the tunnel: 5 each of standing, hands-and-knees and toy demonstration prompts. The session ended when infants navigated all the way to the other end of the tunnel to reach the caregiver (not shown) or when 15 total prompts were reached.

2.2.3. *Reliability*

Studies using the tunnel task have shown that reliability coefficients for prompts, posture shifts, trial duration, and latency are consistently high (e.g., Berger & Scher, 2017; Horger & Berger, 2019; Horger et al., 2021). Reliability analysis was run on 20.7 % (6 out of 29 infants) of the sample for prompts, posture shifts, latencies, tunnel shifts, and time spent in the tunnel. Two-way mixed effects intra-class correlation coefficients (ICCs) using consistency were employed to assess agreement between two coders for each measurement. ICCs ranged from .96 to 1 ($ps < .01$), demonstrating excellent agreement between coders for all measures.

3. Results

3.1. *Data analysis plan*

To account for natural variation in baseline performance, all dependent variables were converted to difference scores (score at test minus score at training). Shapiro-Wilks tests showed that no dependent variable was normally distributed ($ps < .05$). Therefore, the effect of nap timing group on learning (change in prompts, exploratory postural shifts, latency to enter the tunnel, postural shifts in the tunnel, and time in tunnel from training to test) was assessed using nonparametric tests. We used $\eta^2 = Z^2/N$ to calculate effect sizes for Mann-Whitney U tests (Tomczak & Tomczak, 2014).

3.2. *Preliminary analyses*

A series of preliminary analyses revealed no differences between *Nap First* and *Delay First* groups in age ($t(27) = 0.90, p = .38$), days since giving up crawling ($t(26) = 1.36, p = .19$), prior tunnel experience $\chi^2(1, N = 27) = 1.69, p = .19$, nap duration ($t(20) = 0.49, p = .63$), or total delay duration between training and test ($t(20) = 0.88, p = .39$), corroborating that the groups differed only on timing of the nap. See Table 1 for infants' nap and delay durations during the study.

Groups were equivalent in how they approached the task initially at training. Mann-Whitney U tests showed that there were no differences between groups at the training session in prompts, posture shifts, latencies, tunnel shifts, or time spent in the tunnel ($ps > .05$). Seven infants in the sample did not solve the tunnel task during at least one of the two sessions (they received all 15 prompts, but still never entered the tunnel); this did not disqualify them for analyses involving prompts, postural shifts, and latency, but it meant that they did not contribute data to analyses involving time spent in the tunnel and postural shifts in the tunnel ($n = 29$ for analyses involving behaviors outside of the tunnel and $n = 22$ for analyses involving behaviors inside of the tunnel). Nap duration, delay duration, and time of day at test were not correlated with difference scores between training and test for any of the outcome variables (all $ps > .05$).

Table 1
Nap and delay durations in minutes.

	Mean nap duration (min-max)	Mean delay duration (min-max)
Nap First	87.46 (48–120)	332.00 (285–368)
Delay First	94.55 (30–154)	345.10 (280–413)

3.3. Power analysis

An a priori power analysis for the Mann-Whitney *U* test with two between-subjects groups based on an anticipated partial eta squared of .17 (based on the largest effect size found in Berger & Scher, 2017), a power of 0.80, and an alpha level of .05 suggested a sample size of 42 infants (21 per group) to detect a between-group difference. The intended sample size was not achieved because data collection was halted by safety measures taken due to the COVID-19 pandemic.

3.4. Nap timing and learning

3.4.1. Prompts

Infants in the *Nap First* group showed greater improvement as indexed by most infants needing fewer prompts at test (M = -2.40, Mdn = 0.00, SD = 4.58, skewness = -1.97, kurtosis = 2.66) as compared to infants in the *Delay First* group (M = 1.36, Mdn = 0.50, SD = 5.32, skewness = 1.36, kurtosis = 4.40). The distribution of prompts for each group was assessed with a Mann-Whitney U test and were significantly different, U = 59.50, z = -2.062, p = .05, η^2 = .15. Nap timing group accounted for 15 % of the variance in prompts. Fig. 3A shows the distributions, means, and medians for prompts by each group.

3.4.2. Posture shifts

Infants in the *Nap First* group had a larger decrease in posture shifts prior to entering the tunnel (M = -2.80, Mdn = -1.00, SD = 4.51, skewness = -1.10, kurtosis = 0.02) as compared to infants in the *Delay First* group (M = 0.50, Mdn = 0.50, SD = 6.63, skewness = -1.33, kurtosis = 2.91). The difference between distributions was statistically significant, U = 58.00, z = -2.067, p = .04, η^2 = .15 (see Fig. 3B). Nap timing group accounted for 15 % of the variance in posture shifts.

3.4.3. Latency to enter the tunnel

Infants in the *Nap First* group had a larger decrease in latency (M = -71.37, Mdn = -7.83, SD = 125.14, skewness = -1.78, kurtosis = 2.73) as compared to infants in the *Delay First* group (M = 44.66, Mdn = 0.83, SD = 188.67, skewness = 1.29, kurtosis = 5.76). The difference between distributions was statistically significant, U = 53.00, z = -2.271, p = .02, η^2 = .18 (see Fig. 3C). Nap timing group accounted for 18 % of the variance in latency.

3.4.4. Time in the tunnel

Using data from the 22 infants (12 *Nap First*, 10 *Delay First*) who solved the problem, we examined behavior that occurred after

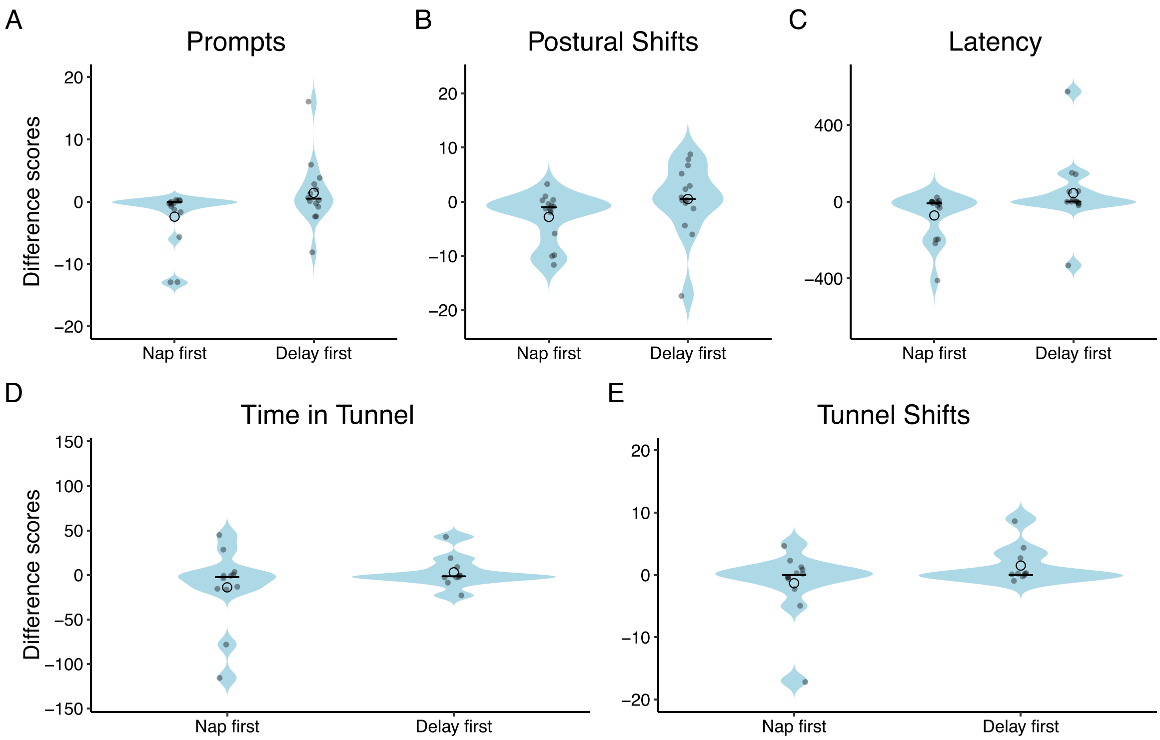

Fig. 3. Violin plot of change in outcome variables from training to test by group. Negative scores indicate an improvement. Solid horizontal lines represent the median while open circles represent the mean. Gray dots represent individual infants.

infants entered the tunnel. We found no difference in the distributions of time spent navigating the tunnel between infants in the *Nap First* group (M = -13.94, Mdn = -2.31, SD = 43.40, skewness = -1.37, kurtosis = 2.18) as compared to infants in the *Delay First* group (M = 2.97, Mdn = -1.53, SD = 17.65, skewness = 1.21, kurtosis = 2.54), U = 48.00, z = -0.79, p = .46, η^2 = .03 (see Fig. 3D).

3.4.5. Posture shifts in the tunnel

Similarly, we found no difference in the distributions of posture shifts in the tunnel between infants in the *Nap First* group (M = -1.33, Mdn = 0.00, SD = 5.47, skewness = -2.38, kurtosis = 6.95) as compared to infants in the *Delay First* group (M = 1.50, Mdn = 0.00, SD = 3.06, skewness = 1.96, kurtosis = 3.78), U = 46.50, z = -0.94, p = .38, η^2 = .04 (see Fig. 3E).

4. Discussion

The aim of this study was to investigate the effect of the timing of a nap relative to learning and test on infants' locomotor problem solving. Newly walking infants were trained to solve a challenging locomotor task which required them to inhibit their preferred locomotor strategy of walking in order to crawl through a tunnel. After initial training, half of the infants napped immediately, and the other half napped four hours later. Learning was assessed with the tunnel a second time six hours after initial training. Only those who napped immediately after training showed consistent improvement across number of prompts, exploratory postural shifts, and latency. However, nap timing did not appear to impact posture shifts made in the tunnel or time spent in the tunnel. The results supported our hypothesis that a period of sleep was most effective at consolidating infants' memory for a solution to a problem when it occurred soon after learning.

Timely napping between learning and test contributed to memory consolidation and did not merely protect against interference from competing information. We explicitly varied the timing of a nap relative to training and test to ensure that no group went without a nap and controlled for the duration of the delay between training and test. This design allowed us to control for fatigue, which has posed a significant challenge in the study of infant sleep. To date, many studies comparing the difference between having a nap versus not having one have been unable to claim that a nap caused memory consolidation per se because comparison groups comprised infants who were possibly tired and at the peak of their homeostatic sleep drive (Jenni & Carskadon, 2007). We contend that our participants were well-rested as they all napped at their typical nap time and experienced a comparable time delay between training and test. Timely daytime sleep assists in memory consolidation for infants over a six-hour period just as it does over a 24 -h period (Hupbach et al., 2009; Konrad et al., 2019; Seehagen et al., 2015).

Infants in the *Delay First* group did not improve at test, and many even got worse. In the current study, the mere presence of a nap was not sufficient to spark improvement in infants' learning on the tunnel task. *Delay First* infants may have experienced interference with consolidation due to the timing of the nap. Previous research found the longer the delay between 6-month-olds' contingency learning and retention, the less likely they were to remember what they learned (Muzzio & Rovee-Collier, 1996). Similarly, a nap may be more likely to consolidate infants' memory the shorter the delay between learning and napping. If the delay between training and napping exceeds four hours (as it did for *Delay First* infants in our study), the consolidating power of a nap decreases. Systematically varying delay times between training and a nap would shed light on how much time can pass after a nap before it stops being beneficial for memory consolidation.

Infants in the *Nap First* group showed more improvement at test compared to the *Delay First* group, despite both groups having a nap and the same amount of time between training and test. Differences between the groups in performance at test may be explained by another factor such as sleep inertia. Sleep inertia is a state of impaired cognition experienced upon awakening from sleep (Wertz, Ronda, Czeisler, & Wright, 2006). In adults, the negative effects of sleep inertia on attention can persist for as long as 30 min after waking from sleep (Ritchie et al., 2017). It remains unknown how long this lasts and whether it exists at all for infants. Because infants in the *Delay First* group were tested shortly after waking up, we cannot rule out the possible impact of sleep inertia on infants' problem solving. Future work may want to investigate this possibility directly, including asking how long sleep inertia lasts in infancy and whether there is an improvement in performance once sleep inertia has worn off.

A well-timed nap may impact different aspects of problem solving in different ways. One advantage of using a locomotor problem to study the impact of napping on learning is that it allowed us to expand upon earlier findings (Berger & Scher, 2017) by differentiating the types of learning, specifically measures of strategy choice and measures of strategy maintenance (Horger & Berger, 2019). Learning associated with decision-making and strategy choice benefitted more from a well-timed nap than the ability to maintain a strategy over the course of solving the problem. When infants napped directly after training, performance became more efficient (fewer prompts, fewer postural shifts, and shorter latencies) than for infants who napped hours after training, who got worse at the task. It is possible that well-timed sleep may not only help infants remember a solution that they previously learned, but also to generalize new insights for approaching a task from an old solution to a new solution (Konrad et al., 2016). In contrast, for learning associated with strategy maintenance, there were no significant group differences in infants' ability to maintain the crawling posture as they navigated the tunnel. It is noteworthy that for the two variables measuring strategy maintenance, we observed independent contributions from the nap itself and from the timing of that nap relative to learning. Napping consolidated execution of the task for both groups, compared to the original study where infants who did not receive a nap between learning and test showed no improvement in strategy maintenance (Berger & Scher, 2017). However, only the *Nap First* group subsequently improved; the *Delay First* group stayed the same.

Successfully solving the tunnel task depends on aspects of executive functioning, such as the inhibitory control required for switching from walking to crawling or for maintaining crawling for the duration of the trial (Berger, 2010). To date, most research on the relation between executive functioning and sleep has been with preschoolers. These studies have generally found that the better the quality of preschoolers' sleep and the more rapid the maturation of sleep patterns, the healthier or more mature the executive functioning, either when measured immediately after a nap (Spencer, 2021) or in the long term (Bernier, Cimon-Paquet, & Tétreault, 2021). There is not yet enough evidence in this area to determine what sleep parameters would optimize different types of learning in infancy, but the impact of night sleep on self-regulation "may be more consistent across infancy and early childhood, whereas the effect of naps on self-regulation vary by task and age" (Breitenstein, Hoyniak, McQuillan, & Bates, 2021, p. 121).

Whereas statistically, sleep may affect different aspects of problem solving differently (napping facilitating strategy discovery and choice, but not strategy maintenance), we cannot rule out the possibility of little to no difference in how sleep affects facets of problem solving. It could be that we were simply unable to disentangle the confound between the reduced sample size in the analyses for postural shifts and time spent in the tunnel because those variables could only be calculated for the infants who solved the task. For about 24 % of our sample, the tunnel task was unsolvable for at least one of the two sessions. Future work should aim to address this confound directly, including using a variety of tasks designed to parse out the skills that do and do not benefit from sleep periods during infancy and toddlerhood (Mason et al., 2021; Seehagen, Zmyj, & Herbert, 2019).

The proportion of time spent in each sleep state changes throughout the first year. By approximately one year of age, most infants enter NREM first after they fall asleep and, if daytime sleep periods are short, it is possible to never enter REM sleep (Mason et al., 2021; Sheldon et al., 2014). Sleep spindles (a feature of NREM sleep) are positively correlated with specific kinds of memory, such as a visuospatial task (Kurdziel et al., 2013), but not others, such as object pairs (Friedrich et al., 2020). While we did not measure sleep architecture in the current work, the unique nature of our task, as a full-body, goal-directed, motor problem-solving challenge, creates an interesting contrast to previous experimental paradigms like visuospatial learning. In both instances, a period of daytime sleep between learning and test was beneficial. Napping may be important for infants learning the tunnel task and visuospatial tasks because both require working memory and planning. Perhaps sleep does not facilitate learning in infancy for tasks like learning object pairs because such tasks tap different cognitive demands.

A challenge to ongoing research will be to identify what memory system the tunnel task relies on. Strategy choice may have elements of the declarative memory system if infants explicitly recalled the action they engaged in during training, whereas the procedural memory system may be involved if infants adapted their motor strategies in real time (King, Hoedlmoser, Hirschauer, Dolfen, & Albouy, 2017). Moreover, the strategy maintenance behaviors performed inside the tunnel may rely on the same or different memory systems. Some researchers have argued that the tunnel task is a procedural memory task (Mason et al., 2021), whereas others have expressed uncertainty (T. Ricker, personal communication, December 10, 2015 and April 1, 2016). Future work can directly answer this question by measuring sleep architecture during naps, particularly state distributions around tasks, to pinpoint whether the patterns are more akin to traditionally declarative or procedural tasks—or something else altogether. The microstructure of sleep can differentially impact types of learning as early as infancy (Mason et al., 2021). The use of a new, low-cost automatic sleep state measurement comparable to polysomnography may prove expedient to answering such research questions and expanding them to more tasks (Horger & Berger, 2021).

4.1. Limitations

The primary limitation of the current study is the small sample size. While we did not meet the sample size requirements of the a priori power analysis, we have no practical reason to suspect that our results are by-chance findings because effect sizes were relatively large, similar to effect sizes found in other studies with the same task, and because prior research with the tunnel task has shown it to be linked to daytime sleep and quality of night sleep prior to administration of the task (Berger & Scher, 2017; Horger et al., 2021). Replication of the current study will be necessary to confirm a robust effect of nap timing on infants' learning.

4.2. Conclusion

This study advances an argument recently proposed by Mason et al. (2021) that the direction of research on the relation between sleep and learning must consider design to understand how research paradigms impact outcomes. Building on previous studies that used the same tunnel task highlighted the importance of nap timing as a design feature and was a first step towards limit-testing the boundaries of the relation between sleep and learning. The timing of a nap relative to learning was a major factor in promoting memory consolidation. Infants' fragile memories require regular consolidation with intermittent periods of sleep to prevent interference or forgetting, but the details of what constitutes "regular" and "well-timed" are being determined as the study of the relation between infants' sleep and learning is still in its infancy.

Author statement

Aaron DeMasi: Validation, Formal Analysis, Investigation, Data Curation, Writing – Original Draft, Writing- Reviewing and Editing, Visualization, Supervision.

Melissa N. Horger: Validation, Formal Analysis, Investigation, Data Curation, Writing – Original Draft, Writing – Reviewing and Editing, Supervision.

Angelina M. Allia: Validation, Investigation, Data Curation, Writing – Original Draft, Writing – Reviewing and Editing.

Sarah E. Berger: Conceptualization, Methodology, Validation, Investigation, Resources, Writing – Original Draft, Writing – Reviewing and Editing, Visualization, Supervision, Project Administration, Funding Acquisition.

Anat Scher: Conceptualization, Methodology, Investigation, Resources, Writing – Reviewing and Editing, Supervision, Project Administration, Funding Acquisition.

Declaration of Competing Interest

The authors report no declarations of interest.

Acknowledgements

This manuscript is based in part on a first doctoral exam submitted to the Graduate Center of the City University of New York by A. D. and on an undergraduate honors thesis submitted to the College of Staten Island Department of Psychology by Pascale Saad in partial fulfillment of the requirements to graduate with honors. Portions of this research were presented at the XXI Biennial Meeting of the International Congress on Infant Studies, Philadelphia, PA, July, 2018; the Joint International Workshop for Understanding and Promoting Change from Early to Complex Skills in Typical and Atypical Development: A Cross-Population Approach, University of Bologna, Bologna, Italy, October, 2018; and the Conference on Cognition Research of the Israeli Society for Cognitive Psychology, Akko, Israel, February, 2019. We gratefully acknowledge the assistance of the Child Development Lab, especially Pascale Saad, Dana Friedman, Fatima Arman, Ruth Marsiliani, Sapir Elmaliah, Salwa Raheel, Daniel Palmieri and we thank the parents and infants who participated. Funding: This work was supported by the National Science Foundation, Division of Behavioral and Cognitive Science [1551703] and Professional Staff Congress–City University of New York (PSC–CUNY) [Award No. 67509-00 45] to S.E.B; a Binational Science Foundation (BSF-2015606) to A.S.; and a CUNY Coordinated Undergraduate Education Research Stipend and International Congress of Infant Studies Undergraduate Summer Research Fellowship to Pascale Saad.

References

Berger, S. E. (2010). Locomotor expertise predicts infants' perseverative errors. *Developmental Psychology, 46*(2), 326.
Berger, S. E., & Scher, A. (2017). Naps improve new walkers' locomotor problem solving. *Journal of Experimental Child Psychology, 162*, 292–300.
Berger, S. E., & Scher, A. (2021). Introduction. In S. E. Berger, A. Scher, & R. T. Harbourne (Eds.), *Advances in child development and behavior, volume 60, interdisciplinary perspectives on the relation between sleep and learning in early development* (pp. 1–8). Burlington: Academic Press. Benson, J. B., Series Editor.
Berger, S. E., Harbourne, R. T., & Horger, M. (2018). Cognition-action trade-offs reflect organization of attention in infancy. In J. B. Benson (Ed.), *Advances in child development and behavior* (vol. 54, pp. 45–86). Burlington: Academic Press.
Berger, S. E., Harbourne, R. T., Arman, F., & Sonsini, J. (2019). Balancing act (ion): Attentional and postural control strategies predict extent of infants' perseveration in a sitting and reaching task. *Cognitive Development, 50*, 13–21.
Berger, S. E., Harbourne, R. T., & Guallpa Lliguichuzhca, C. L. (2019). Sit still and pay attention! Trunk movement and attentional resources in infants with typical and delayed development. *Physical & Occupational Therapy in Pediatrics, 39*(1), 48–59.
Bernier, A., Cimon-Paquet, C., & Tétreault, É. (2021). Sleep development in preschool predicts executive functioning in early elementary school. In S. E. Berger, A. Scher, & R. T. Harbourne (Eds.), *Advances in child development and behavior, volume 60, interdisciplinary perspectives on the relation between sleep and learning in early development* (pp. 159–178). Burlington: Academic Press. Benson, J. B., Series Editor.
Brawn, T. P., Fenn, K. M., Nusbaum, H. C., & Margoliash, D. (2008). Consolidation of sensorimotor learning during sleep. *Learning & Memory, 15*(11), 815–819.
Breitenstein, R. S., Hoyniak, C. P., McQuillan, M. E., & Bates, J. E. (2021). Sleep and self-regulation in early childhood. In S. E. Berger, A. Scher, & R. T. Harbourne (Eds.), *Advances in child development and behavior, volume 60, interdisciplinary perspectives on the relation between sleep and learning in early development* (pp. 111–137). Burlington: Academic Press. Benson, J. B., Series Editor.
Cai, D. J., & Rickard, T. C. (2009). Reconsidering the role of sleep for motor memory. *Behavioral Neuroscience, 123*(6), 1153.
Cao, J., Herman, A. B., West, G. B., Poe, G., & Savage, V. M. (2020). Unraveling why we sleep: Quantitative analysis reveals abrupt transition from neural reorganization to repair in early development. *Science Advances, 6*(38), eaba0398.
Diekelmann, S., & Born, J. (2010). The memory function of sleep. *Nature Reviews Neuroscience, 11*(2), 114–126.
Ednick, M., Cohen, A. P., McPhail, G. L., Beebe, D., Simakajornboon, N., & Amin, R. S. (2009). A review of the effects of sleep during the first year of life on cognitive, psychomotor, and temperament development. *Sleep, 32*(11), 1449–1458.
Friedrich, M., Wilhelm, I., Born, J., & Friederici, A. D. (2015). Generalization of word meanings during infant sleep. *Nature Communications, 6*(1), 1–9.
Friedrich, M., Mölle, M., Friederici, A. D., & Born, J. (2020). Sleep-dependent memory consolidation in infants protects new episodic memories from existing semantic memories. *Nature Communications, 11*(1), 1–9.
Horger, M. N., & Berger, S. E. (2019). The role of walking experience on whole-body exploration and problem solving. *Cognitive Development, 52*, Article 100825.
Horger, M. N., & Berger, S. E. (2021). Noninvasive, in-home state coding in infants and toddlers using an automated coding system. February *Poster presented at the international pediatric sleep association (virtual)*.
Horger, M. N., DeMasi, A., Allia, A. M., Scher, A., & Berger, S. E. (2021). Newly walking infants' night sleep impacts next day learning and problem-solving. In S. E. Berger, A. Scher, & R. T. Harbourne (Eds.), *Advances in child development and behavior, volume 60, interdisciplinary perspectives on the relation between sleep and learning in early development* (pp. 57–83). Burlington: Academic Press. Benson, J. B., Series Editor.
Horváth, K., & Plunkett, K. (2018). Spotlight on daytime napping during early childhood. *Nature and Science of Sleep, 10*, 97.
Horváth, K., Hannon, B., Ujma, P. P., Gombos, F., & Plunkett, K. (2018). Memory in 3-month-old infants benefits from a short nap. *Developmental Science, 21*(3), Article e12587.
Horváth, K., Myers, K., Foster, R., & Plunkett, K. (2015). Napping facilitates word learning in early lexical development. *Journal of Sleep Research, 24*(5), 503–509.
Hupbach, A., Gomez, R. L., Bootzin, R. R., & Nadel, L. (2009). Nap-dependent learning in infants. *Developmental Science, 12*(6), 1007–1012.
Jenni, O. G., & Carskadon, M. A. (2007). Sleep behavior and sleep regulation from infancy through adolescence: Normative aspects. *Sleep Medicine Clinics, 2*(3), 321–329.
Karaman, F., & Hay, J. F. (2018). The longevity of statistical learning: When infant memory decays, isolated words come to the rescue. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 44*(2), 221–232.
King, B. R., Hoedlmoser, K., Hirschauer, F., Dolfen, N., & Albouy, G. (2017). Sleeping on the motor engram: The multifaceted nature of sleep-related motor memory consolidation. *Neuroscience & Biobehavioral Reviews, 80*, 1–22.
Konrad, C., Dirks, N. D., Warmuth, A., Herbert, J. S., Schneider, S., & Seehagen, S. (2019). Sleep-dependent selective imitation in infants. *Journal of Sleep Research, 28*(1), Article e12777.
Konrad, C., Herbert, J. S., Schneider, S., & Seehagen, S. (2016). Gist extraction and sleep in 12-month-old infants. *Neurobiology of Learning and Memory, 134*, 216–220.
Kurdziel, L., Duclos, K., & Spencer, R. M. (2013). Sleep spindles in midday naps enhance learning in preschool children. *Proceedings of the National Academy of Sciences, 110*(43), 17267–17272.
Kuriyama, K., Stickgold, R., & Walker, M. P. (2004). Sleep-dependent learning and motor-skill complexity. *Learning & Memory, 11*(6), 705–713.
Lokhandwala, S., & Spencer, R. M. (2020). Slow wave sleep in naps supports episodic memories in early childhood. *Developmental Science*, Article e13035.
Mason, G. M., Lokhandwala, S., Riggins, T., & Spencer, R. M. (2021). Sleep and human cognitive development. *Sleep Medicine Reviews*, 101472.

Mindell, J. A., Leichman, E. S., Composto, J., Lee, C., Bhullar, B., & Walters, R. M. (2016). Development of infant and toddler sleep patterns: Real-world data from a mobile application. *Journal of Sleep Research, 25*(5), 508–516.

Muzzio, I. A., & Rovee-Collier, C. (1996). Timing effects of postevent information on infant memory. *Journal of Experimental Child Psychology, 63*(1), 212–238.

Rickard, T. C., Cai, D. J., Rieth, C. A., Jones, J., & Ard, M. C. (2008). Sleep does not enhance motor sequence learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 34*(4), 834.

Ritchie, H. K., Burke, T. M., Dear, T. B., McHill, A. W., Axelsson, J., & Wright, K. P., Jr (2017). Impact of sleep inertia on visual selective attention for rare targets and the influence of chronotype. *Journal of Sleep Research, 26*(5), 551–558.

Rovee-Collier, C. (1999). The development of infant memory. *Current Directions in Psychological Science, 8*(3), 80–85.

Seehagen, S., Konrad, C., Herbert, J. S., & Schneider, S. (2015). Timely sleep facilitates declarative memory consolidation in infants. *Proceedings of the National Academy of Sciences, 112*(5), 1625–1629.

Seehagen, S., Zmyj, N., & Herbert, J. S. (2019). Remembering in the context of internal states: The role of sleep for infant memory. *Child Development Perspectives, 13*(2), 110–115.

Sheldon, S. H., Ferber, R., Kryger, M. H., & Gozal, D. (Eds.). (2014). *Principles and practice of pediatric sleep medicine e-book*. Elsevier Health Sciences.

Spencer, R. M. (2021). The role of naps in memory and executive functioning in early childhood. In S. E. Berger, A. Scher, & R. T. Harbourne (Eds.), *Advances in child development and behavior, volume 60, interdisciplinary perspectives on the relation between sleep and learning in early development* (pp. 139–158). Burlington: Academic Press. Benson, J. B., Series Editor.

Tomczak, M., & Tomczak, E. (2014). The need to report effect size estimates revisited. An overview of some recommended measures of effect size. *Trends in Sport Sciences, 21*(1).

Wertz, A. T., Ronda, J. M., Czeisler, C. A., & Wright, K. P. (2006). Effects of sleep inertia on cognition. *Journal of the American Medical Association, 295*(2), 159–164.