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The unique contributions of day and night sleep to infant motor problem solving

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ABSTRACT

The current study sought to tease apart the unique contributions of napping and nighttime sleep to infant learning, specifically in the context of motor problem solving. We challenged 54 walking infants to solve a novel locomotor problem at three time points—training, test, and follow-up the next morning. One group of infants napped during the delay between training and test. Another group did not sleep during the delay. A third group received the test immediately after training with no delay. Only the Nap group's strategy choices continued to improve through the follow-up session, suggesting that daytime sleep has an active role in strengthening otherwise fragile memory. Although group did not affect strategy maintenance, walk experience did, suggesting that task difficulty may shape the impact of sleep on learning. Thus, day sleep and night sleep make independent contributions to the consolidation of motor problem-solving strategies during infancy.

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Introduction

Across a variety of methodological paradigms sleep supports learning during infancy (e.g., Cao et al., 2020; Diekelmann & Born, 2010; Mason et al., 2021) as salient memories are selected, strengthened, and redistributed from the hippocampus to the cortex (Stickgold & Walker, 2013). For example, when tested in a single day, infants who napped between training and test were better able to remember vocabulary and rules for language (Friedrich et al., 2015; Gómez et al., 2006; Horváth et al., 2015; Hupbach et al., 2009; Simon et al., 2017). Researchers explicitly taught infants by pairing novel images with unknown words (Friedrich et al., 2015; Horváth et al., 2015) or by playing snippets of an artificial language (Hupbach et al., 2009). In other examples of declarative memory tasks, such as recalling specific actions, napping also promoted consolidation (Horváth et al., 2018; Lokhandwala & Spencer, 2021; Seehagen et al., 2015; for an exception, see Werchan & Gómez, 2013).

Similarly, in a procedural memory task where infants learned to solve a novel locomotor problem, researchers offered infants a series of structured prompts if they could not figure out how to transition from walking to crawling to navigate through a tunnel on their own. Infants who napped after training reached the solution more efficiently at test than those who did not, needing fewer prompts and exiting the tunnel more quickly (Berger & Scher, 2017). Better quality of sleep the night before training conferred a similar benefit; infants with better sleep displayed more readiness to learn, as indexed by their efficiency of problem solving on the first presentation of the locomotor task (Horger et al., 2021). However, these results may reflect third-factor or more general underlying developmental processes because they are observational and correlational in nature.

Daytime sleep is a regular aspect of the circadian rhythm for the first several years of life. As such, it may be more fitting to study napping and night sleep in tandem. Research with preschoolers suggests that napping and night sleep play complementary roles for consolidating information. For example, 2.5-year-olds who napped after an object categorization task were better able to generalize at test the next day than children who slept only at night, suggesting that the function of napping was to retain new information until it could be generalized during the alternating rapid eye movement (REM) and non-REM (NREM) cycles characterizing night sleep (Werchan et al., 2021). Similarly, napping benefitted preschoolers' procedural learning of a serial reaction time task, but not until the next day after they also had a night of sleep. Improvement was indexed by completing the learned motor sequence more quickly the following morning. In this case, the authors posited that explicit memory may be consolidated immediately with a nap, but implicit procedural learning may take longer to process and may require a night of sleep (Desrochers et al., 2016).

Research examining multiple bouts of sleep in participants younger than 2.5 years is sparser, but it is important because the role of REM sleep is purported to shift from neural reorganization to repair around this time (Cao et al., 2020). In one study of 15-month-olds, only those who napped retained the grammar of an artificial language 24 h after learning it (Hupbach et al., 2009). A second declarative memory paradigm with 6- and 12-month-olds replicated these results; infants who napped within 4 h of training recalled twice as many actions the following day as those who did not nap (Seehagen et al., 2015). When the paradigm was scaled up to include 15- and 24-month-olds, those who napped produced more actions, although the amount was not significantly different from that of those who did not (Konrad et al., 2019). Based on the literature with preschoolers, it is likely that procedural tasks would benefit in a similar way, but no research has directly tested this hypothesis.

Interactions between developmental domains

Studying procedural learning is challenging during infancy because it is a period of dramatic change. Infants' motor abilities are rapidly evolving. As infants transition from novice to expert in a given skill, their cognitive abilities fluctuate in an inverse pattern. Such an interaction is referred to as a cognition–action trade-off and can resemble a regression (Berger et al., 2018). For example, infants who are learning to sit independently revert to a more immature looking pattern, gazing longer at a familiar object. Once they can stabilize their posture, they return to looking quickly, recognizing the object, and looking away again because resources that were allocated to balance control can now be allocated to information processing (Harbourne et al., 2014).

Although it is more common for developmental research to control for infant age, those studies that control for motor ability or experience tend to find those variables more explanatory. When 13-month-olds were presented with a locomotor A-not-B task, for example, walkers perseverated on the old location, whereas crawlers successfully inhibited and went to the new location (Berger, 2010). The current study endeavored to control for locomotor expertise to better understand the contributions of day and night sleep to motor problem solving during infancy.

The current study

Using the motor problem-solving task originally designed by Berger and Scher (2017), during a distinct phase in development—the onset of walking—we examined infants' learning with and without a period of daytime sleep that followed training and after night sleep. The task is ideal because it is a whole-body motor task. Studying children's problem solving in such a context allows for the visualization of the sub-components of problem solving (Berger et al., 2015; DeMasi & Berger, 2021). Here, infants' exploration as they chose a strategy and errors as they tried to maintain that strategy were as visible as their success. Such behavioral coding has confirmed that infants' ability to solve the tunnel task varied as a function of walk experience; expert walkers with more than 30 days of experience and very new walkers who still crawled regularly could navigate the tunnel with ease, whereas those with a moderate amount of experience struggled (Horger & Berger, 2019). Controlling for expertise, and thus task difficulty, is also important because the adult literature suggests that it mediates the role of sleep in consolidation (Fogel et al., 2015).

Aims

Our first aim was to examine the impact of napping on motor problem solving during infancy, specifically strategy choice and maintenance. We expected that a short period of sleep following infants' experience with a challenging task would enhance consolidation, resulting in more efficient problem solving later that day (Berger & Scher, 2017). The remaining infants either did not nap after experiencing the task or experienced it again immediately. The latter group controlled for the impact of a delay, which may present an opportunity for interference and impede consolidation.

Our second aim was to differentiate the contributions of daytime and nighttime sleep to infants' motor problem solving. Toddler and preschool research considering two bouts of sleep saw benefits only the following day, after having both a nap and a night of sleep (Desrochers et al., 2016; Werchan et al., 2021). Thus far, infant research incorporating both has been done only in relation to declarative memories (Hupbach et al., 2009; Seehagen et al., 2015). Such work has suggested that for sleep to benefit learning, infants needed to nap soon after learning new information given that subsequent nocturnal sleep was not sufficient for the group that did not nap to "catch up" (Konrad & Seehagen, 2021; Seehagen et al., 2015). Thus, we predicted that when infants were tested again the following day, infants who napped after training would continue to improve, whereas memories in the other two groups may have been too fragile, resulting in more prompts, exploration of the tunnel, and difficulty in maintaining the strategy.

Previous work with adults has shown that procedural memory can be consolidated after a normal night's sleep (Karni et al., 1994), and several studies have found no differences in improvement on a motor task depending on whether sleep immediately followed learning (nap) or followed a long delay (overnight sleep) (see Diekelmann et al., 2009, for a review). This pattern differs from the findings with infants and preschoolers described above, possibly due to differences in the ages of the samples and/or learning contexts. The adult literature predicts some recovery of performance after training on a novel task at a second test session after a night's sleep, regardless of whether training was followed by a nap, because night sleep offers moderate improvement in motor performance (Walker et al., 2002). Despite sharing the context of motor learning with the adult samples, we expected that napping and night sleep would have a cumulative effect more akin to what has been observed in infant declarative memory research due to infants' still-developing hippocampus.

Method

Participants

Participants were 54 newly walking infants (23 female; M_{age} = 14.03 months, SD = 1.88, range = 9.86–19.10) who met three criteria: (a) the ability to walk 10 feet across a room without stopping to rest or falling, (b) being within 10 days of having given up crawling, and (c) performing below ceiling at training to permit a measure of learning over time. An additional 28 infants were deemed ineligible to participate because they were at ceiling at training. Baseline data from 41 infants were included in Horger et al. (2021), and baseline data from 15 infants were included in Horger and Berger (2019), but the learning data have not yet been reported.

In total, 25 infants were from the New York City metropolitan area and 29 were from the Tel Aviv and Haifa (Israel) metropolitan areas. Independent-samples t tests showed no differences in parent education between the countries. The majority of parents in both samples had a college or graduate degree (93.4%). The U.S. sample was mostly White (58.8%) but also 14.7% multiple races/ethnicities, 11.8% Black/African American, 8.8% Asian/Pacific Islander, and 5.9% unreported. The Israeli sample comprised mothers born in Israel (75.0%), Ukraine (17.9 %), Moldova (3.6%), and unreported (3.6%). Parents or guardians were interviewed about infants' motor milestone acquisition using the protocol from Berger (2010). Infants' locomotor experience is depicted in Fig. 1. A total of 23 infants (42.60%) had prior tunnel experience (9 U.S. and 14 Israeli). Chi-square tests showed no significant differences between the U.S. and Israeli samples regarding sex and tunnel experience distributions. The study was conducted in families' homes or in the Child Development Lab at the College of Staten Island.

Families were recruited through events at branches of the public library and local farmers' markets, through word of mouth and social networks, and through research participation credit for parents enrolled in an introductory psychology course. All research was approved by the institutional review boards of the College of Staten Island and the University of Haifa. Parents or guardians provided written informed consent for participation and video-recording. Families received a small "thank you" gift or a gift card and a "diploma" for participating.

Procedure

A schematic of the full procedure is displayed in Fig. 2. Infants were assigned to one of three groups based on their naturally occurring nap schedule: *Nap* (n = 17), *No Nap* (n = 19), or *Immediate* (n = 18). On Day 1, all infants were trained on a novel motor problem-solving task (*training*). Later that same day, infants were tested on the task a second time (*test*). Infants in the Nap group napped anywhere from 30 min (minimum criterion for napping; Berger & Scher, 2017; DeMasi et al., 2021) to 2 h in between training and test. Infants in the No Nap group did not take a nap between training and test, which were separated by a 2-h delay. As a control group, infants in the Immediate group had no delay between training and test. If infants' sleep behavior was not in concordance with their group assignment, they were reassigned to a group that fit their sleep behavior; thus, infants were not truly randomly assigned to nap groups. The following morning (Day 2), all infants received the problem-solving task a third time (*follow-up*).

Sleep measurement

Sleep diary. Caregivers completed a 24-h sleep diary to indicate the duration and timing of sleep periods. Objectively recorded actigraphy data (Ambulatory Monitoring, Ardsley, NY, USA) confirmed the report of nighttime sleep.

Brief infant sleep questionnaire. Parents completed the Brief Infant Sleep Questionnaire (BISQ), a widely used tool for capturing infants' typical sleep behaviors and problems (Sadeh, 2004). Parents reflected on the week before data collection and reported on their children's sleep pattern, for example, how long their infants typically slept at night, typical number of night wakings, and whether infants had sleep problems.

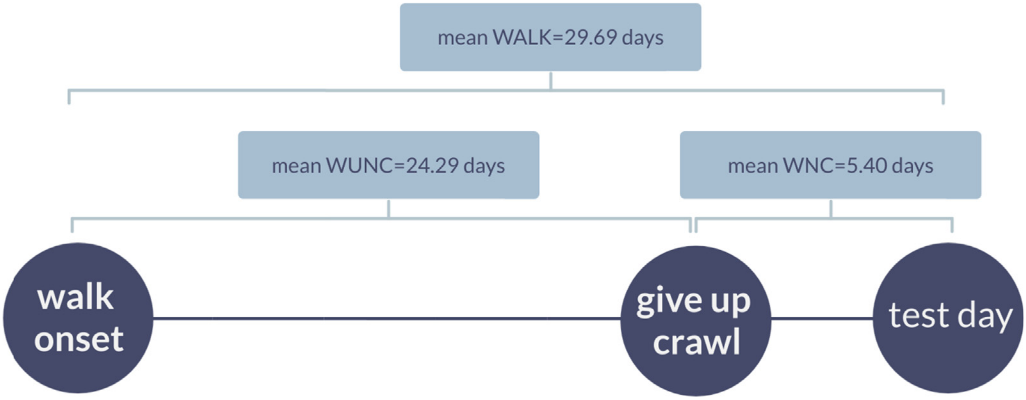

Fig. 1. Walk experience (WALK) was calculated from the first day infants met criterion for independent walking until the date of participation (range = 4–118 days). Walking-until-not crawling (WUNC) was calculated from the first day infants met criterion for independent walking until the date they gave up crawling (range = 0–111 days). Infants gave up crawling (walk-no-crawl or WNC) 0 to 10 days before participating.

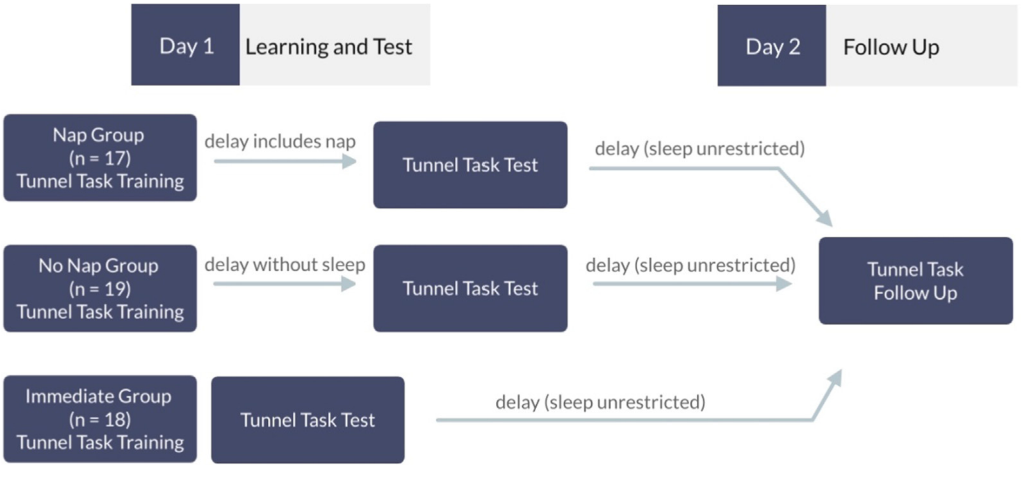

Fig. 2. Schematic of the study protocol. Infants' performance on a novel locomotor problem-solving task was assessed over three sessions.

Motor milestone interview

Prior to the tunnel task, a researcher interviewed parents about their infants' motor development (e.g., Berger, 2010). Parents were encouraged to use their own records of infants' milestones, such as home videos and photo albums, to provide an exact date of the first day that their infants performed the milestones such as crawling, cruising, and walking. The interview primarily served to confirm eligibility by determining the date when infants gave up crawling in favor of walking.

Tunnel task

Infants were tested with the same tunnel task procedure used in Berger and Scher (2017), Horger and Berger (2019), and Horger et al. (2021). This task was challenging because during the developmental transition of giving up crawling infants have not yet solved the problem of shifting between alternative motor strategies (Berger, 2010). At the beginning of the task, infants were placed, standing upright on two feet, at the entrance to a round nylon tunnel (18.5 inches in diameter × 71 inches long). The top of the tunnel reached approximately infants' shoulder height, requiring infants to change position from standing to crawling in order to fit inside (see Fig. 3). A caregiver waited at the other end offering toys, snacks, or verbal encouragement, but the caregiver could not provide instructions for how to crawl through the tunnel.

Experimenters followed a strict 15-step protocol for highlighting task-relevant details, and the correct strategy of crawling through, during training (see Fig. 4). If infants attempted to detour around the tunnel or could not figure out how to go through, the experimenter reset them to a standing posture at the tunnel entrance (up to 5 times), placed them on their hands and knees (up to 5 times), and finally rolled a ball through the tunnel to highlight the path (up to 5 times). The session ended when infants either crawled through the tunnel successfully or exhausted all 15 prompts without going through. The primary outcome measure was total number of *prompts.*

Exploratory behavior prior to entering the tunnel was documented by tallying a *postural shift* each time infants switched posture voluntarily (e.g., from standing to squatting or to hands and knees). Strategy maintenance behavior after entering the tunnel was documented by tallying the number of *posture shifts in the tunnel.*

Data coding

Sessions were recorded and coded from video using Datavyu (https://datavyu.org), data-coding software used by researchers to document frequencies, categories, and durations of behaviors. Reliability analysis was run on 26% of all cases (14 of 54) chosen randomly to include infants from both labs. There were 10 primary coders. Two of them also coded reliability data for other coders. In addition, there were 4 other reliability coders who did not code any primary data. Two-way mixed-effects intraclass correlation coefficients (ICCs) were employed to assess absolute agreement between two coders for prompts, posture shifts before entering the tunnel, and posture shifts in the tunnel. ICCs ranged from .93 to .99 ($ps < .001$), demonstrating very good to excellent agreement between coders for all measures. Discrepancies between coders were resolved through discussion. Only behaviors coded by the primary coder were used in the final analyses.

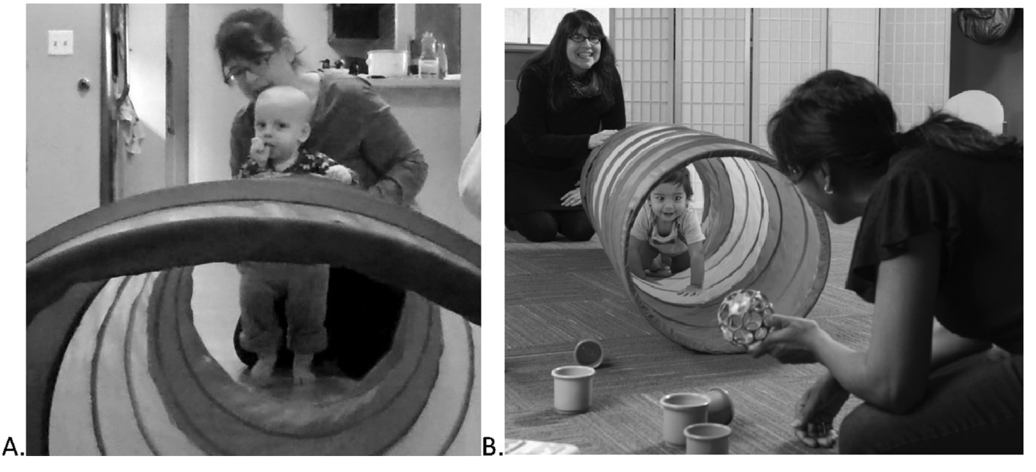

Fig. 3. Infants started each trial upright at the entrance to the tunnel and received training prompts (A) until they figured out how to navigate the tunnel to reach a caregiver at the other end (B) or until they received the maximum number of prompts, whichever came first. Caregivers (shown) sat at the far end of the tunnel and encouraged infants to come to them by offering toys and verbal encouragement but did not provide instructions. (Reprinted with permission from *Advances in Child Development and Behavior.* M. N. Horger, A. DeMasi, A. Allia, A. Scher, & S. E. Berger, Newly walking infants' night sleep impacts next day learning and problem solving, Vol. 60, p. 66. Copyright © 2021 by Elsevier.).

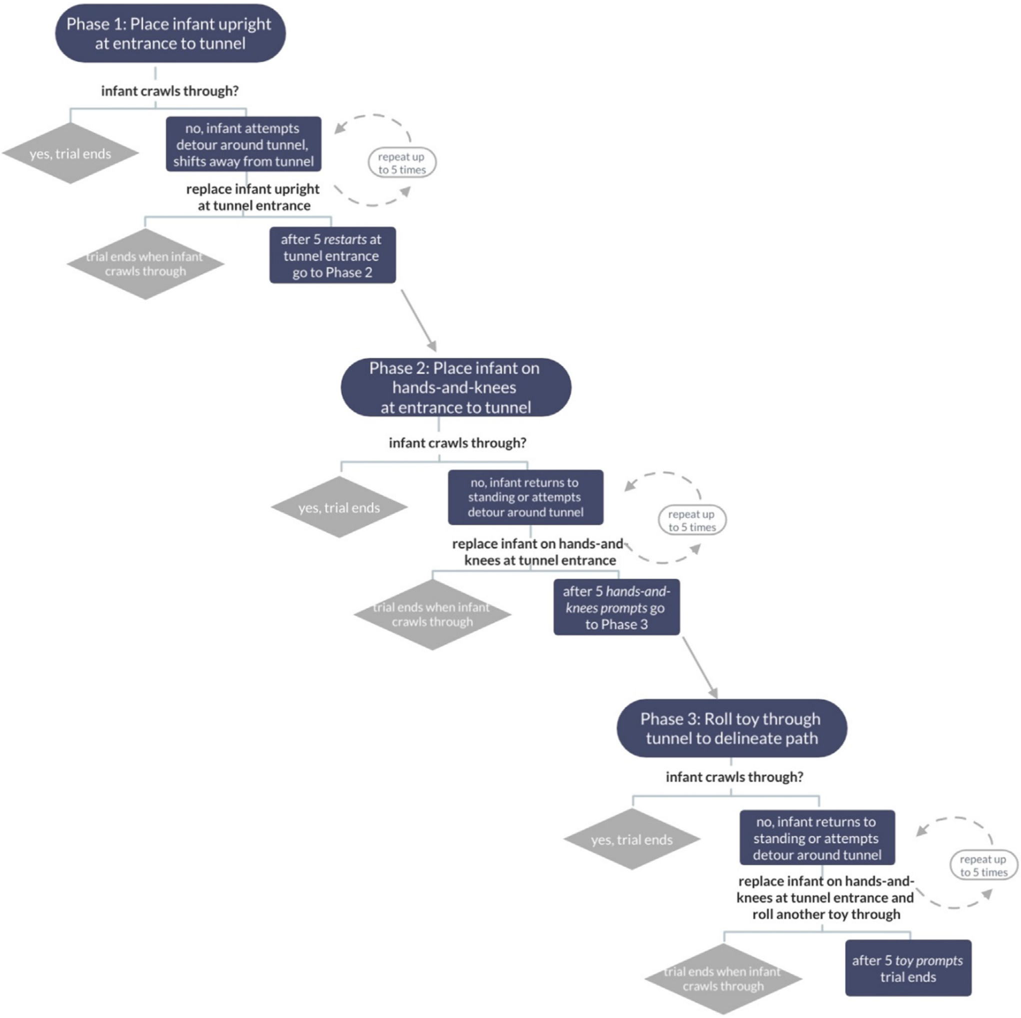

Fig. 4. Schematic diagram of the tunnel training protocol. (Adapted from ‘‘Naps improve new walkers’ locomotor problem solving” by S. E. Berger & A. Scher, 2017, *Journal of Experimental Child Psychology*, Vol. 162, pp. 292–300. Reprinted with permission.).

Results

Preliminary analyses

A priori power analysis

When designing the study, we used G*Power software Version 3.1.5.1 (Faul et al., 2009) to conduct an a priori power analysis for a repeated-measures analysis of variance (ANOVA) with three between-participants groups and three within-participants groups (α =.05 and actual power =.95). The target sample size of 60 (three groups of 20) yielded a required effect size of .23. However, later work reported smaller effect sizes than originally anticipated (Berger & Scher, 2017: η^2 =.14–.17; DeMasi et al., 2021: η^2 =.15–18).

Post hoc power analysis

The achieved sample size was short of the intended because data collection was halted by safety measures taken due to the COVID-19 pandemic. A post hoc power analysis, also using G*Power software Version 3.1.9.7, was run using the updated effect size estimate (η_p^2 = .17) and the median correlation between outcome measures analyzed by Berger and Scher (2017) (r = .43). Achieved power was .59, which is lower than the discipline benchmark of .80.

Baseline group comparisons

To ensure that all infants were equivalent at baseline, outcome variables were compared between groups at training. One infant did not have any data at follow-up, and another infant had no walking-until-not crawling (WUNC) data; therefore, those variables were imputed using the averages for those infants' groups. A series of one-way ANOVAs found no main effects of group (Nap, No Nap, or Immediate) on any problem-solving measures (prompts, shifts, or postural shifts in the tunnel) or walk experience at training.

Sleep data

A total of 49 parents completed the BISQ; infants averaged 10.44 h of night sleep (SD = 1.25) and 1.95 episodes of night wakings (SD = 1.82), with the vast majority (83.70%) not having a parent-reported sleep problem. One-way ANOVAs found no main effect of group on parent-reported night waking and night sleep duration. Nighttime sleep metrics for a subset of infants (n = 38) with actigraphy data are presented in the Appendix. Based on sleep diaries, infants in the Nap condition slept for an average of 98 min (SD = 25; these data were missing for 2 infants) between training and test.

Repeated-measures analyses of covariance

Strategy choice

An analysis of covariance (ANCOVA) with group (Nap, No Nap, or Immediate) as a between-participants factor, session (training, test, or follow-up) as a within-participants factor, and age and WUNC experience as covariates showed a significant quadratic interaction between group and session on number of prompts, $F(2, 49) = 3.57$, p =.036, η_p^2 =.13 (see Fig. 5A). There were no significant between-participants effects of group, $F(2, 49) = 0.64$, p =.531, age, $F(1, 49) = 0.64$, p =.425, or WUNC, $F(1, 49) = 0.12$, p =.729, on number of prompts. There was no linear interaction between group and session on prompts, $F(2, 49) = 1.06$, p =.355. Post hoc pairwise comparisons using Bonferroni correction showed that infants in the Nap group needed significantly fewer prompts at follow-up than at test. Infants in the Immediate group needed significantly more prompts during training than during test or follow-up, but there was no change in prompt number from test to follow-up. Infants in the No Nap group did not improve over time (see Table 1).

An ANCOVA with group as a between-participants factor, session as a within-participants factor, and age and WUNC experience as covariates on postural shifts (Fig. 5B) showed no effects of any factors or covariates. There were no significant between-participants effects of group, $F(2, 49) = 0.11$, p =.892, age, $F(1, 49) = 1.11$, p =.297, or WUNC, $F(1, 49) = 0.18$, p =.675, on number of postural shifts. There were also no linear interactions, $F(2, 49) = 0.45$, p =.639, or quadratic interactions, $F(2, 49) = 0.34$, p =.715, between group and session.

Strategy maintenance

An ANCOVA with group (Nap, No Nap, or Immediate) as a between-participants factor, session (training, test, or follow-up) as a within-participants factor, and age and WUNC experience as covariates on postural shifts in the tunnel revealed a significant quadratic interaction between session (Fig. 6) and WUNC experience (Fig. 7) for shifts in the tunnel, $F(2, 49) = 6.76$, p =.012, η_p^2 =.12. There were no significant between-participants effects of group, $F(2, 49) = 0.53$, p =.591, age, $F(1, 49) = 3.50$, p =.067, or WUNC, $F(1, 49) = 0.02$, p =.877, on number of postural shifts in the tunnel. There were also no linear interactions, $F(2, 49) = 2.79$, p =.071, or quadratic interactions, $F(2, 49) = 0.55$, p =.579, between group and session.

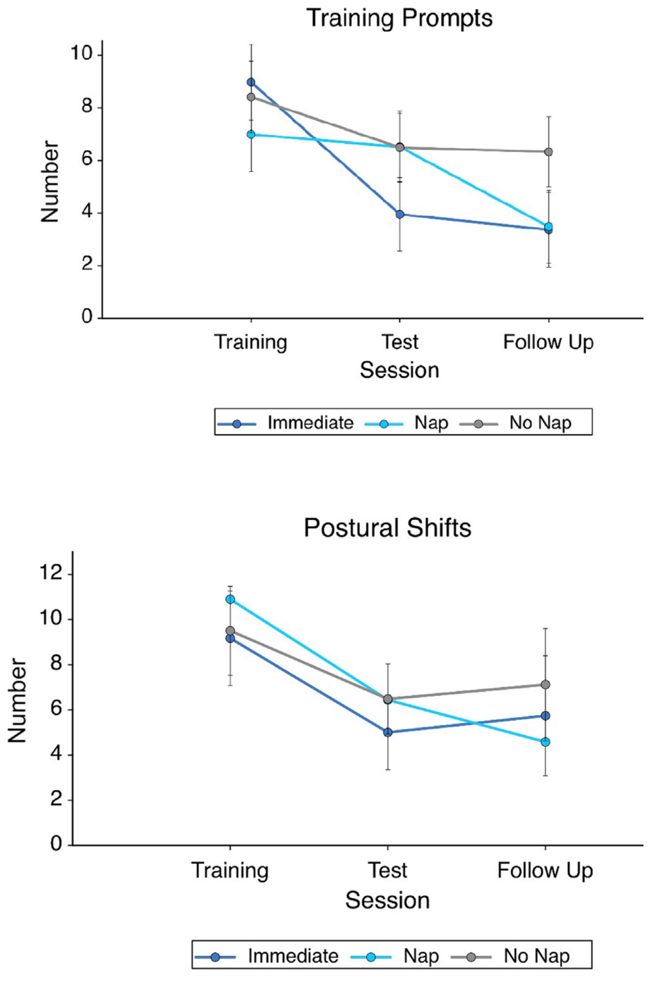

Fig. 5. Effects of group and session on infants' strategy choice: Training prompts (A) and postural shifts (B) outside of the tunnel. Error bars depict ± 1 standard error.

Discussion

This study examined the independent contributions of day and night sleep to locomotor problem solving during infancy. We taught newly walking infants to navigate a tunnel to reach a caregiver at the other end. One group napped during the delay between training and test, another group stayed awake during the delay, and a third group was tested immediately after training without a delay. All infants were presented with the tunnel task again the following morning. Behavioral measures of two aspects of problem solving, strategy choice and maintenance, captured learning across the three sessions.

Our first aim was to examine the impact of daytime sleep on motor problem solving. On measures of strategy choice (prompts and postural shifts before entering the tunnel), all groups improved from training to test, but the Immediate group improved the most. The Immediate group may have benefitted from massed practice by receiving the tunnel task twice in a row with no delay and no opportunity for interference. Although studies with both adults and children have shown that distributed

Table 1
Pairwise comparisons of prompts.

Group	(*I*) Session	(*J*) Session	Mean difference (*J* − *I*)	*SE*	*p*	95% Confidence interval for difference	
						Lower bound	Upper bound
Nap	Training	Test	−0.48	1.30	1	−2.75	3.71
		Follow-up	−3.51	1.67	.122	−0.63	7.64
	Test	Follow-up	−3.03*	1.17	.037	0.14	5.93
No Nap	Training	Test	−1.92	1.25	.395	−1.18	5.02
		Follow-up	−2.08	1.60	.601	−1.89	6.05
	Test	Follow-up	−0.16	1.12	1	−2.62	2.95
Immediate	Training	Test	−5.03*	1.33	.001	1.72	8.33
		Follow-up	−5.61*	1.71	.006	1.38	9.84
	Test	Follow-up	−0.58	1.20	1	−2.38	3.55

Note. Mean differences are based on means adjusted for covariates (age and walking-until-not crawling [WUNC]). The *p* values were calculated using Bonferroni adjustment. I represents one session in the comparison and J represents the other. J-I is the difference between the two sessions.

* $p < .05$

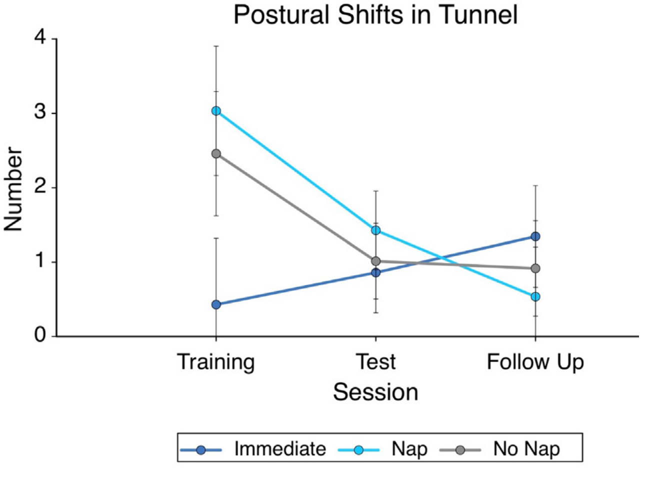

Fig. 6. Effects of group and session on infants' strategy maintenance behavior or postural shifts inside of the tunnel. Error bars depict ± 1 standard error.

practice typically confers greater benefits on memory and learning than massed practice (see Cepeda et al., 2006, 2009, for reviews), infants and younger children may receive equal or more benefit from massed practice than from distributed practice (Barr, Dowden, & Hayne, 1996; Childers & Tomasello, 2002; Toppino & DiGeorge, 1984). Of course, studies of the effects of massed versus distributed practice have traditionally used classic memory paradigms such as recalling lists of items (e.g., Toppino, 1993) and might not be generalizable to a motor problem-solving task that involves such different cognitive demands.

Only the Nap and No Nap groups improved from training to test on strategy maintenance (shifts inside the tunnel), replicating a recent finding that napping does not seem to be associated with learning strategy maintenance (DeMasi et al., 2021). In contrast, in both DeMasi et al. (2021) and the current study, a well-timed nap did facilitate strategy choice. One reason for this dichotomy may be that strategy choice was explicitly taught as infants progressed through the training prompts, whereas strategy maintenance was not. Alternatively, napping may better foster domain-specific cognitive

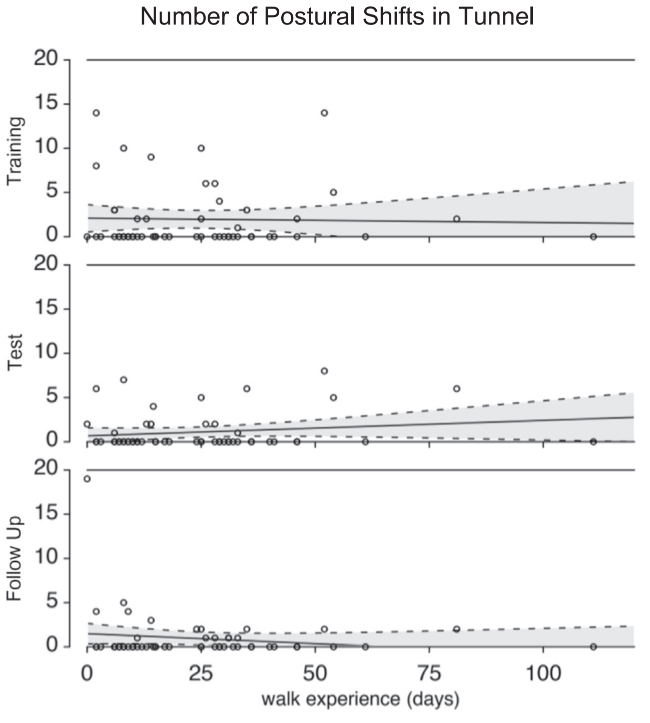

Fig. 7. Strategy maintenance behavior inside of the tunnel as a function of session and walk experience. The gray bands represent 95% confidence intervals.

skills, such as declarative memory, word learning, language generalization (see Horváth & Plunkett, 2018, for a review), and finding the correct postural solution to the motor task, than the domain-general executive functioning that would be required to inhibit walking in favor of crawling through the full length of the tunnel. The former point is more likely because it aligns with sleep as a time for pruning and redistribution of new memories; although longitudinal studies have related sleep quality to more general cognitive abilities (e.g., Scher, 2005).

An unexpected finding about strategy maintenance was that the effect of session on postural shifts inside the tunnel depended on infants' motor experience. One criterion for infants to participate was that they had given up crawling in favor of walking within the prior 10 days. However, the times between walking onset and when infants gave up crawling varied. We found that at training walk experience was unrelated to strategy maintenance. However, by follow-up only infants with the least walk experience still had trouble in inhibiting upright posture and walking in the tunnel as displayed in Fig. 7. It appears that infants with more expertise could allocate less attention to walking and were better able to maintain the alternative strategy of crawling for the length of the tunnel compared with infants with less expertise (Berger et al., 2018). The attentional resources available to allocate to a task may be linked to infants' proficiency at that task. A key component of discovering new problem-solving strategies is being able to maintain them so that they are useful (Berger et al., 2015, 2018).

Our second aim was to tease apart the individual contributions of day and night sleep. Despite all infants having a typical night's sleep after the test session, only the Nap group continued to improve on both strategy choice and maintenance between test and follow-up. For infants in the other groups who did not nap after training, neither night sleep nor massed practice alone was sufficient to confer overnight consolidation. As with infants and preschoolers performing declarative memory tasks, in the context of toddlers' motor problem solving, napping had a "delayed effect" on learning (Desrochers et al., 2016; Werchan et al., 2021). Daytime sleep played an active role in strengthening the otherwise fragile memory of how to solve the task rather than simply preventing interference. This contrasts with some adult findings where nighttime sleep alone was sufficient to benefit motor consolidation (Walker et al., 2002), although in the context of declarative memory (word pair learning) adults also benefitted from a daytime nap, presumably providing a boost to hippocampal functioning (Ong et al., 2020). For infants, additional periods of sleep may be necessary to consolidate information throughout the day until the hippocampus has fully matured (Riggins & Spencer, 2020).

Importantly, there may be opportunities for learning during night sleep that are not available during shorter nap sleep. We hypothesize that night sleep may have been particularly beneficial because it offers the opportunity for infants to cycle through REM and NREM multiple times, both of which affect infant learning (e.g., Cao et al., 2020; Friedrich et al., 2019). Many studies with adult samples also implicate both sleep states for learning (see Rasch & Born, 2013, and Girardeau & Lopes-dos-Santos, 2021, for reviews). To test this, future research will need to balance the intrusion of more in-depth sleep measurement techniques (e.g., polysomnography) with practical concerns of working with infant populations. A limitation of the current study was the use of parent report to describe the daytime nap. Infants and caregivers were given an actigraph but were not required to wear it continuously. Instead, we asked them to prioritize night sleep and put it on during their bedtime routine.

An additional practical concern arose around assigning infants to our three groups. In accordance with previous research, we prioritized maintaining their typical routines and scheduled the sessions at the caregivers' convenience to minimize disruption and fatigue (Hupbach et al., 2009). As such, we also could not control for naps taken before the training session or after the test session. In fact, two naps in a day is still the norm at this age, so most (if not all) infants likely had a bout of daytime sleep several hours after test or even prior to training. Although it is a limitation, this caveat also speaks to the importance of timely sleep given that only the Nap group continued to improve at follow-up.

In sum, our research replicated earlier work with infants, toddlers, and preschoolers showing that the benefits of napping for learning are most robust after a subsequent night of sleep (Desrochers et al., 2016; Seehagen et al., 2015; Werchan et al., 2021). Future work should investigate the extent to which post-nap improvements are associated with individual differences in sleep and more tightly control the timing of sleep around learning. Replication of the work is also necessary due to the small sample and underpowered analysis. This study provides the first evidence suggesting that day sleep and night sleep make unique contributions to the consolidation of a procedural task, motor problem solving, during infancy. Moreover, our data suggest that motor experience, a possible index of subjective task difficulty or effort expended, shapes the impact of sleep on learning.

Data availability

Data will be made available on request.

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Data sharing and data accessibility

The video data are stored on a permanent third-party archive (nyu.databrary.org) with restricted access; request for the data or materials can be sent via e-mail to S.E.B. (sarah.berger@csi.cuny.edu).

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Author contributions

S.E.B. and A.S. developed the study concept. Data collection was performed by M.N.H., A.D., A.M.A., and S.E.B. A.D. performed the data analysis. M.N.H., A.D., A.M.A., and S.E.B. drafted the manuscript. A.S. provided revisions. All authors approved the final version of the manuscript for submission.

Appendix A. Average actigraphy data for a subset of infants (*n* = 38) who wore the actigraph during the night between training/test and follow-up

	Sleep start time	Morning wake time	Sleep duration (min)	Wake episodes
Nap (*n* = 13)	20:47 (*SD* = 132 min)	6:21 (*SD* = 68 min)	574.69 (*SD* = 63.7)	5.84 (*SD* = 1.5)
No Nap (*n* = 12)	21:16 (*SD* = 89 min)	6:43 (*SD* = 60 min)	569.75 (*SD* = 80.3)	4.53 (*SD* = 2.9)
Immediate (*n* = 13)	21:14 (*SD* = 91 min)	7:18 (*SD* = 136 min)	605.15 (*SD* = 69.9)	4.07 (*SD* = 2.8)

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