Naps improve new walkers' locomotor problem solving

Sarah E. Berger a, *, Anat Scher b

a Department of Psychology, College of Staten Island and the Graduate Center of the City University of New York, Staten Island, NY 10314, USA
b Department of Counseling and Human Development, University of Haifa, Haifa 3498838, Israel

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ABSTRACT

In this first study of the impact of sleep on infants' problem solving of a locomotor task, 28 newly walking infants who were within a week of having given up crawling trained to navigate a shoulder-height tunnel to reach a caregiver waiting at the end. During the transitional window between crawling and walking, infants are reluctant to return to crawling, making this task uniquely challenging. Infants were randomly assigned to either nap or stay awake during a delay between training and a later test session. For the Nap group, efficiency of problem solving improved from training to test, but there was no change for the No Nap group. These findings suggest that for newly walking infants, sleep facilitates learning to solve a novel motor problem.

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Introduction

That sleep plays a critical role in memory consolidation of pre-sleep experiences was demonstrated as early as the 1920s (Jenkins & Dallenbach, 1924). Memory consolidation refers to the stabilization of newly learned information without additional practice (Siengsukon & Boyd, 2009). It implies a long-lasting change and may stem from changes at the neuronal level that are triggered by learning (e.g., Laureys et al., 2001). Scores of studies on memory consolidation in adults have demonstrated that sleep enhances learning, especially for motor memory, a type of procedural memory in which a par-
ticular sequence of actions is learned. Most studies have demonstrated that improvement in performance occurs only if a delay between learning and test includes sleep, but not with a delay that is simply the passage of time (e.g., Doyon et al., 2009; Korman et al., 2007; Walker, Brakefield, Morgan, Hobson, & Stickgold, 2002; Walker & Stickgold, 2005). Thus, the old adage to “sleep on it” when trying to work out a solution to a problem is generally good advice.

However, the impact of sleep on problem solving is nuanced. Sleeping after learning a difficult problem helped adults to solve more problems later than adults who did not sleep or who were tested immediately after learning, but sleep did not confer an advantage on trying to solve easy problems (Sio, Monaghan, & Ormerod, 2013). Sleeping after learning how to solve a new problem improved adults’ skill for the specific solution that they first came up with, but not for general information processing or all possible solutions (Stickgold & Walker, 2004).

Despite the abundance of research examining the impact of sleep on learning and problem solving in adults and the fact that sleeping is the primary brain activity of early development, few studies have addressed the effects of sleep on learning in young children (Ednick et al., 2009). Studies that address how sleep affects problem solving are scarcer still. We do know that, in general, the better the quality of 10-month-olds’ sleep, as measured by night wakings or via motor activity and sleep efficiency, the better their recall memory and the higher their cognitive scores on a standardized assessment tool (Lukowski & Milojevich, 2013; Scher, 2005). Similarly, the better the quality of preschoolers’ sleep, as measured via parent report or physiological recordings, the higher their cognitive scores on a standardized assessment tool and the better the consolidation of memories acquired earlier in the day (Jung, Molfese, Beswick, Jacobi-Vessels, & Molnar, 2009; Kurzdziel, Duclos, & Spencer, 2013). When young infants learned to activate an overhead crib mobile by kicking their feet, a reminder benefited infants’ retention over time after forgetting had occurred, especially when the time that elapsed from the demonstration included sleep (e.g., Fagen & Rovee-Collier, 1983).

Although Tarullo, Balsam, and Fifer (2011) pointed out that “conclusions about infant sleep cannot be extrapolated from adult studies” (p. 38), only recently have investigators begun to experimentally address the effect of sleep on infants’ learning. In the few studies designed to examine the effect of sleep on learning during infancy, infants were able to learn an abstract language rule (Gomez, Bootzin, & Nadel, 2006), improve their vocabulary (Horváth & Plunkett, 2016), consolidate a declarative memory (Seehagen, Konrad, Herbert, & Schneider, 2015), generalize beyond specific word meanings to broader categories (Friedrich, Wilhelm, Born, & Friederici, 2015), and demonstrate flexibility of memory retrieval (Konrad, Seehagen, Schneider, & Herbert, 2016) after they took a nap, but not if they stayed awake during a delay. Without a nap, infants could retain specific information only in the short term (Hupbach, Gomez, Bootzin, & Nadel, 2009), whereas a nap that occurred within 4 h of learning was required for complex learning or generalization to occur (Friedrich et al., 2015). Infants appear to need frequent periods of sleep to parse and learn the “continuous stream of new information they are exposed to every day” (Hupbach et al., 2009, p. 1012). Of the studies that have directly examined the impact of sleep on infants’ learning, as far as we can tell, none has examined the relation between sleep and problem solving.

One possible reason for this gap in the literature is that studying problem solving during infancy can be a significant challenge. Methods for studying problem solving in children typically involve verbal or math tasks that are beyond infants’ abilities (Lemaire & Reder, 1999; Lemaire & Siegler, 1995; Tunteler & Resing, 2002). To address the goal of examining the impact of napping on problem solving during infancy, we turned to recent work demonstrating that novel locomotor tasks can be model contexts for studying the development of problem-solving strategies during infancy. For example, microgenetic documentation of 13- and 18-month-olds’ strategy choices during stair descent revealed the same characteristics as older children’s problem-solving behavior on more traditional cognitive tasks, namely variability, utilization deficiencies, and online planning (Berger, Chin, Basra, & Kim, 2014). Likewise, carrying out locomotor tasks can involve the same types of cognitive skills assessed in more classic tests of cognition. For example, to successfully navigate a tunnel to get to a caregiver waiting at the other end, walking infants must inhibit their preferred locomotor method of walking, devise an alternative locomotor strategy of crawling, and maintain that alternate strategy for the duration of the task (Berger, 2010). These demands are especially taxing for new walkers who frequently bump their head on a low entrance, or revert to a familiar but unstable posture, rather than adopt alternative
locomotor strategies (Berger, 2010; Berger et al., 2014; Brownell, Zerwas, & Ramani, 2007). For example, even when 13-month-old novice walkers were able to start out descending a staircase in a stable scooting posture, they found the maintenance of a posture other than walking taxing and ultimately reverted back to walking (Berger et al., 2014)—even though walking is the least posturally stable descent strategy (Andriacchi, Andersson, Fermier, Stern, & Galante, 1980; Cromwell & Wellmon, 2001; McFadyen & Winter, 1988).

A recent locomotor task originally designed to test the effects of motor demands on infants’ ability to inhibit (Berger, 2010) seems to be a promising platform for testing whether sleep affects infants’ problem solving. In the original study, 13-month-old crawlers with several months of crawling experience had no trouble in navigating a tunnel to reach a caregiver at the other end even when it required inhibiting taking a previous path and switching to a new tunnel path. In contrast, a group of 13-month-old walkers with less than 2 months of walking experience found the task sufficiently taxing as to elicit perseveration when it came time to take a new tunnel path to the goal. Navigating the tunnel was especially challenging for the novice walkers, presumably because it required inhibiting a preferred locomotor method and maintaining an alternative method over the course of the trial. One of the advantages of this task is that it does not require participants to follow complex instructions and has already been demonstrated to be feasible for novice walkers (Berger, Kaur, & Taysin, 2010). Moreover, complex configurations of motor sequences and adaptive sensorimotor behaviors appear to be more susceptible to sleep-related improvements than rote behaviors (Brawn, Fenn, Nusbaum, & Margoliash, 2008; Kuriyama, Stickgold, & Walker, 2004). Finally, it is appropriately challenging for new walkers, designed with the possibility for learning in the short term, so that observers can document behavioral change.

To capitalize on the potential of the tunnel task, we set this study at a likely significant but rarely studied motor transition—the brief window soon after the onset of walking once infants had given up crawling. Ease at switching between walking and crawling would be advantageous for solving some types of motor problems such as the task we present here. However, during the tight transitional window between crawling and walking, our task temporarily becomes a significant challenge because infants are reluctant to return to crawling—a skill previously in their motor repertoire—until walking is better established and they can call on crawling again as a possible motor strategy. Infants demonstrate a lack of body awareness when needing to fit their bodies to obstacles or barriers (Brownell et al., 2007), and infants’ problem-solving abilities for motor tasks tend to fluctuate during periods of transition between locomotor postures (Berger, 2010; Berger et al., 2010; Clearfield, Diedrich, Smith, & Thelen, 2006). We expected that a period of sleep following infants’ experience with a challenging novel locomotor task, in this case new walkers’ navigating a tunnel to reach a goal at the other end, would enhance subsequent problem solving for that task via processes of memory consolidation and integration of new information (Stickgold & Walker, 2013).

**Method**

**Participants**

Criteria for participation were being able to walk 10 feet across the room (~3 m) without stopping to rest or falling and within a week of having given up crawling. Infants were assigned to either a Nap or No Nap group, with the stipulation that data collections were scheduled at times that accommodated their usual sleep schedule. No infants were asked to skip or delay their typical nap.

The mean age of infants in the Nap group (n = 14; 7 girls) was 13.37 months (SD = 2.20, range = 8.91–16.14). The mean age of infants in the No Nap group (n = 14; 4 girls) was 13.08 months (SD = 1.73, range = 9.89–14.99). Mean walking experience for infants in the Nap group was 16.79 days (SD = 10.40, range = 3–44) and for infants in the No Nap group was 13.07 days (SD = 8.63, range = 5–33). As per participation criteria, the proportion of time that infants spent crawling was down to 25%, and they had been doing so for only 10 or fewer days. There were no statistically significant differences between groups for age, distribution of gender, or locomotor experience.
Families were recruited through published birth announcements, research participation credit for parents enrolled in an introductory psychology course, collaboration with branches of the local public library, and word of mouth. Informed consent was obtained from parents on enrollment. The sample was ethnically diverse: 46.4% White, 10.7% Asian, 10.7% Hispanic, 7.1% Native American, and 7.1% “other” (18% chose not to report race or ethnicity). For most parents, the highest level of education was a postgraduate degree (57.2%), with 17.9% having a college degree, 10.7% having a high school diploma, and 14.2% not reporting.

Procedure

Tunnel task

At the start of the trial, an experimenter placed infants upright on two feet at the opening to a round nylon tunnel (47 cm [18.5 in.] in diameter × 180 cm [71 in.] long). The top of the tunnel came to about infants’ shoulder height, so they needed to figure out how to switch from standing to crawling to navigate the tunnel most efficiently. Infants were encouraged to make their way through the tunnel to reach a goal (caregiver) at the other end. Infants were motivated by caregivers offering words of encouragement, toys, or snacks, but caregivers did not provide instructions on how to fit into or proceed through the tunnel. The apparatus was collapsible for portability, so data collections took place in the laboratory or in families’ homes.

Training protocol

Experimenters followed a strict training protocol that encouraged infants to solve the problem of navigating the tunnel independently by prompting them with nonverbal hints if they were unsuccessful (see Fig. 1). The protocol consisted of three consecutive phases: placed upright on two feet at the tunnel entrance, placed on hands and knees at the tunnel entrance, and watching the experimenter demonstrate the tunnel path by rolling a toy through the tunnel. Infants received 5 chances at each phase before moving to the next one for a maximum of 15 chances to enter the tunnel. The session

Fig. 1. Schematic diagram of the tunnel training protocol.
ended after infants successfully navigated the tunnel one time or had exhausted all phases of the training without entering the tunnel.

Tunnel task test
Infants received the same tunnel task after a 2-h (±30 min) delay. The Nap group slept during the delay and had their test session within an hour after they woke from their nap (at least 30 min of uninterrupted sleep). The No Nap group did not nap between sessions.

Data coding
Both sessions were digitally recorded. A primary coder coded all data from video using Datavyu (http://datavyu.org), a computerized coding system that records durations and frequencies of behavior. The primary outcome measure was the number of steps (0–15) of the training protocol it took for infants to complete a trial. We also coded for haptic exploration of the tunnel (e.g., patting, rubbing, mouthing) to capture infants’ information-gathering behaviors. We coded number of body–tunnel mismatches to capture how well infants fit their bodies to the tunnel (e.g., bumped head, lifted tunnel for head ignoring feet, postural changes). Trial duration captured how long it took infants to complete the trial after the experimenter placed them in front of the tunnel opening and was indicative of planning or execution of the task that was otherwise not observable behaviorally.

To test interrater reliability, a second coder independently coded 20% of all participants. Sessions chosen for reliability coding were selected at random except to ensure that participants from both groups contributed data to the reliability subsample. For the categorical measures of pre-delay haptic exploration and post-delay body–tunnel mismatch, agreement between coders was 100% (κs = 2.45, ps = .01). For post-delay haptic exploration and pre-delay body–tunnel mismatch, agreement between coders was 83% (κ = 1.55, p = ns and κ = 2.45, p = .01, respectively). Correlation coefficients for measures of duration and frequency ranged from $r = .87$ to $r = 1.0$ ($ps < .03$). Discrepancies between coders ($n = 13$ of the 108 data points coded for reliability) were resolved through discussion, including bringing in a third impartial coder if necessary.

Results
Pearson chi-square tests of infants’ exploratory behaviors and how well they fit their bodies to the tunnel revealed no differences between the Nap and No Nap groups at training, suggesting that there were no differences between how the infants approached the task prior to the training protocol that would contribute to later performance differences.

A repeated-measures analysis of variance (ANOVA) on the number of steps of the training protocol infants took to complete the tunnel task, with session (training vs. test) as a within-participants factor and condition (Nap vs. No Nap) as a between-participants factor, revealed a main effect for session, $F(1,26) = 5.13, p = .03, \eta^2_p = .17$, and an interaction between session and condition, $F(1,26) = 4.12, p = .05, \eta^2_p = .14$ (see Fig. 2). Infants who napped between training and test solved the tunnel task in significantly fewer steps of the training protocol at test than in training, $t(13) = 2.36, p = .03$, whereas infants who did not nap showed no change in the training protocol from training to test.

A repeated-measures ANOVA on the time it took infants to solve the tunnel task, with session (training vs. test) as a within-participants factor and condition (Nap vs. No Nap) as a between-participants factor, revealed a main effect for session, $F(1,26) = 4.68, p = .04, \eta^2_p = .15$, and an interaction between session and condition, $F(1,26) = 5.17, p = .03, \eta^2_p = .17$. Infants who napped between training and test sessions got significantly faster at navigating the tunnel, $t(13) = 2.24, p = .04$, whereas infants who did not nap showed no change in trial duration from training to test.

A repeated-measures ANOVA on the total number of body–tunnel mismatches, with session (training vs. test) as a within-participants factor and condition (Nap vs. No Nap) as a between-participants factor, revealed an interaction between session and condition, $F(1,26) = 3.99, p = .05, \eta^2_p = .13$. Infants who napped decreased the number of body–tunnel mismatches between training and test, $t(13) = 2.19, p = .04$, whereas infants who did not nap showed no change in the number of mismatches between training and test sessions.
Discussion

This study is the first to examine the impact of sleep on motor problem solving during infancy. We taught infants a novel locomotor task and compared the ease with which infants who napped before test came up with the solution to the problem compared with infants who did not nap between training and test. The findings supported our hypothesis that sleep following experience with a novel motor task would facilitate problem solving. We found that performance improved from training to test for the Nap group but that there was no change, or just a slight decrement in performance, from training to test for the No Nap group.

These findings are in keeping with previous work with adult populations showing the benefits of sleep immediately after learning a novel motor behavior for memory consolidation (Doyon et al., 2009; Korman et al., 2007; Walker & Stickgold, 2005; Walker et al., 2002) and for problem solving (e.g., Sio et al., 2013; Stickgold & Walker, 2004). Despite the age difference between our participants and typical adult participants in these types of studies, there is precedent for the consolidation of procedural memory to be the same or similar for adults and children. For example, in one experiment children between 9 and 17 years of age showed “offline” improvement in performance of a novel finger-tapping task, suggesting a consolidation phase in motor memory typically observed in adults (Dorfberger, Adi-Japha, & Karni, 2007). Age differences were observed, however, when the impact of interference was examined. Younger children were seemingly unsusceptible to interference, able to consolidate different motor tasks without the later learned interfering with the earlier learned. In contrast, the 17-year-olds showed the same pattern adults have shown in previous studies—interference in memory consolidation for the task learned first when followed by training on a second motor task (Walker, Brakefield, Hobson, & Stickgold, 2003). The current study expands research on the process of consolidation for motor problem solving to a new age group. If infants are more likely to resemble young children than adolescents or adults, then the No Nap group’s static performance, rather than a decrement in performance, from training to test may be attributed to a weak susceptibility to inter-
ference. Additional work is needed to better understand how sleep facilitates memory consolidation at this age—whether sleep is crucial for memory formation via processes such as activating neural activity or whether it serves to protect against interference.

Studies of the effects of sleep on problem solving in adults have shown a sleep advantage for solving difficult problems but found no difference in performance between participants who slept and those who did not when problems were easy (Sio et al., 2013). It may be that the particular combination of a novel task requiring switching between postures presented at the unique transitional period between crawling and walking created a motor problem that was especially difficult and, in turn, especially susceptible to benefits from sleep. Moreover, in an adult sample, sleep facilitated the analogical transfer of solutions from a training context to a similar but not identical test context, suggesting that sleep likely enhances performance via the restructuring of information (Monaghan et al., 2015). Given these findings, perhaps sleep improved infants’ performance in this motor context by facilitating memory consolidation and integration of earlier experiences (Stickgold & Walker, 2013). Infants were able to generalize a solution originally limited to their everyday locomotor posture (walking) to a posture they had recently relinquished (crawling). Thus, a possible mechanism for how sleep affected infants’ behavior is via consolidation of the new information acquired during training so that it was more easily accessible across postures. Future work will need to examine the generalizability of this effect on motor problems with a range of difficulty and variations between training and testing contexts.

This initial study advances a promising line of research and raises some interesting new questions. One question has to do with the role of fatigue in influencing infants’ problem solving. For the Nap group, one possible interpretation for the differences in performance between training and test is that infants were in the process of learning at training and sleep facilitated the consolidation of the new information (e.g., Doyon et al., 2009; Korman et al., 2007). The other possible interpretation is simply that sleep functioned to primarily or partially eliminate the impact of fatigue on infants’ performance so that they were rested at test (Cai & Rickard, 2009). For the No Nap group, the lack of sleep could have denied infants the opportunity to consolidate the newly experienced solution to the problem, or they may have been fatigued at the time of test. We did not measure fatigue directly, and there may be effects that we cannot capture with our current methodology, but it seems particularly relevant to this question that we observed static performance between training and test for the No Nap group. Previous work suggests that we may expect a deterioration in performance from training to test as a result of fatigue (e.g., Brawn, Fenn, Nusbaum, & Margoliash, 2010). In addition, we found no difference between the Nap and No Nap groups at training on any of our performance measures (exploration and steps to completing the task), suggesting that they started out at equal levels of competence. Future work must systematically control for the timing and order of training, nap, interference, and test to get a more definitive answer about what constitutes fatigue during infancy and how it manifests behaviorally during the development of problem-solving skills during infancy.

If sleep does influence problem solving, specifically in enhancing infants’ memory for new solutions and the consolidation of new experiences, caregivers should ensure adequate daytime napping conditions. This may include having the flexibility to respond to changes in individual children’s sleep needs coinciding with learning experiences. Clarifying the contribution of sleep to the consolidation of new information and experiences to which infants are constantly exposed should guide child-care providers and policymakers with respect to the optimal balance between enrichment and rest.

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