Children benefit differently from night- and day-time sleep in motor learning

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**Abstract**

Motor skill acquisition occurs while practicing (on-line) and when asleep or awake (off-line). However, developmental questions still remain about whether children of various ages benefit similarly or differentially from night- and day-time sleeping. The likely circadian effects (time-of-day) and the possible between-test-interference (order effects) associated with children's off-line motor learning are currently unknown. Therefore, this study examines the contributions of overnight sleeping and mid-day napping to procedural skill learning. One hundred and eight children were instructed to practice a finger sequence task using computer keyboards. After an equivalent 11-h interval in one of the three states (sleep, nap, wakefulness), children performed the same sequence in retention tests and a novel sequence in transfer tests. Changes in the movement time and sequence accuracy were evaluated between ages (6–7, 8–9, 10–11 years) during practice, and from skill training to retrievals across three states. Results suggest that night-time sleeping and day-time napping improved the tapping speed, especially for the 6-year-olds. The circadian factor did not affect off-line motor learning in children. The interference between the two counter-balanced retrieval tests was not found for the off-line motor learning. This research offers possible evidence about the age-related motor learning characteristics in children and a potential means for enhancing developmental motor skills. The dynamics between age, experience, memory formation, and the theoretical implications of motor skill acquisition are discussed.

**1. Introduction**

Motor skill acquisition, in theory, constitutes two sequentially-related and deliberate processes. The on-line learning (within-session improvement) is followed by the off-line learning (between-session improvement) (Dayan & Cohen, 2011; Robertson, Pascual-Leone, & Miall, 2004; Sanes, 2003; Schmidt & Lee, 2005; Wilhelm, Metzkow-Meszaros, Knapp, & Born, 2012). Empirically, skills improve during practice, and still advance after practice or during sleep (Cohen, Pascual-Leone, Pree, & Robertson, 2005; Karni et al., 1998; Robertson, Press, & Pascual-Leone, 2005; Thomas, Yan, & Stelmach, 2000; Walker, Brakefield, Hobson, & Stickgold, 2003). Post-practice sleep is assumed to protect memories from interference and aids off-line learning (Walker, 2005, 2009). Additionally, memory stabilization facilitates the formation of motor skills (Kuriyama, Stickgold, & Walker, 2004; Stickgold & Walker, 2005; Walker & Stickgold, 2004). Importantly, the neural, behavioral, developmental, pedagogical implications of both on- and off-line skill learning for children have attracted considerable attention (Chan, Luo, Yan, Cai, & Peng, 2015; Desrochers, Kurzdziel, & Spencer, 2016; Ren, Guo, Yan, Liu, & Jia, 2015; Wilhelm, Prehn-Kristensen, & Born, 2012).

For instance, the effects of on-line motor learning are reportedly more marked for 6- and 9-year-olds than for adults. Gains in movement speed and smoothness were significant for children who practiced the linear arm motor skills, but not for their no-practice
peers (Thomas et al., 2000). In addition, the 6- to 9-year-olds learned better when the juggling task was first trained in part and then together; whereas the 11-year-olds merely practiced the whole skill and performed better (Chan et al., 2015). Learners may integrate movement experience, motor planning, sensory feedback into their on-line learning process (Thomas et al., 2000; Yan, Thomas, Stelmach, & Thomas, 2000). Furthermore, the 6-year-olds benefitted more from both on- and off-line learning (post-practice naps) of finger movement sequences than their older peers (Ren et al., 2015). It seems that developing brains have a greater potential to be trained than mature ones (Bunge & Wright, 2007; Desrochers et al., 2016; Johnson, Nishimura, Harum, Pekar, & Blue, 2001; Kolb, 2000). However, the greater learning gains observed in younger children may reflect their poorer performance at the start of practice. This is plausible when one considers that several studies have shown that older children and adults acquire motor skills more efficiently than younger children (Janacek, Fiser, & Nemeth, 2012; Lukacs & Kemeny, 2015; Savion-Lemieux, Bailey, & Penhune, 2009; Thomas et al., 2004). In addition to the mixed findings concerning on-line motor learning, a number of uncertainties still exist about the nature of off-line motor learning in children.

Specifically, assisted by day-time napping, children as young as 6 years of age could effectively acquire finger tapping skills (Ren et al., 2015); Day-time napping also enhanced preschoolers' skill learning (age 3–6 yrs; Desrochers et al., 2016). However, the question of whether children of different ages share comparable processes and benefits of off-line procedural motor learning from night-time sleep till remain unclear; Young children may need a longer period of sleep than older ones to consolidate motor memories, due to the reality of developmental trajectories or stages during childhood (Mills, Goddings, Clasen, Giedd, & Blakemore, 2014; Thomas et al., 2000; Yan et al., 2000); Second, circadian effects (time-of-day) were not found in children's on-line motor learning (Ren et al., 2015). But time-of-day could moderate the effects of off-line learning (Cai & Rickard, 2009; Pan & Rickard, 2015), and consequently bear important implications for sleep-induced motor learning in children of different ages (Wilhelm, Prehn-Kristensen, et al., 2012); Third, applying the concept of "skill adaptability" (using the learned skills to a new context or task; Schmidt & Lee, 2005) to memory consolidation research and evaluating skill transfer in children's off-line motor learning are novel and critical (Ren et al., 2015). But the use of both retention and transfer tests in a single experiment can lead to the phenomenon of anterograde interference (effects of learning task B on learning of task A) (Brachers-Krug, Shadmehr, & Bizzi, 1996); This double-assessment approach may result in errors in measuring the off-line learning in children. The understanding of these vital questions or concerns about developmental off-line learning in children is currently limited and requires additional work.

From a developmental view, because of the mismatch in children's cognitive, motor, or physical development, rather than using a "top-down" mechanism, young children typically rely on sensory feedback for motor control and learning to a greater extent than their older peers (Thomas et al., 2000; Yan et al., 2000). Structural and functional disparities in brain maturity (e.g., cognitive or emotional control, executive functioning, planning, inhibiting) between young and older children can cause the developmental gaps in affective domain or motor learning (Mills et al., 2014; Wilhelm, Prehn-Kristensen, et al., 2012). Recently, Chan, Wang, Yan, and Chen (2016) suggested that the improvement in sensory-motor, visual, attention, and fronto-parietal neuronal networks underlies children's brain development. Neuroplasticity-related cognitive or motor learning enhances healthy neuronal networks and remedies abnormal systems in children. Clearly, skill learning is an important avenue for studying issues essential to brain maturation, skill development, and neuronal rehabilitation (Adolph, 2008; Diamond, 2000; Ren et al., 2015; Schlaug et al., 2009; Yan et al., 2000).

Furthermore, motor skills can be learned in both fast and slow processes depends on the demands or characteristics of the motor task (Smith, Ghazizadeh, & Shadmehr, 2006). Fast learning is an explicit process while slow learning is an implicit one (Mcdougle, Bond, & Taylor, 2015; Taylor, Krakauer, & Ivry, 2014). In addition, fast and slow learning processes differentially intensify or weaken the activation levels of the brain regions involved in skill acquisition; The fast skill learning takes place within practice sessions (on-line, practice-dependent), while the continuous learning of the same skill progresses slowly; The between-session off-line learning is a course of slow and practice-independent development (Dayan & Cohen, 2011). What remains unclear, however, is the relationship between the fast-explicit on-line learning and the slow-implicit off-line learning in children of various ages. From a developmental perspective, understanding the interaction of the two types of learning in children helps develop training, education, intervention, or rehabilitation strategies. Procedural motor skills like the serial reaction time task or finger tapping skill would be suitable for young children to learn and perform simple movement sequences (Desrochers et al., 2016; Ren et al., 2015).

In summary, on- or off-line learning involves memory formation. Children usually develop cognitive and motor skills quickly and considerably as a result of the growing experience and brain maturation (e.g., visual search abilities; Yan, Li, & Liao, 2010; neuronal network development; Chan et al., 2016). Insofar as younger children have a greater neural potential to learn than the older cohorts, an experiment and a set of analyses were designed to examine these hypotheses: (1) The 6-year-olds would show better on-line learning than the 8- and 10-year-olds (Thomas et al., 2000); (2) Night- or day-time sleep would improve off-line learning of the 6-year-olds more than their older peers; a waking state has minimal learning benefits (Dorberger, Adi-Japha, & Karni, 2007); (3) Day- and nighttime sleep may not share similar benefits for off-line learning (Rieth, Cai, McDevitt, & Mednick, 2010); (4) The circadian effects would influence off-line motor learning, because children learn skills and perform the tests at different times of the day (Cai & Rickard, 2009; Rieth et al., 2010); (5) The anterograde interference for the retrieval tests was anticipated in off-line skill learning (Krakauer, Ghez, & Ghilardi, 2005).

2. Methods

2.1. Participants

The Institutional Review Board (IRB) of the University approved the research proposal. Written informed consents were attained from the parents or caregivers and the 108 children who were naïve to the experiments (6–11 years; 3 age groups; 36 a group,
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