

The Effect of Sleep on Offline Consolidation of Perceptual and Motor Sequence Implicit Learning

Authors: Sun Peng, Li Xueqing, Zhang Qingyun, Shang Huaqian, Ling Xiaoli, Ling Xiaoli

Date: 2022-06-07T00:00:00+00:00

Abstract

Learning that occurs during offline phases is referred to as offline consolidation, wherein memory traces remain stable or improve even without additional practice following initial knowledge acquisition. Although some studies have preliminarily investigated the effects of sleep on offline consolidation in perceptual and motor sequence implicit learning, these studies failed to achieve complete separation between perceptual and motor sequences, leaving unresolved whether sequence type modulates the influence of sleep on offline consolidation in implicit sequence learning. Moreover, prior research on explicit learning has demonstrated that complex sequences are more likely to benefit from sleep and exhibit sleep-based offline consolidation effects compared to simple sequences. Whether the effects of sleep on offline consolidation in perceptual and motor sequence implicit learning are similarly modulated by sequence complexity remains unclear. To address this question, the present study, under conditions of complete separation between perceptual and motor sequences, manipulated sequence length and structure across three experiments, establishing three sequence rules of varying complexity levels. The results revealed that for motor sequences, low-complexity rules produced offline consolidation effects regardless of sleep involvement, whereas high-complexity rules only yielded offline consolidation effects following sleep; for perceptual sequences, however, no offline consolidation effects were observed irrespective of rule difficulty. These findings indicate that sleep-based offline consolidation of implicit sequence knowledge is modulated by both sequence type and sequence complexity, offering a novel perspective on the ongoing debate regarding offline consolidation in implicit learning.

Full Text

Sleep and the Consolidation of Perceptual and Motor Sequences in Implicit Learning

SUN Peng¹, LI Xueqing², ZHANG Qingyun³, SHANG Huaiqian³, LING Xiaoli³

¹ Mental Health Education and Research Center, Shandong University of Finance and Economics, Jinan, 250014, China

² School of Humanities and Social Science, Beijing Institute of Technology, Beijing, 100081, China

³ School of Psychology, Shandong Normal University, Jinan, 250358, China

Abstract

Learning that occurs during offline periods is referred to as offline consolidation, wherein memory traces remain stable or improve after initial acquisition even without additional practice. While previous research has preliminarily explored the impact of sleep on the offline consolidation of perceptual and motor sequence learning, these studies failed to achieve complete separation of perceptual and motor sequences. Consequently, whether sequence type moderates the effect of sleep on offline consolidation of implicit sequence learning remains unresolved. Furthermore, studies on explicit learning have found that complex sequences benefit more from sleep than simple sequences, exhibiting sleep-based offline consolidation effects. However, it remains unclear whether sleep's influence on offline consolidation of implicit perceptual and motor sequence learning is moderated by sequence complexity.

To address these issues, the present study employed Rose et al.'s (2011) modified serial reaction time task to completely separate perceptual and motor sequences. Through three experiments manipulating sequence length and structure, we examined this question using three levels of sequence complexity. The results revealed that for motor sequences, offline consolidation occurred regardless of sleep when sequence complexity was low, whereas sleep was necessary for offline consolidation when motor sequence complexity was high. For perceptual sequences, no offline consolidation effects were observed regardless of difficulty level. These findings indicate that sleep-based offline consolidation of implicit sequence knowledge is modulated by both sequence type and complexity, providing a novel perspective on the debate surrounding offline consolidation in implicit learning.

Keywords: sleep, implicit learning, perceptual sequences, motor sequences, offline consolidation

Introduction

Learning is a crucial human cognitive ability that occurs not only during learning phases (online periods) but also during non-learning phases (offline periods).

Offline consolidation refers to the process whereby knowledge remains stable or improves after initial acquisition without additional practice (Barham et al., 2021; Hallgató et al., 2013; Robertson, 2009; Simor et al., 2019; Song, 2009). As early as the late 20th century, Karni and colleagues demonstrated that both perceptual and motor learning effects improved after an offline interval using visual texture discrimination and finger-tapping tasks (Karni et al., 1995; Karni et al., 1998; Karni & Sagi, 1993; Karni et al., 1994). In 2004, Robertson et al. investigated this effect using the serial reaction time task and found that sequence learning effects improved after a 12-hour offline interval. As an integral part of learning, offline consolidation stabilizes newly acquired memory traces and plays an irreplaceable role in resisting interference during forgetting, attracting widespread research attention. Numerous studies have validated the existence of offline consolidation effects in explicit learning using various experimental paradigms (Brawn et al., 2010; Kempler & Richmond, 2012; Nettersheim et al., 2015; Sanchez-Mora & Tamayo, 2021; Song et al., 2007; Walker et al., 2003).

However, decades of research have revealed that learning is not necessarily conscious and can occur unconsciously through implicit learning—an automatic, imperceptible process of acquiring knowledge and rules through environmental interaction that plays a vital role in daily life adaptation and event prediction (Reber, 1967; Guo Xiuyan, 2003; Guo Xiuyan et al., 2011; Guo Xiuyan & Yang Zhiliang, 2002). Whether implicitly acquired knowledge exhibits offline consolidation effects and whether such effects depend on sleep remain focal research questions in this field (Cajochen et al., 2004; Kemeny & Lukacs, 2016; Nemeth et al., 2010; Robertson et al., 2004; Romano et al., 2010; Sanchez-Mora & Tamayo, 2021; Song et al., 2007; Spencer et al., 2007; Urbain et al., 2013). While previous studies have confirmed that implicitly acquired knowledge shows offline consolidation effects, no consistent conclusions have emerged regarding sleep's influence on implicit learning consolidation (Backhaus et al., 2016; Borragán et al., 2015; Ertelt et al., 2012; Hallgató et al., 2013; Meier & Cock, 2014; Nemeth et al., 2010; Robertson et al., 2004; Sanchez-Mora & Tamayo, 2021; Song et al., 2007; Spencer et al., 2006, 2007; Vakil et al., 2021).

In studies investigating implicit learning consolidation, researchers typically establish two conditions: a daytime group and a nighttime group, with participants completing the second phase 12 hours after the initial learning task—either during the day or night (Hallgató et al., 2013; Nemeth et al., 2010; Robertson et al., 2004; Sanchez-Mora & Tamayo, 2021; Spencer et al., 2007; Vakil et al., 2021). The daytime group remains awake while the nighttime group sleeps normally. Some studies have found sleep-based offline consolidation effects for implicit knowledge, with larger consolidation effects observed after sleep (Ertelt et al., 2012; Spencer et al., 2007), whereas others have found similar offline consolidation effects between sleep and wake states (Borragán et al., 2015; Nemeth et al., 2010).

Most previous studies examining implicit learning consolidation have employed the classic Serial Reaction Time (SRT) task (Nissen & Bullemer, 1987), which

suffers from a critical limitation: the stimulus presentation order corresponds one-to-one with the finger-pressing order, confounding perceptual and motor learning. Consequently, it remains unclear whether participants implicitly learn the stimulus presentation order (perceptual learning) or the finger-pressing order (motor learning), preventing precise determination of sleep's influence on implicit learning consolidation effects. Previous explicit sequence learning research has revealed differential consolidation of perceptual and motor information, with perceptual representations consolidating in a sleep-dependent manner while motor representations consolidate independently of sleep or wake states (Albouy et al., 2015; Albouy et al., 2013; Witt et al., 2010). Neuroimaging studies have further demonstrated distinct neural substrates: perceptual representations depend on hippocampo-cortical networks, whereas motor representations rely on striato-cortical networks. Hippocampal activity correlates with sleep-based offline consolidation, while striatal involvement in consolidation appears unaffected by sleep (Albouy et al., 2015; Peigneux et al., 2004). These findings support the possibility that sequence type may moderate sleep's effects on implicit sequence learning consolidation.

In light of these considerations, some researchers have attempted to examine sleep's impact on implicit learning consolidation of perceptual and motor sequences while attempting to separate them. Hallgató et al. (2013) employed a modified probabilistic SRT task to separate motor and perceptual sequences, finding better offline consolidation in the motor group than the perceptual group, but no sleep-related enhancement for either. Pace-Schott and Spencer (2013) used a similar paradigm and found differential sleep effects: sleep facilitated offline consolidation of perceptual sequences in young adults but showed no advantage for motor sequences. However, these studies failed to achieve complete separation. For instance, in Hallgató et al. (2013), participants performed a racing game scenario with four directional arrows representing car movement directions, each corresponding to a directional key press. Unknown to participants, the car's direction followed a specific sequence. The task included two phases: in Phase 1, participants were told the steering wheel was malfunctioning and had to rotate the arrow 90 degrees clockwise and press the corresponding key; in Phase 2, participants were randomly assigned to perceptual or motor groups and told the steering wheel was repaired. In the perceptual condition, the perceptual sequence (stimulus order) remained identical to Phase 1, but the motor sequence (key presses) rotated 90 degrees counterclockwise. In the motor condition, the motor sequence remained identical to Phase 1, but the perceptual sequence rotated 90 degrees clockwise. Although the key sequences changed in the perceptual group, they still followed a rule, creating a new motor sequence that corresponded to the perceptual sequence. Similarly, the motor group generated a new stimulus presentation sequence corresponding to the motor sequence. Thus, complete separation was not achieved.

In 2011, Rose et al. developed an improved SRT task that better separated perceptual and motor sequences while investigating whether pure perceptual and motor sequences could be implicitly learned. In this task, a target colored

square and six surrounding colored squares (e.g., red, green, magenta, black, yellow, blue) were presented on screen, with each surrounding square position corresponding to a keyboard key. Participants judged which surrounding square matched the target's color and responded quickly and accurately. In the perceptual group, the target square color followed a fixed sequence (e.g., yellow, black, green, red, magenta, blue) while finger responses were random. In the motor group, finger-press sequences followed a pattern (e.g., k, j, d, s, l, f) while target colors were random. This design effectively separated perceptual and motor sequences. Rose et al. found that both perceptual and motor sequences could be implicitly learned. Recent studies using similar paradigms have also demonstrated that pure motor sequences can be implicitly acquired (Deroost & Coomans, 2018; Ferdinand & Kray, 2017). Therefore, the present study adopted Rose et al.'s (2011) modified SRT task to completely separate perceptual and motor sequences while examining sleep's influence on offline consolidation of pure perceptual and motor sequence learning.

Furthermore, explicit learning research has shown that longer, structurally complex sequences benefit more from sleep than short, simple sequences, exhibiting sleep-based offline consolidation effects (Blischke & Malangré, 2016, 2017; Genzel et al., 2012; Malangré & Blischke, 2016; Malangré et al., 2014). For example, Blischke and Malangré (2017) used a gross motor task where participants inserted a peg into designated positions on a board following a specific sequence. They found that after sleep, execution time significantly decreased for long, complex sequences (e.g., 2-19-15-2-3-13-19-7-11-9-14), whereas no execution time reduction occurred after an equivalent wake period. No sleep-based offline consolidation was observed for short sequences (e.g., 3-13-19-7-11-9) or sequences following conventional movement patterns (e.g., X-shape or rectangle). Whether sleep's effect on offline consolidation of implicitly acquired knowledge is similarly influenced by sequence complexity remains unexplored.

In summary, the present study employed Rose et al.'s (2011) modified SRT task to completely separate perceptual and motor sequences. Through three experiments manipulating sequence complexity and a 12-hour offline interval (daytime vs. nighttime groups), we investigated sleep's impact on offline consolidation of pure perceptual and motor sequence learning. Resolving these questions will help determine whether implicitly acquired knowledge exhibits sleep-dependent consolidation advantages and whether offline consolidation processes differ between perceptual and motor sequence knowledge, providing further empirical evidence for the perceptual-motor debate in implicit sequence learning.

Experiment 1

Method

Participants Previous related studies employed sample sizes of 15-17 participants per group (Hallgató et al., 2013; Lutz et al., 2018). Referencing these studies and using G*Power 3.1 software with statistical power set at 0.90, α

level at 0.05, and effect size f at 0.44, the required sample size was calculated as 57 participants, averaging 15 per group. Eighty-eight university students (66 females, mean age 19.10 ± 0.97 years) were recruited and randomly assigned to perceptual-night, perceptual-day, motor-night, or motor-day groups. The perceptual-night group included 21 participants (17 females), perceptual-day group 21 (16 females), motor-night group 23 (17 females), and motor-day group 23 (16 females). All participants had normal intelligence, were right-handed, had no color blindness, and had normal or corrected-to-normal vision. Nine participants were excluded from subsequent analyses: seven reported discovering partial or complete sequence rules (four in motor-night, three in motor-day), and two perceptual-night participants had low sleep quality ratings (below 4). All participants provided informed consent and received compensation. The study was approved by the Shandong Normal University Ethics Committee.

Design This experiment employed a 2 (sequence: perceptual vs. motor) \times 2 (sleep: present vs. absent) between-subjects design. Dependent variables were error rates and reaction times in the SRT task, and confidence ratings in the prediction task.

Procedure The experiment consisted of two parts: the SRT task and the prediction task.

The SRT task used Rose et al.'s (2011) modified version. During the task, six surrounding colored squares (blue, yellow, black, green, red, magenta) and one target square appeared on screen, with each surrounding square position corresponding to a key (from left to right: s, d, f, j, k, l). Participants judged which surrounding square matched the target's color and responded quickly and accurately. For the perceptual sequence group, target square colors followed a fixed sequence (e.g., blue, yellow, black, green, red, magenta) while surrounding square colors were randomly assigned, making finger-press sequences random. For the motor group, finger-press sequences followed a pattern (e.g., s, l, f, k, j, d) while target square colors were random (see Figure 1A). Participants were unaware of the sequence rules. In each trial, the colored squares remained for a maximum of 2000 ms, disappearing after a key press, with the next set appearing after 300 ms. The formal experiment comprised two phases: Phase 1 included 16 blocks (12 sequence blocks and 4 random blocks at positions 3, 7, 11, and 15); Phase 2 included 4 blocks, with the third being a random block. Each block contained 72 trials with 10-second rest intervals between blocks. Phase 2 occurred 12 hours after Phase 1: for the night group, Phase 1 ran from 7-9 PM and Phase 2 from 7-9 AM; for the day group, Phase 1 ran from 7-9 AM and Phase 2 from 7-9 PM (see Figure 1B). Two perceptual sequences ("blue, yellow, black, green, red, magenta" and "black, blue, green, magenta, yellow, red") and two motor sequences ("s, l, f, k, j, d" and "l, k, f, s, j, d") were counterbalanced across participants. Practice trials preceded the formal experiment to ensure familiarity with the procedure.

After the SRT task, participants were asked whether they detected any rules in the material. If they reported discovering rules, they were required to write them down. A prediction task then assessed possible explicit knowledge. In this task, participants first observed stimuli (six surrounding squares and a target square) for 2000 ms without responding. After 300 ms, a prediction stimulus appeared (six surrounding squares and a question mark), requiring participants to predict the target square's color and respond accordingly. The prediction stimulus remained for a maximum of 2000 ms, disappearing after a response. Participants then rated their confidence (50%-100%, where 50% indicated pure guessing and 100% absolute certainty, allowing any value between) (Dienes & Seth, 2010; Guo et al., 2013; Li et al., 2013; Meador & Dienes, 2012). The task included 24 trials using the same sequence rules from the SRT task, with each sequence interruption presented four times (Rose et al., 2011).

To measure sleep duration and quality (night group: that night's sleep; day group: previous night's sleep), participants completed the Pittsburgh Sleep Quality Index (PSQI) (Buysse et al., 1989) and Morningness-Eveningness Questionnaire (MEQ) (Horne & Ostberg, 1976) after the experiment, following Song et al. (2007). Additionally, participants reported sleep duration and rated their sleep quality on a 1-10 scale (Song et al., 2007), with higher scores indicating better quality. Day group participants were instructed not to nap during the day but had no activity restrictions.

Results

Sleep Status Separate 2×2 ANOVAs on sleep duration, self-rated sleep quality, PSQI scores, and MEQ scores revealed no significant differences among the four groups ($p > 0.05$). Detailed data are presented in Table 1.

Implicit Sequence Learning Effects Error rates were low across groups: perceptual-night ($M = 0.04$, $SD = 0.02$), perceptual-day ($M = 0.05$, $SD = 0.02$), motor-night ($M = 0.03$, $SD = 0.02$), and motor-day ($M = 0.04$, $SD = 0.02$). Consequently, error rates were not analyzed further, with reaction times serving as the primary dependent variable.

Following Ling et al. (2015) and Hallgató et al. (2013), sequence learning effects (SLE) were calculated by subtracting the average reaction time of two adjacent sequence blocks from the random block reaction time: Phase 1 SLE = Block 15 - (Block 14 + Block 16) / 2. One-sample t-tests revealed significant SLEs above zero for all groups: perceptual-night ($t(18) = 2.48$, $p = 0.023$, Cohen's $d = 0.57$), perceptual-day ($t(20) = 2.37$, $p = 0.028$, Cohen's $d = 0.52$), motor-night ($t(18) = 6.71$, $p < 0.001$, Cohen's $d = 1.54$), and motor-day ($t(19) = 5.87$, $p < 0.001$, Cohen's $d = 1.31$), indicating sequence knowledge acquisition (see Figure 2A [Figure 2: see original paper]).

A 2 (sequence) \times 2 (sleep) between-subjects ANOVA on Phase 1 SLE revealed a significant main effect of sequence ($F(1, 75) = 49.06$, $p < 0.001$, $\eta^2 = 0.40$),

with motor sequences showing greater SLE than perceptual sequences. Neither the sleep main effect ($F(1, 75) = 0.31, p = 0.581$) nor the sequence \times sleep interaction ($F(1, 75) = 0.70, p = 0.404$) was significant.

Offline Consolidation Effects Following Ling et al. (2015) and Hallgató et al. (2013), Phase 2 SLE was calculated as Block 19 - (Block 18 + Block 20) / 2, with offline consolidation effects equal to Phase 2 SLE minus Phase 1 SLE. One-sample t-tests on Phase 2 SLE showed significant effects above zero for motor-night ($t(18) = 6.37, p < 0.001, \text{Cohen}'s\ d = 1.46$) and motor-day ($t(19) = 9.95, p < 0.001, \text{Cohen}'s\ d = 2.22$), but not for perceptual-night ($t(18) = 1.44, p = 0.168$) or perceptual-day ($t(20) = 0.24, p = 0.812$) (see Figure 2B [Figure 2: see original paper]).

One-sample t-tests on offline consolidation effects revealed significant effects above zero for motor-night ($t(18) = 2.76, p = 0.013, \text{Cohen}'s\ d = 0.63$) and motor-day ($t(19) = 2.31, p = 0.032, \text{Cohen}'s\ d = 0.51$), but not for perceptual-night ($t(18) = -0.88, p = 0.391$) or perceptual-day ($t(20) = -1.69, p = 0.107$) (see Figure 2C [Figure 2: see original paper]). A 2 (sequence) \times 2 (sleep) ANOVA on offline consolidation effects showed a significant main effect of sequence ($F(1, 75) = 16.47, p < 0.001, \eta^2 = 0.18$), with greater consolidation in the motor group than the perceptual group. Neither the sleep main effect ($F(1, 75) = 0.58, p = 0.448$) nor the sequence \times sleep interaction ($F(1, 75) = 0.001, p = 0.981$) was significant.

Awareness Assessment Dienes and colleagues proposed using the zero-correlation criterion to assess the conscious status of acquired knowledge (Dienes et al., 1995; Dienes & Berry, 1997; Dienes & Perner, 1999), a method widely proven to accurately determine the presence of explicit knowledge (Guo et al., 2013; Li, 2013). Specifically, if acquired knowledge is unconscious, participants cannot distinguish between knowing and guessing states even when making correct judgments, resulting in no correlation between accuracy and confidence ratings.

Following Jiang (2012), we examined confidence ratings for correct versus incorrect trials to assess knowledge consciousness. Fourteen participants were excluded for making all incorrect judgments (three in perceptual-night, nine in motor-night, two in motor-day). Results showed no significant confidence differences between correct and incorrect trials for perceptual-night ($t(15) = -0.63, p = 0.540$), motor-night ($t(9) = -1.77, p = 0.111$), or motor-day ($t(17) = -0.79, p = 0.439$), indicating implicit knowledge. Perceptual-day showed a significant difference ($t(20) = -2.36, p = 0.029, \text{Cohen}'s\ d = 0.51$), with higher confidence for incorrect than correct trials, also suggesting unconscious knowledge. The 14 excluded participants with 0% accuracy likewise indicated no explicit knowledge.

Discussion

Experiment 1 used Rose et al.'s (2011) modified SRT task to examine sleep's influence on offline consolidation of pure perceptual and motor sequence learning. The results showed stronger offline consolidation effects for motor sequences compared to perceptual sequences, but sleep did not facilitate offline consolidation for either sequence type.

Previous explicit learning research has demonstrated that sleep-based offline consolidation occurs only in complex action sequence learning, not in simple sequence learning (Blischke & Malangré, 2016, 2017; Genzel et al., 2012; Malangré et al., 2014). Whether sleep-based offline consolidation in implicit learning is similarly affected by sequence complexity remains an open question. Experiment 2 therefore employed more complex sequence rules to investigate sleep's impact on offline consolidation of pure perceptual and motor sequence learning.

Experiment 2

Method

Participants Previous studies used 15-20 participants per group (Lutz et al., 2018; Meier & Cock, 2014). Referencing these studies and using G*Power 3.1 with power = 0.90, $\alpha = 0.05$, and effect size Cohen's $d = 1.16$, the required sample size was 17 participants per group. Eighty-one university students (61 females, mean age 19.93 years) were recruited and randomly assigned to perceptual-night, perceptual-day, motor-night, or motor-day groups. The perceptual-night group included 20 participants (13 females), perceptual-day 20 (14 females), motor-night 20 (16 females), and motor-day 21 (17 females). All participants had normal intelligence, were right-handed, had no color blindness, and had normal or corrected vision. Six participants were excluded for discovering partial or complete rules (three in motor-night, three in motor-day). All participants provided informed consent and received compensation. The study was approved by the Shandong Normal University Ethics Committee.

Design As in Experiment 1, this experiment used a 2 (sequence: perceptual vs. motor) \times 2 (sleep: present vs. absent) between-subjects design. Dependent variables were error rates and reaction times in the SRT task, and confidence ratings in the prediction task.

Procedure As in Experiment 1, Experiment 2 included SRT and prediction tasks. The difference lay in using more complex sequences: two perceptual sequences ("red, green, black, yellow, blue, magenta, green, yellow, black, magenta, blue" and "blue, red, magenta, green, blue, black, red, black, green, yellow, magenta") and two motor sequences ("d, j, f, k, s, l, j, k, f, l, s" and "s, d, l, j, s, f, d, f, j, k, l").

Results

Sleep Status Separate 2×2 ANOVAs on sleep duration, self-rated sleep quality, PSQI scores, and MEQ scores revealed no significant differences among groups ($p > 0.05$). Detailed data are presented in Table 2 .

Implicit Sequence Learning Effects Error rates were low: perceptual-night ($M = 0.04$, $SD = 0.02$), perceptual-day ($M = 0.04$, $SD = 0.03$), motor-night ($M = 0.04$, $SD = 0.02$), and motor-day ($M = 0.04$, $SD = 0.03$). Error rates were not analyzed further.

As in Experiment 1, Phase 1 SLE was calculated as $\text{Block 15} - (\text{Block 14} + \text{Block 16}) / 2$. One-sample t-tests revealed significant SLEs above zero for motor-night ($t(16) = 4.80$, $p < 0.001$, Cohen' s $d = 1.17$) and motor-day ($t(17) = 6.27$, $p < 0.001$, Cohen' s $d = 1.48$), but not for perceptual-night ($t(19) = 1.92$, $p = 0.070$) or perceptual-day ($t(19) = 0.90$, $p = 0.377$) (see Figure 3A [Figure 3: see original paper]).

A 2 (sequence) $\times 2$ (sleep) ANOVA on Phase 1 SLE showed a significant main effect of sequence ($F(1, 71) = 23.47$, $p < 0.001$, $\eta^2 = 0.25$), with greater SLE for motor than perceptual sequences. Neither the sleep main effect ($F(1, 71) = 0.01$, $p = 0.915$) nor the sequence \times sleep interaction ($F(1, 71) = 0.41$, $p = 0.522$) was significant.

Offline Consolidation Effects Phase 2 SLE was calculated as $\text{Block 19} - (\text{Block 18} + \text{Block 20}) / 2$, with offline consolidation effects equal to Phase 2 SLE minus Phase 1 SLE. One-sample t-tests on Phase 2 SLE showed significant effects above zero for motor-night ($t(16) = 8.21$, $p < 0.001$, Cohen' s $d = 1.99$) and motor-day ($t(17) = 6.49$, $p < 0.001$, Cohen' s $d = 1.53$), but not for perceptual-night ($t(19) = 0.70$, $p = 0.491$) or perceptual-day ($t(19) = 0.89$, $p = 0.385$) (see Figure 3B [Figure 3: see original paper]).

One-sample t-tests on offline consolidation effects revealed significant effects above zero for motor-night ($t(16) = 4.37$, $p < 0.001$, Cohen' s $d = 1.06$), but not for motor-day ($t(17) = -1.50$, $p = 0.153$), perceptual-night ($t(19) = -1.16$, $p = 0.261$), or perceptual-day ($t(19) = -0.02$, $p = 0.987$) (see Figure 3C [Figure 3: see original paper]). A 2 (sequence) $\times 2$ (sleep) ANOVA showed no significant main effect of sequence ($F(1, 71) = 3.13$, $p = 0.081$) but a significant main effect of sleep ($F(1, 71) = 4.50$, $p = 0.037$, $\eta^2 = 0.06$) and a significant sequence \times sleep interaction ($F(1, 71) = 9.20$, $p = 0.003$, $\eta^2 = 0.12$). Simple effects analysis revealed no significant offline consolidation difference between night and day groups for perceptual sequences ($F(1, 71) = 0.44$, $p = 0.507$), but the night group showed significantly greater offline consolidation than the day group for motor sequences ($F(1, 71) = 12.45$, $p = 0.001$, $\eta^2 = 0.15$). With sleep, the motor group showed significantly greater consolidation than the perceptual group ($F(1, 71) = 11.35$, $p = 0.001$, $\eta^2 = 0.14$), but without sleep, no significant difference existed between groups ($F(1, 71) = 0.81$, $p = 0.371$).

Awareness Assessment Using the zero-correlation criterion, we found no significant confidence differences between correct and incorrect trials for any group (perceptual-night: $t(19) = -0.13$, $p = 0.897$; perceptual-day: $t(19) = -0.45$, $p = 0.658$; motor-night: $t(16) = 1.28$, $p = 0.218$; motor-day: $t(17) = 0.78$, $p = 0.447$), indicating implicitly acquired sequence knowledge.

Discussion

Building on Experiment 1, Experiment 2 used more complex sequence rules (sequence length 11) to further examine sleep's influence on offline consolidation of pure perceptual and motor sequence learning. The results showed that participants implicitly learned motor sequences, with the motor-night group demonstrating stronger offline consolidation than the motor-day group. However, participants neither implicitly acquired perceptual sequences nor showed offline consolidation effects for them.

In Experiment 1, using six-element sequences, both pure perceptual and motor sequence knowledge were implicitly acquired, with greater motor sequence knowledge acquisition—consistent with Rose et al. (2011) and Deroost and Soetens (2006). In Experiment 2, using 11-element sequences, only motor sequences were acquired. Previous research suggests perceptual sequence learning occurs only with relatively simple structures, being absent or weak with complex structures (Deroost & Soetens, 2006; Kempler & Richmond, 2012; Remillard, 2003). Thus, the weakened perceptual sequence knowledge in Experiments 1 and 2 may relate to perceptual sequence complexity.

Both experiments found offline consolidation effects for motor but not perceptual sequences. Kemeny and Lukacs (2016) proposed that learning magnitude affects offline consolidation, with smaller learning effects producing smaller consolidation effects. In Experiment 1, the perceptual group's Phase 1 SLE was small (11 ms) and significantly lower than the motor group's (67 ms). Therefore, the absence of perceptual offline consolidation may relate to insufficient perceptual sequence learning magnitude. To address this, Experiment 3 further reduced perceptual sequence complexity to enhance learning effects and re-examined pure perceptual sequence offline consolidation.

Experiment 3

Method

Participants Previous studies used 15-20 participants per group (Lutz et al., 2018; Meier & Cock, 2014). Referencing these studies and using G*Power 3.1 with power = 0.90, $\alpha = 0.05$, and effect size Cohen's $d = 1.16$, the required sample size was 17 participants per group. Forty-six university students (39 females, mean age 19.33 ± 1.30 years) were recruited and randomly assigned to night or day groups. The night group included 23 participants (21 females) and the day group 23 (18 females). All participants had normal intelligence, were

right-handed, had no color blindness, and had normal or corrected vision. Four day-group participants were excluded: two for failing to follow instructions, one for falling asleep during the experiment, and one due to program malfunction. All participants provided informed consent and received compensation. The study was approved by the Shandong Normal University Ethics Committee.

Design This experiment used a single-factor between-subjects design with group (night vs. day) as the independent variable. Dependent variables were error rates and reaction times in the SRT task, and confidence ratings in the prediction task.

Procedure As in Experiments 1 and 2, Experiment 3 included SRT and prediction tasks. The difference was that the SRT task presented only four surrounding colored squares (yellow, green, red, blue) and one target square (see Figure 4 [Figure 4: see original paper]). Each surrounding square position corresponded to a key (from left to right: d, f, j, k). Only perceptual sequences were used, with two sequences (“red, blue, green, yellow” and “green, blue, red, yellow”) counterbalanced across participants.

Results

Sleep Status Independent samples t-tests on sleep duration, self-rated sleep quality, PSQI scores, and MEQ scores revealed no significant differences between groups ($p > 0.05$). Detailed data are presented in Table 3 .

Implicit Sequence Learning Effects Error rates were low: night group ($M = 0.04$, $SD = 0.02$) and day group ($M = 0.04$, $SD = 0.03$). Error rates were not analyzed further.

Phase 1 SLE was calculated as $\text{Block 15} - (\text{Block 14} + \text{Block 16}) / 2$. One-sample t-tests revealed significant SLEs above zero for both night ($t(22) = 4.73$, $p < 0.001$, $\text{Cohen's } d = 0.99$) and day ($t(18) = 6.11$, $p < 0.001$, $\text{Cohen's } d = 1.40$) groups (see Figure 5 [Figure 5: see original paper]), indicating sequence knowledge acquisition. An independent samples t-test showed no significant difference between groups ($t(40) = 0.57$, $p = 0.570$).

Offline Consolidation Effects Phase 2 SLE was calculated as $\text{Block 19} - (\text{Block 18} + \text{Block 20}) / 2$, with offline consolidation effects equal to Phase 2 SLE minus Phase 1 SLE. One-sample t-tests on Phase 2 SLE showed no significant effects for either group (night: $t(22) = 1.25$, $p = 0.226$; day: $t(18) = 0.63$, $p = 0.535$) (see Figure 5 [Figure 5: see original paper]).

One-sample t-tests on offline consolidation effects revealed significant effects below zero for both night ($t(22) = -2.73$, $p = 0.012$, $\text{Cohen's } d = 0.57$) and day ($t(18) = -3.63$, $p = 0.002$, $\text{Cohen's } d = 0.83$) groups, with no significant difference between groups ($t(40) = -0.11$, $p = 0.911$).

Awareness Assessment Using the zero-correlation criterion, five participants were excluded for making all incorrect judgments (two in night group, three in day group). No significant confidence differences emerged between correct and incorrect trials for either group (night: $t(20) = 0.82$, $p = 0.423$; day: $t(15) = -0.42$, $p = 0.677$), indicating no explicit knowledge.

Discussion

Experiment 3 used a simpler, four-element sequence to further examine sleep's impact on offline consolidation of pure perceptual sequence learning. Participants implicitly acquired pure perceptual sequences, but neither group showed offline consolidation effects, consistent with Experiment 1. Compared to Experiments 1 and 2, the perceptual group's learning effect improved (16 ms) but remained substantially lower than motor group effects in Experiment 1 (67 ms) and Experiment 2 (39 ms).

General Discussion

Using Rose et al.'s (2011) modified SRT task to completely separate perceptual and motor sequences, three experiments manipulating sequence complexity systematically examined sleep's influence on offline consolidation of pure perceptual and motor sequence learning. The results demonstrated that sleep's involvement in offline consolidation of implicitly acquired sequence knowledge depends on both sequence type (motor vs. perceptual) and complexity. Specifically, for motor sequences, offline consolidation occurred regardless of sleep when complexity was low (sequence length 6; Experiment 1), but sleep was necessary for consolidation with complex rules (sequence length 11; Experiment 2). For perceptual sequences, no offline consolidation occurred regardless of difficulty (Experiments 1, 2, and 3).

Our findings reveal that in implicit motor sequence learning, complex sequences benefit more from sleep than simple sequences, showing sleep-based offline consolidation effects. This aligns with explicit motor sequence research: sleep promotes offline consolidation only for long, structurally complex sequences (Blischke & Malangré, 2016, 2017; Genzel et al., 2012; Malangré et al., 2014). In implicit motor sequence research, Ertelt et al. (2012) used a complex dual-task paradigm with long, structurally complex sequences (e.g., 231432413421) and found sleep facilitated offline consolidation of implicitly acquired sequences. Conversely, Borragán et al. (2015) used relatively simple touchscreen motor sequences (four-corner positions forming simple path shapes) and found similar offline consolidation effects in sleep and sleep-deprived states. These results collectively indicate that sleep promotes offline consolidation of complex motor sequences, possibly because simple sequence structures cannot actively benefit from systems consolidation processes, limiting subsequent enhancement (Blischke & Malangré, 2017). Additionally, research suggests sleep facilitates complex cognitive learning unique to humans (Stickgold, 2005). However, questions

remain regarding what complexity level or length triggers sleep-based offline consolidation, which sleep stages are involved, and why such consolidation occurs exclusively during sleep.

Our study found no offline consolidation effects for pure perceptual sequence learning regardless of difficulty or sleep condition. Kemeny and Lukacs (2016) noted that learning magnitude affects offline consolidation, with smaller learning effects producing smaller consolidation effects. In Experiment 1, the perceptual group' s Phase 1 SLE was small (11 ms) and significantly lower than the motor group' s (67 ms). Although Experiment 3 used simpler sequences to enhance perceptual sequence learning, Phase 1 SLE remained modest (night: 17 ms; day: 14 ms). Thus, the absence of perceptual offline consolidation may relate to insufficient learning magnitude. However, previous research on pure perceptual sequence learning typically reports SLEs between 10-20 ms (Gheysen et al., 2011; Rose et al., 2011), possibly because key-press responses cannot directly reflect perceptual sequence learning effects. Future research should employ more direct, sensitive measures to investigate pure perceptual sequence consolidation. Additionally, learning duration and block distribution may influence perceptual sequence learning effects, suggesting that increasing learning time could enhance learning magnitude.

Notably, time interval represents another crucial factor affecting offline consolidation (Albouy et al., 2006; Albouy et al., 2008; Hallgató et al., 2013; Schalkwijk et al., 2019). Research on consolidation time courses indicates a critical period after learning during which memory traces stabilize or improve, with duration varying by task (Robertson et al., 2005; Walker et al., 2003). For example, Press et al. (2005) used a standard SRT task to investigate implicit motor sequence consolidation time courses, finding consolidation effects emerged 4 hours after learning and increased with longer offline intervals. Subsequent research using similar tasks found motor sequence consolidation effects persisted after 12 hours, 24 hours, one week, or even one year (Meier & Cock, 2014; Nemeth & Janacsek, 2011; Romano et al., 2010). In contrast, Albouy et al. (2006) used a serial oculomotor reaction time task (SORT) requiring only eye movements (no finger responses) and found consolidation effects at 30 minutes post-learning that disappeared after 5 hours. Similarly, temporal discrimination tasks showed perceptual learning consolidation effects as early as 5 minutes post-learning (Bratzke et al., 2014). These findings suggest perceptual sequence consolidation may be a faster process than motor sequence consolidation. Therefore, the absence of pure perceptual sequence offline consolidation in our study may relate to overly long intervals allowing consolidation followed by decay. Future research should design different time intervals for sleep and wake conditions to investigate the specific time points and dynamic trajectories of sleep-based offline consolidation for pure perceptual and motor sequences.

Consistent with explicit learning research, our study found dissociated effects of sleep on perceptual and motor sequence consolidation. However, unlike explicit learning, we found sleep promoted offline consolidation for complex but

not simple motor sequences, while perceptual sequences showed no consolidation effects. Notably, previous explicit learning studies separating perceptual and motor sequences did not manipulate sequence difficulty, leaving unclear how increased complexity affects sleep's role in explicit sequence consolidation. King et al. (2017) proposed that specific sequence features (e.g., spatial, sequential, contextual information) influence sleep's role in memory consolidation, depending on hippocampal system reactivation. Other researchers suggest sleep's positive effects relate to offline reactivation of learning-related brain regions (e.g., hippocampus, cuneus, premotor cortex, supplementary motor area, striatum) (Maquet et al., 2000; Peigneux et al., 2003; Urbain et al., 2013). Future research should employ ERP and fMRI to investigate the neural mechanisms underlying sleep's influence on sequence learning consolidation, clarifying relationships among sequence type, sleep, and implicit/explicit learning modes.

Additionally, circadian rhythm represents a non-negligible factor, as many skills and cognitive processes are influenced by circadian rhythms (Cajochen et al., 2004; May et al., 2005). In our study, day and night groups showed no Phase 1 learning differences, indicating that learning at different times of day did not affect acquisition. Moreover, the day/night group design is a classic approach in sleep and consolidation research (Hallgató et al., 2013; Sanchez-Mora & Tamayo, 2021; Vakil et al., 2021). Previous attempts to distinguish sleep and circadian effects by controlling time-of-day effects have yielded inconsistent results (Cajochen et al., 2004; Keisler et al., 2007; Tucker et al., 2017). Future studies could investigate sleep's influence on sequence learning using nap paradigms.

Our findings offer methodological implications for real-world complex motor skill implicit learning, such as musical instrument learning, coordinated movements in sports, and complex speech articulation. These domains may benefit from pre-sleep practice schedules to enhance learning.

In conclusion, using a modified SRT task, this study investigated sleep's influence on offline consolidation of pure perceptual and motor sequence learning. The results demonstrate that sleep's promotion of offline consolidation for implicitly acquired sequence knowledge depends on sequence type and complexity. In implicit motor sequence learning, complex sequences benefit more from sleep than simple sequences. For perceptual sequences, no offline consolidation effects occurred regardless of difficulty.

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