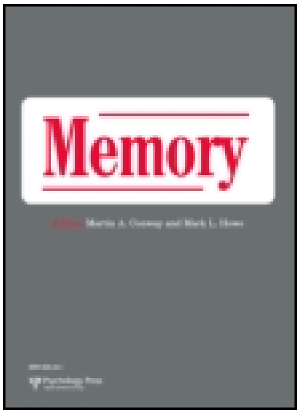

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Effect of sleep on gross motor memory

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Sleep has a beneficial effect on consolidation of newly learned fine motor skills. The aim of the current study was to determine whether sleep has a similar beneficial effect on consolidation of gross motor skills. A total of 70 participants were randomly assigned to either a Sleep-Wake group or a Wake-Sleep group and were trained on an arm coordinated reaching task as a gross motor skill. Initial training occurred in the evening for the Sleep-Wake group and in the morning for the Wake-Sleep group. All participants attended two test sessions 12 and 24 hours following the initial training. Gross motor skill performance improved in both groups following a night of sleep but not after a day of wakefulness. These findings may have implications for learning of new gross motor skills in a range of activities from dance to motor rehabilitation.

Keywords: Consolidation; Learning; Memory; Motor skills; Sleep.

The role of sleep in memory formation has received increasing attention in the past decade. In particular there is evidence to suggest that sleep may play a role in memory consolidation, the process by which ongoing changes in the brain serve to stabilise and/or strengthen recently acquired information and reduce vulnerability to interference (McGaugh, 2000; Brashers-Krug, Shadmehr, & Bizzi, 1996). Memory consolidation has been considered to involve two phases, stabilisation and enhancement (Walker, 2005). Consolidation-based stabilisation is the process by which performance is maintained at the level achieved immediately after learning, and the newly learned skill becomes increasingly resistant to interference over the passage of time. This stabilisation process is not sleep dependent. In contrast, consolidation-based enhancement results in performance improvements in the absence of further practice. Sleep has been shown to result in performance enhancements on both declarative and procedural memory tasks (Gais & Born, 2004; Plihal & Born, 1997; Stickgold, 2005; Tucker & Fishbein, 2008; Walker, Brakefield, Morgan, Hobson, & Stickgold, 2002), however the most convincing evidence for sleep-dependent memory consolidation has been accumulated in studies of motor skill learning (Stickgold, 2005).

A period of sleep following the learning of a fine motor skill task has been shown to improve the speed and/or accuracy on the learned skill in the absence of further practice (Fischer, Hallschmid, Elsner, & Born, 2002; Walker et al., 2002). For example, Walker et al., (2002) trained participants on a finger-tapping task, either in the morning or in the evening. All participants were tested after a 12-hour delay and a second time after a further 12 hours. While performance remained stable across a period of wakefulness, the results showed that following a period of sleep, participants produced a greater number of accurate cycles of the task within the 30-second

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test period relative to their post-training performance. Similar sleep-related enhancements have been shown for performance on a finger-to-thumb tapping task (Fischer et al., 2002) and performance on a mirror-tracing task (Plihal & Born, 1997). There is some evidence to suggest that performance on complex fine motor tasks benefits from sleep to a greater extent than does performance on simple tasks (Kuriyama, Stickgold, & Walker, 2004).

While research demonstrating improvements in performance has been interpreted as evidence for a role for sleep in consolidation-based enhancement, some researchers have suggested that these effects are an artefact of data-averaging practices (Rickard, Cai, Rieth, Jones & Ard, 2008). Rickard et al. (2008) showed that when controlling for within-block reactive inhibition, averaging over learning, time of day, and fatigue following massed training, performance levels were maintained at the level achieved following practice but did not improve. It was suggested that sleep has a role in stabilisation, and the factors listed above can result in false improvements.

While there is considerable evidence for sleep-related performance enhancement in fine motor skill learning, the evidence for a role of sleep in gross motor skill learning is mixed. Learning certain kinds of novel gross motor skills has been shown to produce changes in sleep architecture. For example, Buchegger and Meier-Koll (1988) showed that an 8-week trampolining course produced longer sleep cycles and longer REM phases relative to pre-training baseline levels. Furthermore, increases in the duration of Stage 2 sleep and increases in spindle density have been demonstrated following intense motor learning. The changes in spindle density are also positively correlated with improvements on the tasks (Fogel & Smith, 2006). However, changes in sleep architecture do not occur in response to all gross motor skill training. Subsequent studies showed that changes in REM sleep in response to gross motor skill training were specific to trampolining and did not extend to soccer and dance (Buchegger, Fritsch, Meier-Koll, & Riehle, 1991) or snakeboard riding (Erlacher & Schredl, 2006).

Although gross motor skill learning seems to produce changes in sleep architecture under some circumstances, to date there is little consistent evidence to suggest that the sleep produces improvements in gross motor skill learning in the same way as for fine motor skills. For example, Blischke, Erlacher, Kresin, Brueckner, and Malangré, (2008) trained participants on a finger-tapping task, a diamond-tapping task, a pursuit tracking task, and a counter movement jump task, and tested the effect of sleep on their subsequent performance. While an improvement following sleep was evident in a finger-tapping task, there was no effect of sleep on the other tasks, including the jump task; a gross motor task in which participants were asked to jump at 60% of their maximal height. While differences in task complexity may help to explain differing results across the procedural tasks used (Kuriyama et al., 2004), it also may be that sleep-dependent consolidation effects differ across fine and gross motor skill tasks.

Gross motor skills have been variably defined. While one definition considers gross motor skills to involve tasks using more than 50% of skeletal muscles (Magill, 2011), others make no reference to percentage of skeletal muscles being used for a movement and instead refer to use of body parts such as arms, legs, or torso, and movement examples such as reaching or kicking (Dugdale, 2011; Moore, Dalley, & Agur, 2005; Raszewski, 2007). These skills are used for the most basic everyday functions such as washing, dressing, eating, reaching, and walking, as well as during sport, dance, and so on. Gross motor functions can be impaired in children with developmental difficulties, in elderly people with degenerative disorders, and in patients with diseases and disorders that impair motor functioning such as cerebral palsy, autism, and motor dyspraxia. Gross motor skill in clinical settings is often assessed using standardised tests such as the Test of Gross Motor Development (TGMD) (Ulrich, 2000). This test has two major components: ''locomotor'' and ''object control''. The ''object control'' component includes three throwing and catching tasks that use predominantly arm movements. The task used in the current study is comparable to the ''object control'' component, as it uses arm reaching movements similar to those involved when throwing a ball. However, it is also similar to the ''locomotor'' component as sequential coordinated movements were administered.

Here we investigate the effect of sleep on a gross motor skill, in which the upper limbs were used to combine two different motor patterns. Due to the limited research looking at the relationship between gross motor skill and sleep, our interest was to discern whether a night of sleep following the learning of a gross motor task would produce improvements in performance relative to a day of wakefulness. We hypothesised that the number of accurate cycles of the gross motor task that participants would be able to produce upon testing would be greater following a night of sleep than following a comparable period of wakefulness.

METHOD

Participants

A total of 70 healthy adults between the ages of 18 and 56 ($M = 26$ $SD = 8.0$) participated in this study. Procedures were approved by the Human Research Ethics Advisory Panel, University of New South Wales and all participants provided written informed consent. Participants were randomly assigned by computer generation to either the Sleep-Wake (SW) Group (17 males, 18 females; aged 18–52) or the Wake-Sleep (WS) Group (9 males and 26 females; age 18–55). The groups did not differ in age (SW: $M = 26$, $SD = 7.2$, WS: $M = 25$, $SD = 8.8$). However, there was a chance occurrence of unequal distribution of males and females.

Materials

An instructional video (2 minutes 24 seconds) was used to demonstrate the gross motor skill. The model in the video illustrated the movements required with each arm individually before combining them in slow motion. A digital video camera was used to film each participant to allow for reliability coding. To assess for potential differences in subjective sleepiness between groups, all participants completed the Karolinska Sleepiness Scale (KSS), developed by Akerstedt and Gillberg (1990), before viewing the training video. The KSS has been deemed to have a high validity in measuring sleepiness, determined by a close relation to EEG and behavioural variables (Kaida, et al., 2006). As well as the KSS, participants also completed the Karolinska Sleep Questionnaire (KSQ) (Akerstedt et al., 2002), a sleep logbook, in reference to their night of sleep during experimental hours. Finally, an Actiwatch (Mini Mitter, Philips, USA) was used as an objective marker of sleep duration during the night before the post sleep test. Studies evaluating the reliability and validity of actigraphy methods in measuring sleep and wakefulness have found a high concordance rate in overall minute-by minute sleep time when compared with polysomnography PSG reports (Ancoli-Israel et al., 2003; De Souza et al., 2003).

Design

Participants were randomly assigned to one of two groups. The Wake-Sleep (WS) Group trained in the morning (7:30am to 10:30am) and remained awake during the day. They then returned for Test 1 in the evening and slept before Test 2 the next morning. The Sleep-Wake (SW) group trained in the evening (7:30pm to 10:30pm) and slept during the night. This group returned for Test 1 the next morning and remained awake prior to Test 2 that evening. This meant that all participants returned for testing 12 and 24 hours after their training session and slept nocturnally (see Figure 1).

Procedure

Aside from the time of the initial visit, the procedure administered to the two groups did not differ. Participants were instructed to have their usual night's sleep. However, as we were working primarily with university students where short sleep is often a concern (Steptoe, Peacey, & Wardle, 2006), we asked that they ensure they have an absolute minimum of 5 hours sleep the night before their training and the night before their post-sleep test. They were also asked to refrain from napping during the day before their post-wake test. Before beginning training each participant completed the KSS, a measure of subjective alertness, and was given an Actiwatch

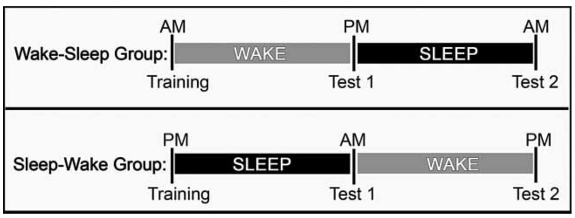

Figure 1. The timeline of training and testing for each group. For the WS group, training occurred between 7:30 and 10:30 am. For the SW group, training occurred between 7:30 and 10:30 pm. Test 1 and Test 2 were scheduled 12 and 24 hours following training, respectively.

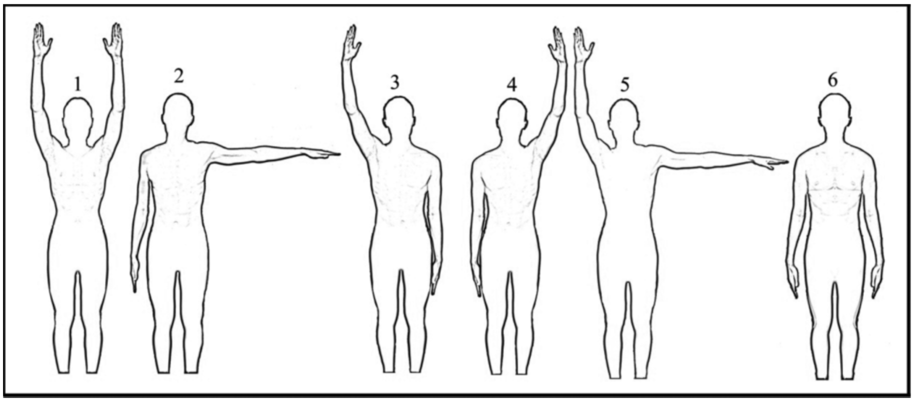

Figure 2. The gross motor task with each combination of arms in the order in which they were set (for video see http://www.youtube.com/watch?v=WCrb8b-tBSk&feature=youtu.be).

to wear for the duration of the experiment. All participants were then trained on the gross motor task. Training on the arm coordination task began with participants watching an instructional video that demonstrated the skill step-by-step. Participants were asked to inform the experimenter if they had seen the skill before; no participants were excluded due to prior skill experience. The task used in the study was a novel coordination task that has not been used in previous studies. It required the participants to point their left arm to the ceiling, the side and to the floor in sequence, while the right arm simultaneously pointed to the ceiling then the floor in sequence (see Figure 2). When each arm executed their movements at the same time, a sequence with six different position combinations was achieved. This sequential combination of arm movements was performed in continuous cycles for a 30 second period. Within the 30-second period the participants were required to complete as many accurate cycles of the sequence as possible. To score one correct movement cycle participants had to accurately reproduce positions 1–3 in sequence. Completing the movement cycle from positions 4–6 was an additional score. Therefore, within the 6-position sequence were two score opportunities for participants. The total number of correct movement cycles in a 30-second period was the final score for that test session. Participants were permitted to start the cycle again within the given 30 seconds if they became overwhelmed and stuck.

Participants were encouraged to imitate the model while watching the video, practising the left arm movement alone, followed by the right arm movement alone, and then combining the two arm movements together for 30 seconds. Immediately after watching the training video participants were video recorded for 30 seconds while they performed the task and the number of accurate repetitions produced at this stage formed their Baseline Test score. Participants were given the opportunity to practice for a total of 6 minutes, delivered in 30-second practice trials alternating with 30-second rest periods. After the first five practice periods, participants were recorded again for 30 seconds while they performed the task and the number of accurate repetitions produced formed their Immediate Test score.

Although other results are not presented in this paper, it is important that we note that two other tasks were learnt during the training session: a finger-tapping task and a serial order learning task. In order to control for potential interference of other learning tasks, the order in which the tasks were learned was randomised across participants. Testing of each task was then performed in the same order that the tasks were learned. There were no differences in task performance based on task learning order.

Then, 12 hours after the training session, participants in both groups returned for Test 1. Participants had been asked not to practise the skill in the hours between tests. In this session participants were tested on their ability to perform as many accurate cycles of the gross motor task as possible in a 30-second period. Participants in the SW group also completed the KSQ with reference to their sleep the previous night. Test 2 was administered in the same fashion after a further 12 hours. The WS group, who had slept in the 12 hours preceding Test 2, completed the KSQ at this point as well. All participants then returned their Actiwatches for analysis.

Statistical analyses

All data were analysed using the PASW Statistics 18 software. Data from two participants were excluded for failure to attend delayed test sessions. Due to chance, a disproportionate number of females to males were included in this study. Preliminary analyses revealed no effect of gender on task performance ($p > .05$) and thus data are combined.

The number of accurate cycles produced by each participant in each 30-second test trial produced an index of speed. The number of errors made by each participant in each 30-second test trial produced an index of accuracy. In examining the data we noted that error scores were not a valid reflection of participants' proficiency on the task. Participants approached the task conservatively, choosing a speed at which they could maintain accurate performance. As a result the mean number of errors was low and did not change over training. For this reason the presented data scores represent the number of accurate cycles performed in the 30-second period only. Incidentally, this was lower for participants with greater errors as incorrect cycles consumed time.

Independent samples *t*-tests were used to test for group differences in subjective and objective hours of sleep, sleepiness at training (KSS score), and in Baseline and Immediate Test scores. To analyse the effect of Sleep and Wake on performance across each of the four test phases, a repeated-measures ANOVA with test phase (Baseline, Immediate Test, Test 1, and Test 2) and group (Sleep-Wake and Wake-Sleep) was conducted. An analysis of difference scores was used to support these results. In all cases two-tailed tests and an alpha level of $p < .05$ were used.

RESULTS

There were no significant differences in age of participants in the SW and WS groups, $t(66) = .58$, $p > .05$. As is illustrated in Table 1, there were no differences in the subjective reports of the amount of sleep obtained as a function of group, $t(66) = 1.33$, $p > .05$. Due to technical problems with several devices, Actiwatch data were only available for 60% of the sample. However, in those participants ($N = 42$), the amount of sleep during the night also did not differ between groups, $t(40) = 1.48$, $p > .05$. The KSS was not completed in the first 14 participants as it was introduced into the study later, however results indicated that there were no group differences in subjective sleepiness at the time of learning, $t(52) = 1.07$, $p > .05$.

TABLE 1
Subjective and objective sleep hours and sleepiness scores of participants in each group

Group	*Mean hours of reported sleep (N = 67)*	*Mean hours of Actiwatch recorded sleep (N = 42)*	*KSS score (N = 54)*
Sleep-Wake	7.3 (1.6)	8.2 (1.8)	4.8 (2.0)
Wake-Sleep	7.8 (1.3)	8.9 (1.6)	4.3 (1.6)

Task performance

Independent samples *t*-tests showed no difference in task performance at either the Baseline Test, $t(66) = .27$, $p > .05$, or the Immediate Test, $t(66) = .64$, $p > .05$ (see Table 2). As is illustrated in Figure 3 there was no group difference in the degree of performance improvement from Baseline to Immediate Test, $t(66) = .69$, $p > .05$.

A repeated-measures ANOVA with test phase (Baseline, Immediate, Test 1, and Test 2) and group (Sleep-Wake, Wake-Sleep) as factors was used. There was no main effect of group, $F(1, 66) = .16$; $p > .05$, however, a main effect of test phase, $F(3, 198) = 130.28$, $p < .01$, was qualified by a significant test phase × group interaction, $F(3, 198) = 3.34$, $p < .05$. Pairwise

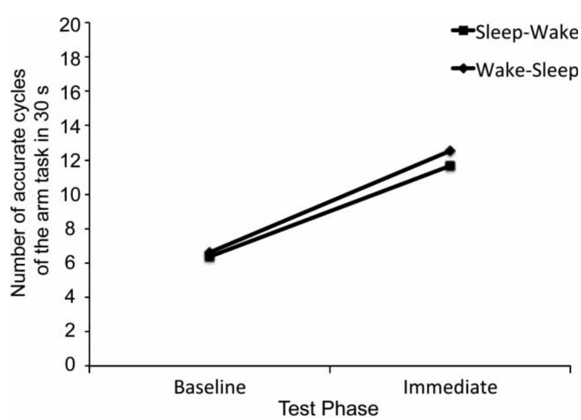

Figure 3. The mean number of accurate cycles of the gross motor task produced at the Baseline Test (which occurred after viewing the task on video) and the Immediate Test (participants' scores after practice). Both groups improved following practice and there were no differences in improvement between groups.

TABLE 2
Mean number of accurate cycles produced as a function of group and test phase

Group		*Baseline*	*Immediate*	*Test 1*	*Test 2*
Sleep-Wake	Mean	6.35	11.65	14.68	15.12
	SD	3.14	5.18	6.11	7.25
Wake-Sleep	Mean	6.59	12.5	13.53	17.18
	SD	4.08	5.82	6.92	7.0

comparisons for the SW group indicated that performance improved significantly between the Baseline Test and Immediate Test ($p < .01$), the Immediate Test, and Test 1 ($p < .01$), but not between Test 1 and Test 2 ($p > 0.5$). Test 1 scores were significantly higher than scores from the Immediate Test, indicating improvement following a night of sleep. In the WS group significant improvements were found between the Baseline Test and Immediate Test ($p < .01$), Test 1 and Test 2 ($p < .01$), but not between the Immediate Test and Test 1 ($p > .05$). Test 2 scores were significantly higher than Test 1 scores indicating improvements following sleep in the WS group. Both groups' scores on the Immediate Test, Test 1, and Test 2 can be seen in Figure 4.

Analysis of difference scores revealed a similar pattern of results. There were no group differences in the degree of improvement from Baseline to Immediate Test, $t(66) = .69$, $p > .05$. Participants in the SW group experienced a significantly greater improvement from Immediate to Test 1 relative to those in the WS sleep group, $t(66) = 2.43$, $p < .05$. In contrast, between Test 1 and Test 2 those in the WS sleep group experienced greater improvement than participants in the SW group, $t(66) = 4.35$, $p < .01$.

DISCUSSION

This study has demonstrated that performance on a newly learned gross motor skill, specifically a coordinated arm-reaching task, improves following a night of sleep but not across a day of wakefulness. Participants produced a greater number of accurate cycles of the task following sleep, while there were no changes were seen after a day of wakefulness.

Our results show a beneficial effect of sleep on gross motor sequential memory. Performance on a gross motor skill task exhibits a similar pattern of sleep-dependent enhancement as seen with fine motor skills. Participants who were trained in the morning performed at a similar level when tested after a 12-hour delay; however, when retested following a night of sleep they produced a significantly greater number of accurate arm coordination cycles. Similarly, participants who were trained in the evening exhibited enhanced performance when tested the following morning after sleep, but no further improvement upon retesting after 12 hours of wakefulness. These results are consistent with the idea that consolidation processes that occur during sleep convey performance improvements for gross motor skills congruent with previous data from

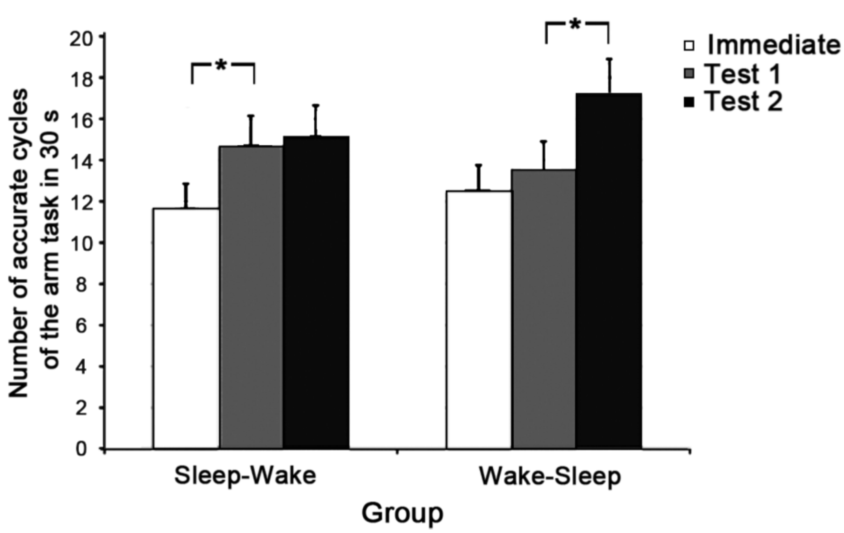

Figure 4. The mean number of accurate cycles of the gross motor task produced by each group at each test session. The asterisk (*) indicates a significant improvement from the previous test. Both groups improved following sleep and neither group improved following wakefulness.

others measuring fine motor skills (Fischer et al., 2002; Plihal & Born, 1997; Walker et al., 2002).

There is a large body of data supporting the view that motor memory is enhanced by sleep but not by wakefulness. However a vast majority of studies have used fine motor tasks such as finger-tapping tasks, finger-to-thumb tasks, mirror tracing tasks, and similar tests (Fischer et al, 2002; Plihal & Born, 1997; Walker et al, 2002). One previous study examined the effect of sleep on gross motor skill performance (Blischke et al., 2008). The gross motor skill used was the counter movement task, requiring participants to jump to a height 60% of their maximal effort or vertical elevation. Participants were trained on the task and returned for testing 12 and 24 hours following their training session. Results from this study indicated that there was no differential effect of sleep and wakefulness on performance on the gross motor task (Blischke et al., 2008).

In contrast, here we found that performance on a gross motor task involving coordinated sequential reaching arm movements improved following a night of sleep but not following a day of wakefulness. The difference in results between these two studies may be due to differences in the predominant muscle groups involved in each task (arms vs legs) or the differences in the sequential vs non-sequential nature of the tasks used. Sleep has shown a consistent positive effect on sequential tasks irrespective of body part or anatomical size (Blischke et al., 2008; Fischer et al., 2002; Plihal & Born, 1997; Walker et al., 2002). Furthermore, non-sequential tasks of both fine and gross motor movements have had less-consistent responses to the effect of sleep (Blischke et al, 2008; Fogel & Smith, 2006). In addition, it is possible that task complexity might have played a role; previous research has shown that sleep is more likely to result in performance improvements on difficult skills than on easy skills (Kuriyama et al., 2004)

There are differences in the neuroanatomical sites involved in fine and gross motor skills learning (Halsband & Lange, 2006). Given that sleep is considered to vary locally across the brain (Krueger et al., 2008), this variation in neuroanatomical sites may also explain the differences in the effect of sleep on fine and gross motor skill acquisition. It was therefore uncertain whether gross motor skills would benefit from sleep as fine motor skills have been shown to do. This notion may be supported by various medical conditions, which can have different effects on fine and gross motor functioning such as Parkinson's disease (Kamsma, Brouwer & Lakke, 1995) and autism (Lloyd, Macdonald, & Lord, 2011). This adds to the importance of determining whether sleep affects fine and gross motor skills in the same manner.

Overall our work is consistent with the idea that both fine and gross motor learning become more stable over wakefulness; however, sleep is critical for consolidation-based enhancement (Walker, 2005). Others have questioned whether such performance improvements following sleep are real, and whether the changes seen relate to homeostatic or circadian effects in the experimental protocols rather than an effect of sleep (Cai & Rickard, 2009). Recent work has also questioned whether sleep does enhance motor-sequence learning or whether sleep simply stabilises memory (Brawn, Fenn, Nusbaum, & Margoliash, 2010). Using a fine motor sequence task they showed that performance deteriorates over a day of wakefulness and recovers following a night of sleep. However, when the night of sleep occurred before the day of wakefulness, daytime deterioration on task performance did not occur as the memory had been stabilised during the preceding night. The varieties in body parts, task complexity, and sequential or non-sequential tasks may explain some of these differential findings.

There were a number of limitations of this study. First, sleep was not directly measured by polysomnography but indirectly through actigraphy. Second, we could not determine with absolute certainty whether participants practised between tests, as their activity outside the laboratory could not be monitored. However, we would assume that the effect of such deviation from protocol would have been minimised by randomisation across the groups. In addition there was a chance occurrence of unequal distribution of males to females between the two groups, with many more females than males in the WS group; however, analyses indicated that gender had no effect on performance. Another possible limitation was that participants learned both a serial learning task and a fine motor task within this same training period. They were subsequently tested on those tasks during the same test periods as the gross motor task. The tasks were learned in random order and post hoc analyses showed there was no effect of task order on performance.

The potential for sleep to enhance gross motor skill learning has implications for a wide range of physical activities, including motor rehabilitation, occupational therapy, as well as dance and sports training. Future research will determine whether "sleeping on it" might enhance gross motor sequential skills and result in significant performance advantages when learning new or relearning skills lost due to illness or injury.

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