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## Sleep Quality Influences Subsequent Motor Sequence Learning

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## **Abstract**

While the influence of sleep on motor memory consolidation has been extensively investigated, its relation to the initial learning phase is less well understood. The purpose of the present study was to investigate the influence of sleep quality and quantity on subsequent motor sequence learning in young adults without sleep disorders. Fifty-five healthy adults (mean age = 23.8 years; 34 women) wore actigraph wristbands for four nights, which provided data on sleep patterns prior to the experiment, and then returned to the laboratory to engage in a motor sequence learning task (explicit 5-item finger sequence tapping task). Indicators of sleep quality and quantity were then regressed on a measure of motor learning (Gains Within Training, GWT). Wake After Sleep Onset (WASO), i.e., the total amount of time the participants spent awake after falling asleep, was significantly and negatively related to GWT. This effect was not due to general arousal level, which was measured immediately before motor learning. Conversely, there was no relationship between GWT and sleep duration or self-reported sleep quality. These results indicate that sleep quality, as assessed by wake after sleep onset and objectively measured with actigraphy prior to learning, significantly impacts motor learning in young healthy adults without sleep disorders.

**Key words:** motor sequence learning, sleep quality, actigraphy

## Introduction

Motor skills are used in many activities of daily living, from simple hand movements such as reaching for an object to more complex, coordinated actions such as walking and dancing. The learning of motor skills requires repeated practice during which substantial behavioral improvements emerge. Moreover, there is ample evidence that learning continues in the absence of task practice during which newly learned skills are transformed into enduring long-term memories via the process of consolidation (e.g., McGaugh, 2000). Although a significant body of research has identified the importance of sleep in facilitating memory consolidation (for reviews, see Diekelmann, Wilhelm, & Born, 2009; Rasch & Born, 2013), the role of sleep on the initial acquisition of motor skills is less well understood.

Much of what is known about the effects of sleep on both cognitive functioning and memory encoding comes from investigations into the effects of sleep manipulations (e.g., deprivation) prior to task performance (e.g., Drummond et al., 2000; Kaida, Niki, & Born, 2015; Van Der Werf et al., 2009; Yoo, Hu, Gujar, Jolesz, & Walker, 2007). This work has demonstrated reliable deficits in encoding and retention following experimental sleep loss (reviewed in Saletin & Walker, 2012). However, the majority of young adults do not suffer from such extreme sleep loss that is classically associated with sleep disorders. To examine the link between natural physiological sleep (i.e., non-experimentally manipulated) and subsequent learning abilities, researchers have correlated behavior with self-report sleep assessments (e.g., Kronholm et al., 2009; Nebes, Buysse, Halligan, Houck, & Monk, 2009) or more objective assessments based on actigraphy or polysomnography (e.g., Mander, Santhanam, Saletin, & Walker, 2011; Oosterman, van Someren, Vogels, Van Harten, & Scherder, 2009; Schabus et al., 2006; Wilckens, Woo, Erickson, & Wheeler, 2014; Wilckens, Woo, Kirk, Erickson, & Wheeler, 2014). Similar to the results based on sleep deprivation, these studies have collectively indicated that physiological sleep patterns influence subsequent learning and cognitive performance. For example, a recent study examining the influence of typical sleep quality assessed with actigraphy on cognitive

functioning found that higher sleep continuity (i.e., time spent asleep after sleep onset), but not total sleep time, was associated with better working memory and inhibitory control in younger adults (Wilckens, Woo, Kirk, et al., 2014). In a subsequent study, higher sleep continuity and total sleep time were also associated with better task-switching performance (Wilckens, Woo, Erickson, et al., 2014).

While this previous research demonstrated a link between typical sleep quality and learning and performance in the cognitive domain, questions remain about the effects of sleep on subsequent motor behavior. Studies of individuals with obstructive sleep apnea have produced inconsistent results on whether these pathological alterations in sleep patterns affected motor skill learning (Djonlagic, Saboisky, Carusona, Stickgold, & Malhotra, 2012; Kloepfer et al., 2009; Landry, Anderson, Andrewartha, Sasse, & Conduit, 2014; Naëgelé et al., 2006; Nemeth, Csábi, Janacsek, Várszegi, & Mari, 2012; Rouleau, Décary, Chicoine, & Montplaisir, 2002). Furthermore, in a sample of young adults with putatively healthy sleep patterns, Borich and Kimberley (2012) reported no relation between actigraphy-measured sleep patterns the night before training on a visuospatial finger-tapping task and subsequent motor performance. It is not clear, however, whether this lack of an effect was specific to the motor task employed. For example, previous research has demonstrated that sleep benefits offline memory consolidation following motor sequence learning, but not motor adaptation (Debas et al., 2010).

The goal of the current study was to examine the influence of sleep patterns, as assessed by actigraphy, on subsequent motor sequence learning abilities in healthy young adults. Although polysomnography (PSG) is often employed to probe the relation between sleep and learning or consolidation, this approach can present logistical difficulties, as it typically requires participants to sleep in a laboratory setting. Sleep in an unfamiliar environment with an extensive experimental set-up can affect sleep patterns, ultimately leading to decreased sleep quality and quantity (Agnew, Webb, & Williams, 1966; Curcio, Ferrara, Piergianni, Fratello, & De Gennaro, 2004; Kis et al., 2014; Le Bon et

al., 2001). Moreover, greater time commitments from both participants and researchers are necessary for PSG acquisition and may result in smaller samples sizes in comparison to other methods. By contrast, actigraphs, which are small devices containing accelerometers worn while a participant sleeps at home, offer an alternative and more ecologically valid method for obtaining information about an individual's usual sleep over an extended period of time. Although actigraphy does not provide detailed information on sleep stages or specific sleep characteristics (i.e., spindles or slow wave activity), previous research has demonstrated high consistency across actigraphy and PSG for the determination of sleep versus wake states (Cole, Kripke, Gruen, Mullaney, & Gillin, 1992; de Souza et al., 2003; Jean-Louis, Kripke, Cole, Assmus, & Langer, 2001; Sadeh, Sharkey, & Carskadon, 1994; Webster, Kripke, Messin, Mullaney, & Wyborney, 1982). Hence, actigraphy can offer insights into the effects of sleep patterns on learning and memory processes.

Accordingly, the current study used actigraphy to determine whether sleep patterns on the four nights prior to engaging in a motor learning task influenced subsequent learning processes. We hypothesized that sleep quality and quantity would both be positively correlated with motor sequence learning.

## **Methods**

### *Ethics Statement*

The research ethics board of the RNQ (Regroupement en Neuroimagerie du Quebec) approved this study and all participants provided written informed consent prior to participation. They received monetary compensation for their participation.

### *Participants*

Sixty-two healthy adults were recruited by local advertising to participate in a larger neuroimaging study (Albouy et al., 2015). They had no history of neurological, psychiatric or sleep disorders and were not taking medications at the time of testing. All were right-handed, as assessed with the

Edinburgh Handedness Questionnaire (Oldfield, 1971). None had experience playing a musical instrument or formal training as a typist, which are common exclusion criteria to ensure minimal experience in tasks requiring dexterous finger movements similar to that employed in the current research. Of the 62 individuals recruited, four were excluded because they did not complete at least four nights of actigraphy prior to participation in the MSL session. An additional three were excluded for being outliers on the MSL task. Specifically, participants were excluded if their averaged movement speed or accuracy was more than 2.5 SD from the group mean. Data from 55 healthy adults (mean age = 23.8 yrs, SD = 3.5; 34 women) were included in subsequent analyses.

### *Procedures*

All participants were asked to follow a 4-day constant sleep schedule (bed-time and wake-time according to their own rhythm  $\pm$  1 hour and a minimum 7 hours of sleep per night) before the experiment. Participants completed a sleep diary (using a modified version of the National Sleep Foundation “Sleep Diary”: <http://sleepfoundation.org>) and wore an actigraph (Actiwatch AW2, Bio-Lynx Inc., Montreal, Canada) on the non-dominant wrist to track their sleep-wake cycle for the four nights prior to returning to the sleep laboratory to complete the experiment. The sleep diaries completed by the participants were used to verify data obtained by the actigraphs, yet no substantial discrepancies between diaries and actigraphs were found. Upon arrival in the laboratory, participants completed the Pittsburgh Sleep Quality Index Questionnaire (PSQI; Buysse, Reynolds, Monk, Berman, & Kupfer, 1989) to provide a measure of subjective sleep quality over the month preceding the experiment. Participants subsequently completed a psychomotor vigilance task (PVT; Dinges & Powell, 1985) in order to assess general alertness/arousal at the time of testing. At approximately 11:30 AM, participants completed the MSL task described below.

### *Motor Sequence Learning Task*

A description of the full MSL protocol was provided in Albouy et al. (2015). For the current study, analyses were limited to performance from the initial training session. The original protocol included fMRI scanning (imaging data not included here); accordingly, the training session was completed while participants were lying supine in a 3.0T TIM TRIO scanner (Siemens, Erlangen, Germany). The motor sequence learning task (coded in Cogent2000 (<http://www.vislab.ucl.ac.uk/cogent.php>) and implemented in MATLAB (Mathworks, Inc., Sherborn, MA)) has been employed extensively in our laboratory (e.g., Debas et al., 2010; Doyon et al., 2009; Fogel et al., 2014). It required participants to use their left (non-dominant) hand to tap a five-element finger sequence on a keypad as rapidly as possible while making as few errors as possible. The sequence to perform (4 1 3 2 4, where 1 corresponds to the index and 4 to the little finger) was explicitly taught to the participants prior to training. The task was performed in 14 successive practice blocks separated by 15-sec rest periods. Each practice block consisted of 60 key presses, ideally corresponding to 12 correct sequences. After 60 key presses, the “practice block” indicated by a green cross displayed in the middle of the screen, was terminated and a “rest block” was initiated during which participants were to fixate on a red cross. This procedure effectively controlled for the number of movements executed in a block. The duration of the practice blocks progressively decreased as participants became faster at performing the 60 key presses. Participants were monitored online to ensure that they appropriately performed the task.

The task was coded to record the number and timing of each specific key press within each practice block. This log of key presses was then used to extract relevant behavioral measures and to verify no extended pauses in task execution due to inattention or sleepiness. Motor skill performance was assessed with a variable Performance Index (PI; Eq. 1) that included both speed (i.e., Sequence Duration) and accuracy (i.e., Errors) measures and used in previous research (Dan, King, Doyon, & Chan, 2015).

$$PI_x = \exp^{-(SeqDur_x)} * \exp^{-(Errors_x/12)} * 100 \quad (\text{Eq. 1})$$

where x = blocks of trials

Sequence Duration was defined as the averaged time to complete correct sequences within each block. Errors were defined as the maximum number of correct sequences (e.g., 12) minus the number of actual correct sequences within each block.

### *Actigraphy Data*

Actigraphy data were extracted and analyzed using Respironics Actiware software (version 6.0) to identify sleep/wake cycles for the four nights prior to the motor sequence learning session. Multiple nights of actigraphy were used in order to be consistent with previous research (Wilckens, Woo, Erickson, et al., 2014; Wilckens, Woo, Kirk, et al., 2014) and to increase the stability of our assessment of typical or habitual sleep quality and quantity. Computer algorithms characterized each 60-second epoch as either awake or sleep. Specifically, for each epoch  $n$ , a weighted activity count (AC) was computed based on the activity count within the epoch in question as well as the two preceding and subsequent epochs (Eq. 2).

$$Weighted\_AC_n = (AC_{n-2} * \frac{1}{25}) + (AC_{n-1} * \frac{1}{5}) + (AC_n) + (AC_{n+1} * \frac{1}{5}) + (AC_{n+2} * \frac{1}{25}) \quad (\text{Eq. 2})$$

The weighted activity count was then compared to a wake threshold value in order to classify the particular epoch as sleep or wake. The wake threshold value was set to 40, which is considered a “medium” threshold selection. Based on the determination of wake / sleep states, the following variables were subsequently extracted: (a) sleep duration = number of minutes coded as sleep; and (b) wake after sleep onset (WASO) = number of minutes coded as wake during the sleep interval (i.e., from sleep onset to wake time). Sleep duration and WASO are thus assessments of objective sleep quantity and quality, respectively.

### *Statistical Analyses*

To assess learning on the motor task, PI was analyzed with a one-way analysis of variance (Blocks of practice; 14 levels). We subsequently quantified the magnitude of learning by computing the difference in PI from the means of the first 2 blocks to the mean of the best 2 consecutive blocks (referred to as Gains Within Training – GWT). Computing learning based on the *best* performance within the initial learning session, as opposed to simply performance reached at the end of the session, decreased the potential influence of non-learning related factors such as attention or boredom that are likely to appear at the end of training (Pereira, Beijamini, Vincenzi, & Louzada, 2015). We elected to use the 2 best *consecutive* blocks to increase the stability of this assessment of peak performance, reflecting a performance plateau that is typically achieved during motor learning paradigms.

To determine the influence of sleep on subsequent motor learning, we conducted a stepwise linear regression with GWT as the dependent variable and the three sleep variables of interest as the independent variables: sleep duration and WASO from actigraphy, and the PSQI score as a measure of subjective sleep quality. The stepwise procedure allowed only those independent variables that accounted for a significant amount of variability to be included in the final model.

## Results

A one-way repeated measures ANOVA on PI (Figure 1A) revealed that the participants significantly improved performance across the 14 blocks of practice ( $F_{(13, 702)}=26.4$ ,  $p<0.0001$ ). For the sake of completeness, Figures 1B and 1C depict the components of the PI measure: Sequence Duration (assessment of speed) and Correct Sequences (accuracy), respectively. Similar to PI, a one-way ANOVA on Sequence Duration indicated that the amount of time to complete a correct sequence decreased as a function of blocks ( $F_{(13, 702)}=40.5$ ,  $p<0.0001$ ). The number of correct sequences performed within each block, reflecting movement accuracy, did not significantly vary across the learning session ( $F_{(13,702)}=0.85$ ,  $p=0.60$ ). These results collectively indicate that participants improved on the MSL task as a function of practice; and, these improvements were predominantly reflected by

increases in movement speed (i.e., decreases in the time to perform a correct sequence). Nonetheless, to account for the small intra-individual fluctuations in accuracy, the GWT variable used in correlation analyses with the sleep measures was based on improvements in the composite speed-accuracy measure (PI).

### **INSERT FIGURE 1 ABOUT HERE**

Average PSQI score was 3.95 (SD=1.83). Average sleep duration across the four analyzed nights was equal to 7.31 hrs/night (SD=0.66 hrs) and mean WASO was 48.95 minutes (SD = 16.7). On average, our participants slept comparably or even slightly better than previous actigraphy studies in healthy young adults (Borich & Kimberley, 2012; Wilckens, Woo, Erickson, et al., 2014; Wilckens, Woo, Kirk, et al., 2014).

The results of the stepwise linear regression revealed that neither sleep duration nor PSQI accounted for a significant amount of variability in GWT, and accordingly, these variables were excluded from the final model. Conversely, WASO explained a significant amount of variability in GWT (Figure 2;  $r=-0.28$ ;  $p=0.039$ ). For the sake of completeness, correlations among GWT and the extracted sleep variables are summarized in Table 1. GWT was significantly correlated with WASO, but not with sleep duration ( $r=0.00$ ,  $p=0.99$ ) or PSQI ( $r=-0.09$ ,  $p=0.50$ ). These results suggest that objectively measured sleep quality, as assessed by WASO, prior to learning influences subsequent motor sequence learning abilities.

### **INSERT FIGURE 2 ABOUT HERE**

Table 1. Correlations among dependent variables

	GWT	WASO	Sleep Duration	PSQI
GWT	1	-	-	-
WASO	<b>-0.28 (0.039)</b>	1	-	-
Sleep Duration	0.00 (0.99)	-0.13 (0.34)	1	-
PSQI	-0.09 (0.50)	-0.06 (0.69)	-0.11 (0.42)	1

*Numbers represent Pearson's correlation coefficient and associated p-values (in parentheses). Bold represents correlations with p-values < 0.05. GWT = Gains Within Training; WASO = Wake After Sleep Onset; PSQI = Pittsburgh Sleep Quality Index.*

One possibility is that poor sleep quality (i.e., higher WASO) reduced vigilance at the time of testing, which in turn negatively influenced learning. To assess the influence of vigilance on motor learning, we examined the correlation between GWT and performance on the psychomotor vigilance task (PVT) administered immediately prior to the MSL task. This correlation was not significant ( $r = -0.21$ ,  $p = 0.12$ ). We also regressed scores from the PVT on GWT and WASO separately; the residuals of these regressions then represented GWT and WASO after partialing out the influence of vigilance at time of testing. The correlation between these GWT and WASO residuals was significant ( $r = -0.27$ ,  $p = 0.049$ ), indicating that the relation between WASO and GWT remained significant after controlling for vigilance. Hence, vigilance levels at the time of testing could not explain the significant relation between sleep quality, as assessed by WASO, and motor sequence learning.

To address the possibility that learning in a subset of participants (for example, those with poorer quality sleep) may be underestimated due to an inability to sustain high performance for two *consecutive* blocks, we computed Gains Within Training (GWT) based on the single best block. The values of GWT computed based on the single best block and the best two consecutive blocks were highly correlated ( $r = 0.99$ ;  $p < 0.001$ ). Moreover, we conducted a stepwise regression with GWT based

on the best block as the dependent variable and WASO, sleep duration and PSQI as the independent variables. Similar to above, the relationship between WASO and GWT remained significant ( $p=0.05$ ). Collectively, these analyses suggest that significant relationship between sleep quality, as assessed by WASO, and motor learning can not be attributed to a reduced ability of participants with poorer sleep to sustain performance levels across two blocks of practice.

Multiple nights of actigraphy were extracted and analyzed in the current study in order to be consistent with previous related research (Wilckens, Woo, Erickson, et al., 2014; Wilckens, Woo, Kirk, et al., 2014) and to increase the stability of the assessment of typical or habitual sleep quantity and quality. We also investigated how sleep immediately (i.e., one night) prior to learning impacted subsequent encoding. Results remained consistent with those based on four nights of sleep recordings, as WASO and GWT from the preceding night only were significantly and negatively correlated ( $r=0.30$ ;  $p=0.024$ ). This thus suggests that the high correlation between the night prior to learning and the previous 3 nights makes it difficult to disentangle the contributions of a particular night of sleep from the typical or habitual sleep patterns assessed across multiple nights on motor learning.

## **Discussion**

We examined healthy young adults with putatively normal sleep and found that relatively poor sleep quality, as assessed with actigraphy and indexed by more time spent awake after sleep onset, was associated with lower learning capacities on a motor sequence task, and that these results could not be accounted for by arousal/alertness levels at time of testing. These results are in line with previous research demonstrating links between sleep continuity and cognitive functioning in young adults (e.g., Wilckens, Woo, Erickson, et al., 2014; Wilckens, Woo, Kirk, et al., 2014). Our results, however, contrast with those of Borich and Kimberley (2012) which reported no relation between sleep-related variables obtained the night before training and performance on a visuospatial motor task. The discrepant results may potentially be explained by differences in the task. Specifically, Borich and

Kimberley (2012) used a visuospatial finger-tracing task, which required participants to track a visual stimulus by modulating the flexion/extension of the index finger. It is possible that the encoding of some, but not all, motor tasks is influenced by sleep prior to learning. In line with this explanation, previous research has indeed indicated that sleep enhances motor memory consolidation following motor sequence learning, but not motor adaptation (Debas et al., 2010). It is also possible that the lack of a significant relation in the report by Borich and Kimberley (2012) can be attributed to a lack of statistical power given the smaller sample size (N=19) as compared to the current research (N=55).

We did not find a significant relation between sleep duration, an objective measure of sleep quantity, and training-related gains in performance. It is possible that the amount of inter-individual variability seen in sleep duration may be insufficient to detect any significant relationship with motor learning. Indeed the coefficient of variation for sleep duration was smaller as compared to that of WASO (0.08 and 0.34, respectively). Additionally, variability in sleep duration in our sample was roughly half what was reported by Borich and Kimberley (2012). This is likely due to the fact that participants in the current study were asked to respect a constant sleep schedule prior to the experiment. Specifically, participants were instructed to maintain wake and bed times  $\pm 1$  hour of their normal schedule and obtain a minimum of 7 hours of sleep per night. These instructions likely limited the inter-individual variability in the measure of sleep quantity. An alternative explanation is that sleep quantity, as opposed to quality, may not exert any influence on subsequent motor learning. For example, interruptions during sleep – reflecting sleep quality and seen here as greater time spent awake after sleep onset – may alter specific features of sleep (e.g., sleep cycles, spindles, slow wave activity, etc.) that may be critical for subsequent motor memory encoding. This explanation is certainly speculative and awaits further investigation.

Although our results demonstrated that sleep quality, as assessed by wake after sleep onset, significantly influenced subsequent motor learning, it should be emphasized that a multitude of factors

beyond sleep quality certainly impact the magnitude of learning. For example, previous research has indicated that learning strategy (Lungu et al., 2014), working memory (Bo & Seidler, 2009; Seidler, Bo, & Anguera, 2012), the ability to group or chunk motor elements (Lungu et al., 2014; Wymbs, Bassett, Mucha, Porter, & Grafton, 2012) as well as the engagement of relevant neural substrates (Albouy et al., 2012; Bernard & Seidler, 2013; Orban et al., 2010) all exert an influence on the initial learning phase of movement sequences. Our results extend this earlier research by demonstrating that individuals' sleep quality, above and beyond the effects of vigilance at time of testing, also impacts subsequent motor learning.

Decades of research have attempted to identify the neural substrates that mediate the effects of sleep on memory, with the majority of work focusing on declarative memory and the role of medial temporal lobe structures, including the hippocampus (reviewed in Rasch & Born, 2013). It has been postulated that sleep influences hippocampal activity during encoding (Saletin & Walker, 2012). Specifically, research has identified selective deficits after sleep deprivation in bilateral regions of the posterior hippocampus known to be important for learning new episodic information, independent of basic arousal levels (Yoo et al., 2007). In the motor domain, fMRI studies have implicated both the cortico-striato-cerebellar and hippocampo-cortical networks in the acquisition and consolidation of motor sequence memories (Albouy, King, Maquet, & Doyon, 2013; Doyon, Bellec, et al., 2009; Penhune & Steele, 2012), and recent work has attempted to disentangle the specific roles of the hippocampus and striatum in these processes (Albouy et al., 2015). As sleep is thought to condition the hippocampus for subsequent encoding (Saletin & Walker, 2012), and in light of the established role of the hippocampus in motor sequence acquisition (Albouy et al., 2015; Albouy, King, et al., 2013; Albouy et al., 2008; Schendan, Searl, Melrose, & Stern, 2003), it is possible that sleep patterns influenced hippocampal activity during the initial learning phase of motor sequences, ultimately modulating both subsequent learning and consolidation processes. However, the influence of sleep on

the functioning of cortico-striato-cerebellar networks during initial learning is unknown and cannot be discounted as a potential mechanism underlying our results. Future research is thus needed to identify how sleep quality influences the cerebral substrates supporting motor learning.

One limitation of our study is that actigraphy was not capable of capturing sleep architecture, and for this reason we cannot determine whether sleep disturbances occurred preferentially during specific sleep stages or influenced particular features such as sleep spindles or slow wave activity. The roles of these particular features on subsequent motor learning should be examined in future research. A second limitation is that objective sleep quality was assessed in the present study with WASO, which is one among many variables reflecting sleep quality. Third, motor learning is typically quantified by examining retention of the learned motor skill and/or transfer to a new skill or context, as opposed to performance improvements within a single training session. It should be noted that in the full experimental paradigm used elsewhere (Albouy et al., 2015), both transfer and retention tests were employed. Data from these assessments were not used for the current research as additional experimental manipulations were employed to address questions outside the scope of the current study. However, results revealed that participants, on average, transferred sequence knowledge to a different experimental condition and retained the skill in a subsequent retest (Albouy et al., 2015). Because we, as well as other laboratories, have routinely demonstrated retention of learned motor sequences following nearly identical experimental protocols (e.g., Albouy et al., 2015; Albouy, Fogel, et al., 2013; Albouy, Sterpenich, et al., 2013; Debas et al., 2010; Doyon, Korman, et al., 2009; Fogel et al., 2014; Korman et al., 2007), we are confident that the improvements in performance reported in this paper reflect learning of the motor sequence.

In conclusion, our results suggest that sleep quality, as assessed by actigraphy and quantified as time awake after sleep onset, is associated with subsequent motor learning. This relationship was not seen when sleep quality was assessed by a subjective questionnaire (PSQI), suggesting that actigraphy

was the more sensitive of the two measures. Actigraphy is an ecologically valid measure that can be incorporated into study designs in order to assess the effects of usual sleep patterns on subsequent behavior. Additionally, it can provide an objective assessment of individual variability in sleep quality over time and of information not captured by self-report questionnaires. Future research should relate actigraphy to higher-resolution methodologies such as polysomnography, in combination with imaging data that can examine the effects of sleep on networks recruited during the learning and consolidation of motor skills.

## Figure Captions

**Figure 1.** Performance on motor sequence learning task as assessed by Performance Index (**A**). PI is computed based on measures reflecting movement speed (Sequence Duration - **B**) and accuracy (Correct Sequences per block - **C**).

**Figure 2.** Wake after sleep onset (WASO) was significantly correlated with gains within training (GWT). This relationship remained significant after partialing out the effects of vigilance. See Table 2 for details for correlations among all variables.

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