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Sleep modulates word-pair learning but not motor sequence learning in healthy older adults

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Abstract

Sleep benefits memory across a range of tasks for young adults. However, remarkably little is known of the role of sleep on memory for healthy older adults. We used 2 tasks, 1 assaying motor skill learning and the other assaying nonmotor/declarative learning, to examine off-line changes in performance in young (20–34 years), middle-aged (35–50 years), and older (51–70 years) adults without disordered sleep. During an initial session, conducted either in the morning or evening, participants learned a motor sequence and a list of word pairs. Memory tests were given twice, 12 and 24 hours after training, allowing us to analyze off-line consolidation after a break that included sleep or normal wake. Sleep-dependent performance changes were reduced in older adults on the motor sequence learning task. In contrast, sleep-dependent performance changes were similar for all 3 age groups on the word pair learning task. Age-related changes in sleep or networks activated during encoding or during sleep may contribute to age-related declines in motor sequence consolidation. Interestingly, these changes do not affect declarative memory.

Keywords: Sleep; Memory; Declarative; Procedural; Aging; Consolidation

1. Introduction

Memories benefit from sleep (e.g., Peigneux et al., 2001; Stickgold and Walker, 2005). While this effect has been extensively documented across a wide range of task domains, this performance enhancement is diminished in older adults: off-line changes in performance on a motor sequence learning task did not differ for intervals of wake and sleep for adults 45–80 years of age (Spencer et al., 2007). Likewise, Siengsukon and Boyd (2008, 2009) found that healthy older adults show no sleep-related changes in motor sequence learning regardless of the participants' level of awareness.

Whether older adults show sleep-dependent gains in other task domains remains unclear. Aly and Moscovitch (2010) recently compared episodic recall of personal events and experimental narratives following an interval of overnight sleep and daytime waking. While older adults (69–80 years) exhibited greater forgetting over both intervals relative to young adults, the protection of memory by sleep, relative to wake, did not differ across the age groups. However, Backhaus and colleagues (2007) suggested that sleep-dependent consolidation (SDC) of declarative memories is reduced in middle-aged adults (48–55 years). In an associated word-pair learning task, young adults had greater recall following early-night (slow wave sleep [SWS]-rich) sleep than late-night (rapid eye movement [REM]-rich) sleep. Middle-aged adults showed no significant change in performance following either sleep epoch. Interestingly, sleep was beneficial for middle-aged adults that garnered the same amount of SWS as the young adults. Thus, changes in SDC with aging may be related to changes in sleep physiology.

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In the present study, we directly compared off-line performance changes in young, middle-aged, and older adults. We adopted this design to examine 2 issues. First, to date, studies of age-related changes in SDC have been contradictory; for example, using tasks associated with declarative learning, 1 study reported spared SDC in older adults (Aly and Moscovitch, 2010), whereas another reported that some middle-aged adults exhibited reduced SDC (Backhaus et al., 2007). A limitation with this work is that these studies used binary contrasts, comparing younger adults with either middle-aged or older adults. By testing young, middle-aged, and older adults on the same set of tasks, we will better characterize age-related changes associated with sleep-dependent consolidation.

Second, we sought to directly compare SDC for 2 tasks across these age groups. Research on SDC in healthy young adults has favored a distinction in the processes underlying SDC for motor and sensorimotor tasks, tasks that are historically classified as procedural learning tasks, relative to processes underlying SDC for nonmotor, declarative learning tasks (e.g., Diekelmann et al., 2009; Payne, 2010; Plihal and Born, 1997; Stickgold et al., 2001; Wilhelm et al., 2008). The 2 tasks adopted here, a motor sequence learning task and a word pair learning task, were chosen to represent this distinction from the SDC literature. Notably, these tasks are both expected to engage the hippocampus at encoding (Keele et al., 2003; Schendan et al., 2003), a feature hypothesized to characterize tasks which are benefited by sleep in young adults (Cai et al., 2009; Rauchs et al., 2011; Spencer et al., 2006). The motor sequence learning task, and the serial reaction time variant in particular, was specifically selected to allow us to replicate the previously observed decline in SDC in healthy older adults (Spencer et al., 2007) given that not all forms of motor sequence learning are subject to such benefits even in young adults (Nemeth et al., 2010; Robertson et al., 2004; Spencer et al., 2006). The word pair learning task was selected given that it has been well established to benefit from sleep in young adults (e.g., Ellenbogen et al., 2006; Plihal and Born, 1997; Tucker and Fishbein, 2008).

One proposed distinction between SDC for motor learning and SDC for classic declarative learning tasks is their unique reliance in regard to physiological measures of sleep. SDC for word pair learning and other episodic memory tasks has been associated with SWS (Plihal and Born, 1997; Tucker et al., 2006) which dramatically drops from young to older adulthood (Danker-Hopfe et al., 2005; Ohayon et al., 2004). SDC for motor sequence learning is associated with non-REM stage 2 (nREM2) sleep (Walker et al., 2002) which is largely protected through the middle-age period (Danker-Hopfe et al., 2005; Ohayon et al., 2004). Based on these distinctions, we predicted a difference in the influence of age on SDC for these 2 tasks.

2. Methods

2.1. Participants

Eighty-seven participants, 20–70 years of age, were tested. Participants were divided into 3 age groups: Young adults (20–34 years; $n = 24$), middle-aged adults (35–50 years; $n = 32$), and Older adults (51–70 years; $n = 31$). Gender was approximately evenly distributed across all age groups (Young: 10 female/14 male; Middle-aged: 14 female/18 male; Older: 13 female/18 male). Data from an additional 6 participants (Young = 2; Middle-aged = 1; Older = 3) were excluded for self-reported mid-day naps greater than 0.5 hours in duration. Based on a questionnaire given at the time of recruitment, none of the participants reported sleep disorders, sleep-affecting medications, uncorrected vision problems, or a history of neurological disorders or impairment. The groups did not differ reliably in terms of education ($F(1,85) = 2.6$; $p = 0.11$), although the mean for the Young group (14.6 years) was lower than for the 2 older groups (Middle: 17.2; Older: 16.5) due to the fact that many in the Young group were still in college. The sample size even within each age group exceeds that used in previous studies of SDC that have used a between-subject design (Ellenbogen et al., 2006; Plihal and Born, 1997; Spencer et al., 2007), and thus, should provide sufficient power to detect group differences. All procedures were approved by the institutional review board at University of California, Berkeley and University of Massachusetts, Amherst.

2.2. Sequence-learning task

The sequence-learning task was a modified serial reaction time task (Nissen and Bullemer, 1987) identical to that used in our previous work demonstrating an age-related decline in SDC (Spencer et al., 2006, 2007). In this task, participants were instructed to press 1 of 4 response keys based on the spatial position of a visual stimulus presented on a computer monitor (Fig. 1A). A horizontal row of 4 boxes was displayed in the center of the screen at all times. A trial was cued with the presentation of an "X" in 1 of the 4 boxes. Participants were instructed to press the key corresponding to the spatial location of the stimulus. Responses were made with the 4 fingers (thumb excluded) of the nondominant hand. Immediately following a response, the cue disappeared and, following a 100-ms intertrial interval, the next cue appeared. Blocks were composed of 120 trials. At the end of each block, feedback indicating the mean reaction time (RT) and number of errors for that block was presented.

On "sequence blocks", the cues were presented in a repeating 10-item sequence. The grammar of the sequence was the same for all participants, but the mapping between sequence element and stimulus/response location was randomly assigned across participants. Thus, for 1 participant, the sequence was 4-3-1-4-2-1-3-4-1-2 whereas for another it

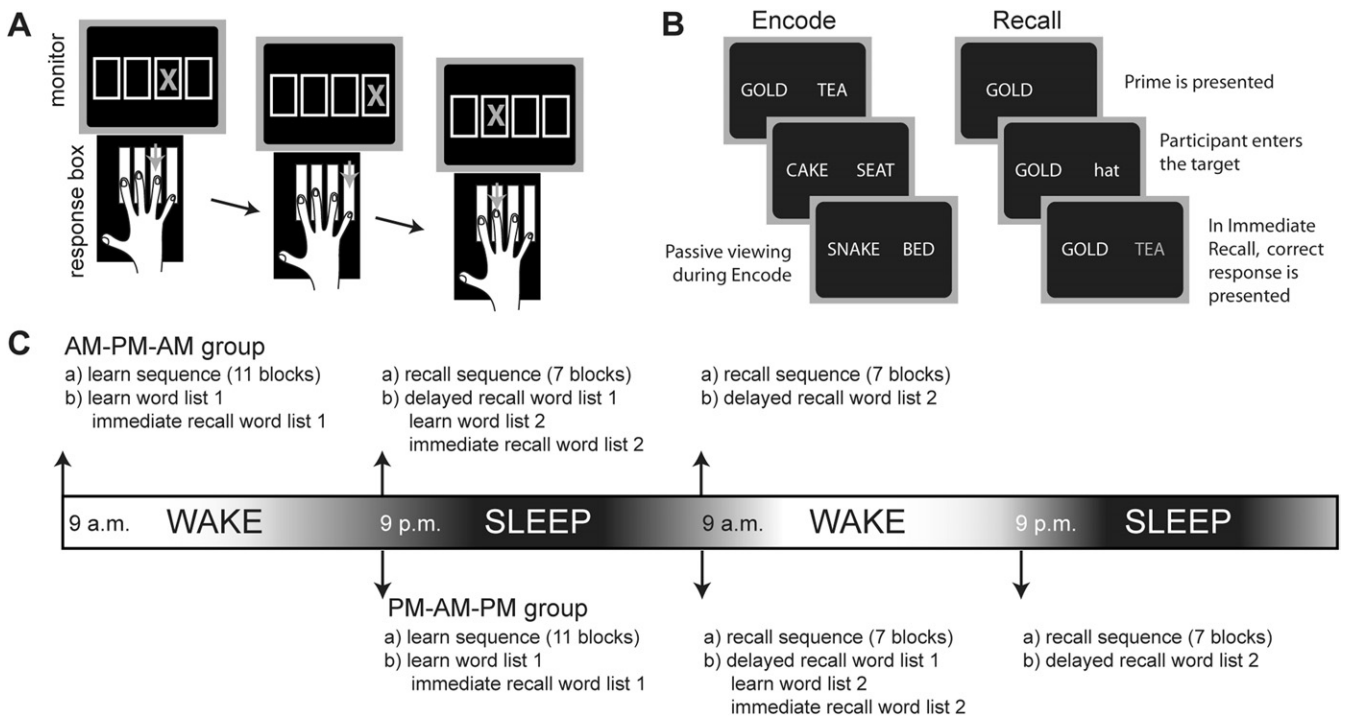

Fig. 1. Task and procedures. (A) In the motor sequence-learning task, participants pressed a key in response to the position of each stimulus. (B) During the encode phase of the word-pair learning task, participants passively viewed the word pairs. During the immediate and delayed recall phases, participants were given a cue and were to respond with the corresponding target word. Feedback was provided in the immediate recall phase. (C) Timeline for the 2 subgroups within each age group (the order of the sequence and word pair tasks was randomized).

would be 1-2-4-1-3-4-2-1-4-3. To probe sequence learning, the cues were selected at random on some blocks (see 2.4. Procedure). In these "random blocks," we imposed 3 constraints that were also present in the sequence blocks: the frequency of each cue location was matched to that in sequence blocks, the cue could not appear in the same location on successive trials, and 3-element trills (e.g., 1-3-1 or 2-4-2) were excluded.

Participants were told that the cues would follow a sequence on most blocks (explicit; Spencer et al., 2006). The instructions emphasized that speed was the primary measure of interest and that by learning the sequence, they would be able to respond faster while maintaining good, but not necessarily perfect, accuracy.

2.3. Word pair learning task

Following Ellenbogen et al. (2009), we used a word pair learning task in which the word-pairs were semantically unrelated. For each participant, 128 words were randomly selected from a list of 168 single-syllable, high-frequency, concrete nouns (see Donohue and Spencer, 2011). Words were randomly paired to create 2 lists of 32 word pairs (e.g., cat-coach, desk-ice). One list was used for the wake condition and the other for the sleep condition (see below). There were 3 phases to the task: encode, immediate recall, and delayed recall (Fig. 1B). During the encode phase, word pairs from a single list were presented for 5 seconds on a computer monitor in front of the participant (inter-stimulus interval between pairs was 100 ms). Participants were instructed to study each pair of words for subsequent recall. To facilitate learning, participants were instructed to use a mnemonic strategy. Specifically, they were told, "To help you remember the pairs, it is helpful to think of associations between the pairs. For instance, if the words were frame-shoe you might try to picture in your mind a framed painting of a shoe."

The immediate recall phase followed the completion of the encode phase. The first word from 28 of the word pairs (eliminating the first and last 2 pairs for primacy and recency effects as in Plihal and Born, 1997) was displayed on the left side of the screen and participants were instructed to say the corresponding word for that pair. Participants were asked to guess if they did not know the answer however a response of "I don't know" was also accepted. The experimenter entered the participant's response into the computer. If the response was incorrect, the correct response was displayed on the computer monitor for 750 ms. The list was repeated until performance reached 62% or when the list had been repeated a maximum of 5 times. The order of items was randomized for each presentation of the list.

The delayed recall phase was administered after a 12-hour break. This test was identical to the immediate recall phase with 2 exceptions. First, the list of words was presented only once. Second, feedback was not presented fol-

Table 1
Demographic and neuropsychological means for each group

Session order	Mean age	Dominant hand	WAIS-III Scores				WMS Spatial span
			WM index	Arithmetic	Digit span	Letter-number sequence	
Young adults							
APA	26.1 (4.9)	12 R, 1 L	107.6 (17.8)	11.9 (3.7)	11.0 (3.4)	11.4 (2.5)	11.1 (3.0)
PAP	25.7 (4.0)	11 R	116.9 (16.8)	12.4 (2.3)	11.4 (4.3)	13.9 (2.2)	12.6 (2.9)
Middle-aged adults							
APA	44.3 (6.8)	13 R, 1 L	100.7 (14.6)	10.0 (3.2)	9.3 (2.9)	11.0 (3.7)	11.5 (3.4)
PAP	43.7 (5.0)	17 R, 1 L	117.3 (11.2)	12.3 (2.3)	12.4 (3.7)	14.0 (2.9)	11.8 (2.1)
Older-age adults							
APA	63.5 (6.2)	14 R, 1 L	107.7 (11.5)	11.0 (3.6)	11.6 (3.3)	11.6 (1.6)	11.6 (2.8)
PAP	62.8 (5.5)	15 R, 1 A	115.3 (7.0)	11.9 (1.3)	13.6 (2.9)	13.0 (1.2)	10.3 (2.5)

Numbers in parentheses are standard deviations. Wechsler Adult Intelligence Scale (WAIS-III) scores are scaled subscores.
Key: A, ambidextrous; APA, AM-PM-AM group; L, left; PAP, PM-AM-PM group; R, right; WMS, Wechsler Memory Scale.

lowing an incorrect response. The order of items was again randomized for each presentation of the list.

2.4. Procedure

Participants in each age group were divided into 2 subgroups (Table 1). The AM-PM-AM group started Session 1 in the morning (between 7 and 10 AM) and learning was assessed that evening (Session 2: 12 hours after Session 1) and on the following morning (Session 3: 24 hours after Session 1; Fig. 1C). The PM-AM-PM group started Session 1 in the evening (between 7 and 10 PM) and Sessions 2 and 3 took place the next day (12 and 24 hours after Session 1, respectively).

During training (Session 1), participants completed 11 blocks of the sequence-learning task (120 responses/block) with the stimuli following the 10-element sequence on Blocks 1–7, 9, and 11. The stimuli were selected at random on Blocks 8 and 10. Participants also completed the encode and immediate recall phases of the word-pair task using the first of 2 generated word-pair lists. In Session 2, participants completed 7 blocks of the sequence-learning task (with the stimuli selected at random on Block 6, only) and the delayed recall phase for the word-pair list learned in Session 1. Following a short delay (approximately 20 minutes in which sleep assessments and other forms were completed), participants completed the encode and immediate recall phases of the word-pair task using the second word list. In Session 3, participants again performed 7 blocks of the sequence-learning task (again only Block 6 being random). For the word-pair task, participants completed the delayed recall phase with the word pairs that had been learned in Session 2. The order of the tasks was counterbalanced across participants, but within subjects, task order was maintained across the 3 sessions.

At the end of Session 3, participants were given a survey to assess their explicit knowledge of the sequence and identify strategies used for the word pair task (i.e., did they imagine an integration of the objects as instructed). They also completed a neuropsychological battery composed of the arithmetic, digit span, and letter-number sequencing subtests from the Wechsler Adult Intelligence Scale (WAIS-III), the spatial-span subtest of the Wechsler Memory Scale (WMS-III), and the Mini Mental State Examination (MMSE). In a limited number of participants ($n = 8$), this battery was not performed due to time constraints; for these participants, only the MMSE was administered.

To assess subjective sleep quality and quantity, an abbreviated Wake-time Diary (Smith et al., 2003) was given following the morning session of the second day (Session 2 for the PM-AM-PM group and Session 3 for the AM-PM-AM group). To assess daytime activities including napping and caffeine intake, an abbreviated Bedtime Diary (Smith et al., 2003) was given in the evening session. Diaries have been shown to have high levels of agreement with polysomnographic measures of sleep duration and overall quality (e.g., Rogers et al., 1993). Participants also completed the Pittsburgh Sleep Quality Index (PSQI) which provides a subjective estimate of sleep over the past 30 days (Buysse et al., 1989).

2.5. Analysis

The median RT was computed for each block on the sequence learning task, following the standard convention (e.g., Gómez-Beldarrain et al., 1998; Nissen and Bullemer, 1987; Shin and Ivry, 2003; Willingham et al., 1989). Given our interest in off-line effects, we compared performance between the end of session x and the beginning of session $x + 1$. Thus, our dependent variable is the change in reaction time for sequence blocks across sessions. For the first intersession interval, this difference is the average of the median RTs for Blocks 9 and 11 from Session 1 minus the average of the median RTs for Blocks 1 and 2 from Session 2. For the second intersession interval, this difference reflects the average of the median RTs for Blocks 5 and 7 in Session 2 minus the average of the median RTs for Blocks 1 and 2 from Session 3. To account for differences in RT across age groups, the off-line changes in performance were normalized to the participant's median RT (for further dis-

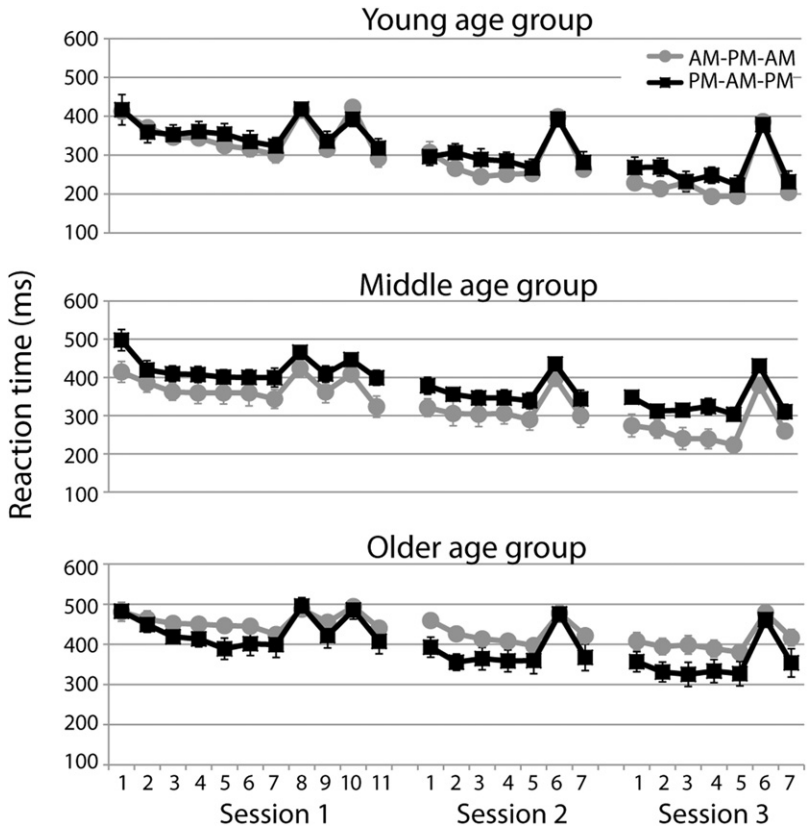

Fig. 2. Median reaction times across blocks for the sequence-learning task. Error bars represent standard error.

cussion, see Spencer et al., 2006, 2007; Walker et al., 2002). Thus, we computed a difference value (DV):

$$DV = (seqRT_{session\ n-1} - seqRT_{session\ n})/seqRT_{session\ n}$$

where *seqRT* is the median RT for the specified sequence blocks from a particular phase.

The primary statistical analyses were based on analysis of variance (ANOVA) with the between-subjects factors Age Group (Young, Middle, Old) and Session Order (PM-AM-PM, AM-PM-AM) and the within-subject factor of Interval Type (Sleep, Wake).

3. Results

3.1. Sleep assessments

We estimated the amount of sleep in the overnight interval from the subjective reports. For the Young, Middle-aged, and Older participants, the mean values were 6.9 hours (SD = 1.0 hours), 6.8 hours (SD = 1.4 hours), and 6.6 hours (SD = 1.3 hours), respectively. While the means suggest a slight decline in sleep duration, the main effect of Age Group was not significant ($F(2,81) = 0.33$, $p = 0.72$). Similarly, the effect of Session Order was not significant ($F(1,81) = 0.01$, $p = 0.93$) nor was the Age Group by Session Order interaction ($F(2,81) = 0.78$, $p = 0.46$). As assessed by sleep diaries, the average reported number of nighttime awakenings was 0.41 (SD = 0.62). This measure did not differ across the age groups ($F(2,81) = 1.6$, $p = 0.21$). Other measures of sleep quality (subjective sleep quality from Pittsburgh Sleep Quality Index and sleep diaries) also did not differ across groups (all F's < 1).

3.2. Neuropsychological evaluations

All participants scored in the normal range on the MMSE, measures of working memory (WM Index, Digit-Span, Letter-Number Sequencing, Spatial Span), and measures of attention/concentration (Arithmetic, Digit-Span, Letter-Number Sequencing). Individuals who did not perform the full neuropsychological battery all scored 29 or higher on the MMSE. Importantly, there were no significant differences between age groups on any of the neuropsychological measures (all $F < 1$; Table 1).

3.3. Sequence-learning task

As is typical for a serial reaction time task, errors were low (mean error rate = 5.8%) and did not differ by Age Group ($F(2,81) = 0.19$, $p = 0.83$). Therefore, subsequent analyses are restricted to the RT-based measures. Learning curves for all groups are presented in Fig. 2.

We first compared the change in RT across sessions separated by intervals with sleep compared with the change over intervals spent fully awake. The main effects of Age

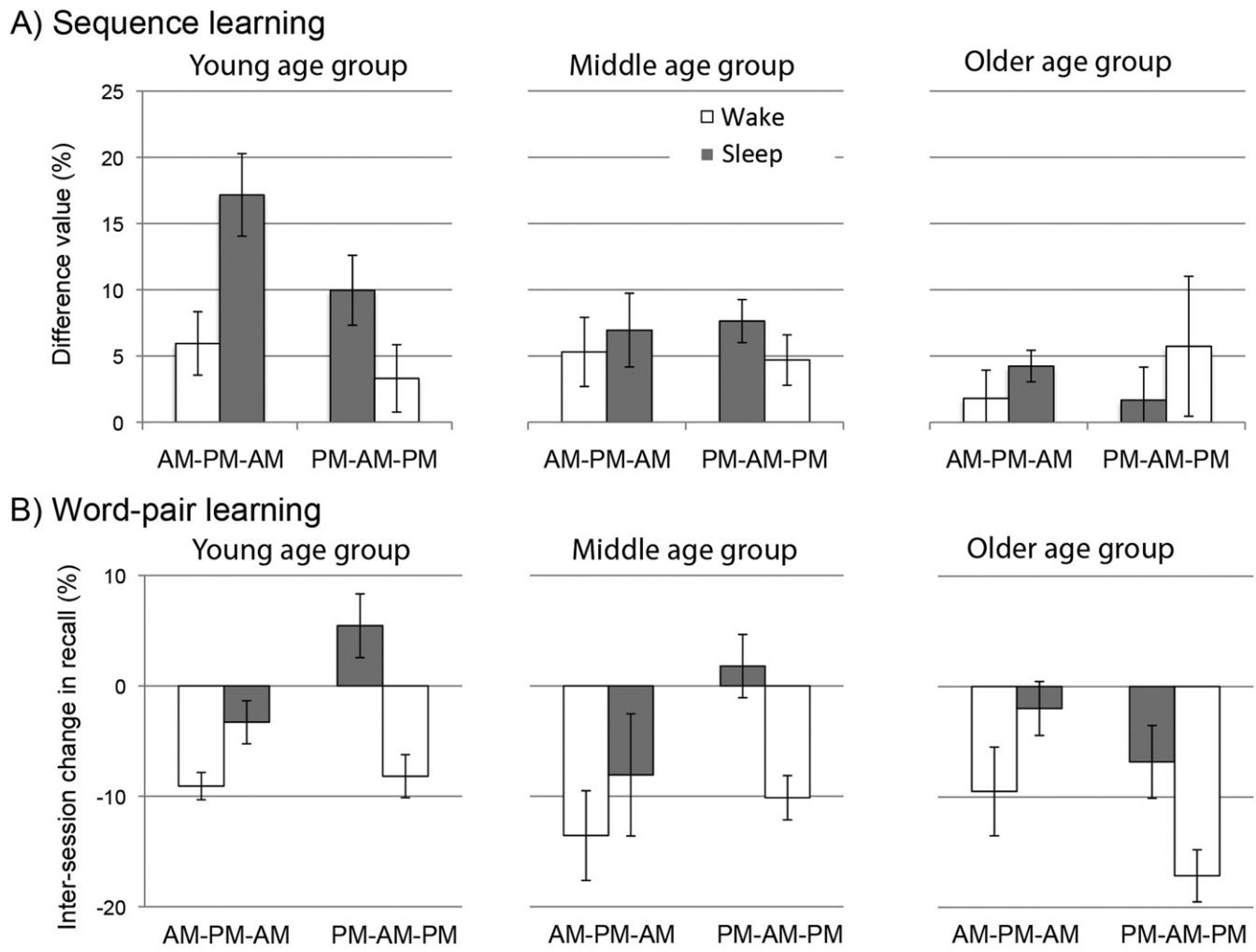

Fig. 3. Intersession performance changes for (A) motor-sequence learning and (B) word-pair learning. Error bars represent standard error.

($F(2,81) = 1.6$, $p = 0.21$) and Session Order ($F(1,81) = 0.77$, $p = 0.38$) were not significant. The main effect of Interval Type neared significance ($F(1,81) = 3.7$, $p = 0.056$). Importantly, this latter effect differed across the age groups as indicated by a significant Age and Interval Type interaction ($F(2,81) = 3.1$, $p = 0.048$; Fig. 3).

Given that RTs differed across age groups (main effect of Age: $F(2,81) = 12.2$, $p < 0.001$; Fig. 2), we also compared a normalized measure of off-line changes in RT (see 2. Methods) as used previously (Spencer et al., 2007; Walker et al., 2002). Based on the DV, significant main effects were observed for the factors Age Group ($F(2,81) = 4.1$, $p = 0.02$) and Interval Type ($F(1,81) = 9.60$, $p = 0.003$). The main effect of Session Order ($F(1,81) = 0.11$, $p = 0.75$) and interactions of Session Order with Interval Type ($F(1,81) = 0.57$, $p = 0.45$) and Age ($F(2,81) = 2.2$, $p = 0.11$) were not significant. Importantly, however, the interaction of Age Group and Interval Type was again significant ($F(2,81) = 4.0$, $p = 0.02$). To explore this interaction, post hoc comparisons were performed on the DV scores for each of the 3 groups. For this analysis, a 2-tailed paired t test was used, comparing the size of the DV after sleep (AM to PM) with the size of the DV after a wake interval (AM to PM). The Young age group showed a clear benefit of sleep ($t(46) = -3.3$, $p = 0.002$). However, performance changes over the sleep and wake intervals did not differ for the Middle-aged ($t(62) = -1.1$, $p = 0.27$) and Older ($t(60) = -0.49$, $p = 0.63$) groups (Fig. 4).

We considered whether diminished sleep-dependent memory consolidation in the Middle-Aged and Older groups might be the result of attenuated sequence learning. That is, if participants fail to learn the sequence initially, there may be less information to consolidate, even given our normalization procedure. To examine this issue, we computed a learning score for Session 1. Motor sequence learning is measured as the slowing exhibited on the random probe blocks (Blocks 8 and 10) relative to the surrounding sequence blocks (Blocks 7, 9, and 11). All 3 groups exhibited robust sequence learning, with means of 72, 60, and 54 ms for the Young, Middle-aged, and Older groups, respec-

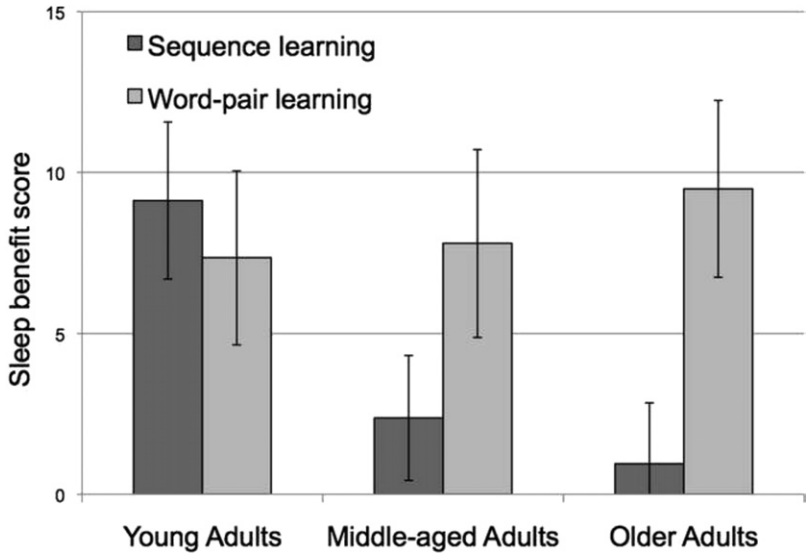

Fig. 4. Sleep benefit scores for each task (see text). Error bars represent standard error.

tively. The main effect of Age was not reliable ($F(2,81) = 2.3$, $p = 0.11$). The main effect of Session Order was marginally significant ($F(1,81) = 3.5$, $p = 0.07$), with slightly larger learning scores when Session 1 was in the morning. The interaction of Session Order and Age was not significant ($F(1,81) = 1.0$, $p = 0.36$). To account for the differences in RT across age groups, we also examined normalized learning scores. The learning score was normalized by dividing by the participants' mean sequence reaction time in Session 1 (mean of Blocks 7, 9, and 11). A similar pattern was observed based on this normalized learning score (main effect of Age: $F(2,81) = 2.34$, $p = 0.103$; Order: $F(1,81) = 2.2$, $p = 0.14$). However, given this near-significant effect of age, we also examined whether the sleep benefit is a function of initial learning by examining the correlation between the learning score and the sleep benefit. To do this, we computed a Sleep Benefit Score, defined as the intersession performance change over sleep minus the intersession performance change over wake:

$$\text{Sleep Benefit Score}_{\text{sequence learning}} = \text{DV}_{\text{sleep}} - \text{DV}_{\text{wake}}$$

The correlation between the Sleep Benefit Score and the normalized learning score was not significant ($r = 0.14$, $p = 0.20$).

We examined whether the age-related decline in SDC might not be specific to sequence learning per se, but rather reflect a more general difference in performance. To address this, changes in performance on the random blocks across sessions were examined. Neither main effects of Interval Type ($F(1,168) = 2.3$, $p = 0.14$) nor Age Group ($F(2,168) = 0.65$, $p = 0.52$) were observed. In addition, the interaction of Age and Interval Type did not approach significance ($F(2,168) = 0.91$, $p = 0.41$). In sum, the diminished SDC in our 2 older groups does not appear to reflect a general problem in sequence learning, nor a general absence of change across 12-hour breaks. Rather, the effect of age was limited to SDC for sequence learning.

Finally, given that age can be considered a continuous variable, we used multiple regression with age and total sleep time as independent predictor variables. The dependent variable was the Sleep Benefit Score defined above. The adjusted R^2 was low (0.03) and the model neared significance ($F(2,84) = 2.4$, $p = 0.09$). Total sleep time was not a significant predictor in this model (b = 0.007, $t(85) = 0.68$, $p = 0.49$). However the negative effect of age on the Sleep Benefit Score was marginally significant (b = −0.002, $t(85) = -1.9$, $p = 0.063$). This result is consistent with the conclusion that SDC was diminished with increasing age as reported previously (Spencer et al., 2007).

3.4. Word pair learning

For the word pair learning task, performance in the delayed recall phase was generally diminished relative to the corresponding immediate recall phase. This pattern indicates that there is some forgetting over the 12-hour breaks, a process that would work at odds with any benefits from off-line consolidation. Nonetheless, we can compare the changes over sleep and wake to determine if forgetting is reduced following sleep.

Despite our imposition of a learning criterion during the immediate recall phase for the word pair learning task (62%), there was a main effect of Age on immediate recall accuracy ($F(2,81) = 4.6$, $p = 0.009$). The Young group performed better (74%) than the Older group (65%) ($F(1,51) = 7.8$, $p = 0.007$), with the Middle-aged group's rate falling between these 2 values (71%). This difference reflects the fact that the number of participants failing to reach criterion by the end of the fifth training list increased

with age (1 Young, 3 Middle-aged, and 6 Older adults). Not surprisingly, after excluding these individuals, the main effect of Age on initial learning scores was no longer significant ($F(2,75) = 2.2$, $p = 0.14$). Comparing the change in recall over intervals with sleep or wake for individuals reaching criterion, the effect of Interval Type was significant ($F(1,151) = 14.3$, $p < 0.001$; Fig. 3B), but the Age Group by Interval Type interaction was not ($F(2,151) = 0.06$, $p = 0.94$). Averaged over all groups, participants recalled 2.5% fewer words during delayed recall following sleep (compared with the last cycle of immediate recall). The comparable value following wake was 10.7%. Thus, sleep attenuated the degree of forgetting over a 12-hour delay. The main effect of Session Order was not significant ($F(1,151) = 0.21$, $p = 0.65$) nor did this factor interact with Age Group ($F(2,151) = 0.49$, $p = 0.61$) or Interval Type ($F(1,151) = 1.8$, $p = 0.18$).

Within-group paired t tests comparing changes in recall over wake and sleep intervals, again using only those meeting the learning criterion, were significant for Young ($t(22) = 3.1$, $p = 0.005$), Middle-aged ($t(28) = -2.7$, $p = 0.01$) and Older adults ($t(24) = -2.9$, $p = 0.007$). Thus, all 3 age groups showed a benefit from sleep on the word-pair learning task. For the Young participants, the mean percentage of correctly recalled pairs was actually greater at the delayed phase compared with immediate recall. For the Middle-aged and Older participants, the rate of forgetting was larger, but sleep reduced the rate of forgetting, and to a similar degree as that observed in the Young participants (Fig. 3B).

We again regressed age and total sleep time against a Sleep Benefit Score computed for each participant on the word-pair learning task. This score was calculated as the difference of the intersession changes in recall accuracy for the sleep interval relative to the wake interval:

$$Sleep\ Benefit\ Score_{word\ pair} = \left(IR_{PM} - DR_{AM}\right) - \left(IR_{AM} - DR_{PM}\right)$$

where IR is immediate recall and DR is delayed recall. However, the model was not significant ($F(2,74) = 0.28$, $p = 0.76$). Thus, age does not account for a significant portion of the variance on this task, consistent with the conclusion that the benefit of sleep was similar across age groups for word-pair learning.

Finally, we considered whether eliminating those who failed to reach our initial learning criterion created a bias against finding an age-related effect on consolidation for word-pair learning. This question seemed especially important given that the motor sequence-learning task did not have a performance criterion. When all participants were included in the analysis, there was a trend for forgetting to be more pronounced with age (main effect of Age Group: $F(2,162) = 2.65$, $p = 0.07$), but the Age Group by Interval Type interaction ($F(2,162) = 0.11$, $p = 0.89$) remained nonsignificant.

3.5. Task interactions

The preceding analyses suggest that age has a differential effect on sleep-dependent changes in memory for sequence learning and word pair learning. A second way to examine this issue is by looking at correlations between the 2 tasks: similar mechanisms should produce a positive correlation between measures of sleep-dependent changes for the 2 tasks. At odds with this hypothesis, there was no correlation between the Sleep Benefit Scores for the 2 tasks ($r = -0.07$, not significant). Interestingly, the correlation was negative, although not significant ($r = -0.29$, $p = 0.17$), when the analysis was restricted to the Young adults, the group that benefited from sleep on both tasks. The Sleep Benefit Scores are also useful for illustrating the relative sleep benefit for the 2 tasks across the age groups (Fig. 4).

One concern with our design is that participants were tested on 2 different tasks in each session. This may have introduced interference between consolidation processes for sequence learning and word-pair learning (Brown and Robertson, 2007). However, Task Order (sequence task first vs. word-pair learning task first) did not affect the Sleep Benefit Score for either task ($F(1,162) = .65$, $p = .42$) or interact with Age Group ($F(2,162) = 2.1$, $p = .12$).

While the preceding analyses suggest that Task Order did not influence performance, we note that the magnitude of sleep-related changes on sequence learning was lower in the Younger group in this study (8.8% improvement) compared with our previous report (18% improvement; Spencer et al., 2006). There is an age difference in that the current study age range was 21–35 year, whereas in our earlier study, it was 18–24. The attenuation of off-line learning may reflect this age difference or it may reflect the inclusion of multiple tasks in the test session.

4. Discussion

These results present an intriguing dissociation between age-related variations in 2 tasks that have been widely employed in the literature on SDC (Diekelmann et al., 2009; Payne, 2010). Consistent with our previous report (Spencer et al., 2007) and work of others (Siengsukon and Boyd, 2008, 2009), older adults failed to show sleep-related changes in performance on a sequence learning task, our proxy of motor learning. Notably, middle-aged adults also showed a reduced performance benefit over sleep relative to wake. In contrast, SDC was observed in all age groups on the word pair task. Sleep benefit scores for the word pair and motor sequence learning tasks were not correlated in the present study, providing further support for the hypothesis that distinct processes underlie sleep-dependent consolidation for these tasks.

At first blush, it would be tempting to argue that this dissociation reflects a disproportionate effect of age on SDC for procedural relative to declarative learning. However, we (Spencer et al., 2006) and others (Keele et al., 2003) have

argued that a simple procedural/declarative distinction cannot be applied to sequence learning, perhaps akin to a similar dissociation emerging in category learning literature (Ashby and Crossley, 2010). In fact, earlier work (Keele et al., 2003; Schendan et al., 2003) suggests that the explicit variant of motor sequence learning used here, engages the hippocampus at encoding just as would be expected of word pair learning. Thus, while we cannot rule out the possibility that the aging-related reductions in hippocampal volume and functional engagement (Buckner, 2004; Hedden and Gabrieli, 2004; Spreng et al., 2010) underlie the present dissociation, we consider this unlikely. However, it is also possible that older adults do not utilize hippocampal-based learning processes at encoding in the same way as young adults. In a recent neuroimaging study, motor sequence learning was associated with increased striatal but decreased medial temporal lobe activation in young adults. However, for older adults, learning was paralleled by increases in both striatal and medial temporal lobe activation (Rieckmann et al., 2010). In the present study, there was no difference in initial learning at a behavioral level. Nonetheless, underlying processes engaged during encoding could contribute to the distinction in SDC for these 2 tasks irrespective of how they may be classified in terms of memory systems. Further examination including neuroimaging is warranted.

Alternatively, the function sleep serves may vary for these tasks. Memory consolidation is often marked by performance enhancements following sleep (Stickgold, 2005), a pattern observed for the young adults here on the motor sequence learning task. We did not observe a similar overall level of postsleep improvement on the word-pair learning task in either group. The sleep benefit for word-pair learning was manifest as an attenuation of forgetting. In contrast, Tucker et al. (2006) reported that recall was enhanced by 45% following a nap compared with 28% following an equivalent wake interval. Likewise, Backhaus et al. (2007) found greater recall following sleep relative to immediate recall prior to the break for both young and middle-aged adults. However, given that feedback was provided throughout immediate recall in those studies, it is difficult to distinguish between changes associated with feedback during the immediate recall phase and sleep-dependent enhancement. In other words, even in the final presentation of the list during immediate recall, the correct response was given for each incorrect response. As such, performance changes between immediate recall and delayed recall not only reflect time but also the benefit of this additional exposure to the correct pairing. While feedback was also provided in the present study, the benefit of feedback and the 12-hour delay was likely different from previous studies (Backhaus et al., 2007; Plihal and Born, 1999; Tucker et al., 2006) given that our study used semantically unassociated pairs. With this in mind, it is possible then that sleep only passively protects word-pair learning in the form used here (i.e., unrelated pairs) while sleep may actively process and enhance motor sequence learning (as well as, perhaps, semantically associated word pairs). If such is the case, our results may reflect a decline in active sleep-dependent processing (e.g., neural replay, shift to cortical storage) with age whereas the function of sleep in passively protecting memories from interference (decreased stimulation and encoding of new memories) is unchanged. Such an explanation could account for the discrepancy between the decline in sleep-dependent consolidation in middle-aged adults reported by Backhaus et al. (2007) and not observed here. In that study, the active enhancement of existing associations by sleep was lost in the middle-aged group. In the present study and, likewise, the report of Aly and Moscovitch (2010), the protection of new associations by sleep was not changed by increasing age.

Finally, one might consider changes in sleep physiology that may account for the present distinction. Sleep-dependent changes for word pair learning tasks have been associated with SWS (Plihal and Born, 1997; Tucker et al., 2006) while SDC for the motor sequence learning task has been associated with nREM2 (Walker et al., 2002). Drawing upon normative data on sleep physiology, the effects of aging do not appear to be uniform across the sleep cycle, nor are they simply related to the total time in sleep stages: SWS declines rapidly across the adult lifespan while the time spent in nREM2 remains relatively constant (Danker-Hopfe et al., 2005; Ohayon et al., 2004). Thus, the current results go against a simple mapping between behavior and sleep stages given that the spared SDC in our older groups was observed for the task linked to a sleep stage that shows an aging effect. Future work measuring related physiological changes is warranted to examine whether measures of the quality of these sleep stages may, instead, be critical.

It is interesting to note that the dissociation we observe here with age parallels that reported in children. Compared with young adults, 6–8 year old children showed a similar magnitude of sleep-dependent consolidation on a word pair task but reduced sleep-dependent changes on a sequence-learning task (Wilhelm et al., 2008). It may be that sleep-related changes for motor learning exhibit an inverted U-shaped function with a peak in early adulthood. This is supported by results in the Middle-aged group; it seems that only in young adults is motor sequence learning enhanced so strongly over sleep for healthy populations (Fischer et al., 2007; Siengsukon and Boyd, 2008, 2009; Wilhelm et al., 2008). While the basis for this function is unknown, it is clear that lifespan changes in SDC require further consideration.

Disclosure statement

The authors have no actual or potential conflicts of interest.

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