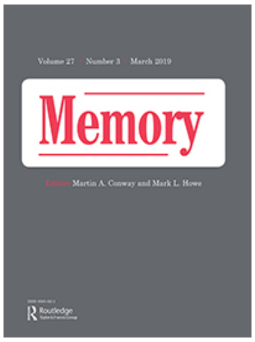

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Sleep facilitates consolidation of positive emotional memory in healthy older adults

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ABSTRACT
Evidence has demonstrated that sleep-related memory consolidation declines in ageing. However, little is known about age-related changes to sleep-related emotional memory consolidation, especially when considering the positivity effect observed in older adults. In the present study, we sought to explore whether there is a positive emotional bias in sleep-related memory consolidation among healthy older adults. Young and older adults were randomly assigned either into a sleep or wake condition. All participants encoded positive, negative, and neutral stimuli and underwent recognition tests immediately (*test 1*), after a 12-hour sleep/wake interval (*test 2*), and 3 days after test 2 (*test 3*). Results showed that age-related differences of sleep beneficial effect were modulated by emotion valence. In particular, sleep selectively enhanced positive memory in older adults, while in young adults sleep beneficial effect was manifested in neutral memory. Moreover, the sleep beneficial effect can be maintained at least 3 days in both young and older adults. These findings suggest that older adults had preserved but positive bias of sleep-related memory consolidation, which could be one of the underlying mechanisms for their generally better emotional well-being in daily life. These findings highlight the dynamic interplay among sleep and emotional memory in older adults.

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KEYWORDS
Aging; sleep; sleep-related memory consolidation; emotion; positivity effect

Decades of research has extensively investigated the behaviour and neural mechanisms underlying sleep-related memory consolidation in both animal models and humans (Stickgold, 2005; Walker & Stickgold, 2004). Findings show that sleep, compared to an equivalent period of wakefulness, promotes memory consolidation, which is associated with information transfer from the hippocampus to the neocortex during sleep (Spencer, Sunm, & Ivry, 2006; Spencer, Walker, & Stickgold, 2017; Walker & Stickgold, 2004; Walker, Stickgold, Alsop, Gaab, & Schlaug, 2005). Because adults tend to experience increases in memory impairment and alterations in sleep patterns with advancing age, investigations have recently focused on developmental changes in sleep-related memory consolidation (Fogel et al., 2014; Harand et al., 2012a, 2012b). For example, our recent meta-analysis showed that older adults experience greater declines in sleep-related memory consolidation relative to young adults. Moreover, this age-related decline was primarily observed in declarative memory relative to procedural memory (Gui et al., 2017).

Emotional salience is a well-known contributing factor to memory performance. That is, emotional information tends to be easier to recall than neutral information, which is potentially facilitated by the amygdala's bidirectional connections with the hippocampus and other regions implicated in memory consolidation (McGaugh, 2004; Phelps, 2004). There is also a growing body of literature on the role of sleep in emotional memory consolidation in young adults (Cellini, Torre, Stegagno, & Sarlo, 2016; Hu, Stylos-Allan, & Walker, 2006; Nishida, Pearsall, Buckner, & Walker, 2009; Payne & Kensinger, 2011; Payne, Chambers, & Kensinger, 2012; Payne et al., 2015; Payne, Stickgold, Swanberg, & Kensinger, 2008; Sterpenich et al., 2007; Wagner, Hallschmid, Rasch, & Born, 2006). With a sleep interval rather than an equivalent time of wakefulness, young adults showed more sleep-related beneficial effect on negative stimuli than neutral ones (Hu et al., 2006; Nishida et al., 2009), and the enhancement of memory for negative stimuli correlated with the amount of rapid eye movement (REM) sleep (Nishida et al., 2009). Similarly, through a set of experimental studies, Payne and colleagues found that a period of post-learning sleep preferentially preserved negative object information (Payne et al., 2008; Payne et al., 2012; Payne et al., 2015; Payne & Kensinger, 2011). However, findings on the influence of emotion on sleep-related memory consolidation are mixed, with some results suggesting that sleep

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promotes the consolidation of neutral stimuli over emotional stimuli (Cellini et al., 2016; McKeon, Pace-Schott, & Spencer, 2012; Wagner, Kashyap, Diekelmann, & Born, 2007), and the effects of age on this process is understudied.

Accumulating evidence suggests that older adults exhibit a positivity effect in attention and memory. That is, compared to young adults, older adults selectively focus and remember more positive information over negative (Mather & Carstensen, 2005). Whether this positive emotional bias in older adults could also be manifested in sleep-related memory consolidation has yet to be discerned. Recently, Jones, Schultz, Adams, Baran, and Spencer (2016) examined the effect of sleep on negative and positive memory in young and older adults. Compared with wakefulness, sleep preserved older adults' memory for positive pictures, whereas sleep preserved memory for negative pictures in young adults. However, this study was limited by the between-subject design in that some participants viewed negative and neutral pictures and the others viewed positive and neutral pictures may be problematic for comparisons across emotion conditions. Instead, a within-subject design would be more ideal, since in this way, the carry-over effects could be minimised between stimulus categories. In addition, it has been suggested that the beneficial effects of sleep on emotional memory consolidation could be lasting. For example, Sterpenich et al. (2009) found that after sleep, negative information was preserved better than neutral information, and this sleep-by-valence effect in young adults was observed even 6 months after the encoding phase. If there is positive emotional bias of sleep-dependent processing shifts from negative to positive with ageing, it is unclear whether this sleep-by-valence effect could also be observed after an extended period of time.

In the present study, we utilised a within-subject design to assess the effects of age-related positivity bias on sleep-related memory consolidation. Based on previous evidence, we predicted that (1) a post-encoding sleep interval can facilitate memory consolidation compared with an equivalent period of wakefulness in both young and older adults; (2) the sleep-by-valence effect will vary between young and older adults. Specifically, sleep will facilitate the consolidation of positive memory in older adults, while this positivity effect will not be observed in young adults; (3) the beneficial effects of sleep on memory consolidation will be observed after several days after encoding. However, whether the age-related emotional bias of sleep-related memory consolidation can last for an extended period of time after encoding is an exploratory aim of the present study.

Methods

Participants

Fifty-seven young (28 in the sleep condition and 29 in the wake condition 29; aged 18–25) and 62 older adults (29 in the sleep condition and 33 in the wake condition 33; aged 58–78) were recruited for the present study. Young adults were students from Southwest University, China and older adults were recruited from adjacent communities. Eligible participants reported no history of neurological diseases or psychiatric conditions or sleep disorders. Older adults were administered the Mini-Mental State Examination (MMSE, Folstein, Folstein, & McHugh, 1975) for dementia screening. Participants were instructed to remain free of caffeine, drugs, and alcohol, and refrain from napping in daytime during the study period. Participants were randomly assigned to the experimental conditions. The demographic and neuropsychological characteristics of each age group for each experimental condition are shown in Table 1. Participants in the wake and sleep conditions were matched in demographic and neuropsychological characteristics across age at baseline. However, older adults were generally less educated, exhibited more "morningness" tendencies, and had more sleep problems in daily life manifested as with higher scores of Pittsburgh Sleep Quality Index (PSQI, Buysse, Reynolds, Monk, Berman, & Kupfer, 1989). Considering that there were significant differences between young and older adults in education, chronotype, and PSQI, we conducted covariance analyses to test for the age-by-sleep-by-valence memory consolidation. The significance of the results for the present study was not changed by these covariates (see Table S1).

Materials

Most stimuli were pictures selected from the International Affective Picture System (IAPS, Lang, Bradley, & Cuthbert, 1997). The rest were gathered from the internet and were chosen to match the IAPS in content (human faces, objects, scenes, animals) and visual characteristics (i.e., image luminance). Four hundred and eighty pictures were selected out of 600 pictures based on emotion ratings (1 = most unpleasant to 9 = most pleasant; Lang, Bradley, & Cuthbert, 1997) from both young ($n = 34$) and older adults ($n = 37$) who did not participate in the present study.

The adopted stimuli set consisted of 160 positive emotional pictures ($M = 6.84$, $SD = 1.19$), 160 negative emotional pictures ($M = 2.99$, $SD = 1.15$) and 160 neutral pictures ($M = 5.20$, $SD = 0.91$). All the stimuli were assigned into 4 sets: taken as the encoding stimuli in the *learning phase*, and taken as novel pictures in *test 1*, *test 2* and *test 3*, respectively. In each set, there were a total of 120 stimuli consisting of 40 positive, 40 negative, and 40 neutral pictures. The nature of sets was counterbalanced across participants.

Procedure

The experiment consisted of 3 sessions (Figure 1(A)). The first session was conducted either in the morning, between 7:30 AM and 9:30 AM (the wake condition), or

Table 1. Participants' characteristics and neuropsychological data.

	YS $n = 28$ M (SD)	YW $n = 29$ M (SD)	YS vs. YW (p-value)	OS $n = 29$ M (SD)	OW $n = 33$ M (SD)	OS vs. OW (p-value)	Young vs. old (p-value)
Demographic information							
Age (years)	21.59 (2.14)	22 (1.32)	.44	66.27 (4.95)	65.49 (3.77)	.25	<.001
Education (years)	16.04 (1.34)	16.03 (1.33)	.92	8.13 (2.83)	7.89 (2.29)	.43	<.001
MMSE	n.a.	n.a.	n.a.	27.31 (2.73)	26.6 (2.57)	.50	n.a.
MEQ	21.54 (3.45)	22.56 (3.12)	.11	25.91 (2.41)	26.29 (2.99)	.99	<.001
CES-D	13.00 (7.63)	16.12 (10.89)	.28	11.59 (6.91)	11.10 (7.78)	.39	.08
PANAS	2.09 (0.61)	2.03 (0.68)	.56	2.12 (0.79)	1.77 (0.54)	.11	.22
PSQI	5.46 (2.85)	4.88 (1.93)	.31	5.76 (2.86)	6.77 (3.60)	.42	<.05
Post-learning Actigraph data							
Sleep latency (min)	417.59 (93.20)	n.a.	n.a.	395.64 (68.29)	n.a.	n.a.	.24
TST (min)	336.00 (103.89)	n.a.	n.a.	315.07 (75.92)	n.a.	n.a.	.30
Sleep efficiency (%)	77.87 (10.18)	n.a.	n.a.	79.35 (12.37)	n.a.	n.a.	.64
Deep sleep (%)	33.08 (13.81)	n.a.	n.a.	21.58 (11.54)	n.a.	n.a.	<.01
Encoding phase							
Probe digit_ACC	97.08 (5.21)	98.08 (3.39)	.38	97.96 (8.32)	97.28 (6.52)	.71	.99
Probe digit_RT (ms)	902.45 (238.92)	957.42 (261.15)	.40	3086.48 (3859.50)	2446.32 (1820.63)	.40	<.001
Valence rating_positive	6.73 (1.07)	6.87 (1.03)	.62	6.52 (1.46)	7.23 (1.07)	<.05	<.05
Valence rating_negative	2.61 (0.94)	2.74 (0.87)	.56	3.28 (1.21)	3.24 (1.36)	.88	.95
Valence rating_neutral	5.03 (0.77)	5.12 (0.60)	.63	5.10 (1.07)	5.53 (1.04)	.09	.11

YS: young adults in the sleep condition; YW: young adults in the wake condition; OS: older adults in the sleep condition; OW: older adults in the wake condition; MMSE: Mini-Mental State Examination; MEQ: Morningness-Eveningness Questionnaire; CES-D: Center for Epidemiologic Studies Depression Scale; PANAS: Positive and Negative Affect Scale; PSQI: Pittsburgh Sleep Quality Index; TST: total sleep time; ACC: accuracy; RT: response time.

in the evening, between 7:30 PM and 9:30 PM (the sleep condition), which included an encoding phase followed by an immediately recognition phase (*test 1*). The second session was a retest conducted 12 hours later (*test 2*). The third session was conducted 3 days (72 hours) later after *test 2* (*test 3*). All study sessions took place in the same laboratory room.

Before encoding, all participants were instructed to complete the PSQI to measure their subjective habitual sleep quality, the Center for Epidemiologic Studies Depression Scale (CES-D) to assess their depressive symptoms (Radloff, 1977), the Morningness-Eveningness Questionnaire (MEQ) to exclude participants categorised as either "extreme morning" or "extreme evening" types (Horne & Ostberg, 1975), and the Positive and Negative Schedule (PANAS) to monitor their baseline mood (Watson, Clark, & Tellegen, 1988). Moreover, participants were instructed to provide a record of their sleep/daily activities of the previous night/daytime prior to each session. Participants in the wake condition were asked not to nap or join in activities which would impact the memory trace, such as learning. Participants in the sleep condition were instructed to wear an actigraph (BodyMedia FIT LINK) on their non-dominant wrist at night. Sleep parameters, such as total sleep time, sleep latency, sleep/wake pattern throughout the night with a sleep efficiency score, were retrieved from Sense Wear Software 8.1 (BodyMedia LINK). Specifically, the deep sleep proportions used in the present study was defined as the deep sleep time divided by the total sleep time.

During encoding, participants viewed 120 stimuli (40 positive, 40 negative, 40 neutral stimuli) in a pseudorandom order. Each trial began with a fixation cross (500 ms) followed by a target picture (3000 ms). After each picture, participants were instructed to rate the valence of the stimulus on a 9-point Likert scale (1 = negative, 5 = neutral, 9 = positive) by a self-paced keyboard button (Figure 1(B)). In addition, 12 alertness trials were randomly intermixed throughout the task. Participants were instructed to type a particular key on the keyboard (i.e., "0" or "1") as fast and accurate as possible during these trials. These trials were obtained to maintain participants' attention, preventing their habituation to the repetitive picture stimuli, and to provide a built-in measure of alertness at both evening and morning sessions, so that possible circadian influences could be examined (Hu et al., 2006).

During each recognition test, participants were presented with 240 stimuli: the same 120 pictures intermixed with 120 novel pictures (new: 40 positive, 40 negative, 40 neutral stimuli). Each picture was displayed for 3000 ms, which was followed by self-paced R/K/N responses. Participants were asked to indicate whether the picture was "old" or "new" by pressing the "S" or "F" key, respectively. If they made an "old" judgment, participants were further asked to indicate whether they "remember" or "know" the picture by tapping "J" or "L" key (Tulving, 1985; Figure 1(B)). Specifically, they were told that a "remember" response should be given to a picture that invoked the recollection of the details specific to the picture, whereas a "know" response should be given to a picture that was familiar, but that they were unable to recollect the details related to that picture.

Data analysis

For the encoding phase, a repeated-measures ANOVA was conducted on the valence ratings of pictures with age

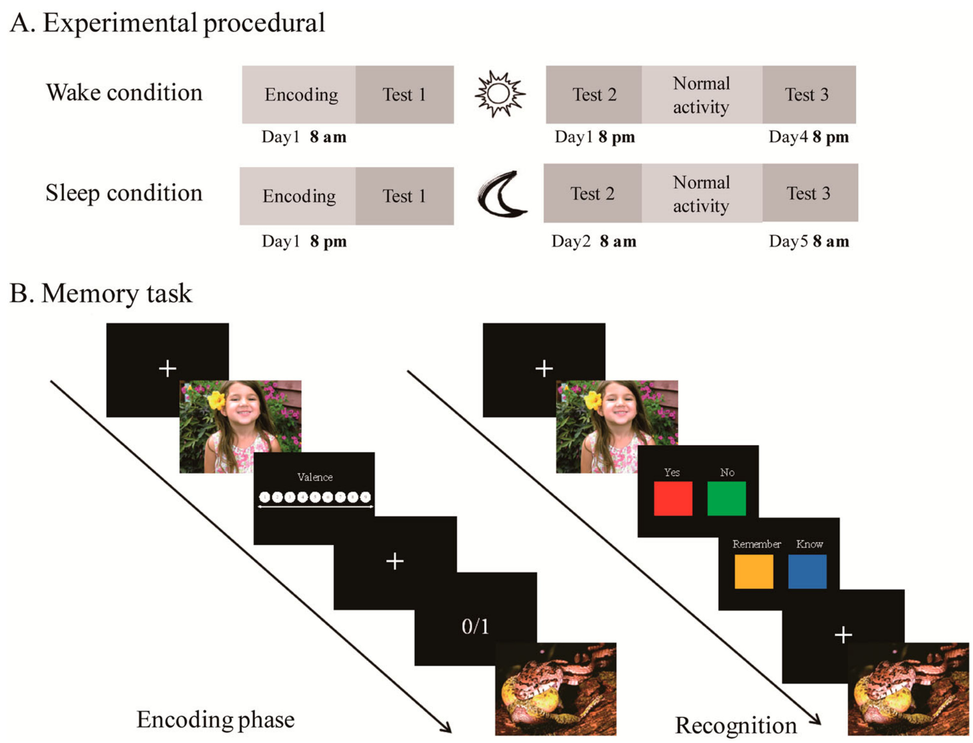

Figure 1. Experimental design and procedure. (A) Encoding phase took place either in the morning (wake condition) or in the evening (sleep condition) followed by *test 1* (baseline), *test 2* (a 12-hour sleep/wake interval after *test 1*), *test 3* (3 days after *test 2*). (B) During encoding, participants viewed 120 pictures and rated the valence of each picture on a 9-point Likert scale. During recognition, participants viewed 240 pictures, a mixture of target and novel foil pictures.

group (young adults, older adults) and experimental condition (wake, sleep) as between-subject factors and valence (positive, neutral, negative) as a within-subject factor. For the recognition phase, hit rate (HR) was calculated as the percentage of old items correctly identified as previously seen; false alarm rate (FAR) was calculated as the percentage of new items incorrectly identified as previously seen; memory discrimination (d') was calculated based on HR and FAR. HR and FAR were transformed into z scores, and $d' = Z(\text{HR}) - Z(\text{FAR})$. The repeated-measures ANOVA analysis of age × condition × valence on d' was performed for each session (i.e., *test 1*, *test 2*, *test 3*). Because there were no significant differences between R and K responses, the two types of responses were collapsed for the further analyses. Moreover, we conducted correlation analyses between the proportion of deep sleep and the change scores of memory performance (*test 2*(d') − *test 1* (d')) in young and older adults to examine the association between sleep-related memory consolidation effect and deep sleep. Statistical analyses were performed using SPSS Version 22.0 (IBM Corporation, Armonk, NY, USA).

Results

Encoding phase

For valence ratings during encoding, we found a main effect of age (F (1, 115) = 4.18, $p < .05$, $\eta^2 = 0.03$), in which older adults ($M = 5.13$, $SD = 0.92$) evaluated the pictures more positive than young adults ($M = 4.86$, $SD = 0.54$), while the sleep and wake condition was matched on the rating scores (F (1, 115) = 3.19, $p = .08$, $\eta^2 = 0.03$). For alertness tests during encoding, we found that there was no significant difference between wake and sleep condition, neither was between young and older adults group on accuracy (Table 1), indicating participants in different groups have maintained the same alertness throughout the encoding phase.

Recognition memory performance (d′)

Test 1 (baseline)

After the encoding phase, we conducted the recognition test immediately. For the recognition memory performance (d') of *test 1*, there was a main effect of age (F(1, 115) = 117.93, $p < .001$, $\eta^2 = 0.51$), in that older adults had a smaller d' than young adults. There was also a main effect of valence (F(2, 230) = 12.95, $p < .001$, $\eta^2 = 0.10$), with superior discrimination for emotional stimuli than neutral stimuli. In addition, there was a significant interaction between valence and age (F(2, 230) = 3.12, $p < .05$, $\eta^2 = 0.03$). Simple effect analyses showed that young adults performed better with emotional stimuli compared to neutral stimuli ($ps < .01$), whereas older adults only performed better with positive stimuli compared to neutral ones ($p < .01$). There was neither significant main effect of condition ($F(1, 115) = 2.10$, $p = .15$, $\eta^2 = 0.02$) nor an interaction effect of condition × valence ($F(2, 230) = 0.30$, $p = .75$, $\eta^2 = 0.003$), condition × age ($F(1, 115) = 1.79$, $p = .18$, $\eta^2 = 0.02$), age × condition × valence ($F(2, 230) = 0.89$, $p = .41$, $\eta^2 = 0.008$), indicating the memory performance of sleep and wake condition was matched at baseline (Table 2 and Figure 2(A)).

Test 2 (a 12-hour sleep/wake interval after test 1)

For the recognition memory performance (d') of *test 2*, similarly as *test 1*, there was a main effect of age ($F(1, 115) = 106.89$, $p < .001$, $\eta^2 = 0.48$) and valence ($F(2, 230) = 12.95$, $p < .001$, $\eta^2 = 0.10$), and a significant interaction between age and valence ($F(2, 230) = 4.78$, $p < .01$, $\eta^2 = 0.04$). Moreover, after a 12-hour sleep/wake interval, there was a main effect of condition ($F(1, 115) = 14.66$, $p < .01$, $\eta^2 = 0.07$), in which participants in the sleep condition exhibited better memory performance compared to the wake condition. This main effect of condition was further qualified by a significant three-way interaction of age, valence, and condition ($F(2, 230) = 3.31$, $p < .05$, $\eta^2 = 0.03$). Simple effect analyses showed that sleep enhanced the consolidation of neutral stimuli in young adults ($p < .05$), whereas sleep enhanced the consolidation of positive stimuli in older adults ($p < .01$; Table 2 and Figure 2(B)). The interaction effect of condition × valence ($F(2, 230) = 1.57$, $p = .21$, $\eta^2 = 0.01$) and age × condition ($F(1, 115) = 0.36$, $p = .55$, $\eta^2 = 0.003$) were not significant.

Test 3 (3 days after test 2)

For the recognition memory performance (d') of *test 3*, there was a main effect of age ($F(1, 113) = 113.93$, $p < .001$, $\eta^2 = 0.50$) and condition ($F(1, 113) = 8.71$, $p < .01$, $\eta^2 = 0.07$), indicating that the beneficial effect of sleep can last for at least 3 days. Moreover, there was an interaction between age and valence ($F(2, 226) = 9.13$, $p < .001$, $\eta^2 = 0.08$). Simple effect analyses revealed that young adults performed better with positive stimuli than with neutral ones ($p < .05$), whereas older adults performed better with neutral stimuli than with emotional stimuli ($ps < .01$). Although the interaction effect of age × condition × valence was not significant ($F(2, 226) = 0.19$, $p = .83$, $\eta^2 = 0.002$), both young and older adults in the sleep condition performed better with positive stimuli than in the wake condition, and older adults also showed sleep-related memory enhancement with neutral stimuli (Table 2 and Figure 2(C)). The interaction effect of valence × condition ($F(2, 226) = 1.72$, $p = .18$, $\eta^2 = 0.02$) and age × condition ($F(1, 113) = 1.33$, $p = .25$, $\eta^2 = 0.01$) were not significant.

Moreover, we conducted two 4-way ANOVAs (age × condition × valence × time) for the relatively short-term (*test1*, *test2*) and long-term (*test1*, *test3*) period of time between tests, respectively. The results supported our finding that the beneficial effect of sleep on memory performance was maintained, but the age- and sleep-related emotional bias did not last in the long term. We provided the results of the two models in the supplementary material for reference.

Sleep and memory performance correlations

In the sleep condition, there was a significant age effect on the deep sleep proportion of the post-encoding nocturnal sleep ($t = 2.79$, $df = 51$, $p < .01$), in which older adults demonstrated a decreased proportion of deep sleep compared to young adults (Table 1). In young adults, the proportion of deep sleep was significantly related to memory retention of negative emotional stimuli ($r(28) = -0.45$, $p < .05$; Figure 3(A)), but this association was not significant in older adults ($r(29) = -0.29$, $p = .15$; Figure 3B). Correlations between sleep and memory retention were not found for positive nor neutral stimuli.

Discussion

Previous studies have suggested that sleep, compared to an equivalent time of wakefulness, promotes memory consolidation. Moreover, this beneficial effect of sleep on memory could be modulated by the characteristics of encoding stimuli, such as emotion valence (Diekelmann, Wilhelm, & Born, 2009). In recent years, substantial

Table 2. Memory performance (d').

	YS (d')	YW (d')	YS vs. YW (p-value)	OS (d')	OW (d')	OS vs. OW (p-value)	Young vs. Old (p-value)	Sleep vs. Wake (p-value)
Test 1								
Positive	3.43 (0.63)	3.52 (0.60)	.57	2.33 (0.99)	1.95 (0.82)	.10	<.001	.33
Negative	3.62 (0.56)	3.58 (0.71)	.84	2.23 (1.09)	1.82 (0.89)	.11	<.001	.21
Neutral	3.31 (0.52)	3.21 (0.66)	.53	2.05 (0.89)	1.75 (0.76)	.16	<.001	.20
Test 2								
Positive	3.73 (0.50)	3.44 (0.70)	.08	2.51 (1.09)	1.82 (0.87)	<.01	<.001	<.01
Negative	3.74 (0.62)	3.53 (0.72)	.23	2.27 (0.96)	1.85 (0.77)	.06	<.001	.08
Neutral	3.51 (0.62)	3.04 (0.71)	<.05	2.19 (1.01)	1.82 (0.93)	.16	<.001	<.05
Test 3								
Positive	3.98 (0.47)	3.64 (0.69)	<.05	2.55 (1.04)	1.89 (0.91)	<.05	<.001	<.05
Negative	3.82 (0.55)	3.69 (0.49)	.34	2.46 (1.01)	1.96 (0.97)	.06	<.001	.11
Neutral	3.78 (0.49)	3.52 (0.69)	.11	2.70 (0.98)	2.20 (0.80)	<.05	<.001	<.05

YS: young adults in the sleep condition; YW: young adults in the wake condition; OS: older adults in the sleep condition; OW: older adults in the wake condition.

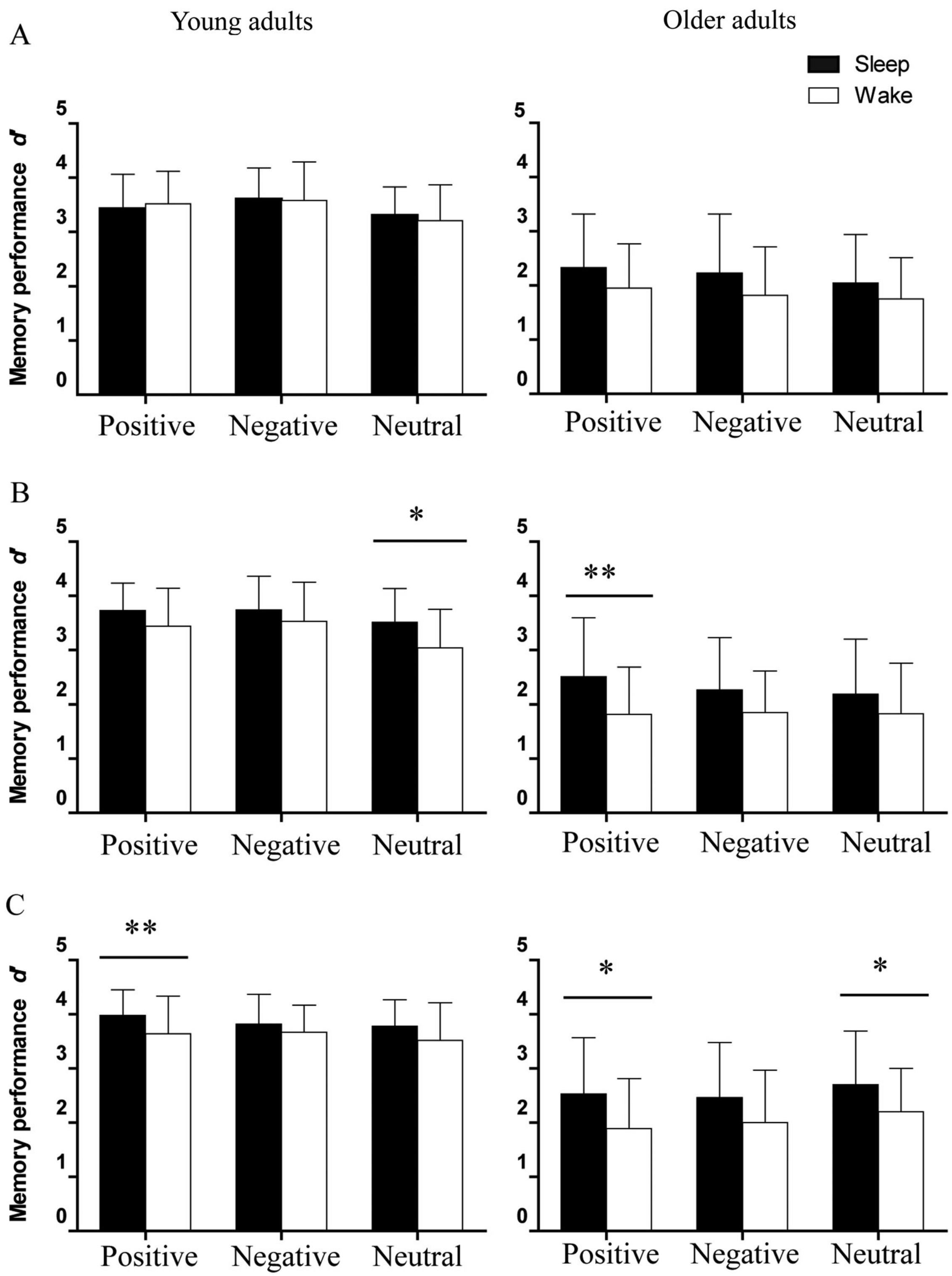

Figure 2. Influence of sleep and wake on positive, negative and neutral stimuli in young and older adults. Memory performance was reflected by the index of *d'*. Error bars represent the standard deviation of means. (A) *test 1*, immediately recognition after encoding phase; (B) *test 2*, a retest conducted 12 hours later; (C) *test 3*, a retest conducted 3 days (72 hours) later after *test 2*. $^*p < .05$; $^{**}p < .01$.

evidence has demonstrated that memory consolidation for emotional stimuli, relative to neutral ones, is enhanced by sleep (Hu et al., 2006; Nishida et al., 2009). With advanced age, however, older adults experience declines in sleep and memory, whereas their ability to regulate emotions maintained or even improved with ageing. Two important findings emerged from the present study. First, we found that enhanced memory performance due to sleep varied by emotional valence in young and older adults. In particular, sleep selectively enhanced positive memories in older

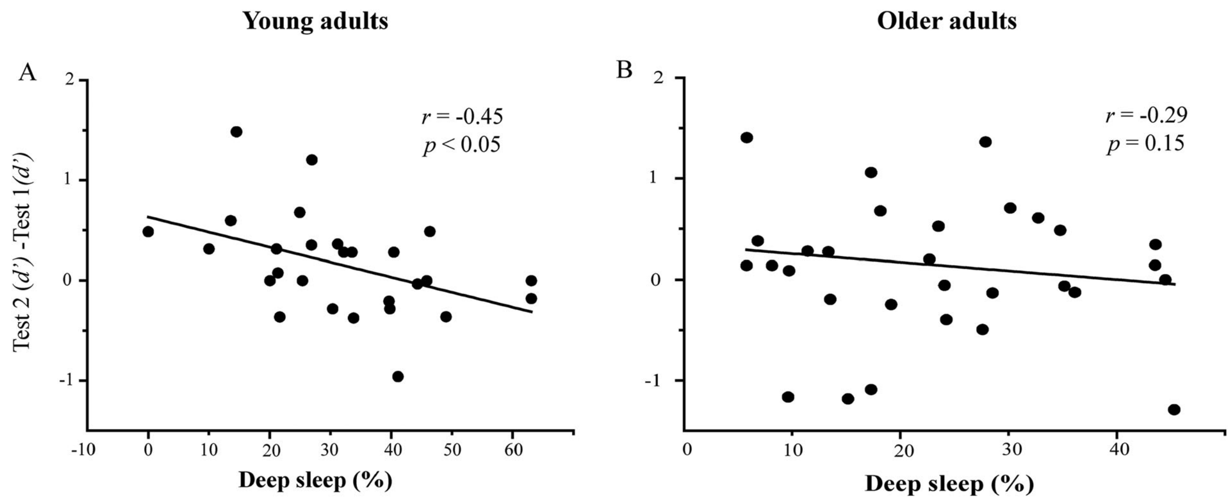

Figure 3. Relationships between sleep and change scores of negative memory performance between *test 1* and *test 2* in (A) young and (B) older adults.

adults, while in young adults sleep enhanced memory performance for neutral stimuli. Moreover, the results revealed a significant correlation between sleep and memory retention in young adults, whereas such a correlation was not found in older adults. Second, the benefits of sleep on memory can be maintained for at least 3 days in both young and older adults. However, the age-related emotional bias of sleep effect was not observed over time.

At baseline (*test 1*), the memory performance in sleep and wake condition was matched in both young and older adults. After a 12-hour interval at retest (*test 2*), both young and older adults showed enhancement of memory consolidation after nocturnal sleep compared to an equivalent period of wakefulness. Contrary to previous findings that suggested that the function of sleep-related memory consolidation declined with aging (Backhaus et al., 2007; Gui et al., 2017; Mander et al., 2013; Scullin, 2013), the current results illustrate the beneficial effect of sleep on memory is preserved in older adults, though it is qualified by the emotional valence of stimuli. One possible explanation the preserved beneficial effect of sleep on memory for older adults in current study is that we adopted emotional stimuli for declarative memory, which is assumed to have an enhancing influence on memory consolidation during sleep (Diekelmann et al., 2009; Hu et al., 2006; Nishida et al., 2009; Payne & Kensinger, 2010; Wagner, et al., 2006). Emotional arousal elicited by affective stimuli during sleep might be characterised by increases in activation of the amygdala and ventral medial prefrontal cortex (vmPFC) and strengthened the brain functional connectivity among the amygdala, hippocampus and vmPFC (Payne & Kensinger, 2011). Enhanced connectivity between the amygdala and other cognitive-related brain regions contribute to emotional memory consolidation during sleep (Lewis, Cairney, Manning, & Critchley, 2011). The emotional material promoting the sleep-related memory consolidation in general; thus, in the present study, we found relatively preserved sleep beneficial effect in older adults.

To the best of our knowledge, very few studies have investigated the emotional bias of sleep-related memory consolidation with ageing, which could be crucial in clarifying older adults' selective sleep-related memory processing and the underlying mechanisms of their enhanced emotional well-being in daily life. In the present study, we observed a valence-based bias in sleep-related memory consolidation with ageing, that is, neutral memories were benefited by sleep in young adults, whereas in older adults positive memories were benefited by sleep. This finding consisted with the recent literature that found sleep preserved valence ratings and memory for positive, but not negative pictures, in older adults and negative, but not positive, pictures in young adults (Jones et al., 2016). These findings are in line with the socio-emotional selectivity theory, which hypothesised that motivational priorities, as a function of future time horizons, shift across the lifespan (Carstensen, Isaacowitz, & Charles, 1999). As future time horizons become narrow in late life, older adults increasingly prioritise present-focused goals relating to emotional meaning and satisfaction, and information processing also shifts toward prioritising positive emotion (Carstensen, 2006; Reed, Chan, & Mikels, 2014). When it comes to sleep-related memory consolidation, we found that positive memories can be preferentially facilitated by sleep in older adults, which could support their emotional well-being in daily life. Additionally, we found an association between the proportion of deep sleep and negative memory consolidation in young adults but not in older adults. It is suggested that the link between sleep and declarative memory, which is typically observed in young adults, may be weakened or otherwise functionally changed in healthy older adults (Scullin, 2013). Moreover, older adults' weakened link between sleep and negative memory performance could also be representative of the positivity effect as manifested by the avoidance of negative memory (Charles, Mather, & Carstensen, 2003). However, further research is needed to better understand these relationships. In addition, we found that neutral, but not negative, memories were preserved by sleep in young adults. This finding is somewhat inconsistent with previous studies reporting that sleep selectively benefits negative memory in young adults (Hu et al., 2006; Jones et al., 2016; Nishida et al., 2009; Payne et al., 2008; Wagner, Gais, & Born, 2001). On one hand, there are discrepancies between published findings on this issue. For instance, sleep was found to facilitate memory consolidation regardless of the valence of stimuli (Cairney, Durrant, Power, & Lewis, 2015; Wagner et al., 2007) and enhance the consolidation of neutral, but not emotional, words (McKeon et al., 2012a). On the other hand, researchers indicate that emotional information may enhance memory at the expense of specific details (Brainerd, Holliday, Reyna, Yang, & Toglia, 2010; Reyna & Brainerd, 2011). The neutral stimuli, due to lack of emotional information, the details of them would receive more attention.

The present study also tested whether the age-related emotional bias of sleep-dependent memory consolidation can be maintained for an extended period of time after encoding. We found that sleep-related memory performance was maintained in both young and older adults' within 3 days, compared to participants in the wake condition. This is consistent with a neuroimaging study that observed similar effects at 6-month retest. Specifically, participants who had normal sleep, compared with participants who were sleep deprived, showed significant correlations between recollection performance and activation in the precuneus and the vmPFC, as well as in the extended amygdala and the occipital cortex, which was modulated by emotion at encoding (Sterpenich et al., 2009). Moreover, both young and older adults showed sleep-related enhancement of positive memory after 3 days. Post-encoding sleep adequately regulates emotion and provides restoration of appropriate emotion and selectively enhanced positive memories in both young and older adults (Goldstein & Walker, 2014). However, it should be noted that in the present study older adults generally performed better in neutral, rather than emotional, memory after 3 days. One possible explanation may be related to the arousal level of stimuli. Because of the low arousal level for neutral stimuli, it is possible that neutral stimuli received more attention for the details of pictures, whereas participants viewing highly arousing emotional stimuli may attend more to the emotional quality of the image rather than specific details. As time passes by, the emotion information decays, resulting in lower discrimination of emotional pictures compared to neutral ones (Cellini et al., 2016).

With respect to limitations, first we did not find age-related differences for "R" and "K" responses, and these two responses were collapsed for analysing in the current study. Hu et al. (2006) found a selective benefit for "know" responses but not "remember" responses, and we did not find an age effect in the current study. One possibility is that older adults may have not clearly understood the instructions. For example, we found that two older adults responded with only "remember" during *test 2*, which may be indicative of response bias. Second, in the present study actigraphy was used. Although it is convenient for data collection and minimises the influence of experimental manipulation on normal sleep, it is unable to differentiate slow wave sleep and REM sleep. In order to explore the relationships between memory performance and a specific sleep stage, it is more ideal for future studies to use actigraphy as well as polysomnography to collect participants' sleep data comprehensively. Third, although the "AM-PM" experiment design is typically used in the sleep-related memory consolidation studies, it might involve confounding variables such as circadian rhythms. Especially in consideration of age-related differences, it is important to note that young and older adults usually have different morningness-eveningness tendencies. However, in the present study, the significance of the results was not changed when we controlled MEQ which reflected the morningness-eveningness tendencies of participants. In the future studies, the "AM-PM-AM"/"PM-AM-PM" design (Spencer, Gouw, & Ivry, 2007) could be adopted to further control the influence of sleep–wake cycles.

Conclusion

In summary, the present study found that older adults had preserved, but positively biased, sleep-related memory consolidation, which could underlie older adults' generally better emotional well-being in daily life. These findings highlight the dynamic interplay of sleep- and emotional memory-related changes in older adults. Future research is needed to explore the neural mechanisms that potentially underlie the positivity bias of sleep-related memory consolidation in ageing.

Disclosure statement

No potential conflict of interest was reported by the authors.

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