SUPPLEMENTARY INFORMATION

Memory quality modulates the effect of aging on memory consolidation during sleep: Reduced maintenance but intact gain

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Supplementary Table 1. Bivariate correlations between sleep variables, brain regions of interest, and memory measures ***across age groups***

		1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*
1	*Fast SP density*													
2	*Slow SP density*	**0.517** ***(<.001)***												
3	*SO density*	0.183 *(.182)*	–0.132 *(.335)*											
4	*SWA*	0.285 *(.035)*	0.059 *(.669)*	**0.458** ***(<.001)***										
5	*mPFC*	**0.583** ***(<.001)***	**0.434** ***(<.001)***	0.229 *(.098)*	**0.481** ***(<.001)***									
6	*Thalamus*	0.440 *(.001)*	0.390 *(.004)*	–0.065 *(.644)*	0.160 *(.253)*	**0.635** ***(<.001)***								
7	*Hippocampus*	**0.556** ***(<.001)***	0.313 *(.023)*	0.074 *(.595)*	0.413 *(.002)*	**0.726** ***(<.001)***	**0.662** ***(<.001)***							
8	*Entorhinal cortex*	**0.489** ***(<.001)***	0.372 *(.006)*	0.052 *(.712)*	0.393 *(.004)*	**0.616** ***(<.001)***	**0.548** ***(<.001)***	**0.800** ***(<.001)***						
9	*Age*	**–0.682** ***(<.001)***	**–0.460** ***(<.001)***	–0.180 *(.194)*	**–0.426** ***(<.001)***	**–0.758** ***(<.001)***	**–0.603** ***(<.001)***	**–0.722** ***(<.001)***	**–0.666** ***(<.001)***					
10	*Low quality (gain)*	–0.013 *(.925)*	0.028 *(.839)*	–0.071 *(.607)*	–0.160 *(.243)*	0.108 *(.400)*	0.318 *(.011)*	0.142 *(.267)*	0.131 *(.306)*	–0.088 *(.488)*				
11	*Medium quality (maintenance)*	**0.674** ***(<.001)***	0.337 *(.012)*	0.274 *(.043)*	0.396 *(.003)*	**0.665** ***(<.001)***	**0.568** ***(<.001)***	**0.584** ***(<.001)***	**0.527** ***(<.001)***	**–0.766** ***(<.001)***	0.264 *(.032)*			
12	*High quality (maintenance)*	**0.512** ***(<.001)***	0.338 *(.012)*	0.329 *(.014)*	0.360 *(.007)*	**0.610** ***(<.001)***	**0.575** ***(<.001)***	**0.458** ***(<.001)***	**0.406** ***(<.001)***	**–0.688** ***(<.001)***	0.325 *(.008)*	**0.808** ***(<.001)***		
13	*LSPS*	**–0.867** ***(<.001)***	**–0.572** ***(<.001)***	–0.419 *(.002)*	**–0.610** ***(<.001)***	**–0.712** ***(<.001)***	**–0.414** ***(<.001)***	**–0.575** ***(<.001)***	**–0.533** ***(<.001)***	**0.727** ***(<.001)***	0.057 *(.680)*	**–0.689** ***(<.001)***	**–0.640** ***(<.001)***	
14	*LBSS*	**–0.609** ***(<.001)***	–0.429 *(.002)*	–0.090 *(.525)*	–0.421 *(.002)*	**–0.870** ***(<.001)***	**–0.813** ***(<.001)***	**–0.919** ***(<.001)***	**–0.848** ***(<.001)***	**0.775** ***(<.001)***	–0.219 *(.087)*	**–0.680** ***(<.001)***	**–0.608** ***(<.001)***	**0.653** ***(<.001)***

Note. Spearman's correlation coefficients. Correlations in black fall below an α-level of .05. Bold black correlation coefficients fall below the Bonferroni-adjusted α-level of .00028. LBSS: latent brain structure score, LSPS: latent sleep profile score, mPFC: medial prefrontal cortex, SP: spindle, SO: slow oscillation, SWA: slow-wave activity.

Supplementary Table 2. Bivariate correlations between sleep variables, brain regions of interest, and memory measures in ***younger adults***

		1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*
1	*Fast SP density*													
2	*Slow SP density*	0.661 *(.001)*												
3	*SO density*	–0.447 *(.030)*	–0.107 *(.618)*											
4	*SWA*	–0.333 *(.112)*	–0.275 *(.193)*	0.503 *(.013)*										
5	*mPFC*	0.042 *(.835)*	0.064 *(.765)*	–0.066 *(.759)*	–0.013 *(.953)*									
6	*Thalamus*	0.349 *(.075)*	0.250 *(.237)*	–0.351 *(.093)*	–0.379 *(.069)*	0.444 *(.015)*								
7	*Hippocampus*	0.093 *(.642)*	–0.210 *(.324)*	–0.366 *(.079)*	–0.283 *(.180)*	0.322 *(.083)*	0.477 *(.008)*							
8	*Entorhinal cortex*	0.209 *(.293)*	0.154 *(.471)*	–0.237 *(.265)*	–0.138 *(.518)*	0.022 *(.910)*	0.342 *(.065)*	0.483 *(.007)*						
9	*Age*	–0.441 *(.025)*	–0.370 *(.083)*	0.308 *(.152)*	0.023 *(.919)*	–0.081 *(.676)*	–0.129 *(.503)*	–0.067 *(.731)*	–0.111 *(.564)*					
10	*Low quality (gain)*	–0.008 *(.967)*	0.306 *(.146)*	–0.134 *(.531)*	–0.407 *(.049)*	0.176 *(.351)*	0.232 *(.217)*	0.060 *(.752)*	0.155 *(.414)*	0.153 *(.427)*				
11	*Medium quality (maintenance)*	0.207 *(.299)*	0.365 *(.080)*	0.086 *(.688)*	–0.163 *(.444)*	–0.017 *(.929)*	0.200 *(.287)*	–0.244 *(.193)*	–0.190 *(.313)*	–0.359 *(.057)*	0.305 *(.101)*			
12	*High quality (maintenance)*	0.127 *(.527)*	0.358 *(.086)*	0.096 *(.657)*	0.002 *(.993)*	0.179 *(.344)*	0.279 *(.136)*	–0.248 *(.187)*	–0.132 *(.486)*	–0.382 *(.041)*	0.219 *(.244)*	0.535 *(.002)*		
13	*LSPS*	–0.593 *(.003)*	–0.588 *(.041)*	–0.218 *(.315)*	–0.396 *(.062)*	–0.065 *(.767)*	0.054 *(.806)*	0.322 *(.134)*	–0.016 *(.944)*	0.259 *(.232)*	0.094 *(.670)*	–0.114 *(.604)*	–0.132 *(.548)*	
14	*LBSS*	–0.247 *(.223)*	–0.079 *(.719)*	0.328 *(.127)*	0.239 *(.271)*	**–0.620 *(<.001)***	**–0.808 *(<.001)***	**–0.841 *(<.001)***	**–0.628 *(<.001)***	0.178 *(.353)*	–0.198 *(.302)*	0.052 *(.790)*	–0.049 *(.802)*	–0.079 *(.719)*

Note. Spearman's correlation coefficients. Correlations in black fall below an α-level of .05. Bold black correlation coefficients fall below the Bonferroni-adjusted α-level of .00028. LBSS: latent brain structure score, LSPS: latent sleep profile score, mPFC: medial prefrontal cortex, SP: spindle, SO: slow oscillation, SWA: slow-wave activity.

*Supplementary Table 3. Bivariate correlations between sleep variables, brain regions of interest, and memory measures in **older adults***

		1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*
1	*Fast SP density*													
2	*Slow SP density*	0.306 *(.094)*												
3	*SO density*	0.151 *(.415)*	–0.402 *(.026)*											
4	*SWA*	–0.114 *(.541)*	–0.107 *(.566)*	0.312 *(.087)*										
5	*mPFC*	–0.052 *(.788)*	0.232 *(.225)*	0.127 *(.511)*	0.033 *(.867)*									
6	*Thalamus*	–0.006 *(.977)*	0.133 *(.488)*	–0.142 *(.461)*	–0.039 *(.839)*	0.364 *(.038)*								
7	*Hippocampus*	0.101 *(.599)*	0.160 *(.405)*	–0.027 *(.889)*	0.065 *(.739)*	0.228 *(.201)*	0.457 *(.008)*							
8	*Entorhinal cortex*	–0.068 *(.723)*	0.029 *(.881)*	–0.196 *(.308)*	0.023 *(.905)*	0.082 *(.648)*	0.183 *(.306)*	**0.648 *(<.001)***						
9	*Age*	–0.143 *(.444)*	–0.130 *(.486)*	0.060 *(.747)*	0.131 *(.482)*	–0.171 *(.341)*	–0.374 *(.032)*	–0.380 *(.029)*	–0.198 *(.270)*					
10	*Low quality (gain)*	0.052 *(.779)*	–0.063 *(.734)*	–0.049 *(.794)*	–0.005 *(.978)*	0.252 *(.156)*	0.489 *(.004)*	0.324 *(.067)*	0.194 *(.278)*	–0.409 *(.013)*				
11	*Medium quality (maintenance)*	0.338 *(.063)*	–0.281 *(.126)*	0.097 *(.603)*	–0.128 *(.492)*	–0.021 *(.908)*	0.338 *(.054)*	0.234 *(.189)*	0.030 *(.867)*	–0.255 *(.133)*	0.463 *(.004)*			
12	*High quality (maintenance)*	0.118 *(.527)*	–0.169 *(.362)*	0.218 *(.237)*	–0.017 *(.928)*	0.202 *(.259)*	0.469 *(.006)*	0.228 *(.201)*	0.003 *(.987)*	–0.358 *(.032)*	0.502 *(.002)*	**0.620 *(<.001)***		
13	*LSPS*	**–0.690 *(<.001)***	–0.426 *(.018)*	–0.379 *(.036)*	–0.408 *(.023)*	–0.203 *(.290)*	–0.012 *(.950)*	–0.237 *(.214)*	0.090 *(.641)*	0.114 *(.541)*	0.008 *(.968)*	–0.004 *(.982)*	–0.094 *(.612)*	
14	*LBSS*	–0.033 *(.867)*	–0.180 *(.348)*	0.073 *(.706)*	–0.049 *(.799)*	–0.554 *(.001)*	**–0.640 *(<.001)***	**–0.789 *(<.001)***	**–0.694 *(<.001)***	0.278 *(.117)*	–0.465 *(.007)*	–0.260 *(.144)*	–0.311 *(.078)*	-0.130 *(.500)*

Note. Spearman's correlation coefficients. Correlations in black fall below an α-level of .05. Bold black correlation coefficients fall below the Bonferroni-adjusted α-level of .00028. LBSS: latent brain structure score, LSPS: latent sleep profile score, mPFC: medial prefrontal cortex, SP: spindle, SO: slow oscillation, SWA: slow-wave activity.

Supplementary Table 4. Memory gain and maintenance by latent sleep profile subgroup

	LATENT SLEEP PROFILE			
	Younger adults		Older adults	
	young–Young (n = 12)	old–Young (n = 11)	young–Old (n = 7)	old–Old (n = 24)
GAIN				
low-quality memory	10.11 [7.11; 11.13]	8.76 [6.91; 12.53]	9.64 [4.05; 11.26]	11.36 [6.09; 15.71]
MAINTENANCE				
medium-quality memory	91.55 [89.73; 94.71]	89.29 [85.29; 94.95]	62.82 [59.57; 72.92]	66.35 [55.8; 71.47]
high-quality memory	98.88 [95.00; 100.00]	97.62 [94.39; 100.00]	88.43 [84.57; 91.72]	85.48 [80.27; 90.1]

Note. Sleep profile subgroups correspond to the subgroups marked in Figure 3b that pinpoint younger and older adults with comparable and distinct latent sleep profile scores: young–Young (= younger adults showing a clearly distinct sleep profile from older adults), old–Young (= younger adults exhibiting a latent sleep profile comparable to older adults), young–Old (= older adults with a 'youth-like' latent sleep profile), old–Old (=older adults with a latent sleep profile clearly distinct from younger adults).

Supplementary Table 5. Memory gain and maintenance by latent brain structure profile subgroup

	LATENT BRAIN STRUCTURE PROFILE			
	Younger adults		Older adults	
	young–Young (n = 17)	old–Young (n = 12)	young–Old (n = 5)	old–Old (n = 28)
GAIN				
low-quality memory	9.60 [7.86; 11.72]	8.57 [5.86; 10.3]	15.28 [13.51; 18.9]	8 [4.64; 11.91]
MAINTENANCE				
medium-quality memory	89.29 [87.76; 94.40]	90.71 [83.45; 92.05]	66.04 [59.52; 70.42]	65.97 [56.36; 71.47]
high-quality memory	97.62 [96.42; 100.00]	98.91 [92.72; 100.00]	88.43 [87.23; 90.00]	87.41 [79.81; 90.5]

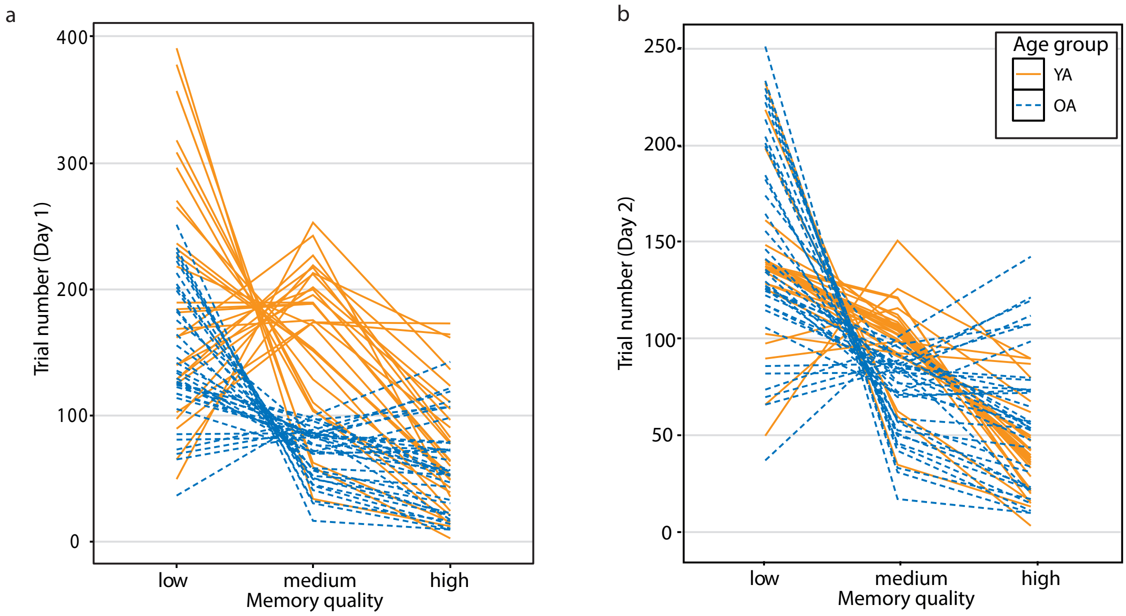
Note. Brain structure subgroups correspond to the subgroups marked in Figure 4b that pinpoint younger and older adults with comparable and distinct latent brain structure scores: young–Young (= younger adults with structural brain integrity clearly distinct from older adults), old–Young (= younger adults exhibiting a latent brain structure profile comparable to older adults), young–Old (= older adults with ‘youth-like’ latent brain structure profile), old–Old (=older adults with a latent brain structure profile clearly distinct from younger adults).

Supplementary Table 6. Trial numbers on Day 1 and Day 2

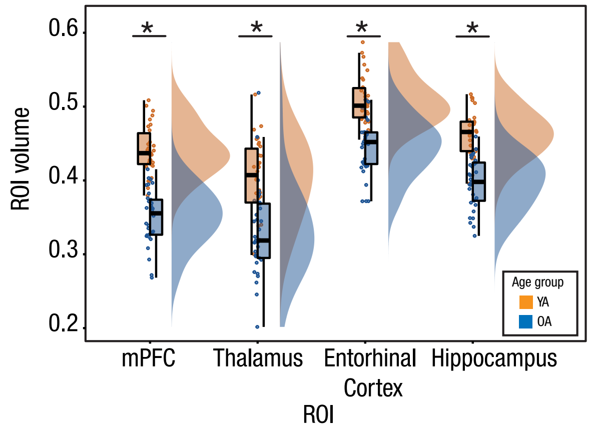
	Day 1				Day 2			
	low quality	medium quality	high quality	excluded	low quality	medium quality	high quality	excluded
YA	182.50 [128.00; 266.25]	174.50 [141.50; 203.75]	61.50 [38.00; 98.25]	3.00 [1.00; 4.00]	137 [129.25; 140.00]	103.69 [95.00; 109.50]	37.57 [26.25; 48.25]	2.00 [1.00; 3.25]
OA	134.50 [117.00; 187.75]	76.50 [53.00; 86.00]	54.00 [24.00; 76.75]	4.00 [2.25; 6.00]	134.50 [117.00; 187.75]	76.50 [53.0; 86.0]	54.00 [24.00; 76.75]	4.00 [2.25; 6.00]

Note. Memory-quality categories were defined by the overall learning trajectory on Day 1 (cf. Figure 2a). Item pairs that were forgotten during learning (i.e., not remembered in the final cued recall on Day 1 but in the preceding recall round) were excluded from the analyses. Note that younger adults studied 440 scene–word pairs, whereas older adults 280 pairs. As in older adults all 280 studied pairs had to be recalled on Day 2, the numbers of Day 2 match those of Day 1. YA: younger adults, OA: older adults.

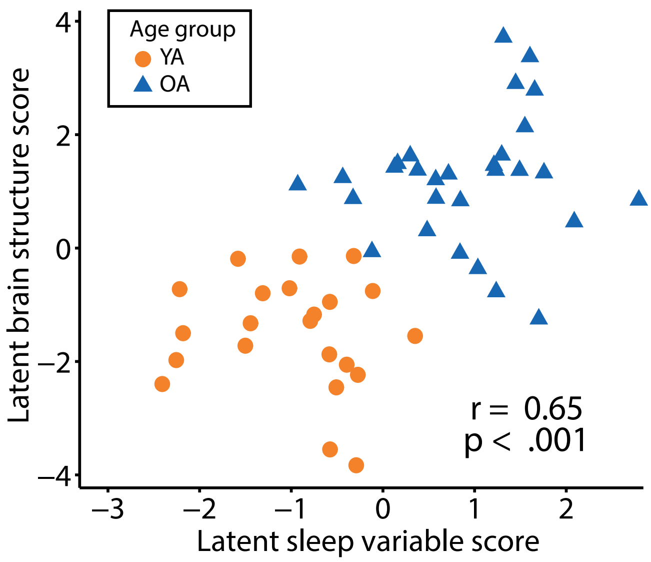
Supplementary Figures



Supplementary Figure 1. Trial numbers on Day 1 and Day 2. (a) Number of pairs with high, medium, and low memory quality during final cued recall on Day 1 (defined by the overall learning trajectory on Day 1). Lines represent single subjects. Note that younger adults (orange) studied 440 scene–word pairs, whereas older adults (blue) 280 pairs. (b) The number of trials during delayed retrieval on Day 2 is displayed for each memory quality condition (as defined by recall success on Day 1). Note the great inter-individual variability in trial numbers for each memory-quality condition on Day 2, which is caused by differential learning trajectories on Day 1. As in older adults all 280 studied pairs had to be recalled on Day 2, the numbers of Day 2 match those of Day 1. YA: younger adults, OA: older adults.



Supplementary Figure 2. Age differences in gray matter volume. Gray matter volume (quantified using voxel-based morphometry) in the extracted ROIs is consistently reduced in older (blue) compared to younger adults (orange). Asterisks mark p-values < .001 derived from non-parametric Mann-Whitney U tests comparing ROI volumes between younger and older adults. mPFC: medial prefrontal cortex, ROI: region of interest, YA: younger adults, OA: older adults.



Supplementary Figure 3. Latent variable association. Each participant's latent brain structure score is plotted against the latent sleep profile score. Spearman's rank-order correlation coefficient for the whole sample is displayed. YA: younger adults, OA: older adults.

Supplementary Analyses

Using Partial Least Squares Correlation (PLSC), within the manuscript we constructed two latent variables (i.e., a latent sleep profile and a latent brain structure profile) based on shared variance with chronological age. Below, we provide an alternative analysis based on traditional linear regression models. Here, we invert our initial research question by asking which indicators out of the set of sleep and brain variables considered relevant in the manuscript is most likely to explain inter-individual and age differences in memory maintenance of medium-quality memories – our main behavioral variable of interest.

Using hierarchical linear regression models, the behavioral outcome variable (i.e., memory maintenance of medium-quality memories) was predicted based on: each participant's chronological age, the four NREM sleep variables relative SWA, slow oscillation density, and slow and fast spindle density, as well as gray matter volume in four regions of interest (that is mPFC, thalamus, entorhinal cortex, and hippocampus).

To test for the amount of inter-individual variance in the behavioral outcome measure that is explained by age only, we first ran a regression that only included age as predictor variable.

$$\text{MaintenanceMediumQuality} \sim \text{Intercept} + \text{Age} \tag{1}$$

In a second step, we added all sleep and brain structure variables based on which we had defined the latent variables in the manuscript.

$$\begin{aligned}\text{MaintenanceMediumQuality} \sim \text{Intercept} &+ \text{Age} + \\ &\text{mPFC} + \text{Thalamus} + \text{EntorhinalCortex} + \text{Hippocampus} + \\ &\text{RelativeSWA} + \text{SODensity} + \text{SlowSpDensity} + \text{FastSpDensity}\end{aligned} \tag{2}$$

The analyses reveal that chronological age is a strong predictor of differences in memory maintenance ($t = -8.937$, $p < 0.001$; cf. Supplementary Analyses Table 1). Overall, chronological age can explain 60.7 % of inter-individual differences in the maintenance of medium-quality memories. Adding the sleep and brain variables improved the amount of explained variance ($F = 2.444$, $p < 0.029$, $R^2 = 0.681$). Yet, age remains a significant predictor even when simultaneously controlling for the influence of NREM sleep and brain structure ($t = -4.420$, $p < 0.001$; cf. Supplementary Analyses Table 2).

Altogether, these results indicate that the presence of slow oscillations, slow waves, slow and fast sleep spindles as well as the structural integrity in sleep- and memory-relevant brain regions does not account for the extent of observed age differences in memory consolidation. In line with the results displayed in Figure 3c and 4c, age remains the strongest predictor of memory consolidation.

Supplementary Analyses Table 1. Results of a linear regression model predicting the maintenance of medium-quality memories based on chronological age.

Predictor	Estimate	Standard error	t-value	p	F	df	p	adj. R^2
					79.87	1, 50	< 0.001	0.607
(Intercept)	1.055	0.038	27.751	< 0.001				
Age	–0.006	0.001	–8.937	< 0.001				

Note. Model formula is expressed in Equation (1). Statistically reliable estimates are printed in bold letters.

Supplementary Analyses Table 2. Results of a linear regression model predicting the maintenance of medium-quality memories based on chronological age, NREM sleep, and brain structure.

Predictor	Estimate	Standard error	t-value	p	F	df	p	adj. R^2
					13.1	9, 42	< 0.001	0.681
(Intercept)	1.324	0.338	3.914	< 0.001				
Age	-0.006	0.001	-4.420	< 0.001				
mPFC	-0.517	0.491	-1.053	0.299				
Thalamus	1.108	0.348	3.182	0.003				
EntorhinalCortex	-0.233	0.531	-0.438	0.664				
Hippocampus	-0.869	0.652	-1.333	0.19				
RelativeSWA	-0.094	0.187	-0.505	0.616				
SODensity	0.018	0.022	0.819	0.417				
SlowSpDensity	-0.119	0.048	-2.468	0.018				
FastSpDensity	0.080	0.031	2.593	0.013				

Note. Model formula is expressed in Equation (2). Statistically reliable estimates are printed in bold letters. mPFC: medial prefrontal cortex, SWA: slow-wave activity, SO: slow oscillation, Sp: spindle.