

**Supplemental material for Tamminen, J., Lambon Ralph, M. A., & Lewis, P. A. *The role of sleep spindles and slow-wave activity in integrating new information in semantic memory.***

Table S1. Novel words used in the study. Note that both lists were used in both semantic neighborhood conditions.

List 1	List 2
aggrood	ardoff
anniby	blontack
bochor	boumnet
chebbor	chisdow
criddin	cosmer
distap	daxon
erotron	dobbir
femmet	entelem
foostel	feckton
gittow	fevous
goolat	gahoon
heprit	glain
horrot	hoddit
jommer	horand
kerple	jabbary
loodit	konrith
luddilat	lanbir
mearton	lidgy
molbit	lupitat
onnith	meckalen
peckolet	milgium
poffren	ospont
quammish	pannetor
sluckmor	quellop
smetton	slethy
terum	somture
tobir	speth
uvar	tobbin
vilchy	velchur
vorent	volbor
vuckor	whadal
waba	wiblid

Table S2. Novel semantic concepts used in the dense and sparse semantic neighborhood conditions as meanings of novel words learned in the training phase (the word in bold determines the neighborhood density). Displayed also are the stimulus triplets used in the synonym judgment task: two semantic associates of the novel concept (words in bold) and two unassociated foils for each associate. One of the associates was used in Session 1 and the other in Session 2. The allocation of associates to sessions was counterbalanced. The associate used in Session 2 was always also used in Session 3.

Condition	Novel word meaning	Semantic associates (in bold) and foils (in italics)
<i>Dense</i>	<b>lobster</b> that is poisonous	<i>sea, bible, cow; shrimp, demon, partner</i>
	<b>fog</b> that appears in an instant	<i>mist, tissue, bridge; cloud, loop, bean hair, boar, writing; flesh, painting, trolley</i>
	<b>skin</b> that has never been sunburned	<i>glass, ground, tea; wine, lime, board wash, map, mouth; shower, slave, pin mud, plum, horn; lake, captain, napkin meat, gymnastic, tar; pork, joy, eagle war, twin, blood; rocket, heat, diner carrot, dollar, century; hare, village, stem</i>
	<b>bottle</b> that is unbreakable	<i>reptile, towel, coat; green, flower, lady</i>
	<b>soap</b> that has no smell	<i>cake, nude, island; pie, cellar, prince tree, limb, chest; forest, gift, barrel vacation, shadow, foot; camera, river, nurse</i>
	<b>swamp</b> where nothing can live	<i>death, hat, street; coffin, waste, rat city, roof, eel; leader, music, nose attack, point, spring; bite, glove, knob stone, dew, sick; statue, park, flea howl, lunch, ear; bear, battle, auditorium</i>
	<b>sausage</b> fed to cats	<i>party, aunt, sleep; ball, milk, fudge game, guard, smile; sport, church, young</i>
	<b>missile</b> that explodes in the air	<i>crawl, jury, cliff; beach, sky, lace broom, heart, football; magic, bay, palace</i>
	<b>rabbit</b> that eats meat	<i>leap, hollow, cotton; pond, mine, orange</i>
	<b>lizard</b> that lives in arctic areas	<i>moth, team, trail; caterpillar, hammock, hill</i>
	<b>pastry</b> that tastes sour	<i>vase, life, season; pot, holiday, leak artist, litter, day; brush, bed, steal work, passport, mirror; industry, ivy, wind</i>
	<b>jungle</b> where it rarely rains	<i>article, passion, granny; magazine, ceiling, branch</i>
	<b>tourist</b> that stays with a friend	<i>fishing, cook, breast; snake, tape,</i>
	<b>grave</b> where people are buried with their pets	
	<b>mayor</b> who works for free	
	<b>shark</b> that has no eyes	
	<b>marble</b> that is transparent	
	<b>wolf</b> that was born in a zoo	
	<b>balloon</b> filled with scented air	
	<b>referee</b> who works with amateur tennis players	
	<b>crab</b> that has a beak	
	<b>witch</b> who can travel in time	
	<b>frog</b> that has one leg only	
	<b>butterfly</b> that has furry wings	
	<b>clay</b> found at the bottom of the sea	
	<b>painter</b> who only paints in black and white	
	<b>factory</b> that makes toys	
	<b>newspaper</b> that is printed on blue paper	
	<b>worm</b> that can swim in water	

	<b>jewel</b> that has no value	register <b>diamond</b> , <i>tap, story</i> ; <b>gem</b> , <i>bulb, onion</i> <b>office</b> , <i>bucket, medicine</i> ; <b>desk</b> , <i>moon,</i> <i>pine</i>
	<b>secretary</b> who only works during holidays	<b>hen</b> , <i>kite, drug</i> ; <b>egg</b> , <i>uniform, drug</i>
	<b>chicken</b> that can fly long distances	
<i>Sparse</i>	<b>thread</b> used in sewing machines	<b>needle</b> , <i>hotel, reed</i> ; <b>string</b> , <i>face, slip</i> <b>gas</b> , <i>furniture, corpse</i> ; <b>power</b> , <i>write,</i> <i>beaver</i>
	<b>fuel</b> that doesn't pollute	<b>fur</b> , <i>men, shoe</i> ; <b>fox</b> , <i>cream, frame</i>
	<b>mink</b> that has been domesticated	<b>train</b> , <i>prison, chair</i> ; <b>track</b> , <i>dream, lens</i>
	<b>railroad</b> that runs in a tunnel underwater	<b>plane</b> , <i>lord, angel</i> ; <b>travel</b> , <i>beer, cross</i>
	<b>airport</b> located on small islands	<b>honey</b> , <i>body, court</i> ; <b>insect</b> , <i>kidney, jail</i>
	<b>bee</b> whose sting feels pleasant	<b>kitten</b> , <i>wrist, clothes</i> ; <b>dog</b> , <i>sister, dress</i>
	<b>puppy</b> that grows in the wild	<b>summer</b> , <i>woman, accident</i> ; <b>snow</b> , <i>clock, hammer</i>
	<b>winter</b> that lasts for only a few weeks	<b>horse</b> , <i>light, fan</i> ; <b>ride</b> , <i>pistol, bedroom</i>
	<b>pony</b> that can climb up mountains	<b>blade</b> , <i>sergeant, pocket</i> ; <b>shave</b> , <i>hoof,</i> <i>coin</i>
	<b>razor</b> that can't break the skin	<b>fish</b> , <i>coke, window</i> ; <b>gill</b> , <i>beard, mystery</i>
	<b>trout</b> that communicates by making sounds	<b>knife</b> , <i>sofa, beg</i> ; <b>paper</b> , <i>baron, touch</i>
	<b>scissors</b> that are safe for children to use	<b>dove</b> , <i>cattle, shirt</i> ; <b>wing</b> , <i>sale,</i> <i>policeman</i>
	<b>pigeon</b> that flies south in the winter	<b>food</b> , <i>patient, person</i> ; <b>dinner</b> , <i>nun,</i> <i>mast</i>
	<b>meal</b> consisting of sandwiches only	<b>teacher</b> , <i>throat, door</i> ; <b>student</b> , <i>sun,</i> <i>slope</i>
	<b>instructor</b> who specialises in distance learning	<b>marriage</b> , <i>bath, dummy</i> ; <b>wedding</b> , <i>wire, beef</i>
	<b>bride</b> who makes her own dress	<b>claw</b> , <i>soldier, rose</i> ; <b>mouse</b> , <i>nail, hay</i>
	<b>cat</b> that never goes indoors	<b>bird</b> , <i>coffee, phone</i> ; <b>nest</b> , <i>gym, gold</i>
	<b>robin</b> that has no feathers	<b>pencil</b> , <i>oil, uncle</i> ; <b>ink</b> , <i>floor, sleigh</i>
	<b>pen</b> that writes on any material	<b>leg</b> , <i>judge, cola</i> ; <b>hand</b> , <i>officer, pull</i>
	<b>arm</b> with poor blood circulation	<b>lightning</b> , <i>sand, profile</i> ; <b>rain</b> , <i>kiss, ring</i>
	<b>thunder</b> that is almost too quiet to be heard	<b>smoke</b> , <i>gravy, pig</i> ; <b>pipe</b> , <i>rock, road</i>
	<b>cigar</b> that can be used several times	<b>seat</b> , <i>art, till</i> ; <b>leather</b> , <i>goat, fat</i>
	<b>saddle</b> used on reindeer	<b>book</b> , <i>pickle, chip</i> ; <b>silence</b> , <i>bunch, gun</i>
	<b>library</b> that charges admission fees	<b>salt</b> , <i>casket, camp</i> ; <b>spice</b> , <i>earth, school</i>
	<b>pepper</b> that is used in Russian food	<b>ant</b> , <i>pool, gang</i> ; <b>spider</b> , <i>wharf, globe</i>
	<b>beetle</b> that lives inside wood	<b>teeth</b> , <i>crow, web</i> ; <b>doctor</b> , <i>van, bunny</i>
	<b>dentist</b> who is self-taught	<b>croak</b> , <i>rib, shell</i> ; <b>slime</b> , <i>hockey, human</i>
	<b>toad</b> that is the size of a football	<b>dirt</b> , <i>apron, sunset</i> ; <b>farm</b> , <i>wig, spasm</i>
	<b>soil</b> that is fertile only once in ten years	<b>novel</b> , <i>coach, cage</i> ; <b>poet</b> , <i>blanket,</i> <i>sheep</i>
	<b>author</b> who only uses a typewriter	<b>cry</b> , <i>cent, table</i> ; <b>child</b> , <i>daisy, machine</i>
	<b>infant</b> that was born premature	<b>king</b> , <i>disease, ape</i> ; <b>crown</b> , <i>tiger, soccer</i>
	<b>queen</b> who is elected	

Note: in the synonym judgment task, the foils unassociated with the novel word meaning were matched to the associated target words in frequency, imageability, and length (in number of letters).

Table S3. Psycholinguistic variables on which the novel word meanings in the different semantic neighborhood conditions were matched.

	NoA	Frequency	Imageability	Length
Dense	22.28	17.04	597.63	5.84
Sparse	5.53	17.33	596.28	5.41

Note: NoA = number of semantic associates

Table S4. Accuracy rates in the meaning matching and cued recall training tasks across the three training blocks ( $\pm$  standard error).

		Block 1	Block 2	Block 3
Meaning matching	Sparse-SN	67( $\pm 2$ )%	95( $\pm 1$ )%	96( $\pm 1$ )%
	Dense-SN	69( $\pm 2$ )%	94( $\pm 2$ )%	97( $\pm 1$ )%
Cued recall	Sparse-SN	33( $\pm 4$ )%	67( $\pm 4$ )%	79( $\pm 4$ )%
	Dense-SN	33( $\pm 5$ )%	68( $\pm 5$ )%	83( $\pm 4$ )%

We analyzed accuracy rates in two training tasks (meaning matching and cued recall) to ensure that difficulty of learning did not differ between the two semantic neighborhood conditions. We used ANOVAs over both participants ( $F_1$  or  $t_1$ ) and items ( $F_2$  or  $t_2$ ) with training block and semantic neighborhood condition as within-subjects factors. In meaning matching we discovered a main effect of block,  $F_1(2,46)=299.11$ ,  $p<.001$ ,  $F_2(2,124)=518.76$ ,  $p<.001$ , reflecting an increase in accuracy from block 1 to block 2,  $t_1(23)=-20.14$ ,  $p<.001$ ,  $t_2(63)=-26.15$ ,  $p<.001$ , and from block 2 to block 3,  $t_1(23)=-2.07$ ,  $p=.05$ ,  $t_2(63)=-4.43$ ,  $p<.001$ . No other main effects or interactions reached significance.

In cued recall we found a main effect of block,  $F_1(2,46)=348.68$ ,  $p<.001$ ,  $F_2(2,124)=656.40$ ,  $p<.001$ , reflecting an increase in accuracy from block 1 to block 2,  $t_1(23)=-20.03$ ,  $p<.001$ ,  $t_2(63)=-28.34$ ,  $p<.001$ , and from block 2 to block 3,  $t_1(23)=-8.59$ ,  $p<.001$ ,  $t_2(63)=-11.98$ ,  $p<.001$ . No other main effects or interactions reached significance. These data suggest that participants did not find learning one neighborhood condition more difficult than the other.

Table S5. Error rates (percentage errors) in the test tasks ( $\pm$  standard error).

		Session 1	Session 2	Session 3
Animacy	Sparse-SN	16 ( $\pm 2$ )%	12 ( $\pm 2$ )%	17 ( $\pm 2$ )%
	Dense-SN	15 ( $\pm 3$ )%	13 ( $\pm 2$ )%	20 ( $\pm 3$ )%
Synonym	Sparse-SN	10 ( $\pm 2$ )%	11 ( $\pm 2$ )%	15 ( $\pm 2$ )%
	Dense-SN	18 ( $\pm 2$ )%	12 ( $\pm 2$ )%	19 ( $\pm 3$ )%
Reading	Sparse-SN	5 ( $\pm 2$ )%	3 ( $\pm 1$ )%	2 ( $\pm 1$ )%
	Dense-SN	4 ( $\pm 2$ )%	4 ( $\pm 2$ )%	3 ( $\pm 1$ )%
PDM	Sparse-SN	2 ( $\pm 1$ )%	1 ( $\pm 0.5$ )%	1 ( $\pm 0.5$ )%
	Dense-SN	3 ( $\pm 1$ )%	2 ( $\pm 1$ )%	1 ( $\pm 0.3$ )%

Error rates in the four test tasks were analyzed using ANOVAs and post hoc t-test by participants ( $F_1$  or  $t_1$ ) and by items ( $F_2$  or  $t_2$ ). In the animacy decision task we found a main effect of time  $F_1(2,46)=8.67, p=.001, F_2(2,124)=11.58, p<.001$ , reflecting increasing error rates from S2 to S3,  $t_1(23)=3.63, p=.001, t_2(63)=4.94, p<.001$ . No other main effects or interactions reached significance.

In the synonym judgment task we found a main effect of time  $F_1(2,46)=6.23, p=.004, F_2(2,124)=11.65, p<.001$ , a main effect of semantic neighborhood,  $F_1(1,23)=6.08, p=.02, F_2(1,62)=4.87, p=.03$ , and an interaction between the two,  $F_1(2,46)=3.92, p=.03, F_2(2,124)=4.31, p=.02$ . Planned contrasts showed a difference between the neighborhood conditions in S1 only,  $t_1(23)=-5.39, p<.001, t_2(62)=3.15, p=.003$ .

The reading aloud task showed a main effect of time  $F_1(2,46)=6.64, p=.003, F_2(2,124)=8.53, p<.001$ , reflecting decreasing error rates from S1 to S2,  $t_1(23)=-2.95, p=.007, t_2(63)=-2.50, p=.02$ . No other effects reached significance.

In the progressive demasking (PDM) task there was a main effect of time  $F_1(2,46)=3.39, p=.03, F_2(2,124)=23.43, p<.001$ , reflecting decreasing error rates from S1 to S3,  $t_1(23)=-2.84, p=.009, t_2(63)=-6.90, p<.001$ . No other effects reached significance.

Table S6a. Statistical analyses (ANOVA) of behavioral tasks, analysis over participants as reported in the main text, and analysis over items.

Task	Main effect of session	Main effect of neighborhood	Session x neighborhood interaction
Free recall	$F_1(2,46)=17.08, p<.001$ $F_2(2,124)=29.41, p<.001$	ns	ns
Meaning recall	$F_1(2,46)=124.46, p<.001$ $F_2(2,124)=237.10, p<.001$	ns	ns
Animacy decision	$F_1(2,46)=47.76, p<.001$ $F_2(2,124)=96.06, p<.001$	ns	$F_1(2,46)=3.23, p=.05^\dagger$ $F_2(2,124)=4.29, p=.02$
Synonym judgment	$F_1(2,46)=18.70, p<.001$ $F_2(2,124)=36.33, p<.001$	$F_1(1,23)=15.49, p=.001$ $F_2(1,62)=15.82, p<.001$	ns
Reading aloud	$F_1(2,46)=10.82, p<.001$ $F_2(2,124)=103.51, p<.001$	$F_1(1,23)=5.52, p=.03$ $F_2(1,62)=5.98, p=.02$	ns
PDM	$F_1(2,46)=101.59, p<.001$ $F_2(2,124)=512.81, p<.001$	ns	$F_1(2,46)=3.86, p=.03$ $F_2(2,124)=6.53, p=.002$

Notes:  $F_1$ =ANOVA over subjects,  $F_2$ =ANOVA over items (word meanings), ns=not significant, PDM=progressive demasking.  $^\dagger$ Greenhouse-Geisser corrected  $p=.06$

Table S6b. Planned comparisons in the behavioral tasks, analysis over participants as reported in the main text, and analysis over items.

Task	S1-S2 change	S2-S3 change	Difference between neighborhood conditions
Free recall		$t_1(23)=4.91, p<.001$ $t_2(63)=7.45, p<.001$	
Meaning recall		$t_1(23)=11.82, p<.001$ $t_2(63)=20.04, p<.001$	
Animacy decision	Sparse-SN: $t_1(23)=3.88, p=.001$ $t_2(31)=4.83, p<.001$  Dense-SN: $t_1(23)=5.75, p<.001$ $t_2(31)=7.66, p<.001$	Sparse-SN: $t_1(23)=5.07, p<.001$ $t_2(31)=7.10, p<.001$	Session 3 (other sessions ns): $t_1(23)=2.45, p=.02$ $t_2(62)=2.42, p=.02$
Synonym judgment	$t_1(23)=3.46, p=.002$ $t_2(63)=4.83, p<.001$		
Reading aloud	$t_1(23)=4.52, p<.001,$ $t_2(63)=11.35, p<.001$		
PDM	Sparse-SN: $t_1(23)=8.64, p=.001$ $t_2(31)=13.95, p<.001$  Dense-SN: $t_1(23)=9.98, p<.001$ $t_2(31)=13.63, p<.001$	Sparse-SN: $t_1(23)=4.52, p<.001$ $t_2(31)=9.75, p<.001$  Dense-SN: $t_1(23)=2.80, p=.01$ $t_2(31)=5.70, p<.001$	

Notes:  $t_1$ =t-test over subjects,  $t_2$ =t-test over items (word meanings). PDM=progressive demasking.

Table S7. Correlation between change in reaction times overnight and percentage of time spent in different sleep stages in the dense semantic neighborhood condition. *P*-values are uncorrected for multiple comparisons.

	Stage 1	Stage 2	SWS	REM
Free recall	$r=0.31, p=.16$	$r=-0.09, p=.69$	$r=0.08, p=.74$	$r=-0.12, p=.59$
Meaning recall	$r=-0.06, p=.81$	$r=-0.22, p=.34$	$r=0.03, p=.91$	$r=0.30, p=.18$
Animacy decision	$r=-0.05, p=.83$	$r=-0.31, p=.17$	$r=0.28, p=.20$	$r=0.11, p=.64$
Synonym judgment	$r=-0.02, p=.92$	$r=-0.26, p=.25$	$r=-0.08, p=.72$	$r=-0.46, p=.03$
Reading aloud	$r=-0.37, p=.09$	$r=-0.06, p=.80$	$r=0.05, p=.84$	$r=0.20, p=.36$
PDM	$r=-0.21, p=.36$	$r=-0.28, p=.22$	$r=0.33, p=.14$	$r=0.08, p=.71$

Note: SWS = slow wave sleep. REM = rapid eye movement sleep.

Table S8. Correlation between change in reaction times overnight and percentage of time spent in different sleep stages in the sparse semantic neighborhood condition. *P*-values are uncorrected for multiple comparisons.

	Stage 1	Stage 2	SWS	REM
Free recall	$r=0.20, p=.36$	$r=-0.03, p=.90$	$r=-0.27, p=.23$	$r=0.22, p=.34$
Meaning recall	$r=-0.16, p=.48$	$r=0.36, p=.10$	$r=-0.17, p=.46$	$r=-0.24, p=.27$
Animacy decision	$r=-0.16, p=.48$	$r=0.23, p=.31$	$r=-0.007, p=.98$	$r=-0.25, p=.26$
Synonym judgment	$r=0.09, p=.69$	$r=0.06, p=.79$	$r=-0.07, p=.78$	$r=-0.08, p=.73$
Reading aloud	$r=-0.09, p=.70$	$r=0.15, p=.49$	$r=-0.28, p=.22$	$r=-0.24, p=.29$
PDM	$r=-0.20, p=.36$	$r=-0.19, p=.93$	$r=0.42, p=.06$	$r=-0.32, p=.15$

Note: SWS = slow wave sleep. REM = rapid eye movement sleep.

Table S9. Correlation between change in reaction times overnight and spindle density in both semantic neighborhood conditions. *P*-values are uncorrected for multiple comparisons.

	Dense	Sparse
Free recall	$r=-0.14, p=.60$	$r=-0.41, p=.10$
Meaning recall	$r=0.13, p=.61$	$r=-0.12, p=.66$
Animacy decision	$r=-0.29, p=.25$	$r=0.50, p=.04$
Synonym judgment	$r=-0.08, p=.76$	$r=-0.36, p=.16$
Reading aloud	$r=0.09, p=.74$	$r=0.37, p=.15$
PDM	$r=-0.003, p=.99$	$r=0.20, p=.45$