

The direction of theta and alpha travelling waves modulates human memory processing

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Video S1: Example traveling wave (TW) on a trial where memory encoding was successful. *Animation of a TW in patient 34 during successful encoding (Related to Figure 2). Animation includes filtered signals during trial, local directions indicated on brain map, single arrow of mean direction across electrodes, and topography of TWs phase over time. Single arrow indicating mean direction across electrodes is visible when wave is reliable.*

Video S2: Example traveling wave (TW) on a trial where memory encoding was unsuccessful. *Data from patient 34. Same format as Supp. Video S1.*

Region	Patients	Surface Electrodes	Electrodes in oscillation clusters	Oscillatory Range	# clusters	# clusters with TWs	# nondirectional clusters	# unidirectional clusters	# bidirectional clusters	# memory related bidirectional clusters
ENCODING										
Frontal	76	2583	1913							
				Theta	95	77	19	11	47	30
				Alpha	22	19	6	1	12	9
				Beta	98	75	20	7	48	36
Temporal	73	1810	1220							
				Theta	36	31	7	4	20	15
				Alpha	35	30	8	6	16	12
				Beta	45	39	17	5	17	12
Parietal/ Occipital	77	1527	1209							
				Theta	35	30	7	2	21	12
				Alpha	28	19	2	3	14	8
				Beta	44	39	11	1	27	17
RECALL										
Frontal	81	2906	2142							
				Theta	99	84	30	10	44	22
				Alpha	22	20	8	2	10	6
				Beta	104	85	31	8	47	31
Temporal	76	1874	1350							
				Theta	33	30	6	6	19	6
				Alpha	41	37	10	8	19	9
				Beta	44	38	23	5	10	6
Parietal/ Occipital	81	1338	1328							
				Theta	41	34	11	5	18	9
				Alpha	29	19	5	2	12	5
				Beta	45	40	17	1	22	11

Table S1: Prevalence of traveling waves by brain region. *The numbers in the left column of this table indicate the total number of participants with surface grid and strip electrodes in each region, the number of individual surface electrodes located in each region, and the number of those electrodes that were identified as being part of at least one oscillation cluster. For each combination of region and oscillatory range, we measured the number of oscillation clusters, the number of those clusters with TWs, and then categorized them by their directional patterns: nondirectional, unidirectional, and bidirectional. Lastly, we report the number of bidirectional clusters in each category that showed significant memory effects. Rows denote combinations of brain region and oscillatory frequency range, separately during memory encoding and recall. Columns denote the category of each TW clusters.*

Participant ID	Sex	Age	Handedness	Surface electrode coverage	Traveling waves	Mean recall rate
1	F	48	Right	LF (10), LO (5), LP (8), LT (9), RF (9), RO (2), RP (12), RT (11)	RP (7.6), LP (8.0), LP (14.0)	19.2
2	F	49	Right	LF (18), LT (9), RF (16), RT (12)	LF (19.4), LF (21.3), LF (8.0), RF (19.8)	39
3	F	39	Ambidextrous	LF (50), LO (1), LP (14), LT (27)	LF (19.6), LT (8.3), LP (16.8), LF (5.2), LT (11.0), LF (5.8)	33.2
4	F	51	Right	LF(65), LP(15), RP(2)	LF(5.4), LF(16.6), LF(17.9), LF(13.6)	4.3
13	F	36	Right	LT(3), LP(8), LO(7)	RP(9.4), RP(21.1)	26.7
16	F	31	Right	LF(73), LT(4), LP(17), RF(30)	LF(6.2), LF(16.4), RF(6.2), RF(17.6), RF(13.3)	28.2
18	M	47	Left	LF(22), LT(10), LP(14), LO(4), RF(19), RT(12), RP(11), RO(6)	LF(4.7), LF(20.6), RF(4.6), RF(4.6), RT(9.7), LF(4.3), RF(20.0), RT(8.4), RF(18.1)	22.3
20	F	49	Left	RF (32), RO (12), RP (8), RT (29)	RF(14.7), RO(13.7), RT(16.2), RT(6.7), RT(8.9), RP(11.8)	38
21	M	38	Right	LF(12.0), LT(6), LP(6), RF(8), RT(10), RP(6)	LF(23.8), RF(6.1), RF(23.2), RT(4.2)	28.7
24	F	36	Right	RF(9), RT(19), RP(40), RO(30)	RP(9.3), RP(17.6), RP(8.6)	47
26	F	25	Right	LO (18), LP (29), LT (4)	LP (5.4), LO (17.5), LP (10.6), LP(20.9); LP(13.6), LP(23.7)	22.7; 33.3
32	F	20	Right	LF (6), LP (2), LT (8), RF (4), RP(6), RT (6)	LF(8.4), RP(7.9); LF(7.6), RT(15.8), RP(7.3)	31.7; 27.7
33	F	32	Right	LF (6), LP (3), LT (7), RF (8), RO (2), RP (2), RT (12)	RF(22.6), LF(23.1), RT(20.4)	21.3
34	F	29	Ambidextrous	LF(61.0), LT(10.0), LP(2.0), RF(6.0), RP(2)	LT(9.0), LP(8.7), LP(17.9), LF(5.7), RP(10.1), LF(14.4), LP(24.9)	9.1
36	M	49	Right	LF (20), LO (1), LP (22), LT (35)	LT (6.0); LT(7.4), LT(17.2)	16.3; 26.1
39	F	28	Right	RF(62.0), RT(13.0), RP(25.0)	RF(4.7), RF(28.7), RP(7.4), RF(13.6); RF(27.0), RF(4.4), RF(6.9), RF(12.6), RF(4.0), RP(7.6)	22.2; 27.8
41	M	34	Right	LF(50), LT(1), LP(1), RF(29), RT(1), RP(6)	RF(5.9), LF(5.7), RF(13.4), LF(14.4), LF(4.5)	7.8
42	F	28	Left	RF (21), RP (24), RT (27)	RP(8.6), RP(4.8), RF(18.4); RP(8.3), RF(18.3), RT(13.0), RF(4.9), RT(13.2)	63; 54.2
45	M	51	Right	LF (21), LP (3), LT (11), RF (5), RP (1), RT (6)	LF(8.3), LF(23.7), LF(6.8), RF(7.8); LF(7.4), LF(21.5), LF(6.6)	32.7; 40.5
50	M	20	Right	LF (6), LP (35), LT (23)	LP (7.0), LP (16.2); LP(7.1), LP(17.1)	42; 45.8
51	F	25	Right	LF (15), LP (9), RF (8), RP (14), RO(2)	LF (19.3), RP (14.2), LF (5.4), RP (3.4)	39.6
53	F	39	Right	RF (27), RP (9), RT (27)	RF(15.7), RF(6.5)	17.8
60	F	37	Right	RF (35), RP (5), RT (21)	RT(8.6), RT(16.7), RF(6.7), RF(21.4), RF(18.5); RT(7.5), RT(15.9), RF(7.0), RF(18.8)	30.4; 41.7
66	M	39	Right	LO (1), LP (8), LT (11), RF (5), RT (9), RO (1)	RF(8.1), RT(10.3); LP(8.9)	33.2; 25.7
67	F	45	Right	LF(43), LT(33), LP(15), RF(2), RT(4), RP(1)	LF(6.4), LF(26.5), LT(16.7), LF(10.0), LT(12.8)	20.3
68	F	39	Ambidextrous	RO(11), RP (17), RT (31)	RT(17.7), RT(15.4)	52
69	M	27	Right	LF(46), LP(34), LT(7), LO(1)	LF(15.6), LF(4.8), LP(7.3), LF(21.9), LP(5.8), LP(10.6); LF(19.0), LF(5.1), LP(7.8), LP(11.3), LP(8.7)	28.7; 49.3
75	M	50	Right	LF(49.0), LP(6), RF(39), RT(7), RP(12)	LF(5.9), RF(22.5), RF(5.9), LF(24.5), LF(22.8), RF(6.1), RF(23.1), RF(18.6); RF(6.0), LF(5.7), RF(24.4), LF(27.8), LF(26.1), RF(26.7), RF(5.7)	25; 33.7
76	M	30	Right	LF(32), RF(1), RP(8)	LF(5.8), LF(18.9), RP(5.8), LF(11.8), RP(17.1)	25.7
81	F	33	Right	LF(37), LP(13), RF(30), RP(10)	RF(6.3), LP(9.1), LF(6.2), LF(8.2), LP(20.6), RF(8.5), RF(10.3), RP(17.1), LF(5.9)	30.8
83	F	49	Right	LT(18), LP(3), LO(5)	LO(13.0), LT(8.0); LT(8.0)	22.4; 6
84	M	25	Right	LF(40), LT(2), LP(41), RF(3)	LF(5.4), LF(20.7), LP(8.6)	17.7
86	M	21	Left	LF(29), LT(39), LP(2), LO(1), RF(3)	LF(20.8), LF(5.9); LF(6.0)	30; 12
89	M	36	Left	LF(2), LT(6), RF(26), RT(37), RP(26)	RP (7.7), RP(18.9); RP(7.7), RF(21.0), RP(8.6)	16; 17
93	M	29	Right	LF(16), LT(15), RF(16), RT(29), RO(2)	LF(5.2), RT(8.5), RT(18.2), RF(5.6)	28.7
98	F	38	Right	LF(5), RF(64)	RF(5.8), RF(18.6), RF(4.6), RF(34.2), LF(5.6)	24.6
102	M	35	Right	LF(12), LP (6), LT (12), RF (10), RT (11)	LF(20.4), RF(5.8), RF(20.0), LF(5.8), RT(3.5), LF(5.9), LP(7.1); RF(20.5), RF(5.9), LF(21.0)	25.3; 31.9
104	M	22	Right	RF (49), RP (21), RT (22)	RF(6.3), RF(26.6), RP(19.5)	31.3
111	M	20	Right	LT(40), LP(38), LO(10)	LT(8.6), LT(18.3), LP(6.9), LT(22.7)	57.9
112	F	30	Right	LF (3), RF (17), RO (1), RP (1), T (24)	RT(7.0); RF(7.4), RT(16.6)	12.7; 19.4
118	M	33	Right	LF(22), LT(44), LP(10), LO(7)	LT(22.6), LF(6.6), LF(21.0), LT(6.4), LT(12.9), LF(21.6), LT(26.8), LT(8.1)	17.8
119	F	26	Left	LF(45), LT(30), LP(32), LO(1), RF(11), RO(1)	LF(20.6), LT(10.9), LF(5.6), RF(19.8), RF(5.5)	8.9
120	F	33	Left	LT(11), LP(8), RF(3), RT(2), RP(10), RO(4)	RP(6.2), LT(7.6), RP(14.5)	34.5
127	F	40	Right	LT(5), RF(17), RT(5), RP(2)	RF(6.8), RF(18.8); RP(7.0), RP(18.4), RP(13.8), RF(20.7), RF(27.6)	25.7; 21.7
128	M	26	Right	RF (10), RP (8), RT (6)	RF (6.7)	47

Table S2: Participant Table: Verbal Memory Task Each row summarizes an individual patient's sex, age, handedness, clinical electrode coverage of surface grid and strip electrodes, frequency and regional properties of clusters with TWs, and memory performance. The "Surface electrode coverage" column denotes the hemisphere, region, and number of surface electrodes in the region. The "Traveling waves" column denotes the hemisphere and region where the majority of electrodes in the cluster were located. The mean frequency of oscillations for the cluster is in parentheses. Region Key: F, frontal; T, temporal; O, occipital; P, parietal. All traveling wave and recall rates in blue were calculated during the version of the task with semantic categorizations of words while those written in black are for the uncategorized version of the verbal memory task.

Participant ID	Sex	Age	Handedness	Surface electrode coverage	Traveling waves	Mean recall rate
129	F	35	Right	LF (30), LOther (10), LP (4), RF (29), RP (2), Rother (2)	LF(13.4), RF(13.3), LF(4.5), RF(4.0), LF(14.8), LF(4.9)	17.5
130	M	57	Right	LF (42), LP (30), RF (8)	LF(5.6), LF(11.0), LF(19.2), RF(5.3), LP(4.2), LP(11.7); LF(5.4), LF(20.5), LF(9.9), RF(5.3), RF(9.1)	19.6; 27.5
135	M	48	Right	RF(15), RO (5), RP (8), RT (7)	RF(23.4), RF(4.5), RF(12.8); RF(5.2), RF(25.2), RO(9.0)	8.9; 14.7
136	F	57	Right	LF (23), LT (4), LO (1), LP (7), LT (34), RF (1), RT (18)	LT (8.3), LT (18.7), RT (7.6), RT (16.2)	19.8
142	F	44	Left	LF (13), RF(47), RP (2), RT (18)	LF(10.9), RF(5.5), RF(11.0), LF(5.3), RT(15.0), RF(10.3), RT(5.7)	16
144	M	53	Right	RF(21),RT(3),RP(6)	RF(22.7), RF(9.8)	37.9
147	M	48	Right	LF (32), LO (6), LP (28), LT (41), RF (1)	LT (20.0), LT (6.3), LT (10.1), LP (13.6); LT(6.6), LF(20.3), LT(14.0), LT(10.9), LT(3.4)	18.1; 20.3
149	F	28	Right	LF(18), LP (5), LT (39)	LT(8.8), LT(19.3), LF(23.4), LT(4.6)	21.3
151	M	36	Right	LF(9), LP(4), LT (7)	LP (7.6), LP (18)	27.5
154	F	36	Right	LF(20), LP (4), LT (40)	LT (11.4), LF (22.9), LT (17.8), LT (4.5), LP (21.8)	30.1
155	M	37	Right	LF (43), RF (23), RP (22), RT(1), RP(5)	LF(5.0), LF(16.1), RP(5.0), RP(14.5), RF(17.0), RF(4.8), RF(5.1)	27.5
156	M	27	Right	LF(42),LP(2),RF(61),RT(8),RP(7)	RF(21.1), LF(19.9), RF(6.9), RP(9.2), RF(8.8)	21.3
159	F	43	Right	LF (38), LP(14), LT(34), RF (9), RP(2), RT (10)	LF(21.2), LT(8.0), LP(10.7), LT(15.5), RF(4.9), RT(7.2)	23.8
162	F	31	Right	RF (11), RO (3), RP (6), RT (23)	RT(7.8), RT(17.4), RF(8.2), RF(5.3), RF(19.3), RP(4.9)	25.7
164	M	37	Right	LF(10),LT(5),LP(5)	LF(6.1)	18.3
167	M	33	Right	LF (20), LO (1), LP (4), LT (42), RF (1)	LT(8.0), LT(21.2), LF(7.9), LF(19.6); LT(8.7), LT(22.4), LF(7.9), LF(17.4), LT(5.2), LF(20.7), LT(9.0)	44.6; 51.7
172	F	22	Right	RF(10), RP (2), RT (12)	RF (22.7)	19.3
175	M	34	Right	LT (17), RF (29), RO (1), RP (26), RT (19)	RF(6.0), RP(15.8), LT(6.2), RT(13.9), RF(19.1), LT(14.4), LT(6.2)	22.7
177	F	23	Right	LF(21),LT(31),LP(27),LO(1)	LT(18.3), LT(6.3), LP(7.9), LP(10.3)	24
184	M	42	Right	RF (6), RO (4), RP (25), RT (13)	RP(5.8), RP(15.6); RP(5.6), RP(15.5), RP(19.8), RT(11.6)	25.5; 28.4
185	M	20	Right	LF(55),LT(50),LP(2),LO(2),RF(5)	LT(5.8), LT(9.4), LT(4.2), LF(6.6), LT(4.8), LT(22.5), LF(30.4)	33.3
186	M	28	NONE	LP (3), LT(8), RF (32), RP (29), RT (31)	RF(6.3), RF(20.0), RP(14.0), RT(9.4), LT(17.8); RP(17.2), RF(7.1), RF(20.7)	8.3; 11.5
187	F	52	Right	LF(56),LT(11),LP(32),LO(1),RF(1)	LF(16.0), LP(7.7); LF(16.8), LP(8.0), LF(3.7)	13; 24.4
190	F	57	Right	LF(31),LT(34),LP(18),RF(11),RT(9)	LT(7.3), LT(17.5), RF(7.1), RT(18.7), RT(8.0), LF(4.2), RF(19.4)	15.7
195	M	44	Right	LF (11), LP (8), LT(7), RF(13), RP (5)	RF(24.7), RF(9.4), LP(21.5), LF(14.7), RP(20.1), LT(7.9), LT(24.7)	30.4
196	M	19	Left	LF (30), LO (1), LP (28), LT (11)	LP(7.2), LP(19.1), LT(21.6), LT(6.8)	37.3
201	M	37	Right	LO(1), RF (17), RO (10), RP (29), RT (33)	RP(10.8), RP(15.8), RF(21.0); RP(10.2), RT(21.7), RP(14.5)	23; 38.3
202	F	30	Right	LF (4), RF(14), RO (7), RP (6), RT (32)	RT(11.2), RT(20.3), RO(24.2); RT(20.3), RT(11.4), RF(5.4)	18.8; 30.8
212	M	46	Right	LF(2),RF(44),RT(15),RP(13)	RF(19.4), RT(10.1), RF(5.2)	12.8
215	F	51	Right	LF (16), LT (30)	LT(7.9), LT(16.9); LT(7.4), LT(16.6)	24.3; 21.7
221	M	57	Right	LF (41), LT (38), LP (18), RF (1), RP (1)	LT(14.9), LF(22.1), LT(8.4), LF(17.7), LF(10.7), LP(13.0); LF(20.0), LT(8.9), LP(15.8)	30; 27.6
222	F	21	Right	LF(57),LT(16),LP(8),RF(11)	LF(20.0), LF(5.6), LF(8.8), LT(5.6), RF(18.5); LF(20.3), LF(5.8)	27.2; 30.2
223	F	42	Right	LF(19),LT(7),LP(1)	LF(19.2)	15.9
226	F	42	Right	LF (31), LP (8), LT (35)	LF(22.3), LT(9.1), LF(5.2)	25.6
232	M	28	Ambidextrous	LF (12), LP (13), LT(17), RF (12), RP (12), RT (14)	LF(6.0), LP(15.6), RP(6.2), RT(15.9)	47
234	M	25	Right	LF (2), LP (5), LT (49), RT (24)	LT (13.7), LT (3.9), RT (13.9), LT (22.4), LT (6.2), RT (3.7)	25.5
235	M	48	Left	LF(6),RF(12),RP(12),RO(6)	RO(19.0)	10.8
250	M	30	NONE	LF (1), LO (4), LP (8), RF (11), RO (27), RP (48), RT (20)	RP(20.2), RP(6.6), RP(12.2), LP(12.2), LP(20.4), LP(6.7), RO(5.3), RP(12.6)	45.7
251	M	31	Left	RF(11),RT(30),RP(11)	RT(9.0), RT(18.3)	42.9
254	M	29	Right	LF(35),LT(12),LP(17)	LF(7.3), LF(21.5), LP(20.1)	14
260	F	57	Right	LF (28), LT (45), LO (4), LP (18)	LT(9.7), LT(19.7), LT(3.6); LT(10.6), LT(20.8), LT(4.0)	25.4; 27.8
291	M	35	Right	LF (23), LP (22), LT (31)	LT(6.8), LT(20.3); LF(6.8), LT(20.4)	35.7; 53.7
302	M	48	Right	LF(8),LT(46),LP(18),LO(6)	LP(8.4), LT(5.9), LT(8.7), LT(11.8), LP(19.0); LO(7.7), LT(5.9)	14.9; 21.2
304	F	33	Right	LF(5),RF(45)	RF(7.4), RF(6.6)	5.4
309	F	22	Right	RF(24),RT(43),RP(23),RO(2)	RP(6.4), RF(6.2), RP(15.3)	36.2
317	M	36	Right	LF(9),LT(33),LP(22),LO(4)	LP(7.6), LT(18.7), LP(20.2)	37.5
318	M	26	Right	LF(55),LT(1),RF(38),RP(6)	LF(5.4), RF(5.8), LF(29.0), RP(5.2), RF(26.7), LF(5.9)	48.1
339	M	29	Left	RF(6)	RF(5.3), RF(14.0)	16.8

Table S2: Participant Table: Verbal Memory Task (continued)

Oscillatory Range	Wave directional consistency across trials			Local directional consistency across electrodes (Planarity)			Wave strength (R ²)			Narrowband power (normalized by removing 1/f background from log(power) spectra)			Propagation phase velocity (m/s)			Spatial wavelength (cm)		
	S	U	T stat, P value	S	U	T stat, P value	S	U	T stat, P value	S	U	T stat, P value	S	U	T stat, P value	S	U	T stat, P value
Frontal																		
Theta	0.15	0.11	t = 10.28, p < 10 ⁻¹⁶	0.34	0.34	t = 0.57, p = 0.57	0.51	0.51	t = -1.8, p = 0.08	1.5	1.51	t = -2.37, p = 0.02	0.51	0.51	t = 0.53, p = 0.6	25.37	25.24	t = 1.03, p = 0.31
Alpha	0.15	0.11	t = 7.55, p < 10 ⁻⁵	0.4	0.4	t = -1.81, p = 0.08	0.51	0.51	t = 0.56, p = 0.58	1.45	1.45	t = 1.09, p = 0.29	0.91	0.92	t = -1.26, p = 0.23	23.35	23.5	t = -1.08, p = 0.29
Beta	0.12	0.08	t = 9.92, p < 10 ⁻¹⁵	0.36	0.36	t = -0.56, p = 0.58	0.51	0.51	t = -0.04, p = 0.97	1.26	1.27	t = -1.67, p = 0.1	1.6	1.59	t = 0.67, p = 0.51	23.26	23.24	t = 0.22, p = 0.83
Temporal																		
Theta	0.2	0.17	t = 4.62, p < 10 ⁻⁴	0.34	0.34	t = 0.35, p = 0.73	0.52	0.52	t = 0.44, p = 0.66	1.78	1.78	t = -1.18, p = 0.24	0.66	0.66	t = -0.98, p = 0.34	26.91	26.92	t = -0.09, p = 0.93
Alpha	0.15	0.11	t = 5.44, p < 10 ⁻⁵	0.33	0.33	t = -1.22, p = 0.23	0.49	0.49	t = -1.01, p = 0.32	1.58	1.58	t = -2.27, p = 0.03	0.90	0.91	t = -0.93, p = 0.37	25.03	24.96	t = 0.93, p = 0.36
Beta	0.11	0.08	t = 5.45, p < 10 ⁻⁵	0.35	0.35	t = 0.24, p = 0.81	0.45	0.45	t = -1.46, p = 0.15	1.4	1.4	t = -0.07, p = 0.94	1.45	1.45	t = 0.15, p = 0.88	21.61	21.63	t = -0.39, p = 0.7
Parietal/Occipital																		
Theta	0.16	0.14	t = 3.94, p < 10 ⁻⁵	0.37	0.37	t = -1.26, p = 0.21	0.48	0.49	t = -0.91, p = 0.37	1.45	1.45	t = -2.65, p = 0.01	0.58	0.59	t = -0.73, p = 0.47	25.02	25.26	t = -2.37, p = 0.02
Alpha	0.16	0.14	t = 4.87, p < 10 ⁻⁴	0.44	0.44	t = -0.87, p = 0.39	0.51	0.51	t = -0.75, p = 0.46	1.49	1.5	t = -0.98, p = 0.33	1.17	1.16	t = 0.18, p = 0.86	29.66	29.56	t = 0.56, p = 0.58
Beta	0.12	0.08	t = 6.16, p < 10 ⁻⁵	0.36	0.36	t = -1.84, p = 0.07	0.44	0.44	t = 0.71, p = 0.48	1.33	1.33	t = -1.64, p = 0.11	1.3	1.31	t = -1.02, p = 0.32	22.35	22.37	t = -0.25, p = 0.81

Table S3: Relation between memory encoding and traveling wave characteristics. Rows denote each combination of region and oscillatory range. Each group of columns shows the relation between memory and the following TW features: wave directional consistency across trials, local directional consistency within a wave (measured across electrodes), wave strength, narrowband power, propagation phase velocity, and spatial wavelength. Within each group, columns "S" and "U" indicate the mean value of each traveling-wave characteristic (see Methods) on trials with successfully and unsuccessfully encoding, respectively. We measured the statistical significance across clusters with TWs with two-sided paired t-tests.

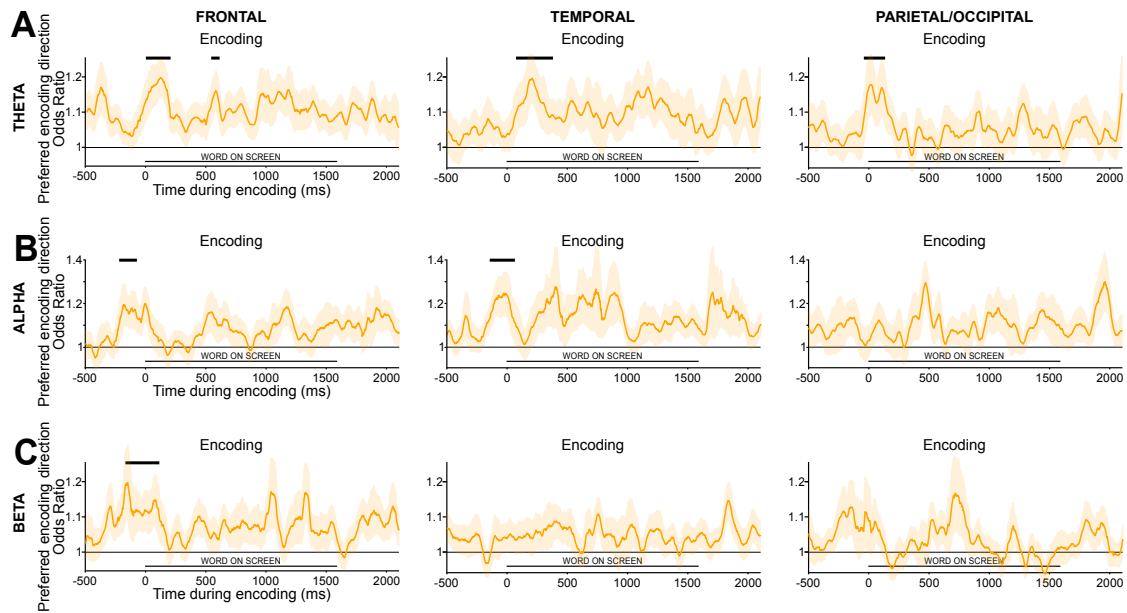


Figure S1: Timecourse of odds ratio during encoding comparing trials when waves are going in preferred encoding vs recall directions (A) Timecourse of odds ratio of recall rates comparing encoding trials when TWs propagate toward or away from clusters' preferred encoding direction for all theta TWs measured on oscillation clusters in the Frontal, Temporal, and Parietal/Occipital regions during memory encoding (top). Horizontal black lines and shading indicate timing of statistical significance at $p < 0.05$ using two-sided cluster-based permutation testing, with the position at top or bottom of the plot indicating the direction of the effect. Error bands denote ± 1 SEM. **(B)** Same as (A) for alpha-band TWs **(C)** Same as (A) for beta-band TWs

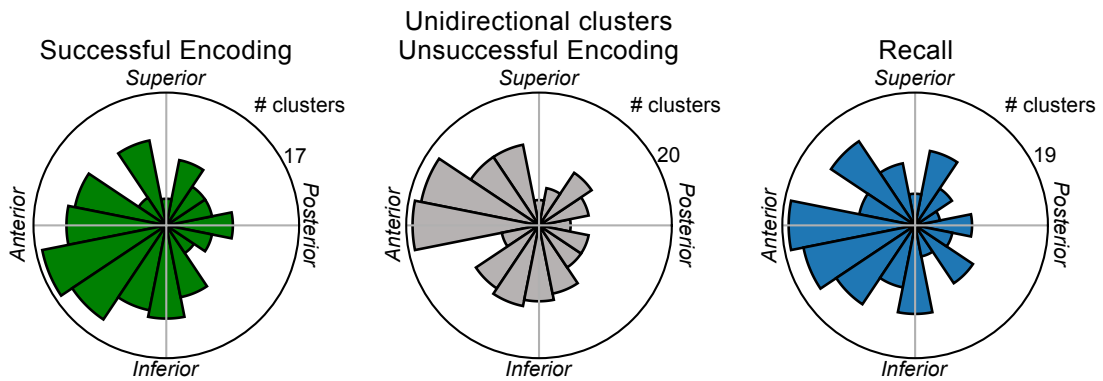


Figure S2: Mean propagation directions of unidirectional clusters. Mean propagation directions measured during successful encoding (left) and unsuccessful encoding (center) and prior to verbal word recall (right) for the clusters labeled as unidirectional. A direct comparison showed that the propagation directions of unidirectional clusters did not significantly differ between successful encoding, unsuccessful encoding, and recall phases (Circular Kruskal–Wallis test: non parametric multi-sample test for equal medians, successful vs unsuccessful encoding: $z = 3.42$, $p = 0.064$; successful encoding vs recall : $z = 0.57$, $p = 0.45$; unsuccessful encoding vs recall : $z = 0.50$, $p = 0.48$).

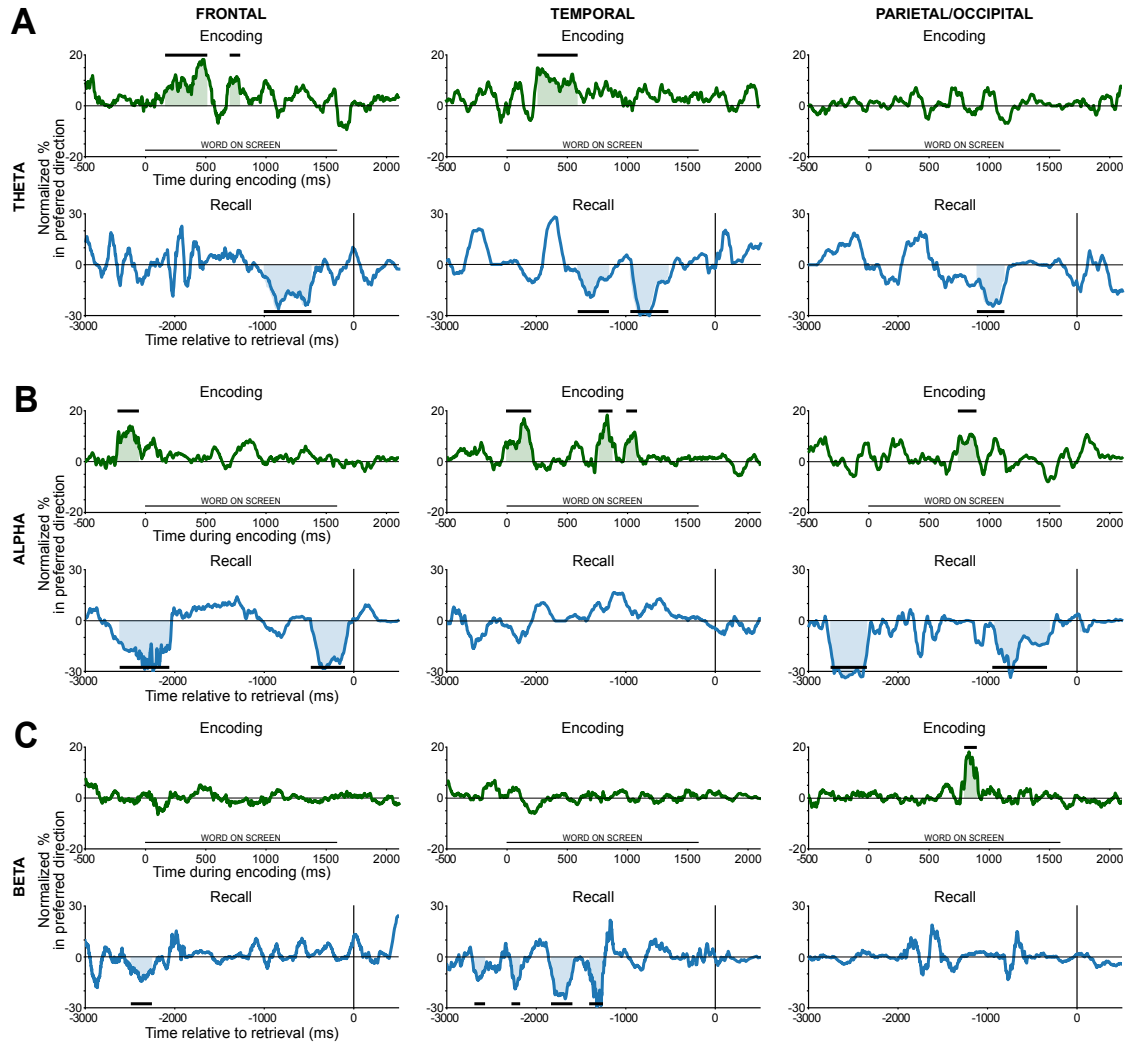


Figure S3: Timecourse of TW direction shifts during memory encoding and recall (A) *Timecourse of TW direction shifts toward or away from clusters' preferred encoding direction for all theta TWs measured on oscillation clusters in the Frontal, Temporal, and Parietal/Occipital regions during memory encoding (top) and recall (bottom). Horizontal black lines and shading indicate timing of statistical significance at $p < 0.05$ using two-sided cluster-based permutation testing, with the position at top or bottom of the plot indicating the direction of the effect. (B)* *Same as (A) for alpha-band TWs (C)* *Same as (A) for beta-band TWs*