## Supplementary materials for: High-level cognition during story listening is reflected in high-order dynamic correlations in neural activity patterns

Lucy L. W. Owen<sup>1</sup>, Thomas H. Chang<sup>1,2</sup>, and Jeremy R. Manning<sup>1,†</sup>

<sup>1</sup>Department of Psychological and Brain Sciences,

Dartmouth College, Hanover, NH

<sup>2</sup>Amazon.com, Seattle, WA

<sup>†</sup>Address correspondence to jeremy.r.manning@dartmouth.edu

November 20, 2020

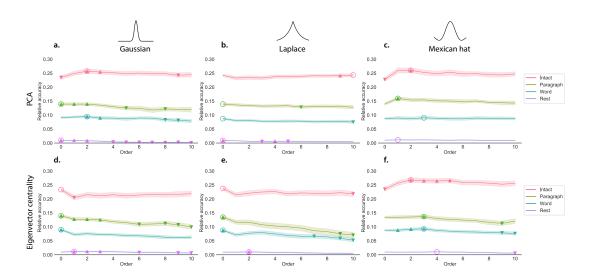


Figure S1: Across-participant timepoint decoding accuracy varies with correlation order and cognitive engagement across kernels. a.-c. Timepoint decoding accuracy as a function of order: PCA. Order (x-axis) refers to the maximum order of dynamic correlations that were available to the classifiers (see Feature weighting and testing). The reported across-participant decoding accuracies for **a.** Gaussian, **b.** Laplace, and **c.** Mexican hat kernels are averaged over all widths (see Identifying robust decoding results). The y-values are displayed relative to chance accuracy (intact:  $\frac{1}{300}$ ; paragraph:  $\frac{1}{272}$ ; word:  $\frac{1}{300}$ ; rest:  $\frac{1}{400}$ ). The error ribbons denote 95% confidence intervals across cross-validation folds (i.e., random assignments of participants to the training and test sets). The colors denote the experimental condition. Arrows denote sets of features that yielded reliably higher (upwards facing) or lower (downward facing) decoding accuracy than the mean of all other features (via a two-tailed test, thresholded at p < 0.05). The circled values represent the maximum decoding accuracy within each experimental condition. Panels a.-c. used PCA to project each high-dimensional pattern of dynamic correlations onto a lower-dimensional space. **d.-f. Timepoint decoding accuracy as a function of order: eigenvector centrality.** This panel is in the same format as Panel a.-c., but here eigenvector centrality has been used to project the high-dimensional patterns of dynamic correlations onto a lower-dimensional space.

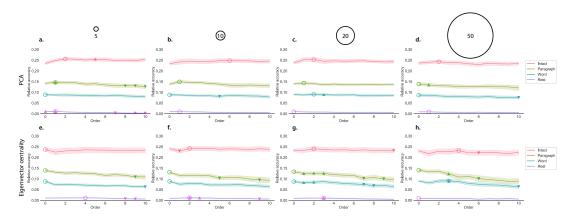
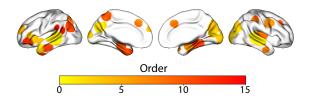
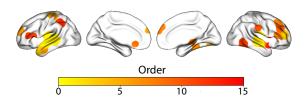


Figure S2: Across-participant timepoint decoding accuracy varies with correlation order and cognitive engagement across widths. a.-d. Timepoint decoding accuracy as a function of order: PCA. Order (x-axis) refers to the maximum order of dynamic correlations that were available to the classifiers (see Feature weighting and testing). The reported across-participant decoding accuracies for a. 5, b. 10, c. 20, and d. 50 are averaged over all kernel shapes (see Identifying robust decoding results). The y-values are displayed relative to chance accuracy (intact:  $\frac{1}{300}$ : paragraph:  $\frac{1}{272}$ ; word:  $\frac{1}{300}$ : rest:  $\frac{1}{400}$ ). The error ribbons denote 95% confidence intervals across cross-validation folds (i.e., random assignments of participants to the training and test sets). The colors denote the experimental condition. Arrows denote sets of features that yielded reliably higher (upwards facing) or lower (downward facing) decoding accuracy than the mean of all other features (via a two-tailed test, thresholded at p < 0.05). The circled values represent the maximum decoding accuracy within each experimental condition. Panels a.-d. used PCA to project each high-dimensional pattern of dynamic correlations onto a lower-dimensional space.e.-h. Timepoint decoding accuracy as a function of order: eigenvector centrality. This panel is in the same format as Panel a.-d., but here eigenvector centrality has been used to project the high-dimensional patterns of dynamic correlations onto a lower-dimensional space.



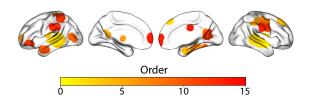
Order 1	Order 2	Order 3	Order 4	Order 5
voice speech superior temporal listening temporal gyrus sts speech perception spoken superior temporal sulcus	voice precuneus temporal speaker temporal gyrus spoken heard sounds comprehension speech perception	cuneus v1 visual early visual lingual gyrus occiplital lingual visual cortex integrate	anterior insula insula inferior inferior frontal insula executive inferior frontal pole frontal gyrus asd	integrate spatially anterior hippocampus occipital recollection orbital hippocampal visual stream visual cortex visual
Order 6	Order 7	Order 8	Order 9	Order 10
putamen face ffa ffa subsequent fusiform face images selective basal ganglia ganglia basal	hippocampal hippocampus amygdala hippocampu anterior hippocampus medial temporal parahippocampal mtl temporal lobe parahippocampal corte lobe	s fusiform face face ffa ffa faces fusiform gyrus	monitoring error conflict task frontal cortex read errors insula anterior color demands	posterior insula insular extrastriate insular cortex lateral occipital letter occipital visual painful insula
Order 11	Order 12	Order 13	Order 14	Order 15
memory encoding subsequent hippocampus hippocampal associative memory lobe mtl mtl retrieval episodic		parahippocampal navigation objects parahippocampal cortex parahippocampal gyrus anterior hippocampus encoding memory encoding fusiform face ffa	inferior frontal inferior words pseudowords frontal gyrus semantic reading chinese word orthographic	motor task sensorimotor cortex contralateral hand sensorimotor finger primary spatially tapping index finger

**Figure S3: Top terms associated with the endpoints of the strongest correlations for the** *intact* **experimental condition.** Each color corresponds to one order of inter-subject functional correlations. The inflated brain plots display the locations of the endpoints of the 10 strongest (absolute value) correlations at each order, projected onto the cortical surface (Combrisson et al., 2019). The lists of terms display the top 10 Neurosynth terms (Rubin et al., 2017) decoded from the corresponding brain maps for each order. (Also see Fig. 7, top row, in the main text.)



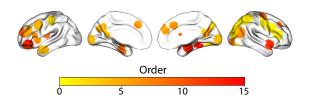
Order 1	Order 2	Order 3	Order 4	Order 5
sounds auditory cortex listening auditory listened auditory stimuli speech primary auditory sound acoustic	voice precuneus temporal speaker temporal gyrus spoken heard sounds comprehension speech perception	auditory cortex sound sounds auditory heschl gyrus heschl acoustic gyrus stg planum listened	gyri temporo posterior temporal posterior middle temporo parietal visual stream secondary somatosensory insular verb temporal gyri	occipital extrastriate visual reaching objects arm dlpfc incorrect occipital gyrus index finger
Order 6	Order 7	Order 8	Order 9	Order 10
anterior temporal mental states lateral temporal tom pole temporal pole comprehension virtual mind tom pa	fusiform object memory encoding fusiform gyrus fusiform gyrus venral visual faces reaching arahippocampal gyrus objects	ventrolateral fusiform gyrus inferior frontal inferior fusiform intentions pfc cognitive impairmen semantic mild cognitive		prefrontal prefrontal cortex dorsolateral prefrontal cortex precuneus precuneus posterior medial dorsolateral precuneus dorsomedial prefrontal medial prefrontal
Order 11	Order 12	Order 13	Order 14	Order 15
tactile secondary somatosensory precuneus somatosensory cortex pain temporo parietal primary somatosensory somatosensory somatosensory cortices precuneus posterior	ifg / gyrus ifg viewing angular gyrus v5 angular motion social interaction visual temporo parietal	inferior parietal parietal lobule working memory ipl working anterior intraparieta parietal cortex frontoparietal fronto parietal posterior parietal	musical anterior superior superior temporal listening spoken I music comprehension voice speech frontal operculum	tom mind tom temporal medial temporal sulcus dorsomedial prefrontal theory mind sts dorsomedial medial prefrontal

Figure S4: Top terms associated with the endpoints of the strongest correlations for the *paragraph* experimental condition. This figure is in the same format as Figure S3, but displays results for the paragraph-scrambled story listening condition. (Also see Fig. 7, second row, in the main text.)



Order 1	Order 2	Order 3	Order 4	Order 5
listening	voice	temporal gyrus	anterior temporal	mild cognitive
speech	temporal gyrus	voice	expression	memory
voive sounds	sounds listening	superior temporal temporal sulcus	lateral temporal temporal lobes	medial temporal lobe
speeck perception	speech	speaker	lobes	mtl
spoiken	spoken	sts	temporal lobe	retrieval
listened	audisotry	speech	fearful faces	episodic
audiory	superior temporal	listening	temporal	temporal lobe
superior temporal	listened	spoken	lobe	lobe mtl
temporal gyrus	speech perception	superior	neutral faces	episodic memory
Order 6	Order 7	Order 8	Order 9	Order 10
inferior parietal	anterior temporal	parahippocampal	face	extrastriate
default mode	amygdala insula	episodic	fusiform face	occipitotemporal cortex
default	expression	parahippocampal gyrus	face ffa	occipitotemporal
inhibition	amygdala	hippocampus	ffa	videos
pcc	anterior prefrontal	hippocampal	fusiform	v5
posterior cingulate response inhibition	neutral faces temporal lobbe	memory medial temporal	faces	visual mt
medial	anxiety	anterior hippocampus	fusiform gyrus reaching	perception
autobiographical	fearful faces	episodic memory	occipital	fusiform
dmn	amygdala responses		face recognition	objects
Onder 11	0.412	O. J 12	Out at 14	Onder 15
Order 11	Order 12	Order 13	Order 14	Order 15
primary somatosensory		reaching	locations	medial
premotor	medial	retrosplenial	precuneus	posterior cingulate
anterior temporal	anterior temporal	visuomotor	body	pcc modial profrontal
somatosensory premotor cortex	prefrontal cortex prefrontal	tools precuneus	supramarginal videos	medial prefrontal cortex precuneus
inferior parietal	semantic memory	videos	actions	referential
s1	negative positive	touch	mt	self referential
ventral premotor	mpfc	cortex precuneus	video clips	cortex posterior
execution	autobiographical	navigation	video	autobiographical
somatosensory cortex	temporal lobe	retrosplenial cortex	occipitotemporal	hippocampus

**Figure S5: Top terms associated with the endpoints of the strongest correlations for the** *word* **experimental condition.** This figure is in the same format as Figure S3, but displays results for the word-scrambled story listening condition. (Also see Fig. 7, third row, in the main text.)



Order 1	Order 2	Order 3	Order 4	Order 5
cortex parietal intraparietal parietal cortex ips posterior parietal parietal intraparietal sulcus symbbolic superior parietal prefrontal parietal	occipital visual etrastriate vision occipital cortex visual cortex visual stream motion v1 mt	parietal conflict task visual cortex working memory supplementary moto working arithmetic supplementary anterior temporal a	early visual mental imagery	dorsolateral frontal middle frontal motion mt verbal memory visual motion dorsolateral prefrontal vision
Order 6	Order 7	Order 8	Order 9	Order 10
locations navigation medial medial prefrontal orienting precuneus memory retrieval location retrieval dorsomedial	insual anterior error anterior insula monitoring insula conflict frontal cortex insular taste errors	occipital precuneus letter inferior occipital visual cortex precuneus occipital cortex lateral occipital spatially sulcus	posterior insula temporal lobe mtl amygdala responses lobe mtl insula lobe mild cognitive insular cognitive impairment	inferior occipital anterior prefrontal face selective face ffa dlpfc ffa fusiform face dorsolateral cortex dlpfc
Order 11	Order 12	Order 13	Order 14	Order 15
hippocampal hippocampus anterior hippocampus lobe c amygdala hippocampus n parahippocampal gyrus mtl medial temporal temporal lobe lobe mtl	food ofc cortex ofc orbitofrontal cortex sucleus accumbes accumbes orbitofrontal value orbital hypothalamus	insula taste insular insular cortex unpleasant pleasant amygdala amygdala insula posterior insula pain	amygdala hippocampus hippocampal hippocampus anterior hippocampus medial temporal amygdala parahippocampal navigation unpleasant episodic	s1 striatal outcomes monetary memory encoding accumbens mesolimbic nucleus accumbens frontal money

**Figure S6: Top terms associated with the endpoints of the strongest correlations for the** *rest* **experimental condition.** This figure is in the same format as Figure S3, but displays results for the resting state condition. (Also see Fig. 7, bottom row, in the main text.)

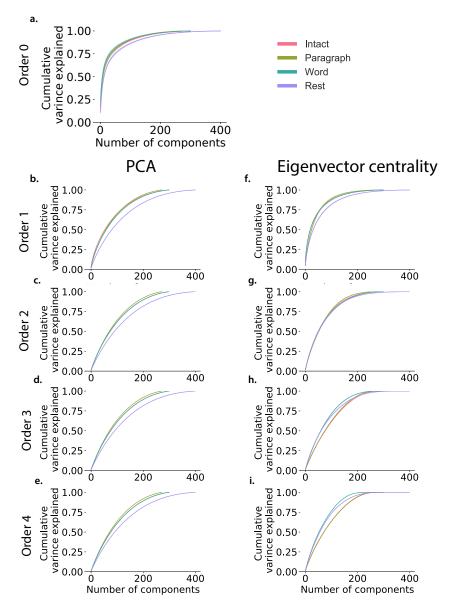


Figure S7: Cumulative percent variance explained as a function of the number of principle components for correlation orders and reduction types. *Order* refers to the order of the dynamic correlations calculated. Principle components analysis was performed, and reduced independently for each subject. Maximum number of components varies with the total time for each condition (intact: 300; paragraph: 272; word: 300; rest: 400). a. Cumlative percent variance as a function of number of components for Order 0. PCA was performed on the raw actitivity patterns (Order 0). b.-e. Cumlative percent variance as a function of number of components for Orders 1.-4.: PCA Dynamic correlation were calculated for orders 1-4 using PCA to project each high-dimensional pattern of dynamic correlations onto a lower-dimensional space. f.-i. Cumlative percent variance as a function of number of components for Orders 1.-4.: eigenvector centrality. These panels arer in the same format as Panel b.-e., but here eigenvector centrality has been used to project the high-dimensional patterns of dynamic correlations onto a lower-dimensional space.

## Supplementary references

Combrisson, E., Vallat, R., O'Reilly, C., Jas, M., Pascarella, A., 1 Saive, A., Thiery, T., Meunier, D., Altukhov, D., Lajnef, T., Ruby, P., Guillot, A., and Jerbi, K. (2019). Visbrain: a multipurpose GPU-accelerated open-source suite for multimodal brain data visualization. *Frontiers in Neuroinformatics*, 13(14):1–14.

Rubin, T. N., Kyoejo, O., Gorgolewski, K. J., Jones, M. N., Poldrack, R. A., and Yarkoni, T. (2017). Decoding brain activity using a large-scale probabilistic functional-anatomical atlas of human cognition. *PLoS Computational Biology*, 13(10):e1005649.