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

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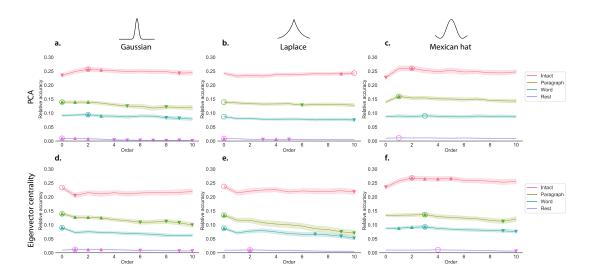


Figure S1: Across-participant timepoint decoding accuracy varies with correlation order and cognitive engagement across kernels. a.-c. Timepoint decoding accuracy as a function of order: PCA. Order (x-axis) refers to the maximum order of dynamic correlations that were available to the classifiers (see Feature weighting and testing). The reported across-participant decoding accuracies for **a.** Gaussian, **b.** Laplace, and **c.** Mexican hat kernel shapes 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 (upward facing) or lower (downward facing) decoding accuracy than the mean of all other features (via a two-tailed t-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.** These panels are in the same format as Panel a.-c., but here eigenvector centrality has been used to project the high-dimensional patterns of dynamic correlations into lower-dimensional spaces.

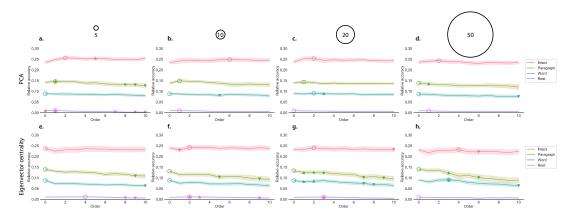


Figure S2: Across-participant timepoint decoding accuracy varies with correlation order and cognitive engagement across widths. a.-d. Timepoint decoding accuracy as a function of order: PCA. *Order* (*x*-axis) refers to the maximum order of dynamic correlations that were available to the classifiers (see *Feature weighting and testing*). The reported across-participant decoding accuracies for kernel widths of **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 (upward facing) or lower (downward facing) decoding accuracy than the mean of all other features (via a two-tailed *t*-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.** These panels are in the same format as Panel a.-d., but here eigenvector centrality has been used to project the high-dimensional patterns of dynamic correlations into lower-dimensional spaces.

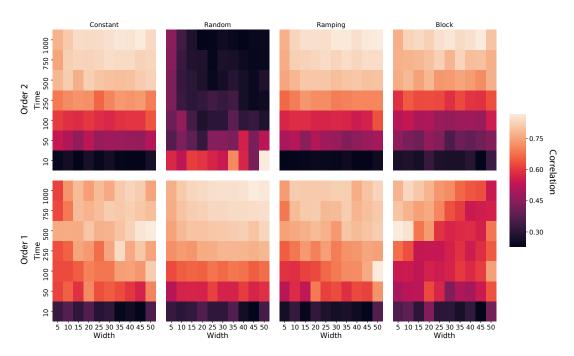


Figure S3: Recovery heatmap of simulated first-order and second-order dynamic correlations across time and widths. Each panel displays a heatmap of the average correlations between the vectorized upper triangles of the recovered first-order and second-order correlation matrices and the true (simulated) first-order and second order correlation matrices. The averages are taken across several randomly generated synthetic datasets for each timeseries pattern (constant, random, ramping, and data; see *Synthetic data: simulating dynamic higher-order correlations*). The *x*-axes of each heatmap denote varying Laplace-shaped kernel widths (see Figs. S1 and S2), and the *y*-axes of each heatmap denote varying durations (in samples) of the synthetic datasets. A total of 10 synthetic datasets were generated for each duration (row) and timeseries pattern (panel).

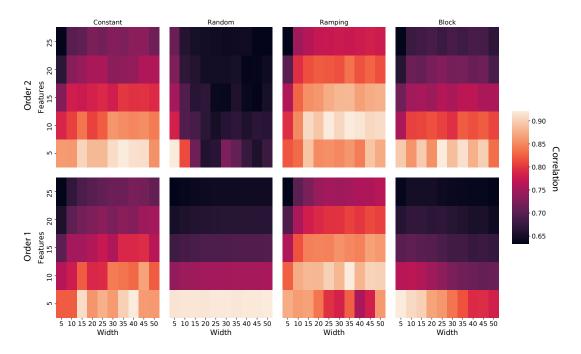
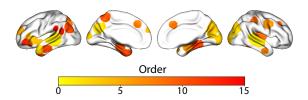
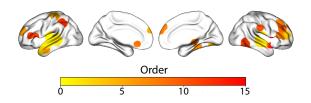


Figure S4: Recovery heatmap of simulated first-order and second-order dynamic correlations across features and widths. Each panel displays a heatmap of the average correlations between the vectorized upper triangles of the recovered first-order and second-order correlation matrices and the true (simulated) first-order and second order correlation matrices. The averages are taken across several randomly generated synthetic datasets for each timeseries pattern (constant, random, ramping, and data; see *Synthetic data: simulating dynamic higher-order correlations*). The *x*-axes of each heatmap denote varying Laplace-shaped kernel widths (see Figs. S1 and S2), and the *y*-axes of each heatmap denote varying numbers of features (*K*) used in each of the synthetic datasets. A total of 10 synthetic datasets were generated for each number of features (row) and timeseries pattern (panel).



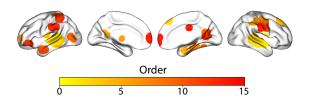
| Order 1 | Order 2 | Order 3 | Order 4 | Order 5 |
|--|--|--|--|--|
| voice speech superior temporal listening temporal gyrus sts speech perception spoken superior temporal sulcus | voice precuneus temporal speaker temporal gyrus spoken heard sounds comprehension speech perception | cuneus v1 visual 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 S5: Top terms associated with the most strongly correlated nodes at each order, 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. 6, top row, in the main text.)



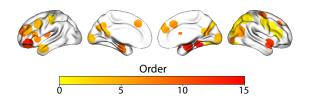
| Order 1 | Order 2 | Order 3 | Order 4 | Order 5 |
|---|---|---|--|--|
| sounds auditory cortex listening auditory listened auditory stimuli speech primary auditory sound acoustic | voice precuneus temporal speaker temporal gyrus spoken heard sounds comprehension speech perception | auditory cortex 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 dipfc 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 theory of mind | 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 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 S6: Top terms associated with the most strongly correlated nodes at each order, for the *paragraph* experimental condition. This figure is in the same format as Figure S5, but displays results for the paragraph-scrambled story listening condition. (Also see Fig. 6, second row, in the main text.)



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

Figure S7: Top terms associated with the most strongly correlated nodes at each order, for the *word* **experimental condition.** This figure is in the same format as Figure S5, but displays results for the word-scrambled story listening condition. (Also see Fig. 6, 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 S8: Top terms associated with the most strongly correlated nodes at each order, for the *rest* **experimental condition.** This figure is in the same format as Figure S5, but displays results for the resting state condition. (Also see Fig. 6, bottom row, in the main text.)

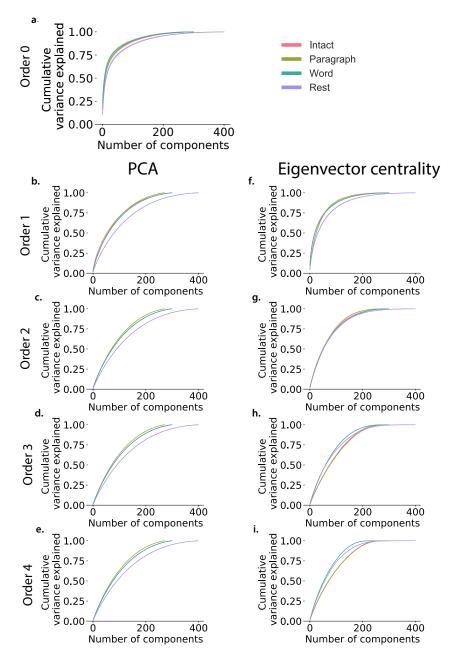


Figure S9: Cumulative percent variance explained as a function of the number of principle components. Order refers to the order of the dynamic correlations calculated. Principle components analysis was performed, and reduced independently for each subject. Maximum number of components varies with the total time for each condition (intact: 300; paragraph: 272; word: 300; rest: 400). a. Cumulative percent variance as a function of number of components for Order 0. PCA was performed on the raw activity 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 are 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.