

1 High-level cognition is supported by at least second order
2 dynamic correlations in neural activity patterns

3 Lucy L. W. Owen¹, Thomas H. Chang^{1,2}, and Jeremy R. Manning^{1,†}

¹Department of Psychological and Brain Sciences,
Dartmouth College, Hanover, NH

³Amazon.com, Seattle, WA

†Address correspondence to jeremy.r.manning@dartmouth.edu

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5 **Abstract**

6 Our thoughts arise from coordinated patterns of interactions between brain structures that change
7 with our ongoing experiences. High-order dynamic correlations in brain activity patterns reflect different
8 subgraphs of the brain’s connectome that display homologous lower-level dynamic correlations. We tested
9 the hypothesis that high-level cognition is supported by high-order dynamic correlations in brain activity
10 patterns. We developed an approach to estimating high-order dynamic correlations in timeseries data,
11 and we applied the approach to neuroimaging data collected as human participants either listened to a
12 ten-minute story or a temporally scrambled version of the story, or underwent a resting state scan. We
13 trained across-participants pattern classifiers to decode (in held-out data) when in the session each activity
14 snapshot was collected. We found that classifiers trained to decode from high-order dynamic correlations
15 yielded better performance on data collected as participants listened to the (unscrambled) story. By
16 contrast, classifiers trained to decode data from scrambled versions of the story or during the resting
17 state scan yielded the best performance when they were trained using first-order dynamic correlations
18 or raw activity patterns. We suggest that as our thoughts become more complex, they are supported by
19 higher-order patterns of dynamic network interactions throughout the brain.

20 **Introduction**

21 A central goal in cognitive neuroscience is to elucidate the *neural code*: the mapping between (a) mental
22 states or cognitive representations and (b) neural activity patterns. One means of testing models of the
23 neural code is to ask how accurately that model is able to “translate” neural activity patterns into known
24 (or hypothesized) mental states or cognitive representations (e.g., Haxby et al., 2001; Huth et al., 2016, 2012;
25 Kamitani & Tong, 2005; Mitchell et al., 2008; Nishimoto et al., 2011; Norman et al., 2006; Pereira et al., 2018;
26 Tong & Pratte, 2012). Training decoding models on different types of neural features can also help to elucidate
27 which specific aspects of neural activity patterns are informative about cognition– and, by extension, which
28 types of neural activity patterns might comprise the neural code. For example, prior work has used region
29 of interest analyses to estimate the anatomical locations of specific neural representations (e.g., Etzel et al.,
30 2009), or to compare the relative contributions to the neural code of multivariate activity patterns versus

31 patterns of dynamic correlations between neural activity patterns (e.g., Fong et al., 2019; Manning et al.,
32 2018). An emerging theme in this literature is that cognition is mediated by complex dynamic interactions
33 between brain structures (Bassett et al., 2006; Demertzi et al., 2019; Sporns & Honey, 2006; Turk-Browne,
34 2013).

35 Studies of the neural code to date have primarily focused on univariate or multivariate neural pat-
36 terns (for review see , NormEtal06) or (more recently) on patterns of dynamic first-order correlations (i.e.,
37 interactions between pairs of brain structures; Fong et al., 2019; Manning et al., 2018). We wondered what
38 the future of this line of work might hold. For example, is the neural code mediated by higher-order
39 interactions between brain structures? Second-order correlations reflect *homologous* patterns of correlation.
40 In other words, if the changing patterns of correlations between two regions, *A* and *B*, are similar to those
41 between two other regions, *C* and *D*, this would be reflected in the second-order correlations between (*A*-*B*)
42 and (*C*-*D*). In this way, second-order correlations identify similarities and differences between subgraphs
43 of the brain’s connectome. Analogously, third-order correlations reflect homologies between second-order
44 correlations– i.e., homologous patterns of homologous interactions between brain regions. More generally,
45 higher-order correlations reflect homologies between patterns of lower-order correlations. We can then ask:
46 which “orders” of interaction are most reflective of high-level cognitive processes?

47 Another central question pertains to the extent to which the neural code is carried by activity patterns
48 that directly reflect ongoing cognition (e.g., following Haxby et al., 2001; Norman et al., 2006), versus the
49 dynamic properties of the network structure itself, independent of specific activity patterns in any given set
50 of regions (e.g., following Bassett et al., 2006). For example, graph theoretic measures such as centrality and
51 degree (Bullmore & Sporns, 2009) may be used to estimate how a given brain structure is “communicating”
52 with other structures, independently of the specific neural representations carried by those structures. If
53 one considers a brain region’s graph theoretic position in the network (e.g., its eigenvector centrality) as a
54 dynamic property, one can compare how the positions of different regions are correlated, and/or how those
55 patterns of correlations change over time. We can also compute higher-order patterns in these correlations
56 to characterize homologous subgraphs in the connectome that display similar changes in their constituent
57 brain structures’ interactions with the rest of the brain.

58 To gain insights into the above aspects of the neural code, we developed a computational framework
59 for estimating dynamic high-order correlations in timeseries data. This framework provides an important
60 advance, in that it enables us to examine patterns in higher-order correlations that are computationally
61 intractable to estimate via conventional methods. Given a multivariate timeseries, our framework provides
62 timepoint-by-timepoint estimates of the first-order correlations, second-order correlations, and so on (up to
63 tenth-order correlations in this manuscript). Our approach combines a kernel-based method for computing

64 dynamic correlations in timeseries data with a dimensionality reduction step that projects the resulting dy-
65 namic correlations into a low-dimensional space. We explored two dimensionality reduction approaches:
66 principle components analysis (PCA; Pearson, 1901), which preserves an approximately invertable transfor-
67 mation back to the original data; and a second non-invertible algorithm that explored patterns in eigenvector
68 centrality (Landau, 1895). This latter approach characterizes correlations between each feature dimension's
69 relative *position* in the network in favor of the specific activity histories of different features.

70 We validated our approach using synthetic data where the underlying correlations were known. We
71 then applied our framework to a neuroimaging dataset collected as 125 participants listened to either an
72 audio recording of a ten-minute story or a temporally scrambled version of the story, or underwent a resting
73 state scan (Simony et al., 2016). We used a subset of the data to train across-participant classifiers to decode
74 listening times using a blend of neural features (comprising neural activity patterns, as well as different
75 orders of correlations between those patterns that were inferred using our computational framework).
76 We found that both the PCA-based and eigenvector centrality-based approaches yielded neural patterns
77 that could be used to decode accurately. Both approaches also yielded the best decoding accuracy for
78 data collected during (intact) story listening when high-order (PCA: second-order; eigenvector centrality:
79 fourth-order) dynamic correlation patterns were included as features. When we trained classifiers on the
80 scrambled stories or resting state data, only lower-order dynamic patterns were informative to the decoders.
81 Taken together, our results indicate that high-level cognition is supported by high-order dynamic patterns
82 of communication between brain structures.

83 Methods

84 Our general approach to comprises four general steps. First, we derive a kernel-based approach to comput-
85 ing dynamic pairwise correlations in a T (timepoints) by K (features) multivariate timeseries, \mathbf{X}_0 . This yields
86 a T by $O(K^2)$ matrix of dynamic correlations, \mathbf{Y}_1 , where each row comprises the upper triangle of the corre-
87 lation matrix at a single timepoint, reshaped into a row vector (this reshaped vector is $(\frac{K^2-K}{2})$ -dimensional).
88 Second, we apply a dimensionality reduction step to project the matrix of dynamic correlations back onto
89 a K -dimensional space. This yields a T by K matrix, \mathbf{X}_1 , that reflects an approximation of the dynamic
90 correlations reflected in the original data. Third, we use repeated applications of the kernel-based dynamic
91 correlation step to \mathbf{X}_n and the dimensionality reduction step to the resulting \mathbf{Y}_{n+1} to estimate high-order
92 dynamnic correlations. Each application of these steps to a T by K time series \mathbf{X}_n yields a T by K matrix, \mathbf{X}_{n+1} ,
93 that reflects the dynamic correlations between the columns of \mathbf{X}_n . In this way, we refer to n as the *order* of
94 the timeseries, where \mathbf{X}_0 (order 0) denotes the original data and \mathbf{X}_n denotes n^{th} -order dynamic correlations

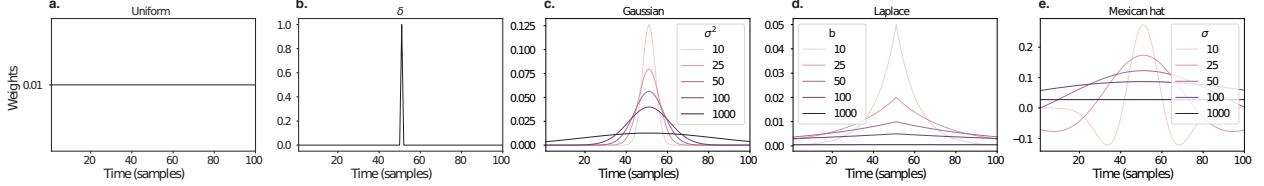


Figure 1: **Examples of kernel functions.** Each panel displays per-timepoint weights at $t = 50$, evaluated for 100 timepoints ($\tau \in [1, \dots, 100]$). **a. Uniform kernel.** The weights are timepoint-invariant; observations at all timepoints are weighted equally, and do not change as a function of τ . This is a special case of weight function that reduces dynamic correlations to static correlations. **b. Dirac δ kernel.** Only the observation at timepoint t is given a non-zero weight (of 1). **c. Gaussian kernels.** Each kernel’s weights fall off in time according to a Gaussian probability density function centered on time t . Weights derived using several different example variance parameters (σ^2) are displayed. **d. Laplace kernels.** Each kernel’s weights fall off in time according to a Laplace probability density function centered on time t . Weights derived using several different example scale parameters (b) are displayed. **e. Mexican hat (Ricker wavelet) kernels.** Each kernel’s weights fall off in time according to a Ricker wavelet centered on time t . This function highlights the *contrasts* between local versus surrounding activity patterns in estimating dynamic correlations. Weights derived using several different example width parameters (σ) are displayed.

95 between the columns of \mathbf{X}_0 . Finally, we use a cross-validation-based decoding approach to evaluate how
 96 well information contained in a given order (or weighted mixture of orders) may be used to decode relevant
 97 cognitive states. If including a given \mathbf{X}_n in the feature set yields higher classification accuracy on held-out
 98 data, we interpret this as evidence that the given cognitive states are reflected in patterns of n^{th} -order
 99 correlations.

100 Kernel-based approach for computing dynamic correlations

Given a matrix of observations, we can compute the (static) Pearson’s correlation between any pair of columns, $\mathbf{X}(\cdot, i)$ and $\mathbf{X}(\cdot, j)$ using (Pearson, 1901):

$$\text{corr}(\mathbf{X}(\cdot, i), \mathbf{X}(\cdot, j)) = \frac{\sum_{t=1}^T (\mathbf{X}(t, i) - \bar{\mathbf{X}}(\cdot, i))(\mathbf{X}(t, j) - \bar{\mathbf{X}}(\cdot, j))}{\sqrt{\sum_{t=1}^T \sigma_{\mathbf{X}(\cdot, i)}^2 \sigma_{\mathbf{X}(\cdot, j)}^2}}, \text{ where} \quad (1)$$

$$\bar{\mathbf{X}}(\cdot, k) = \sum_{t=1}^T \mathbf{X}(t, k), \text{ and} \quad (2)$$

$$\sigma_{\mathbf{X}(\cdot, k)}^2 = \sum_{t=1}^T (\mathbf{X}(t, k) - \bar{\mathbf{X}}(\cdot, k))^2 \quad (3)$$

101 We can generalize this formula to compute time-varying correlations by incorporating a *kernel function* that
 102 takes a time t as input, and returns how much the observed data at each timepoint $\tau \in [-\infty, \infty]$ contributes
 103 to the estimated instantaneous correlation at time t (Fig. 1).

Given a kernel function $\kappa_t(\cdot)$ for timepoint t , evaluated at timepoints $\tau \in [1, \dots, T]$, we can update the

static correlation formula in Equation 2 to estimate the *instantaneous correlation* at timepoint t :

$$\text{timecorr}_{\kappa_t}(\mathbf{X}(\cdot, i), \mathbf{X}(\cdot, j)) = \frac{\sum_{\tau=1}^T (\mathbf{X}(\tau, i) - \tilde{\mathbf{X}}_{\kappa_t}(i))(\mathbf{X}(\tau, j) - \tilde{\mathbf{X}}_{\kappa_t}(j))}{\sqrt{\sum_{\tau=1}^T \tilde{\sigma}_{\kappa_t}^2(\mathbf{X}(\cdot, i)) \tilde{\sigma}_{\kappa_t}^2(\mathbf{X}(\cdot, j))}}, \text{ where} \quad (4)$$

$$\tilde{\mathbf{X}}_{\kappa_t}(t, k) = \sum_{\tau=1}^T \kappa_t(\tau, k) \mathbf{X}(\tau, k), \quad (5)$$

$$\tilde{\sigma}_{\kappa_t}^2(\mathbf{X}(\cdot, k)) = \sum_{\tau=1}^T (\mathbf{X}(\tau, k) - \tilde{\mathbf{X}}_{\kappa_t}(t, k))^2. \quad (6)$$

- ¹⁰⁴ Here $\text{timecorr}(\mathbf{X}(\cdot, i), \mathbf{X}(\cdot, j), \kappa_t)$ reflects the correlation at time t between columns i and j of \mathbf{X} , estimated using
¹⁰⁵ the kernel κ_t .

¹⁰⁶ **Dynamic inter-subject functional connectivity (DISFC)**

Equation 5 provides a means of taking a single observation matrix, \mathbf{X}_n and estimating the dynamic correlations from moment to moment, \mathbf{Y}_{n+1} . Suppose that one has access to a set of multiple observation matrices that reflect the same phenomenon. For example, one might collect neuroimaging data from several experimental participants, as each participant performs the same task (or sequence of tasks). Let $\mathbf{X}_n^1, \mathbf{X}_n^2, \dots, \mathbf{X}_n^P$ reflect the T by K observation matrices ($n = 0$) or reduced correlation matrices ($n > 0$) for each of P participants in an experiment. We can use *inter-subject functional connectivity* (ISFC; Simony et al., 2016) to compute the degree of stimulus-driven correlations reflected in the multi-participant dataset at a given timepoint t using:

$$\bar{\mathbf{C}}(t) = M \left(R \left(\frac{1}{2P} \sum_{p=1}^P Z(Y_n^p(t))^T + Z(Y_n^p(t)) \right) \right), \quad (7)$$

where M extracts and vectorizes the diagonal and upper triangle of a symmetric matrix, Z is the Fisher z -transformation (Zar, 2010):

$$Z(r) = \frac{\log(1+r) - \log(1-r)}{2} \quad (8)$$

R is the inverse of Z :

$$R(z) = \frac{\exp(2z-1)}{\exp(2z+1)}, \quad (9)$$

and $\mathbf{Y}_n^p(t)$ denotes the correlation matrix (Eqn. 2) between each column of \mathbf{X}_n^p and each column of the average \mathbf{X}_n from all *other* participants, $\bar{\mathbf{X}}_n^{\setminus p}$:

$$\bar{\mathbf{X}}_n^{\setminus p} = R \left(\frac{1}{P-1} \sum_{q \in \setminus p} Z(\mathbf{X}_n^q) \right), \quad (10)$$

107 where $\setminus p$ denotes the set of all participants other than participant p . In this way, the T by $\frac{K^2-K}{2}$ DISFC matrix
108 $\bar{\mathbf{C}}$ provides a time-varying extension of the ISFC approach developed by Simony et al. (2016).

109 Low-dimensional representations of dynamic correlations

110 Given a T by $\frac{K^2-K}{2}$ matrix of dynamic correlations, \mathbf{Y}_n , we propose two general approaches to computing
111 a T by K low-dimensional representation of these correlations, \mathbf{X}_n . The first approach uses dimensionality
112 reduction algorithms to project \mathbf{Y}_n onto a K -dimensional space. The second approach uses graph-theoretic
113 measures to characterize the relative positions of each feature ($k \in [1, \dots, K]$) in the network defined by the
114 correlation matrix at each timepoint.

115 Because \mathbf{X}_n will have the same shape as the original data \mathbf{X}_0 , approximating \mathbf{Y}_n with a lower-dimensional
116 \mathbf{X}_n enables us to estimate high-order dynamic correlations in a scalable way. Given a T by K input matrix, the
117 output of Equation 5 requires $O(TK^2)$ space to store. Repeated applications of Equation 5 (i.e., computing
118 dynamic correlations between the columns of the outputted dynamic correlation matrix) each require
119 exponentially more space; in general the n^{th} -order dynamic correlations of a T by K timeseries occupies
120 $O(TK^{2n})$ space. However, when we approximate the output of Equation 5 with a T by K matrix (as
121 described next), it becomes feasible to compute even very high-order correlations in high-dimensional data.
122 Specifically, approximating the n^{th} -order dynamic correlations of a T by K timeseries requires only $O(TK^2)$
123 space— the same as would be required to compute first-order dynamic correlations. **JRM STOPPED HERE**

124 Dimensionality reduction-based approaches to computing \mathbf{X}_n

125 Commonly used dimensionality reduction algorithms include Principal Components Analysis (PCA; Pear-
126 son, 1901), Probabilistic PCA (PPCA; Tipping & Bishop, 1999), Exploratory Factor Analysis (EFA; Spearman,
127 1904), Independent Components Analysis (ICA; Comon et al., 1991; Jutten & Herault, 1991), t -Stochastic
128 Neighbor Embedding (t -SNE; van der Maaten & Hinton, 2008), Uniform Manifold Approximation and
129 Projection (UMAP; McInnes & Healy, 2018), non-negative matrix factorization (NMF; Lee & Seung,
130 1999), Topographic Factor Analysis (TFA) Manning et al. (2014), Hierarchical Topographic Factor analysis
131 (HTFA) Manning et al. (2018), Topographic Latent Source Analysis (TLSA) Gershman et al. (2011), Dictio-

132 nary learning (J. Mairal et al., 2009; J. B. Mairal et al., 2009), deep autoencoders (Hinton & Salakhutdinov,
133 2006), among others. While complete characterizations of each of these algorithms is beyond the scope of
134 the present manuscript, the general intuition driving these approaches is to compute the $\hat{\mathbf{Y}}$ with i columns
135 that is closest to the original \mathbf{Y} with j columns, and where (typically) $i \ll j$. The different approaches place
136 different constraints on what properties $\hat{\mathbf{Y}}$ must satisfy and which aspects of the data are compared (and
137 how) to characterize the match between $\hat{\mathbf{Y}}$ and \mathbf{Y} .

138 Applying dimensionality reduction algorithms to \mathbf{Y} yields a $\hat{\mathbf{Y}}$ whose columns reflect weighted combi-
139 nations (or nonlinear transformations) of the original columns of \mathbf{Y} . This has two main consequences. First,
140 with each repeated dimensionality reduction, the resulting $\hat{\mathbf{Y}}_n$ has lower and lower fidelity (with respect to
141 what the “true” \mathbf{Y}_n might have looked like without using dimensionality reduction to maintain scalability).
142 In other words, computing $\hat{\mathbf{Y}}_n$ is a lossy operation. Second, whereas the columns of \mathbf{Y}_n may be mapped
143 directly onto pairs of columns of \mathbf{Y}_{n-1} , that mapping either becomes less cleanly defined in $\hat{\mathbf{Y}}_n$ due to the
144 reweightings and/or nonlinear transformations.

145 **Graph theoretic approaches to computing \mathbf{X}_n**

146 Graph theoretic measures take as input a matrix of interactions (e.g., using the above notation, an $F \times F$
147 correlation matrix or binarized correlation matrix reconstituted from a single timepoint’s row of \mathbf{Y}) and
148 return as output a set of F measures describing how each node (feature) sits within that interactions matrix
149 with respect to the rest of the population. Common measures include betweenness centrality (the proportion
150 of shortest paths between each pair of nodes in the population that involves the given node in question; e.g.,
151 Barthélémy, 2004; Freeman, 1977; Geisberger et al., 2008; Newman, 2005; Opsahl et al., 2010); diversity and
152 dissimilarity (characterizations of how differently connected a given node is from others in the population;
153 e.g., Lin, 2009; Rao, 1982; Ricotta & Szeidl, 2006); Eigenvector centrality and pagerank centrality (measures of
154 how influential a given node is within the broader network; e.g., Bonacich, 2007; Halu et al., 2013; Lohmann
155 et al., 2010; Newman, 2008); transfer entropy and flow coefficients (a measure of how much information is
156 flowing from a given node to other nodes in the network; e.g., Honey et al., 2007; Schreiber, 2000); k -coreness
157 centrality (a measure of the connectivity of a node within its local sub-graph; e.g., Alvarez-Hamelin et al.,
158 2005; Christakis & Fowler, 2010); within-module degree (a measure of how many connections a node has to
159 its close neighbors in the network; e.g., Rubinov & Sporns, 2010); participation coefficient (a measure of the
160 diversity of a node’s connections to different sub-graphs in the network; e.g., Rubinov & Sporns, 2010); and
161 sub-graph centrality (a measure of a node’s participation in all of the network’s sub-graphs; e.g., Estrada &
162 Rodríguez-Velázquez, 2005).

163 As an alternative to the above dimensionality reduction approach to embedding \mathbf{Y}_n in a lower-dimensional
164 space, but still allowing for scalable explorations of higher-order structure in the data, we also explore using
165 the above graph theoretic measures as a means of obtaining $\hat{\mathbf{Y}}_n$. In particular: for a given graph theoretic
166 measure, $\eta : \mathcal{R}^{F \times F} \rightarrow \mathcal{R}^F$, we can use η to transform each row of \mathbf{Y}_n in a way that characterizes the cor-
167 responding graph-theoretic properties of each column. Whereas the dimensionality reduction approach
168 to computing $\hat{\mathbf{Y}}_n$ is lossy, the graph-theory approach is lossless. However, whereas the dimensionality
169 reduction approach maintains ties (direct or indirect) to the original activity patterns reflected in \mathbf{Y}_{n-1} , the
170 graph-theory approach does not. Instead, the graph-theory characterizes the nature and timecourse of each
171 feature's *participation* in the network.

172 Higher-order correlations

173 Given a timeseries of dynamic correlations (e.g., obtained using Eqn. 5), higher-order correlations reflect the
174 dynamic correlations between columns of \mathbf{Y} . Given unlimited computing resources, one could use repeated
175 applications of Equation 5 to estimate these higher-order correlations (i.e., substituting in the previous
176 output, \mathbf{Y} , for the input, \mathbf{X} in the equation). However, because each output \mathbf{Y} has $O(F^2)$ columns relative
177 to F columns in the input \mathbf{X} , the output of Equation 5 grows with the square of the number of repeated
178 applications (total cost of computing n^{th} order correlations is $O(F^{2n})$ for $n \in \mathcal{J}, n > 0$). When F or n is large,
179 this approach quickly becomes intractable.

180 To make progress in computing \mathbf{Y}_{n+1} , we can approximate \mathbf{Y}_n by computing an $O(F)$ -dimensional em-
181 bedding of \mathbf{Y}_n , termed $\hat{\mathbf{Y}}_n$, and then we can apply Equation 5 to $\hat{\mathbf{Y}}_n$ rather than directly to \mathbf{Y}_n . This enables
182 us to maintain $O(n)$ scaling with respect to n , rather than exponential scaling via the direct approach.

183 There are many possible methods for computing $\hat{\mathbf{Y}}_n$ from \mathbf{Y}_n , including traditional dimensionality
184 reduction approaches and graph theory based approaches as described next. In the *Discussion* section we
185 elaborate on other potential approaches.

186 Evaluation metrics

187 We evaluate our approach to extracting dynamic correlations and higher-order correlations using several
188 metrics detailed next. First, we generated synthetic data using known time-varying correlations, and then
189 we evaluated the fidelity with which Equation 5 could recover those correlations (for synthetic datasets
190 with different properties, and using different kernels to define the weights; Fig. 1). We then turned to a
191 series of analyses on a (real) neuroimaging dataset where the ground truth correlations were *not* known.
192 We evaluated whether the recovered correlations could be used to accurately label held-out neuroimaging

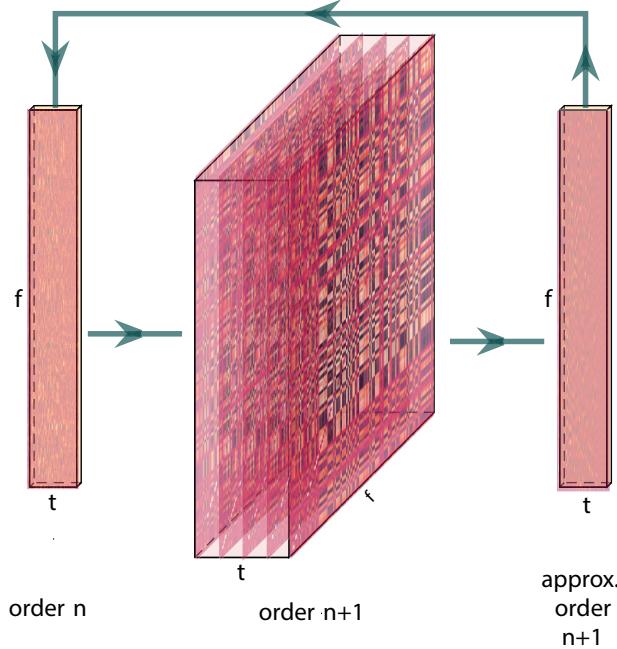


Figure 2: Computing higher order correlations. Dynamic correlations are computed then approximated to the same size as original data using dimensionality reduction. This process is repeated, and can be used to compute up to any arbitrary order with computations scaling linearly (as opposed to exponentially) with order.

193 data with the time at which it was collected. We used this latter evaluations (using timepoint decoding)
 194 as a proxy for gauging how much explanatory power the recovered correlations held with respect to the
 195 observed data.

196 **Generating synthetic data**

197 To explore recovery of a constant covariance (Fig. 3, a.), we generated synthetic data sampled from a constant
 198 covariance matrix. To do this, we created one random covariance matrix, K , with 50 features, and for each
 199 of the 300 timepoints we sampled from a Gaussian distribution centered on K . Similarly, we generated
 200 synthetic data sampled from a random covariance matrix (Fig. 3, b.) by creating a new random covariance
 201 matrix $K(t)$, for each of the 300 timepoints and sampled from a Gaussian distribution centered on $K(t)$.

To generate synthetic data from a dynamically changing covariance matrix (Fig. 3, c.), we generated two random covariance matrices, K_1 and K_2 . We then computed a weighted average covariance matrix for each of the 300 timepoint, $K(t)$, by taking the linearly spaced weights (w) of the two random matrices,

$$K(t) = w(t) * K_1 + (1 - w(t)) * K_2, \quad (11)$$

$$(12)$$

202 and for each of the 300 timepoints sampled from a Gaussian distribution centered on $K(t)$.

203 Lastly, for the synthetic data containing block structure (Fig. 3, d.), we followed the same process of
204 creating synthetic data sampled from a constant covariance matrix (see above) but sampled from a new
205 random covariance matrix after 60 consecutive timepoints. We then pieced the blocks together to create a
206 sythetic dataset with 300 total timepoints but drawn from 5 separate covariance matrices.

207 **Recovery of ground truth parameters from synthetic data**

208 We applied timecorr, using delta and gaussian (width = 10) kernels Fig. 1) to each of these synthetic datasets,
209 then correlated each recovered correlation matrix with the ground truth. We repeated this process 10 times
210 and explored how recovery varies with the kernel and the specific structure of the data. For the ramping
211 synthetic dataset (Fig. 3, c.) and for the block synthetic dataset (Fig. 3, d.) we made further comparisons
212 of the timecorr recovered correlation matrices. We compared the ramping recovered correlation matrices to
213 only the first random covariance matrix K_1 (First, Fig. 3, c.) and to only the last random covariance matrix
214 K_2 (Last, Fig. 3, c.) from Equation 12. We also compared the block recovered correlation matrices in to the
215 block specific covariance matrix (Block 1-5, Fig. 3, d.).

216 **Timepoint decoding**

217 To explore how higher-order structure varies with stimulus structure and complexity, we used a previous
218 neuroimaging dataset Simony et al. (2016) in which participants listened to an audio recording of a story;
219 36 participants listen to an intact version of the story, 17 participants listen to time-scrambled recordings of
220 the same story where paragraphs were scrambled, 36 participants listen to word-scrambled version and 36
221 participants lay in rest condition.

222 Prior work has shown participants share similar neural responses to richly structured stimuli when
223 compared to stimuli with less structure. To assess whether the moment-by-moment higher order correlations
224 were reliably preserved across participants, we used inter-subject functional connectivity (ISFC) to isolate
225 the time-varying correlational structure (functional connectivity patterns that were specifically driven by
226 the story participants listened to. Following the analyses conducted by (HTFA) Manning et al. (2018), we
227 first applied *hierarchical topographic factor analysis* (HTFA) to the fMRI datasets to obtain a time series of
228 700 node activities for every participant. We then computed the dynamic weighted ISFC using a range of
229 kernels and widths. Specifically, we used Gaussian, Laplace, and mexican hat kernels, as well as widths of
230 5, 10, 20, and 50. We then approximated these dynamic correlation using two reduction measures, PCA and
231 eigenvector centrality, and computed the dynamic weighted ISFC on the approximations. We repeated this

232 process up to 10th order approximated correlations.

233 To assess decoding accuracy, we randomly divided participants for each stimulus into training and
234 testing groups. For the zeroth order, we computed the mean factor activity for each group. For all subsequent
235 orders up to the tenth order, we computed the mean approximated dynamic ISFC of factor activity for each
236 group. To assess how additional higher-order correlations contribute to decoding accuracy, for each order
237 we included a weighted-mixture (described below) of the activity patterns of all previous orders. For each
238 group of participants in turn, we compared these activity patterns (using Pearson correlations) to estimate
239 the story times each pattern corresponded to. Specifically, we asked, for each timepoint: what are the
240 correlations between the first group's and second group's activity patterns at each order. We note that the
241 decoding test we used is a conservative in which we count a timepoint label as incorrect if it is not an exact
242 match.

243 For each order we obtained the weighted-mixture of the correlation matrices for the current order and
244 all previous orders using mixing parameter, ϕ , where $0 < \phi < 1$ reflects a weighted mixture of order based
245 decoding Fig. 4 Panel c.). We calculated ϕ , by subdividing the training group and using the quasi-Newton
246 method of Broyden, Fletcher, Goldfarb, and Shanno (BFGS (Nocedal & Wright, 2006)) for optimization. We
247 repeated this cross-validation process 10 times for each parameter set.

248 Results

249 Synthetic data

250 To assess the performance of dynamic correlation recovery using timecorr, we varied width the kernel and
251 the specific structure of the data. We applied timecorr, using delta and gaussian kernels Fig. 1) to each of
252 the following synthetic datasets: constant, random, ramping, and block. We then correlated each recovered
253 correlation matrix with the ground truth.

254 For the constant synthetic dataset, a gaussian kernel (width=10) outperformed the delta kernel (Fig. 3,
255 a.). This is in contrast with the random synthetic dataset, for which the delta kernel best captures the rapidly
256 changing structure (Fig. 3, b.). For the ramping synthetic dataset, the slow changing strucutre within the
257 data is best captured by the gaussian kernel and the best recovery occurs in the middle (Ramping, Fig. 3,
258 c.). In addition to comparing the timecorr recovered correlation matrices to the ground truth, we further
259 compared the ramping recovered correlation matrices to only the first random covariance matrix K_1 (First,
260 Fig. 3, c.) and to only the last random covariance matrix K_2 (Last, Fig. 3, c.), both of which perform best at
261 the beginning and end respectively.

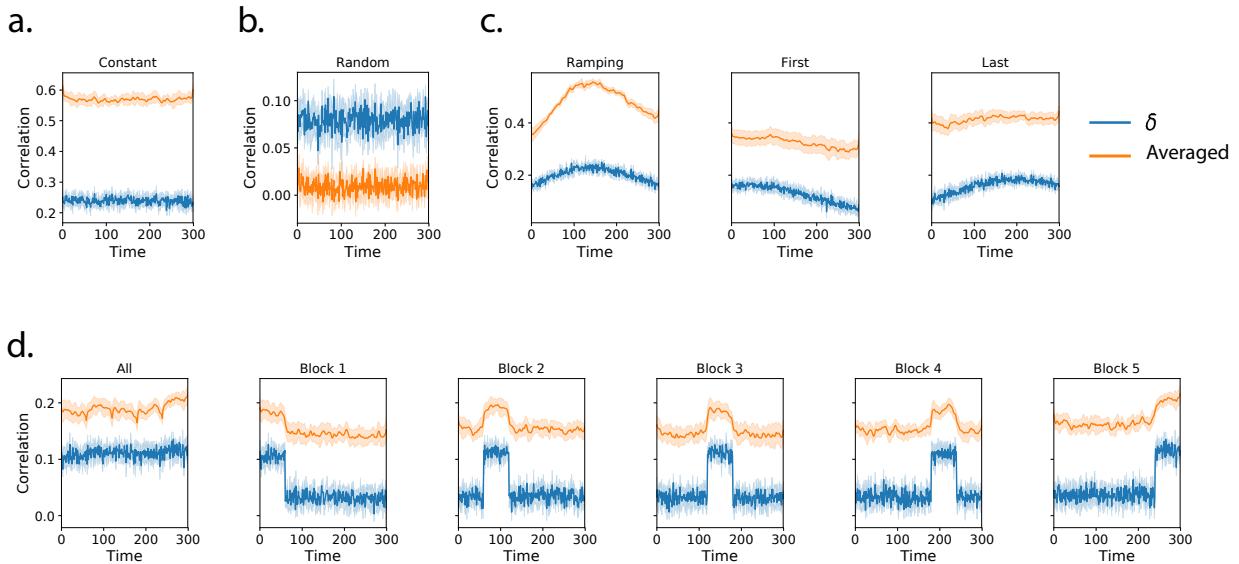


Figure 3: Dynamic correlation recovery with synthetic data. Using synthetic data containing different underlying correlational structure, we test how well we can recover dynamic correlation matrices using different kernels when compared to ground truth. We compare the results using a delta kernel with averaged results from several kernels (Gaussian, Laplace, and mexican hat) and several widths (5, 10, 20, and 50). We plot recovery using of datasets containing the following underlying structure: **a. Constant.** **b. Random.** **c. Ramping.** **d. Block.**

262 Similary for the block sythetic dataset, we compared the timecorr recovered correlation matrices to
 263 the ground truth as well as to each block-specific covariance matrix (Block 1-5, Fig. 3, d.). Although the
 264 structure is changing by block, the gaussian kernel once again outperforms the delta kernel. Performance
 265 does however drop near even boundaries for when using the gaussian kernel.

266 **Neuroimaging dataset (Simony et al., 2016)**

267 For our decoding analysis, we used HTFA-derived node activities Manning et al. (2018) from fMRI data
 268 collected as participants listened to an audio recording of a story (intact condition; 36 participants), lis-
 269 tened to time scrambled recordings of the same story (17 participants in the paragraph-scrambled condition
 270 listened to the paragraphs in a randomized order and 36 in the word-scrambled condition listened to
 271 the words in a randomized order), or lay resting with their eyes open in the scanner (rest condition; 36
 272 participants). We sought to demonstrate how higher-order correlations may be used to examine dynamic
 273 interactions of brain patterns in (real) multi-subject fMRI datasets. This story listening dataset was col-
 274 lected as part of a separate study, where the full imaging parameters, image preprocessing methods, and
 275 experimental details may be found (Simony et al., 2016). The dataset is available at [http://arks.prince-
 276 ton.edu/ark:/88435/dsp015d86p269k](http://arks.princeton.edu/ark:/88435/dsp015d86p269k).

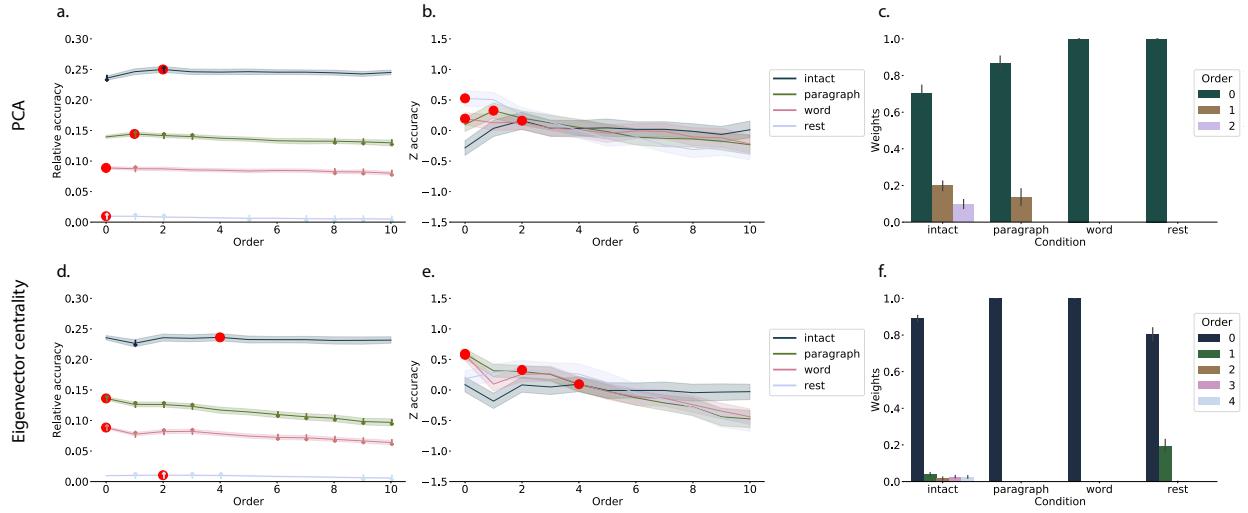


Figure 4: **Decoding by order.** **a.&d. Relative decoding accuracy by order.** Ribbons of each color display cross-validated decoding performance averaged over all parameters for each condition (intact, paragraph, word, and rest) using PCA (a.) or eigenvector centrality (d.) to approximate correlations. Decoders were trained using increasingly more higher-order information and this ribbon are displayed relative to chance at 0. The red dots indicates maximum decoding accuracy for each condition. **b.&e. Z-transformed decoding accuracy by order.** We Z-transformed the decoding accuracy by order to better visualize the order with the maximum decoding accuracy for each condition using PCA (b.) or eigenvector centrality (e.) to approximate correlations. **c.&f. Optimized weights.** Bar heights indicate the optimized mixing parameter ϕ of each contributing order up to and including the order with the maximum decoding accuracy for each contributing order using PCA (c.) or eigenvector centrality (f.) to approximate correlations. For the order with maximum decoding accuracy by condition, we show barplots of the optimized weights ϕ for each contributing order.

277 We next evaluated if our model of high-order correlations in brain activity can capture cognitively
278 relevant brain patterns. We performed a decoding analysis, using cross validation to estimate (using other
279 participants' data) which parts of the story each weighted-mixture of higher-order brain activity pattern
280 corresponded to (see *Materials and methods*). We note that our primary goal was not to achieve perfect
281 decoding accuracy, but rather to use decoding accuracy as a benchmark for assessing whether different
282 neural features specifically capture cognitively relevant brain patterns.

283 Separately for each experimental condition, we divided participants into two groups. For the zeroth
284 order, we computed the mean factor activity for each group. For all subsequent orders up to the tenth
285 order, we computed the mean approximated dynamic ISFC of factor activity for each group (see *Materials*
286 and *methods*), and combined in a weighted mixutre with all previous orders (i.e. cross-validation for the
287 second order contained a weighted-mixture of zeroth, first, and second order (Fig. 4, c.&f.). For each
288 order, we correlated the group 1 activity patterns with group 2 activity patterns. We then subdivided
289 the group 1 to obtain an optimal weighting parameter for each order's correlation matrix using the same
290 cross validation method. We used the optimal weighting parameters to obtain a weighted-mixture (see
291 *Materials and methods*) of each order's correlation matrix. Using these correlations, we labeled the group 1
292 timepoints using the group 2 timepoints with which they were most highly correlated; we then computed
293 the proportion of correctly labeled group 1 timepoints. (We also performed the symmetric analysis whereby
294 we labeled the group 2 timepoints using the group 1 timepoints as a template.) We repeated this procedure
295 100 times (randomly re-assigning participants to the two groups each time) to obtain a distribution of
296 decoding accuracies for each experimental condition. There were 272 timepoints for paragraph condition,
297 300 timepoints for intact and word conditions, and 400 timepoints for rest condition, so chance performance
298 on this decoding test is was $\frac{1}{272}$, $\frac{1}{300}$, and $\frac{1}{400}$ respectively.

299 We repeated this process for each set of parameters, varying kernel type and width, and averaged over the
300 reduction technique used to approximate the higher-order correlations (PCA Fig. 4, a.-c. and eigenvector
301 centrality Fig. 4, d.-f.). Since there is no ground truth in these analyses, and we did not know which
302 parameters best capture the data, we instead report a robustness search by averaging over the parameters
303 and reporting which results consistently showed up across all parameters.

304 The two methods used to approximate the higher-order correlations (PCA Fig. 4, a.-c. and eigenvector
305 centrality Fig. 4, d.-f.) capture different facets of the activity patterns. Using PCA, the higher-order
306 correlations are all linked to the original activity patterns, whereas eigenvectory centrality breaks the
307 immediate link with specific brain areas and instead characterizes the position of the nodes in the network
308 that are similar over time.

309 We found for both PCA and eigenvector centrality, during the intact condition in the experiment,

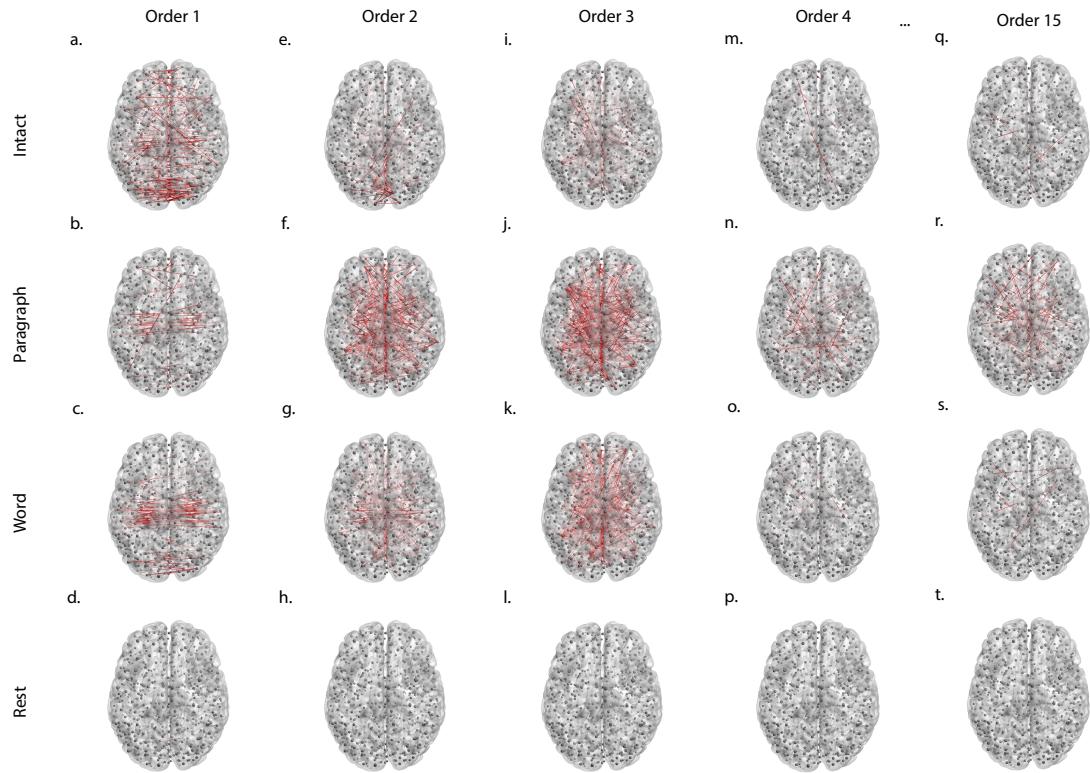


Figure 5: Average correlations by order for the intact listening condition. Using eigenvector centrality to approximate higher-order correlations for the intact, paragraph scrambled, word scrambled, and rest condition. We plot the strongest 50% absolute value mean correlation for **a.-d. first order, e.-h. second order, i.-l. third order, and m.-p. fourth order**, representing the degree of agreement by location pair over time. To demonstrate how this method is computationally scalable, we also approximated **a.-d. fifteenth order** dynamic correlation, which would be possible to compute using conventional methods since it would require more bits to represent the solution than there are molecules in the universe.

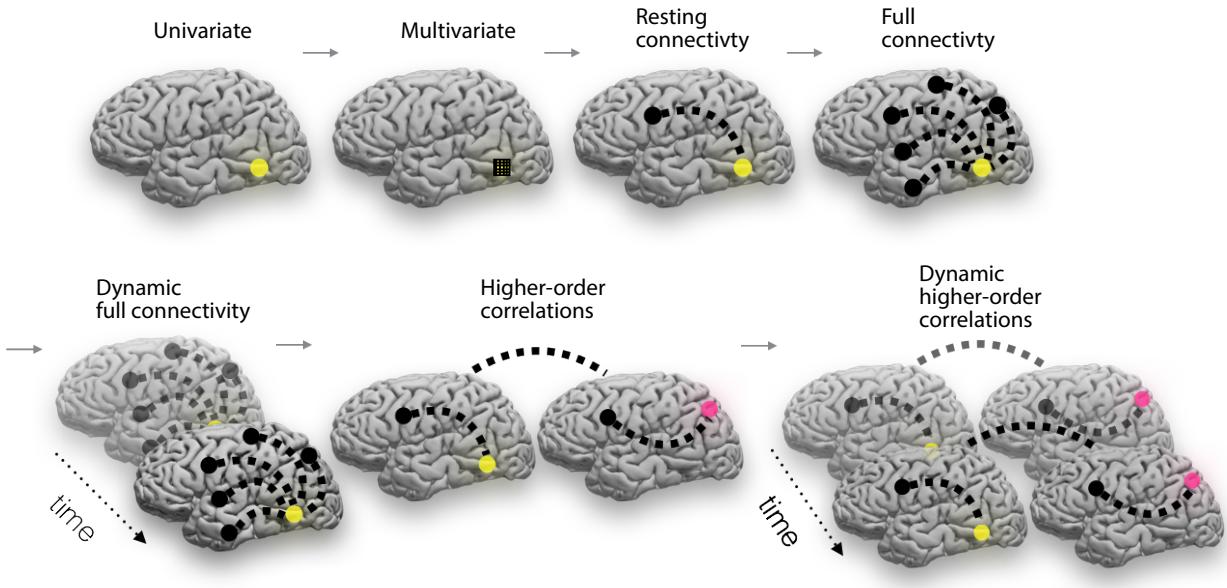


Figure 6: Direction of the field (adapted from (Turk-Browne, 2013)). The evolution of fMRI analyses started with univariate activation, which refers to the average amplitude of BOLD activity evoked by events of an experimental condition. Next, multivariate classifiers are trained on patterns of activation across voxels to decode distributed representations for specific events. The next, resting connectivity, is the temporal correlation of one or more seed regions with the remainder of the brain during rest. Additionally, task-based connectivity examines how these correlations differ by cognitive state. Following this increasing trajectory of increasing complexity, full connectivity considers all pairwise correlations in the brain, most commonly at rest. Next, dynamic full connectivity considers how full connectivity changes over time. Continuing this line of reasoning, we expect higher-order network dynamics might provide even richer insights into the neural basis of cognition.

310 classifiers that incorporated higher-order correlations yielded consistently higher accuracy than classifiers
 311 trained only on lower-order patterns (Fig. 4, a.&d.). We plot the average correlations for up to the fourth
 312 order for the intact condition (Fig. 5) representing the degree of agreement by location pair over time. By
 313 contrast, we found that incorporating higher-order (greater than first order) correlations did not further
 314 improve decoding accuracy for the other listening conditions or rest condition. This suggests that the
 315 cognitive processing that supported the most cognitively rich condition involved higher-order network
 316 dynamics.

317 Discussion

318 Based on prior work (Demertzi et al., 2019) and following the direction of the field (Turk-Browne, 2013)
 319 we think our thoughts might be encoded in dynamic network patterns, and possibly higher order network
 320 patterns (Fig. 6). We sought to test this hypothesis by developing an approach to inferring high-order
 321 network dynamics from timeseries data.

322 One challenge in studying dynamic interactions is the computational resources required to calculate
323 higher-order correlations. We developed a computationally tractable model of network dynamics (Fig. 2)
324 that takes in a feature timeseries and outputs approximated first-order dynamics (i.e., dynamic functional
325 correlations), second-order dynamics (reflecting homologous networks that dynamically form and disperse),
326 and higher-order network dynamics (up to tenth-order dynamic correlations).

327 We first validated our model using synthetic data, and explored how recovery varied with different
328 underlying data structures and kernels. We then applied the approach to an fMRI dataset (Simony et al.,
329 2016) in which participants listened to an audio recording of a story, as well as scrambled versions of the
330 same story (where the scrambling was applied at different temporal scales). We trained classifiers to take
331 the output of the model and decode the timepoint in the story (or scrambled story) that the participants
332 were listening to. We found that, during the intact listening condition in the experiment, classifiers that
333 incorporated higher-order correlations yielded consistently higher accuracy than classifiers trained only
334 on lower-order patterns (Fig. 4, a.&d.). By contrast, these higher-order correlations were not necessary
335 to support decoding the other listening conditions and (minimally above chance) during a control rest
336 condition. This suggests that the cognitive processing that supported the most cognitively rich listening
337 conditions involved second-order (or higher) network dynamics.

338 Although we found decoding accuracy was best when incorporating higher-order network dynamics
339 for all but rest condition, it is unclear if this is a product of the brain or the data collection technique. It could
340 be that the brain is second-order or it could be that fMRI can only reliably give second-order interactions.
341 Exploring this method with other data collection technique will be important to disentangle this question.

342 Concluding remarks

343 How can we better understand how brain patterns change over time? How can we quantify the potential
344 network dynamics that might be driving these changes? One way to judge the techniques of the future is
345 to look at the trajectory of the fMRI field so far has taken so far (Fig. 2). The field started with univariate
346 activation, measuring the average activity for each voxel. Analyses of multivariate activation followed,
347 looking at spatial patterns of activity over voxels. Next, correlations of activity were explored, first with
348 measures like resting connectivity that take temporal correlation between a seed voxel and all other voxels
349 then with full connectivity that measure all pairwise correlations. Additionally, this path of increasing
350 complexity also moved from static to dynamic measurements. One logical next step in this trajectory would
351 be dynamic higher-order correlations. We have created a method to support these calculations by scalably
352 approximating dynamic higher-order correlations.

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360 **Author contributions**

361 Concept: J.R.M. Implementation: T.H.C., L.L.W.O., and J.R.M. Analyses: L.L.W.O and J.R.M.

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