A New Metric to Quantify Functional & Effective Connectivity for Individual Brains

Curtis A. Bagne, Ph.D. • DataSpeaks, Inc.

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QUOTATION: "Almost universally in fMRI, functional connectivity is assessed with the correlation coefficient"

K. J. Friston, "Functional and Effective Connectivity: A Review," BRAIN CONNECTIVITY, Volume 1, Number 1, page 21

It appears that the correlation coefficient has become the "default mode" for assessing functional connectivity.

QUESTION: Are correlations the best metric to quantify functional connectivity?

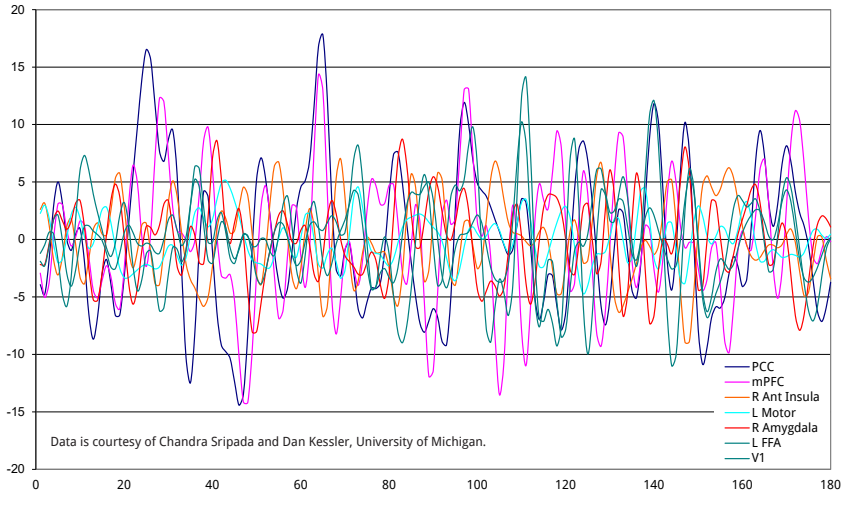
METHODS: Compare capabilities of two methods for quantifying connectivity using multiple time series.

Method 1: A statistical measure of correlation initially developed for groups in which each x-y pair is independent of other x-y pairs. The repeated measurements in time series are not independent.

Method 2: Interaction over Time scores from DataSpeaks Health Solutions, Inc. (DataSpeaks) for repeated measurements and time series about individuals. For this application, Interaction over Time scores will be called Connectivity Scores.

DATA: Figure 1 shows corrected resting state data for one individual and seven brain regions of interest (ROI). These data have 180 repeated measurements.

FIGURE 1. Action Level Data for Seven ROIs



RESULTS: Tables 1, 2, & 3 • Figures 2, 3

Table 1 shows the summary Connectivity Scores from DataSpeaks. These quantify the direction (positive or negative) and the amount of evidence for functional connectivity for all 7 ROIs investigated pairwise.

Each score in Table 1 is the most extreme positive or negative score in a four-dimensional array of 5,040 inherently standardized scores. This number, 5,040, results from a DataSpeaks software user selected scoring protocol with 12 levels of the predictor or Independent Variable (IV), 12 levels of the predicted or Dependent Variable (DV), 7 levels of delay of response (0 thru 6), and 5 levels of persistence of response (1 thru 5). Get computational details from the author using the contact information shown below.

Each Connectivity Score in Table 1 is one score from a distribution of potential scores, defined by the data in combination with a user specified scoring protocol. Each such distribution has mean = 0 and standard deviation = 1 unless zero is the only potential score.

Figure 2 shows this distribution of potential scores for the Connectivity Score in Table 1 with a value of 33.8322. DataSpeaks can estimate the probability of getting each score in Table 1 by chance alone.

Table 2 shows strength of evidence type of scores from DataSpeaks. The scores in Table 2 are like correlation coefficients in that they are not standardized and can range in value from -1 to 1 inclusive. Table 2 shows one of three strength type scores offered by DataSpeaks.

Figure 3 shows an important difference between DataSpeaks (i) amount of evidence and (ii) strength of evidence type scores from Table 1 and Table 2 respectively.

The magnitudes of the amount of evidence scores (Table 1) can increase indefinitely with the number of repeated measurements. In contrast and like correlations, the strength type scores (Table 2) can reach their maximum magnitude of 1 with only two repeated measurements. Obtain such results by processing the data iteratively over repeated measurements.

Table 3 shows the Pearson product-moment correlations for the data in Figure 1.

DataSpeaks Results

TABLE 1. Amount & direction of evidence type of scores

IV	PCC	mPFC	R_Ant_Ins	L_Motor	R_Amyg	L_FFA	V1
PCC	-	16.4640	14.2183	20.6708	12.7547	12.9168	-7.9832
mPFC	19.1540	-	-24.4104	-14.6552	9.6754	-9.9122	-6.9986
R_Ant_Ins	-15.8990	-21.3711	-	-13.5378	-17.6191	-9.1955	17.6473
L_Motor	-19.7380	-13.5591	12.1734	-	-6.2974	10.3190	-14.3231
R_Amyg	-16.1748	11.8201	-6.6791	8.5366	-	15.5402	21.9781
L_FFA	-15.1247	7.6575	-7.0733	-13.1032	-11.2415	-	33.8322
V1	7.3881	9.0968	-7.9347	8.8104	-9.2900	33.8322	-

TABLE 2. Strength & direction of evidence type scores

IV	PCC	mPFC	R_Ant_Ins	L_Motor	R_Amyg	L_FFA	V1
PCC	-	0.1616	0.1400	0.2058	0.1252	0.1279	-0.0791
mPFC	0.1849	-	-0.2351	-0.1415	0.0935	-0.0959	-0.0692
R_Ant_Ins	-0.1534	-0.2059	-	-0.1326	-0.1725	-0.0903	0.1748
L_Motor	-0.1900	-0.1357	0.1207	-	-0.0615	0.0994	-0.1421
R_Amyg	-0.1605	0.1154	-0.0643	0.0831	-	0.1518	0.2153
L_FFA	-0.1484	0.0758	-0.0686	-0.1304	-0.1106	-	0.3267
V1	0.0717	0.0886	-0.0764	0.0879	-0.0896	0.3267	-

Correlation Results

TABLE 3. Correlations

IV	PCC	mPFC	R_Ant_Ins	L_Motor	R_Amyg	L_FFA	V1
PCC	1	0.4599	-0.3140	-0.4426	-0.0749	0.0382	0.1961
mPFC	0.4599	1	-0.4831	-0.2609	0.0169	-0.2109	-0.0837
R_Ant_Ins	-0.3140	-0.4831	1	0.1014	-0.0452	-0.0911	-0.1610
L_Motor	-0.4426	-0.2609	0.1014	1	0.0911	0.2119	0.1360
R_Amyg	-0.0749	0.0169	-0.0452	0.0911	1	0.0367	-0.1786
L_FFA	0.0382	-0.2109	-0.0911	0.2119	0.0367	1	0.5572
V1	0.1961	-0.0837	-0.1610	0.1360	-0.1786	0.5572	1

FIGURE 2: Distribution of Potential Scores

Distribution of Potential Scores of Which the Observed Score, 33.8322, is a Member

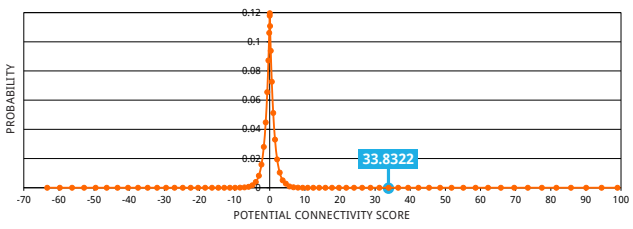


FIGURE 3: Iterative Processing

Connectivity Scores as a Function of Repeated Measurement Number for the Amount of Evidence Score with a Value of 33.8322

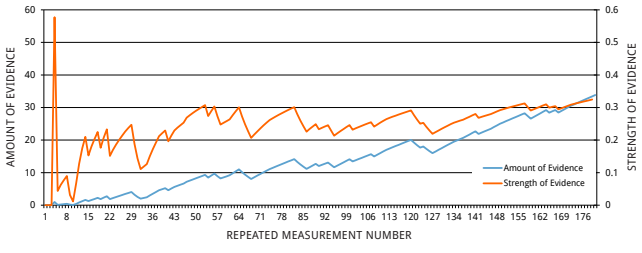
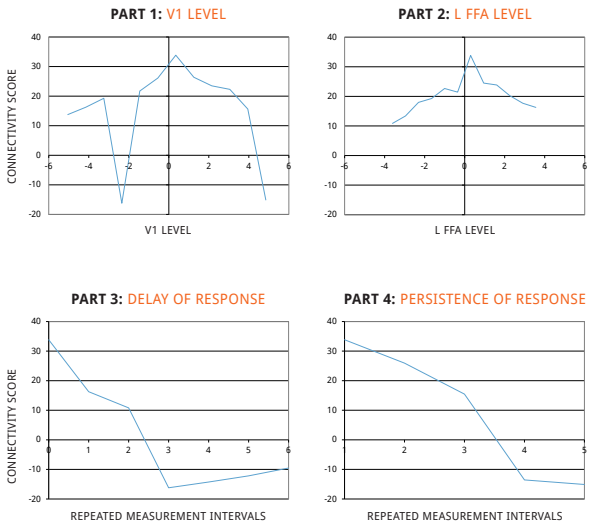


FIGURE 4: Drill Down Capabilities



RESULTS: Drill Down Capabilities with DataSpeaks

Each Connectivity Score in Table 1 summarizes a detailed 4-dimensional array of 5,040 standardized scores as explained above. DataSpeaks allows users to drill down into such arrays to gain more insight about connectivity. This will be illustrated for the Connectivity Score in Table 1 with a value of 33.8322.

Figure 4 shows summary Connectivity Scores as functions of the four analysis parameters used to form the array of 5,040 standardized scores. Figure 4 has four parts.

Part 1: V1 Level shows Connectivity Scores as function of the 12 levels of activity in the visual area, V1, functioning as the IV.

Part 2: L_FFA Level shows the Connectivity Scores as a function of the 12 levels of the left fusiform face area, L_FFA. Note from Parts 1 and 2 that functional connectivity does not appear to be linear. Correlations assume that relationships are linear. DataSpeaks can help quantify nonlinear relationships.

Part 3: Delay of Response shows Connectivity Scores as a function of Delay of Response

Part 4: Persistence of Response shows Connectivity Scores as a function of Persistence of Response. Parts 3 and 4 indicate that connectivity from V1 to L_FFA is positive, rapid, and does not persist within the temporal resolution (about 2 seconds) of the data in Figure 1. Notice that the most extreme Connectivity Score (33.8322) is the same for all four parts of Figure 4.

DataSpeaks offers an Effective Connectivity Index that helps quantify evidence for causality. This index assesses the temporal criterion of causal relationships by differencing Connectivity Scores obtained with optional temporal analysis parameters as from V1 to L_FFA versus from L_FFA to V1.

CONCLUSIONS & TAKEAWAYS: DataSpeaks appears to be superior to correlation coefficients for quantifying connectivity. Here are some reasons.

Unlike correlation coefficients, DataSpeaks was specifically invented for two or more time-varying variables about individuals such as brains, patients, and other Complex Adaptive Systems.

DataSpeaks users can quantify connectivity as functions of levels of the interactants (e.g., ROI action levels) as illustrated in Parts 1 and 2 of Figure 4. Unlike correlations, DataSpeaks does not assume that connectivity is linear.

Connectivity Scores can be investigated as functions of Delay and Persistence of Response as illustrated in Parts 3 and 4 of Figure 4. In addition, the current version of DataSpeaks software can do this for up to four additional parameters used to investigate episodes of independent and dependent events. All these can help users investigate temporal dynamics and the temporal criterion of causal relationships.

Results such as those in Figure 4 can be differenced to investigate effects of interventions such as drugs and learning on connectivity. This can help reveal mechanisms of treatment effect.

Users can investigate effects how fast-acting interventions such as some drugs and anesthesia up- or down-regulate connectivity within an imaging session by looking for changes in slope for the amount of evidence line that is illustrated in Figure 3.

This poster illustrates the use of DataSpeaks to assess function—all time series were internal to the individual. DataSpeaks applies to both internal and external variables as well as about individuals' behaviors. This includes verbal reports as about pain and mood. This can help elucidate brain-behavior relationships. More generally, DataSpeaks helps measure how individual work over time – function internally, respond to their environments, and act as agents on their environments.

DataSpeaks is well suited to process data when IVs are under randomized experimental control as with transcranial magnetic stimulation.

DataSpeaks claims to measure emergent system properties such as coordinated action from time-ordered data such as activity or action levels in ROIs.

The Diagnostic and Statistical Manual for Mental Disorders is based on signs and symptoms of disorder. DataSpeaks has potential to help form taxonomies based on measures of order and disorder per se.

DataSpeaks helps enable The Science of Individuality. Consciousness is personal.

Scores from DataSpeaks are well suited for statistical analyses when there are two or more individuals. BRAIN Initiative, anyone?

CONTACT: Curtis A. Bagne, Ph.D. • cbagne@DataSpeaks.com • 248 854-6816