Visual word recognition: Functional connectivity using Granger causation analysis in EMEG source space

Fawad Jamshed [1], Caroline M. Whiting[1,2], David Whitcomb Gow Jr.[3,4]

& William D. Marslen-Wilson[1,2]

[1]Department of Psychology, University of Cambridge, UK; [2]MRC Cognition and Brain Sciences Unit, Cambridge, UK; [3]Harvard Medical School, US; [4]Massachusetts General Hospital, US

Introduction

A neurobiological theory of visual word recognition will need to specify the major brain regions that support this important component of skilled reading, and to map out the timing and the manner in which these regions contribute to word identification and meaning extraction. This in turn requires an analysis of the dynamic functional connectivity between these brain regions over time.

To achieve this we used Granger Causal Modelling [1] applied to source localised MR-constrained combined MEG and EEG (EMEG) data [3] with 1 ms temporal resolution and up to 5 mm spatial resolution.

We applied the Granger Processing Stream (GPS) Toolbox to two different sets of written words, varying in their linguistic complexity (simple vs morphologically complex: e.g. *biscuit* vs *jumped*) to address four questions:

- Do simple words primarily engage ventral temporal streams supporting basic access to lexical representations in visual word recognition?
- Do complex words preferentially engage dorsal ROIs involved in combinatorial lexical processing and aspects of cognitive control?
- What are the major hubs in these pathways?
- How does dynamic functional connectivity evolve over time?

Methods

Stimuli

Two sets of written words were used:

- **Complex** words are all composed of a stem and an affix, and include 50 derivational (*farmer*), 50 inflectional (*jumped*), 50 pseudo-derivational (*corner*) and 50 pseudo-inflected (*ashed*) forms.
- **Simple** words are either missing stem or affix or both, and include 50 pseudo-stem (*blemish*), 50 pseudo-affix (*scandal*), and 50 no stem/no affix (*biscuit*) forms.
- The functional connectivity analyses focused on later lexical analysis processes falling within a 300-450 ms time window (from stimulus onset).

Acquisition and Source Reconstruction

- concurrent MEG-EEG data acquired with 306-channel Vector view system and 70-channel EEG cap
- epochs from -100 to 500 ms from word onset
- three-layer boundary element model using FreeSurfer from individual structural MRIs
- L2 minimum norm estimation (MNE) is used for source reconstruction

Activation-based Bottom-Up ROIs

An activation-based bottom-up approach was used to extract regions of interest for the functional connectivity analyses using the GPS Toolbox. This employs a Kalman Filter approach to overcome stationarity problems in time series analysis [2].
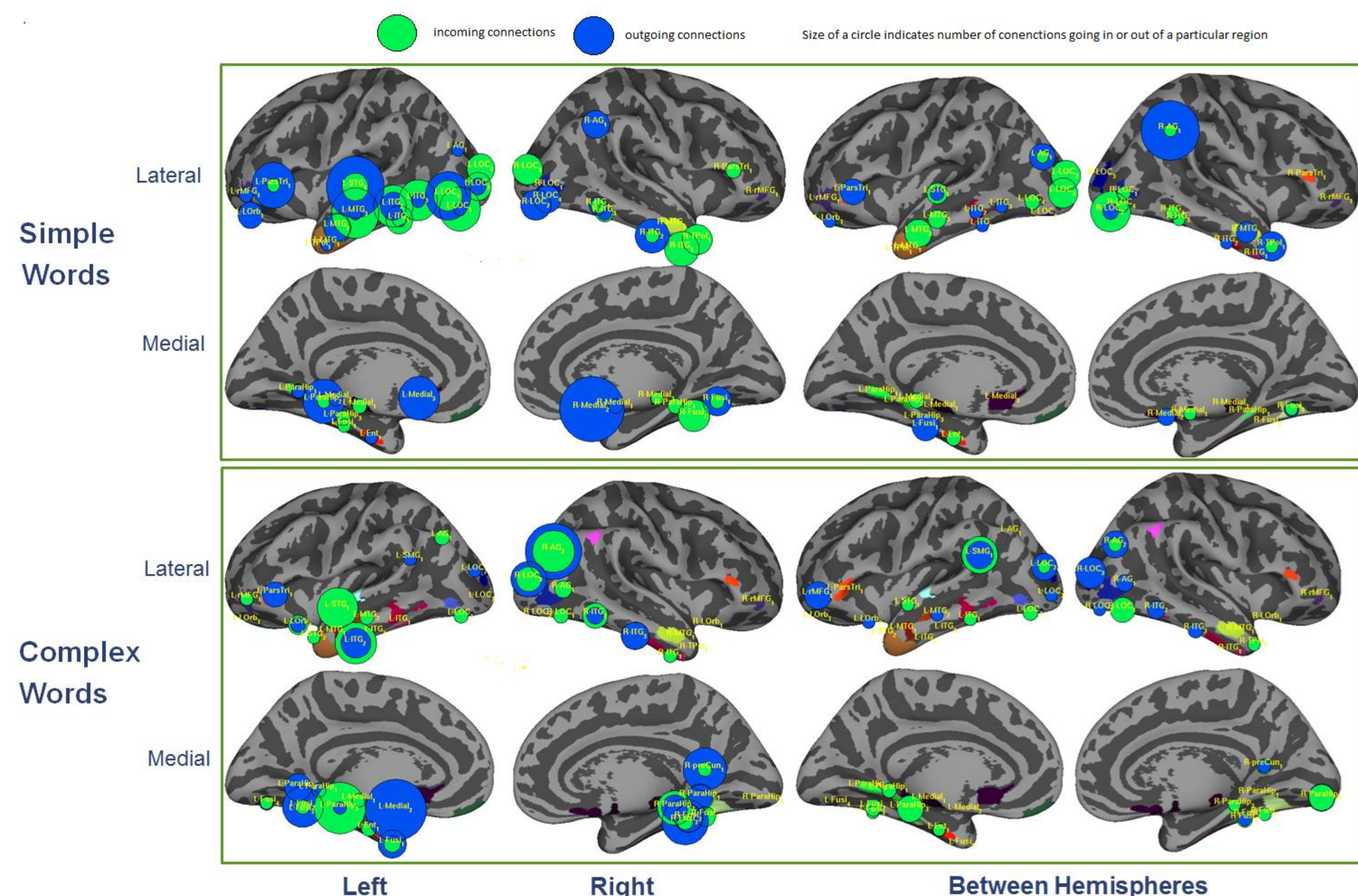
Results

The GPS analysis shortlists potential ROIs for granger connectivity analysis, using the following procedure:
- Centroids are defined using bottom up activation as the regions that have the top 10 percentile of activation.
- These centroids are processed by normalising their activity and removing regions that have similar normalised activity.
- Bottom up ROIs are generated by grouping vertices that pass the weighted threshold values for their continuity from the centroid.

Simple Words   Complex Words

a. Bottom Up activation

b. Bottom Up ROIs
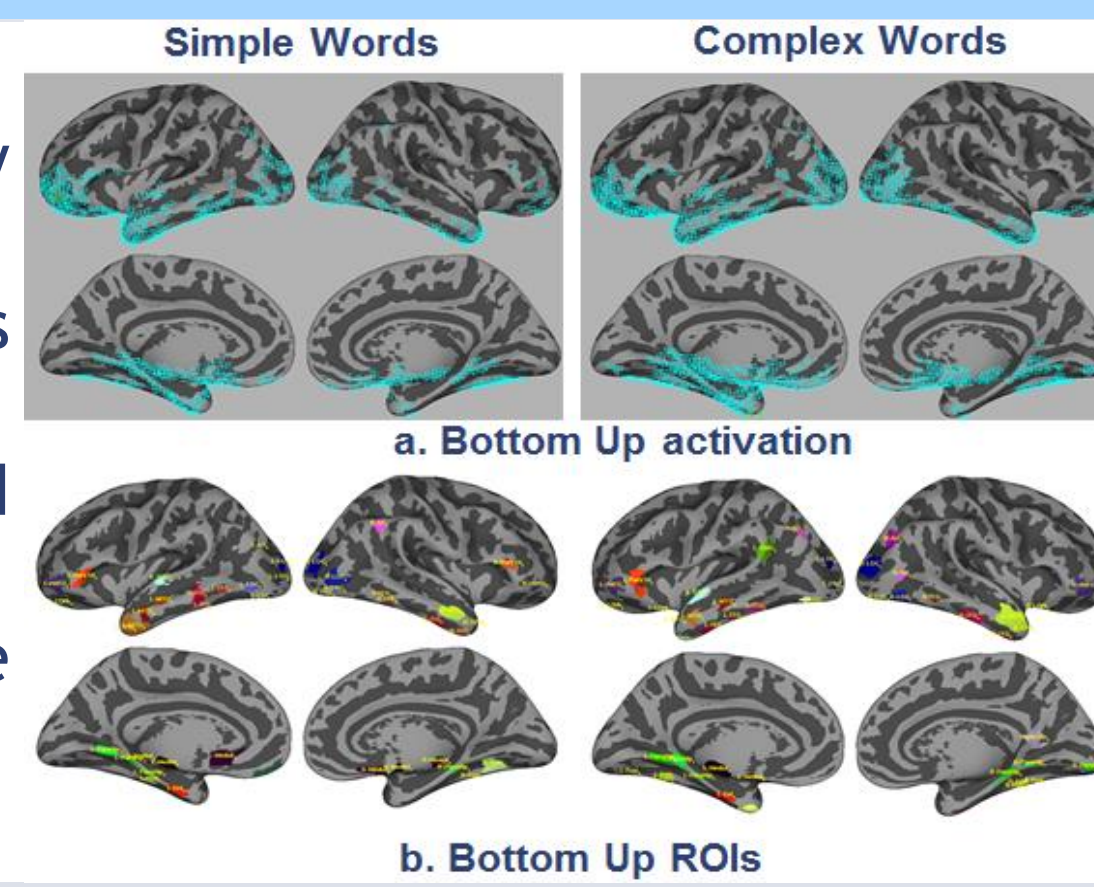
### 1. Major Hubs over the 300-450ms epoch

Hubs are defined as regions with higher connectivity that link together different smaller functional networks . The figure below gives the major hubs for **simple** and **complex** words.

incoming connections   outgoing connections   Size of a circle indicates number of connections going in or out of a particular region

Simple Words — Lateral, Medial
Complex Words — Lateral, Medial
Left   Right   Between Hemispheres

Simple words engage ventral pathways relatively more than complex words, whereas complex words engage dorsal regions more strongly. For simple words L-MTG, L-STG and L-ParsTri emerge as major LH hubs, and R anterior temporal areas and R-AG in the RH. For between hemisphere connectivity R-AG showed strong connectivity. For complex words the L-STG, L-ITG, and L_ParaHippocampal emerged as major LH hubs, with R-AG as the major RH hub. For between hemisphere connectivity L-SMG and R-AG showed strong connectivity.

Results

2. Major Connectivity Analysis: Three 50ms bins over the 300-450ms epoch

Simple Words
Left   Right   Between Hemispheres
300-350ms
350-400ms
400-450ms
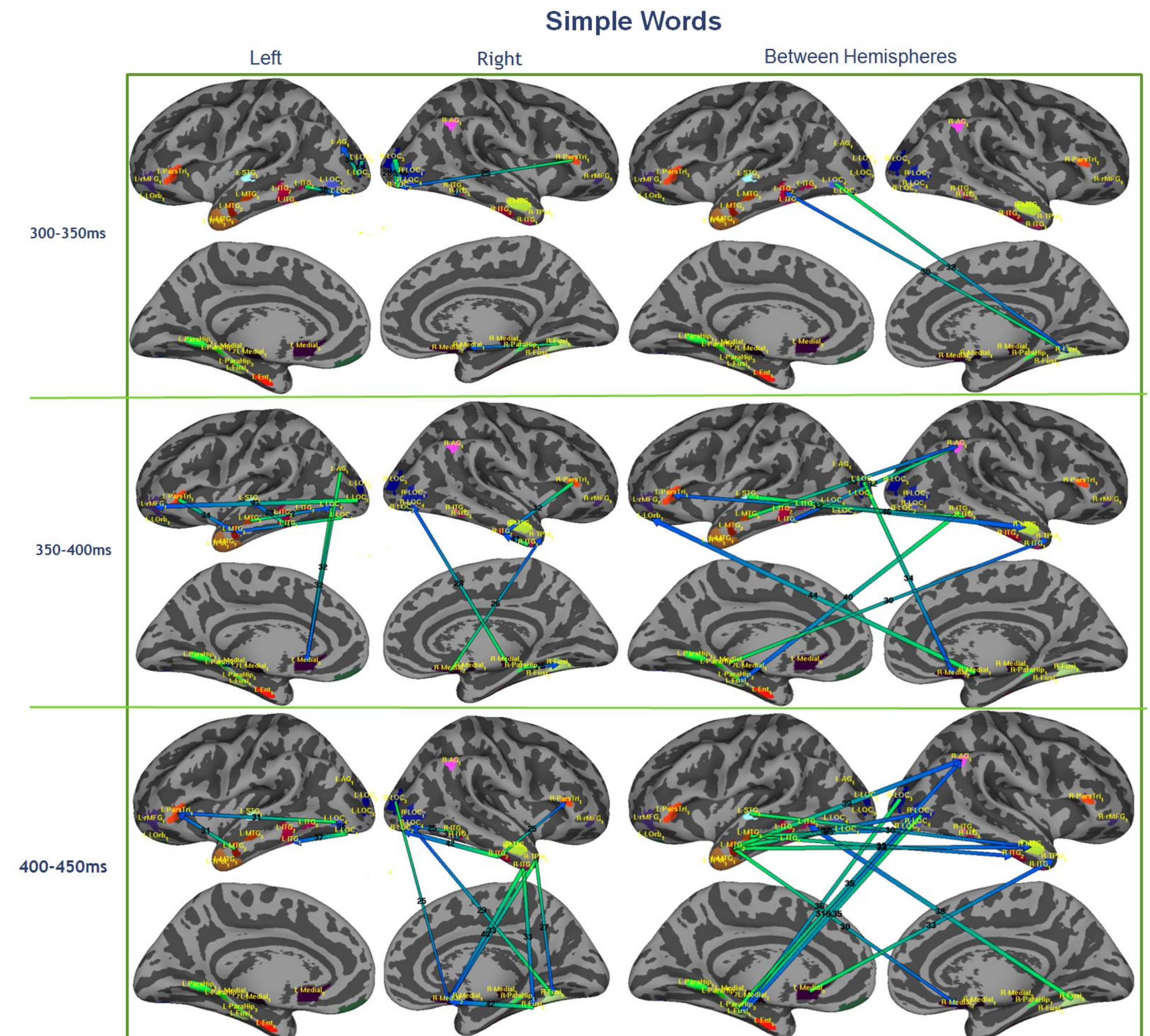
- 300-350ms there is little significant within-hemisphere connectivity.
- 350-400ms connectivity between anterior temporal and parietal regions suggests lexical and semantic processing .
- 400-450ms high connectivity between BA45 and anterior temporal regions may indicate more combinatorial lexical processing.
- For between-hemispheric connectivity L-MTG and R-AG are active between 350-450ms with highest connectivity after 400ms.
- Higher connectivity of left hemisphere is consistent with a stronger role in semantic and lexical processing.

Complex Words
Left   Right   Between Hemispheres
300-350ms
350-400ms
400-450ms
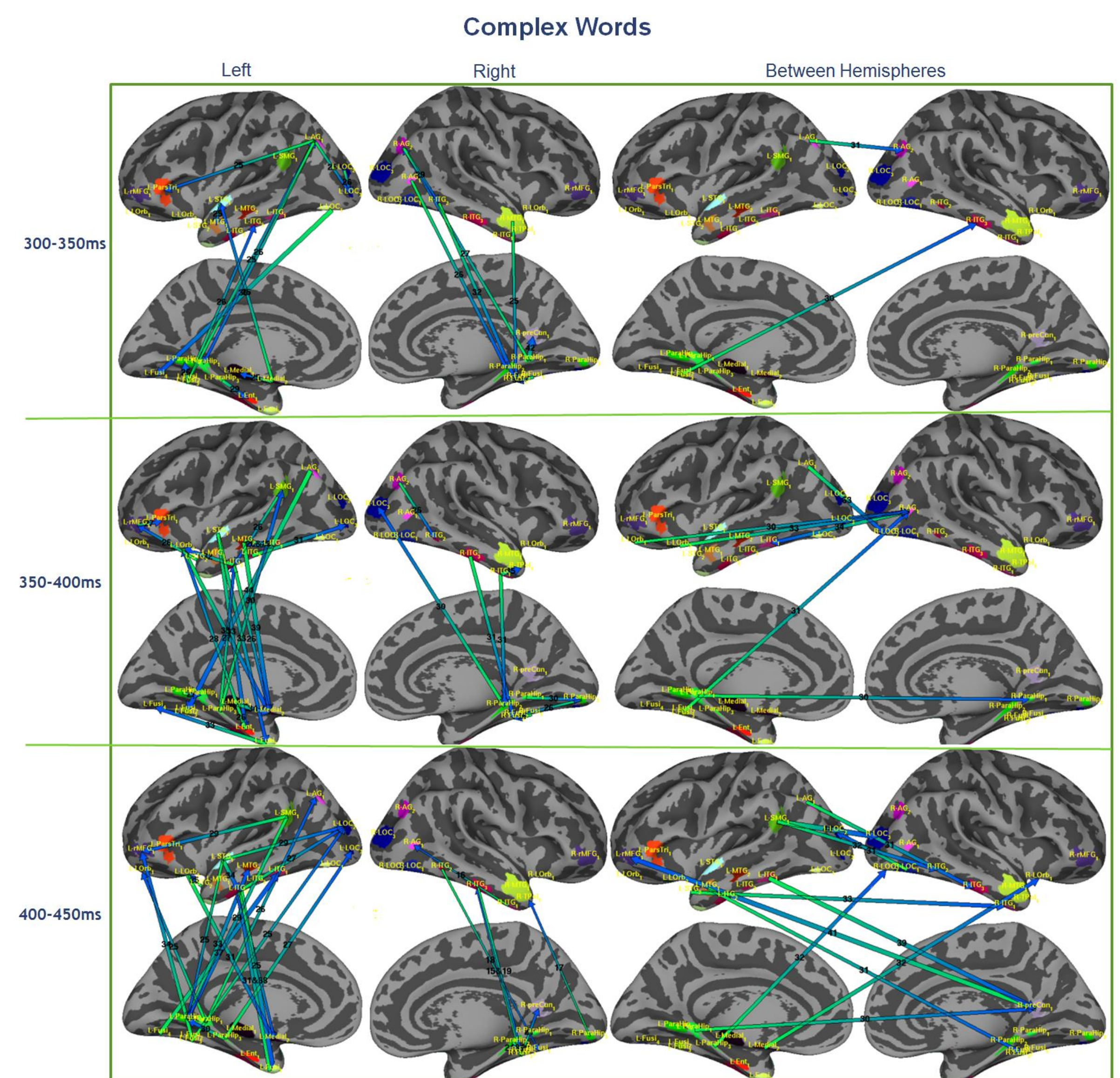
- Within-hemisphere connectivity is much stronger at earlier time points than for simple words, with stronger dorsal-ventral and lateral-medial links.
- 300-350ms connectivity between AG and BA45 area may indicates both combinatorial and cognitive control processing
- 350-400ms connectivity between partial and anterior temporal regions suggests increase in lexical analysis processes.
- 400-450ms higher connectivity between inferior frontal gyrus and temporal regions suggests continued high activity in combinatorial and cognitive control processes.
- Strong asymmetry between LH and RH, especially after 350 ms, consistent with prior evidence for LH dominance in complex word processing.
- Between hemispheres left SMG and right AG are actively connected.
- Between hemisphere activity again increases at later time points.

Conclusions

- There are major differences in the spatio-temporal patterns of functional connectivity exhibited by complex and simple words.
- Complex words engage dorsal ROIs relatively more than simple words.
- Simple words primarily engage LH lateral ventral ROIs
- The advantage of Granger Causal Modelling is that it does not required prior specification of potential neurobiological interpretations (like Dynamic Causal Modelling) and is a weighted directional connectivity analysis of the whole brain with temporal resolution of 1ms (unlike Phase Locking Values connectivity analysis).

References

1. Gow, D.et al. (2012). New levels of language processing complexity and organization revealed by Granger causation. Frontiers in Psychology.
2. Milde, et al. (2010). A new Kalman filter approach for the estimation of high-dimensional time variant multivariate AR models and its application in analysis of laser-evoked brain potentials. NeuroImage,.
3. Whiting, C., Shtyrov, Y., & Marslen-Wilson, W.D. (2014). Real-time functional architecture of visual word recognition. Journal of Cognitive Neuroscience.