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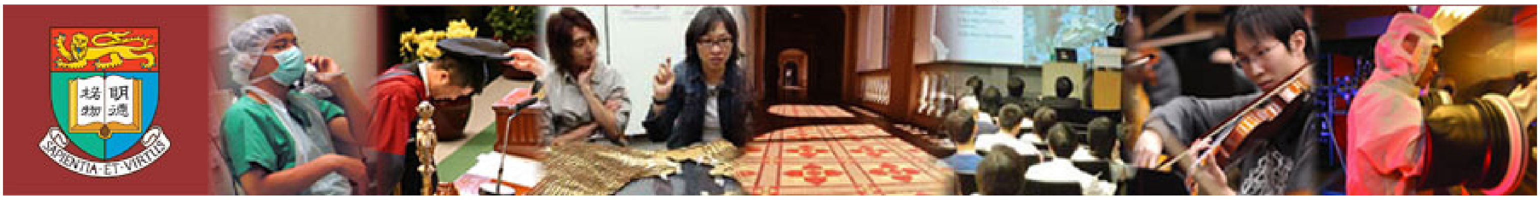

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Author(s)	Qiu, D; Ngan, SSC; Tan, LH; Chan, AH; Mak, HK; Khong, PL
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Brain connectivity during the processing of nouns and verbs: a dynamic Bayesian network analysis

D. Qiu[1], S-C. Ngan[1], L-H. Tan[2], A. H. Chan[2], H. K. Mak[1], and P-L. Khong[1]

[1]Diagnostic Radiology, The University of Hong Kong, Hong Kong, Hong Kong, China, People's Republic of, [2]Linguistics, The University of Hong Kong, Hong Kong, Hong Kong, China, People's Republic of

Introduction: The human brain can be considered as a distributed processing system, where different regions specialize in different functions and interact with each other through the white matter. Studying how these brain regions interact with each other could shed light on understanding how the brain works. In this study, by imposing simplifying assumptions on the dynamic Bayesian network (DBM) technique, we arrived at an efficient algorithm and used it to investigate the effective connectivity of various brain regions during language processing.

Methods:Eleven undergraduate students were recruited for a language fMRI study[1]. The experiment was performed with a 1.5T scanner (GE) using a gradient-echo EPI sequence (TR/TE/FA=3000ms/60ms/90deg, in-plane resolution = 4.3mm×4.3mm, slice thickness=5mm, 24 axial slices). The subjects were asked to perform a lexical decision task in which they judged whether or not a visually presented stimulus was a real word and responded as quickly and accurately as possible by pressing a key. We used a block design with two experimental conditions, in which the displayed words, if real, were noun and verb respectively, and a baseline condition. Three blocks was prescribed for each experimental condition, each block preceded by one block of the baseline condition. Each block lasted for 45 seconds. The fMRI data was processed to detect activated regions using SPM. Six of the activated regions during noun processing and nine during verb processing were selected and time course extracted. The regions selected for the noun task included two regions in left middle frontal gyrus (LMFG1,LMFG2), left medial frontal gyrus (LMedFG), left precentral gyrus (LPrcG), left inferior parietal gyrus (LIPG), left cerebellum (LCrblm), right cerebellum (RCrblm). The regions selected for the verb task included LMFG, LMedFG, LPrcG, right medial frontal gyrus (RMedFG), right precentral gyrus (RPrcG), LIPG1, LIPG2, LCrblm and RCrblm.

Dynamic Bayesian network models time-varying variables as a stochastic process and uses graphical model to encode the dependences between variables as arrows. Consider *n* time courses X_i , *i*=1,2,…,n, and let $X(t)=\{x_i(t), i=1,2,...,n\}$ denote a vector of the node variables X_i 's at time *t*, where *i=1,2…,n,* and *t = 1,2…,T.* If the conditional probability $p(x_i(t) \mid X(1), X(2), ...X(t-1))$ depends on $x_j(p)$, then an arrow from $x_j(p)$ to $x_i(t)$ is drawn. Our task is to infer the network structure (and hence the brain connectivity pattern) from data. In this study, we considered first order Markov process. Under such a setting, we allowed connections from $X(t-1)$ to $X(t)$, but not from older time points. Also, we do not include hidden nodes, so that the network structure inference problem is decomposable and can be solved in exponential instead of super-exponential time. Specifically, the connection patterns from the parent nodes can be determined for each child node separately, leading to computational complexity of $n \times 2^n$, rather than ~ $2^{n \times n}$ (*n*=number of nodes). We exhaustively generated all possible connectivity models and used the fMRI time courses extracted above to learn the most likely connectivity patterns for noun and verb processing separately. The Bayesian information criteria (BIC) score is used to select the best models.

Result: The best models produced for noun and verb processing are shown in Fig 1 and Fig 2, respectively. The squares indicate the stimuli, and the circles indicate the brain regions activated during the task and chosen for the connectivity analysis. Circles with light blue background indicates that the regions were in the left lateral aspect of the cortex, pink in the medial aspect and dark blue the right lateral aspect. The same color was used for connections from the same region/stimulus. All regions had connections pointing to themselves and are not shown in the figures.

- For the noun task, our model showed that the stimulus of noun words directly influenced LIPG, LPrcG and LMedFG, and then the influence propagated anteriorly to LMFG1 and LMFG2. LMedFG influenced LMFG1 which in turn influenced LMFG2. A direct connection from LMedFG to LMFG2 was also found. The LPrcG connected to LIPG, LMFG2 and LCrblm. All regions had connections from and/or to the cerebellum. Interestingly, there was no connection between LCrblm and RCrblm.
- For verb processing, the overall pattern of connections was similar to that of noun. The stimulus of verb words directly influenced LIPG1, LIPG2, LPrcG and RPrcG. These regions then radiated connections anteriorly to LMedFG, RMedFG, and LMFG. The LMedFG had large number of connections from and/or to other regions, including LPrcG, RPrcG, RMedFG, LMFG and LCrblm. In contrast to noun processing, more connections from and/or to LPrcG and RPrcG as well as feedback connections from the cerebellum were found.

Discussion: We successfully applied DBN to learn the effective connectivity of brain regions during the processing of noun and verb words. A main advantage of our method over other methods is that with our simplifying assumptions, the structure inference problem becomes decomposable, effectively reducing the problem complexity from super-exponential to exponential. Hence, when a moderate number of brain regions (up to 20+) are under consideration, all possible connectivity patterns among the regions can be tried and compared to select the best connectivity model. This is not possible when the structure learning problem is not decomposable or properly decomposed [2]. The best models estimated by our methods for noun and verb processing clearly suggest a posterior to anterior flow of language processing, supporting previous linguistic hypotheses[3]. Our result suggests that LMedFG plays an important role in the brain network during the processing of both noun and verb. During verb processing, connections of other regions with left and right precentral gyrus involving primary motor cortex suggest imagining of actions related to the verbs heard may be carried out and feedback sent to other regions for further analysis. More feedback connections from cerebellum in verb processing compared to noun processing also indicate the importance of motor processing in the understanding of verb.

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