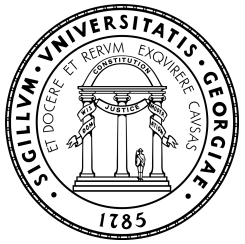
Diathesis Alternations and Selectional Restrictions in Sentence Processing: A fMRI Study

Shohini Bhattasali
Cornell University

John Hale
University of Georgia



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Introduction

- Human study of natural language comprehension
- Brain areas that correspond to different aspects of sentence processing, as exemplified through verbs
- Present neuroimaging study using fMRI

Background

- Verbal argument structure
  - Diathesis alternations

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  - Diathesis alternations

break

1. Fred broke the window
   AGENT THEME
2. Fred broke the window with a rock
   AGENT THEME INSTRUMENT
3. The rock broke the window.
   INSTRUMENT THEME
4. The window broke.
   THEME
5. The window was broken by Fred.
   THEME AGENT

Background

- Verbal argument structure
  - Diathesis alternations
  - Selectional restrictions
    - *pour, sing* vs. *make, give*

General Approach

- Incorporating computational linguistics:
  - Operationalize cognitive hypotheses
  - Often based on incremental, expectation-based theories of sentence comprehension (Hale, 2001; Levy, 2008)
  - Statistical/probabilistic language models (along with information-theoretic complexity measures)
  - Estimate word-by-word comprehension difficulty during real time language processing,

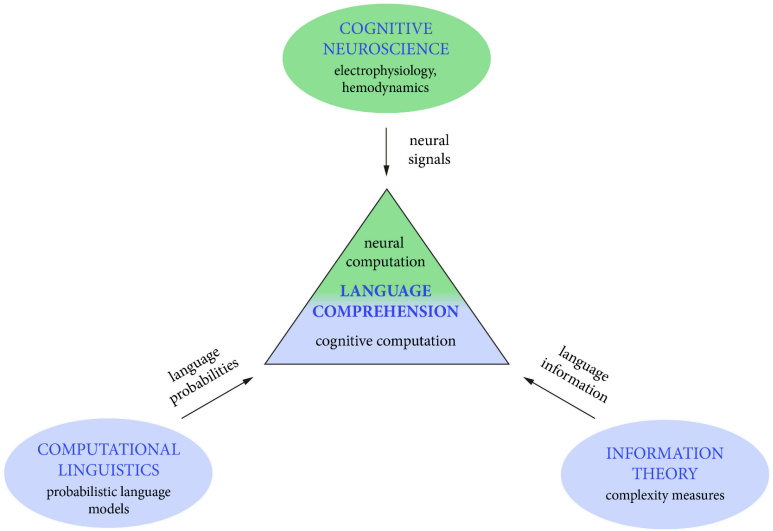

Fig. 1: Schematic depiction from Armeni et al., (2017)

General Approach

- Using naturalistic stimulus:
  - Computational modeling makes it easier to study the brain responses to naturalistic stimuli (Brennan, 2016)
  - Ecologically valid stimuli
  - Complement experimental approaches with controlled task-based designs
  - Easily reusable and shareable for different research questions

Research Question

- Do diathesis alternations and selectional restrictions on a verb have different neural bases?

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- Do diathesis alternations and selectional restrictions on a verb have different neural bases?
  - Use PropBank (Kingsbury, 2002) & Resnik (1996)'s selectional preference strength metric

fMRI Experiment

- Dataset:
  - The audio stimulus was Antoine de Saint-Exupery's The Little Prince, translated by David Wilkinson and read by Nadine Eckert-Boulet.
  - 1970 verbs attested in the story (401 unique); excluding modals, auxiliaries, and gerunds using the NLTK tagger & Stanford POS tagger

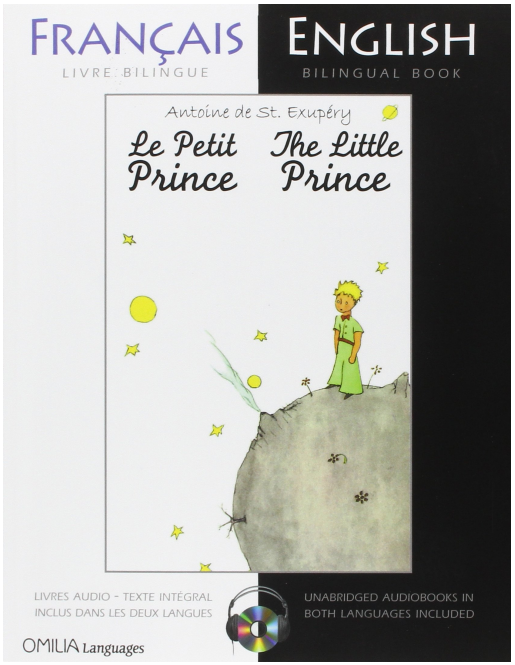


Fig. 2: Cover of *The Little Prince*

fMRI Experiment

- Experimental Design:
  - Participants (n=51, 32 female) were college-aged, right-handed, native English speakers
  - Listened to *The Little Prince*'s audiobook for 1 hour 38 minutes across nine sections. (15,388 words total; 1,453 sentences)
  - Comprehension was confirmed through multiple-choice questions (90% accuracy, SD 3.7%).

fMRI Experiment

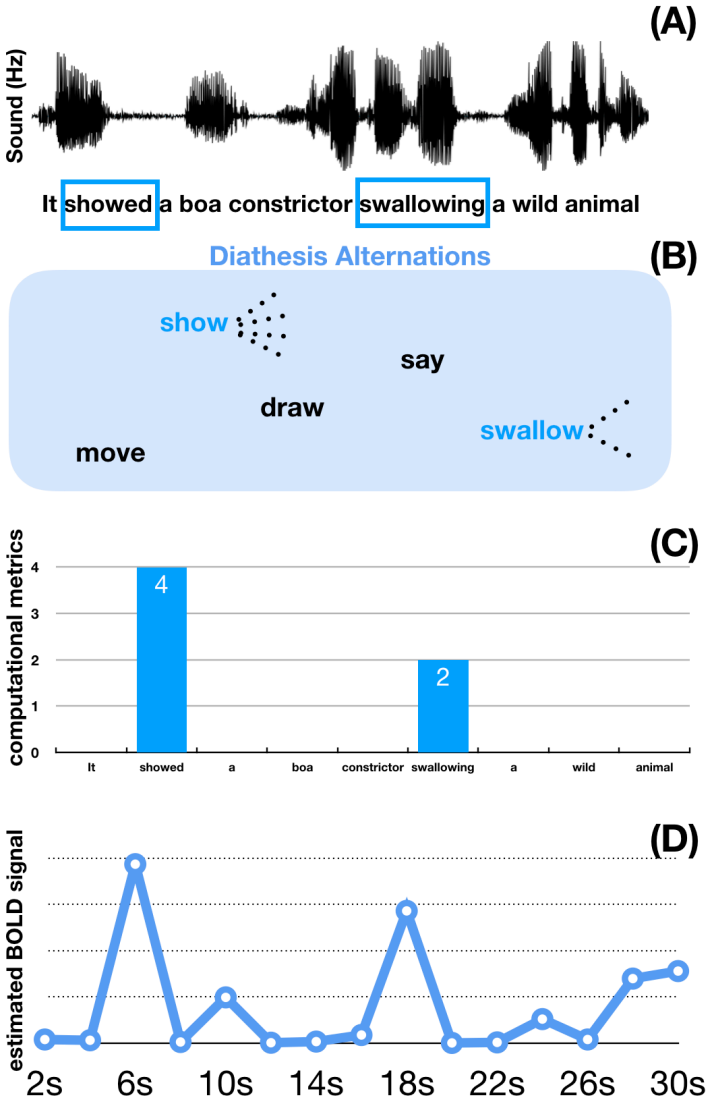


Fig. 3: Pipeline adapted from Bhattasali et al. (2018)

- Overview of analysis:
  - The General Linear Model (GLM) typically used in fMRI data analysis is a time series linear regression (Poldrack et al., 2011).
  - The regressors are convolved with the canonical HRF to create the estimated fMRI signal (BOLD), which is compared against the observed BOLD signal during passive story listening.

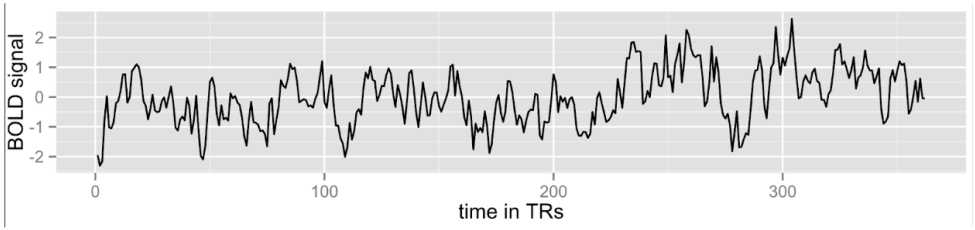


Fig. 4: Sample BOLD signal

fMRI Experiment

- Data Analysis:
  - Preprocessing was carried out with AFNI version 16 and ME-ICA v3.2 (Kundu et al., 2011)
    - Images were normalized to the MNI–152 template
    - ME-ICA denoises T2* signal using ICA into BOLD and noise components from physiology, motion, scanner artifacts
  - Statistical analyses carried out in SPM12 (Friston et al., 2007).
  - 8 mm FWHM Gaussian smoothing kernel was applied on the contrast images from the first-level analysis to counteract inter-subject anatomical variation.
  - Group-level results reported underwent FWE voxel correction for multiple comparisons which resulted in T-scores > 5.3

Statistical Analysis

- GLM Regressors:
  - PropBank score: Represents the number of diathesis alternations for a verb
  - Selection preference strength: Represent selectional restrictions on a verb
  - Word rate: Indicator of spoken word offset
  - Word frequency: log-frequency in movie subtitles (Brysbaert & New, 2009)
  - f0: fundamental frequency of the narrator's voice,reflects pitch
  - RMS amplitude: intensity, an acoustic correlate of volume

Statistical Analysis

- PropBank scores: Calculated from PropBank (Kingsbury, 2002), which consists of all the sentences from the Penn Treebank annotated with semantic roles with higher scores indicating more diathesis alternations.

Statistical Analysis

- PropBank scores
- *hang* ⇛ 8
  - **hang,** *suspend, suspending*
  - **hang**, *exist, be*
  - **hang_on** , *wait*
  - **hang_on,** *maintain possession of*
  - **hang_up,** *terminate a phone call*
  - **hang_up**, *stuck on*
  - **hang_out,** *spend time socially*
  - **hanging**, *execution*

Statistical Analysis

- Selectional preference strength: Calculated according to Resnik (1996) by estimating verb-direct object pairs from the Gigaword (Ferraro et al., 2014) & WaCkypedia (Baroni et al., 2009) corpora and then calculating the number of different WordNet semantic classes a given verb's direct objects falls into.

$$\Pr(v,c) = \frac{1}{N} \sum_{n \in \text{words}(c)} \frac{1}{|\text{classes}(n)|} \text{freq}(v,n)$$

Statistical Analysis

- Selectional preference strength:

- *pour*: <pour, juice>, <pour, milk>, <pour, water>, …

{*act, action, activity*}	{*natural object*}
{*animal, fauna*}	{*natural phenomenon*}
{*artifact*}	{*person, human being*}
{*attribute, property*}	{*plant, flora*}
{*body, corpus*}	{*possession*}
{*cognition, knowledge*}	{*process*}
{*communication*}	{*quantity, amount*}
{*event, happening*}	{*relation*}
{*feeling, emotion*}	{*shape*}
{*food*}	{*state, condition*}
{*group, collection*}	{*substance*}
{*location, place*}	{*time*}
{*motive*}	

Table 1: The 25 noun semantic classes in WordNet (Miller, 1993)

Statistical Analysis

- Diathesis alternations vs Selectional restriction

Verb	PropBank scores	Selectional Preference Strength
pour	0.22	1
hang	0.33	0.91
call	1	0.52
catch	0.89	0.27
read	0.11	0.49
open	0.33	0.48
make	0.33	0.54
give	0.44	0.28

Table 2: Comparing diathesis alternation and selectional restriction metrics

Results

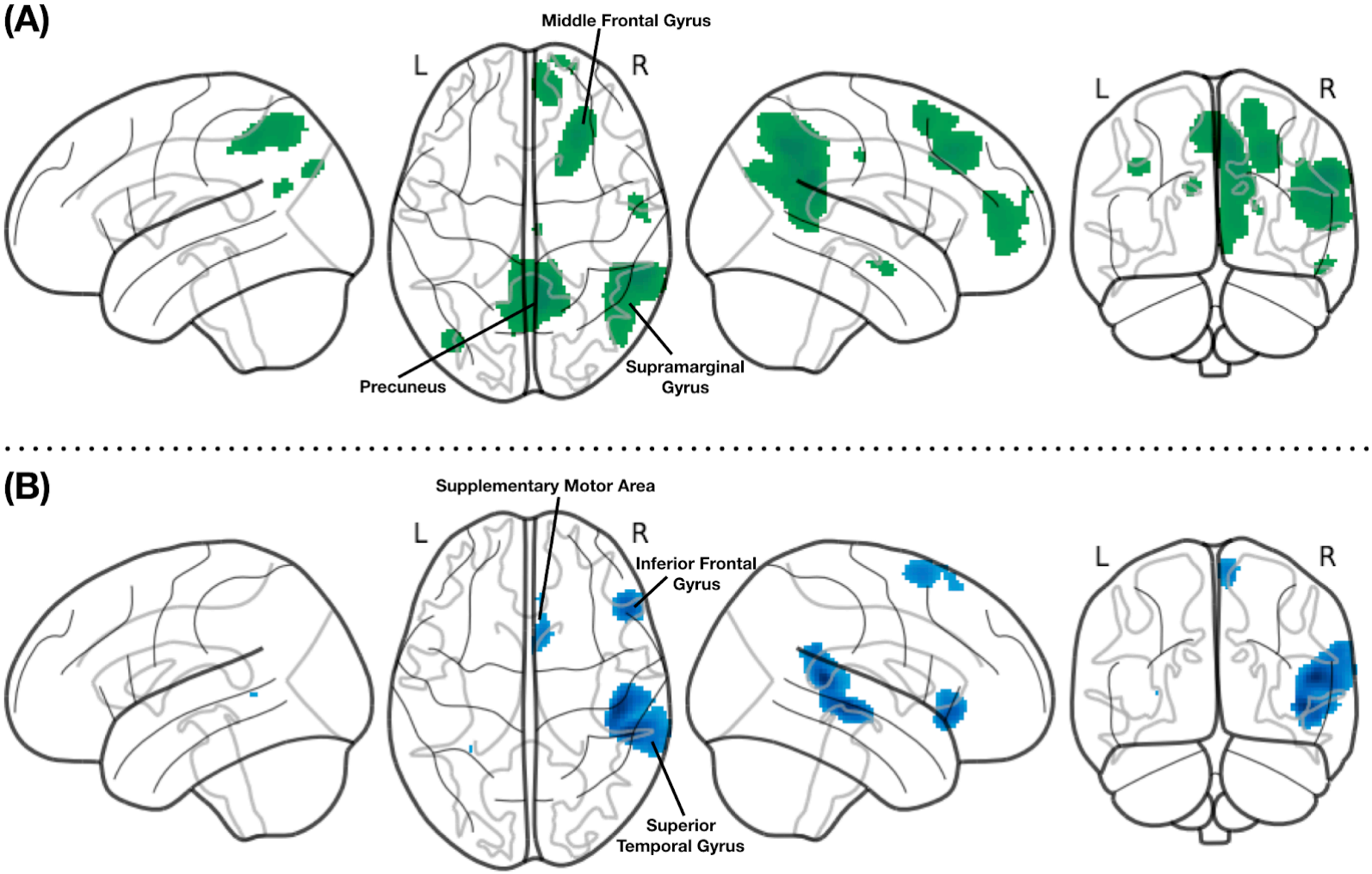
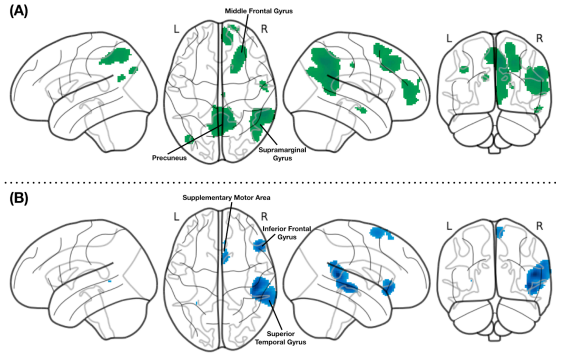


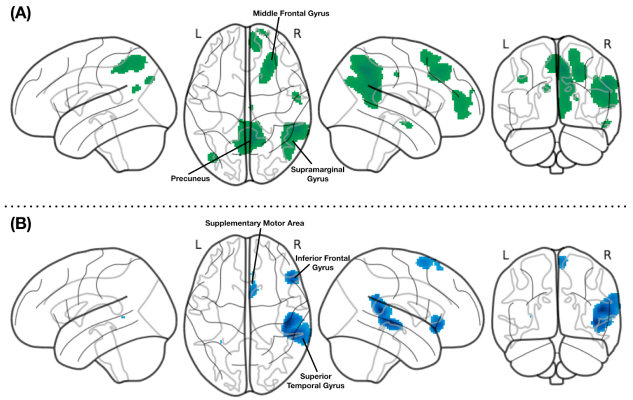
Fig. 5: (A): Whole-brain contrasts for diathesis alternations in green
(B): Whole brain contrasts for selectional restriction in blue

Results



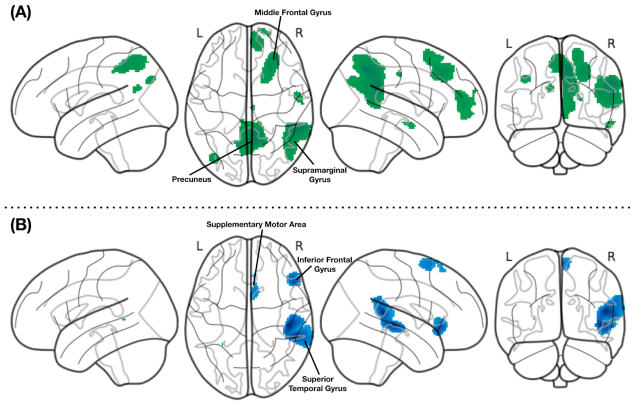
- Results:
  - Significant clusters for the diathesis alternations were observed in the right Supramarginal Gyrus and Middle Frontal Gyrus and bilateral Precuneus
  - Significant clusters for selectional restrictions were observed in the right Superior Temporal Gyrus, Inferior Frontal Gyrus, and Supplementary Motor Area

Results



- Results:
  - Diathesis alternations results corroborate previous neuroimaging studies related to semantic roles and subcategorization (Shetreet et al., 2006; Thompson et al., 2010; Thompson et al., 2007; Meltzer-Asscher et al., 2013)
  - Previous studies were controlled, task-based, block design experiments (e.g., lexical decision); our results replicate the findings with ecologically valid stimulus

Results



- Results:
  - Selectional restrictions are consistent with other neuroimaging studies related to lexical-semantic processing (Kuperberg et al., 2000; Baker et al., 2001; Zempleni et al., 2007)

Conclusion

- Diathesis alternations and selectional restrictions evoke different pattern of activation in the brain
- Both metrics operationalize a degree of constraint: form and meaning
- Suggests that C-selection and S-selection have different neurobiological correlates.

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Thank you