fMRI reveals language-specific predictive coding during naturalistic sentence comprehension

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Question

Is incremental linguistic prediction primarily carried out by language-specific or domain-general mechanisms?

Hypotheses

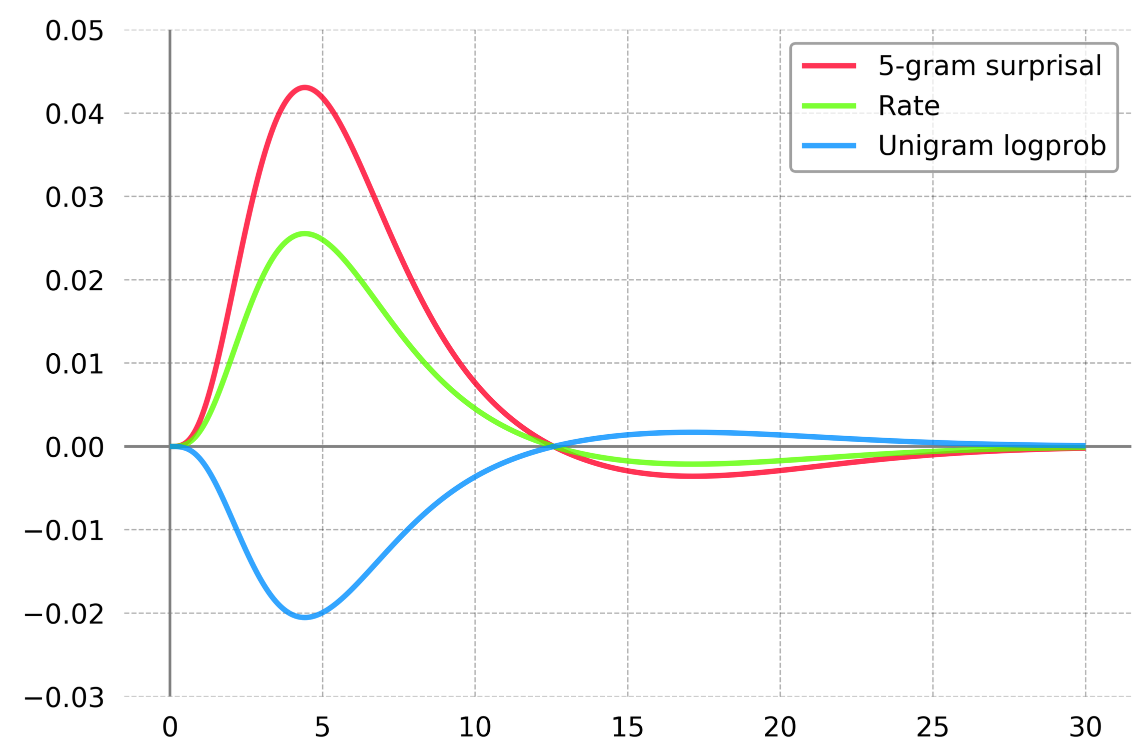
- **Hypothesis 1:** *Primarily language specific.*
  - **Rationale:**
    - Other kinds of prediction (e.g. visual and auditory) are directly implemented in specialized circuits [11, 24]
- **Hypothesis 2:** *Primarily domain general.*
  - **Rationale:**
    - Prediction effects are diminished in populations with reduced executive resources [8, 3, 17]
    - Studies have shown domain-general executive activity during language comprehension [10, 19, 20]

Background

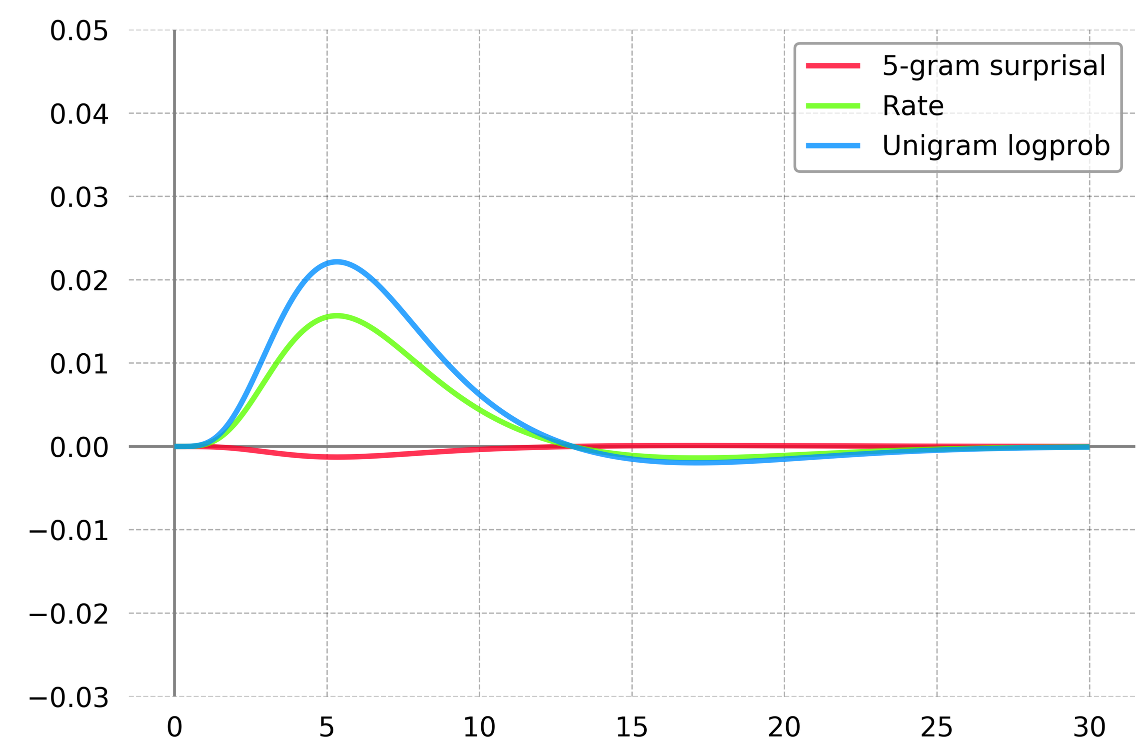
- Two sources of evidence for incremental prediction
  - Behavioral/electrophysiological [14, 16, 27, 21, 5, 25, 26, 6, 13]; cannot precisely localize effects in the brain
  - Neuroimaging with constructed stimuli [12, 18, 22]; may spuriously engage executive resources by increasing cognitive load [9, 2]
- Few naturalistic fMRI studies of word-by-word prediction, mixed results [28, 1, 15]
- **Our contributions:**
  - Naturalistic stimuli
  - Large number of participants (78)
  - Functional localization for each participant
  - Data-driven HRF identification
  - Rigorous out-of-sample statistical tests

Experimental Design

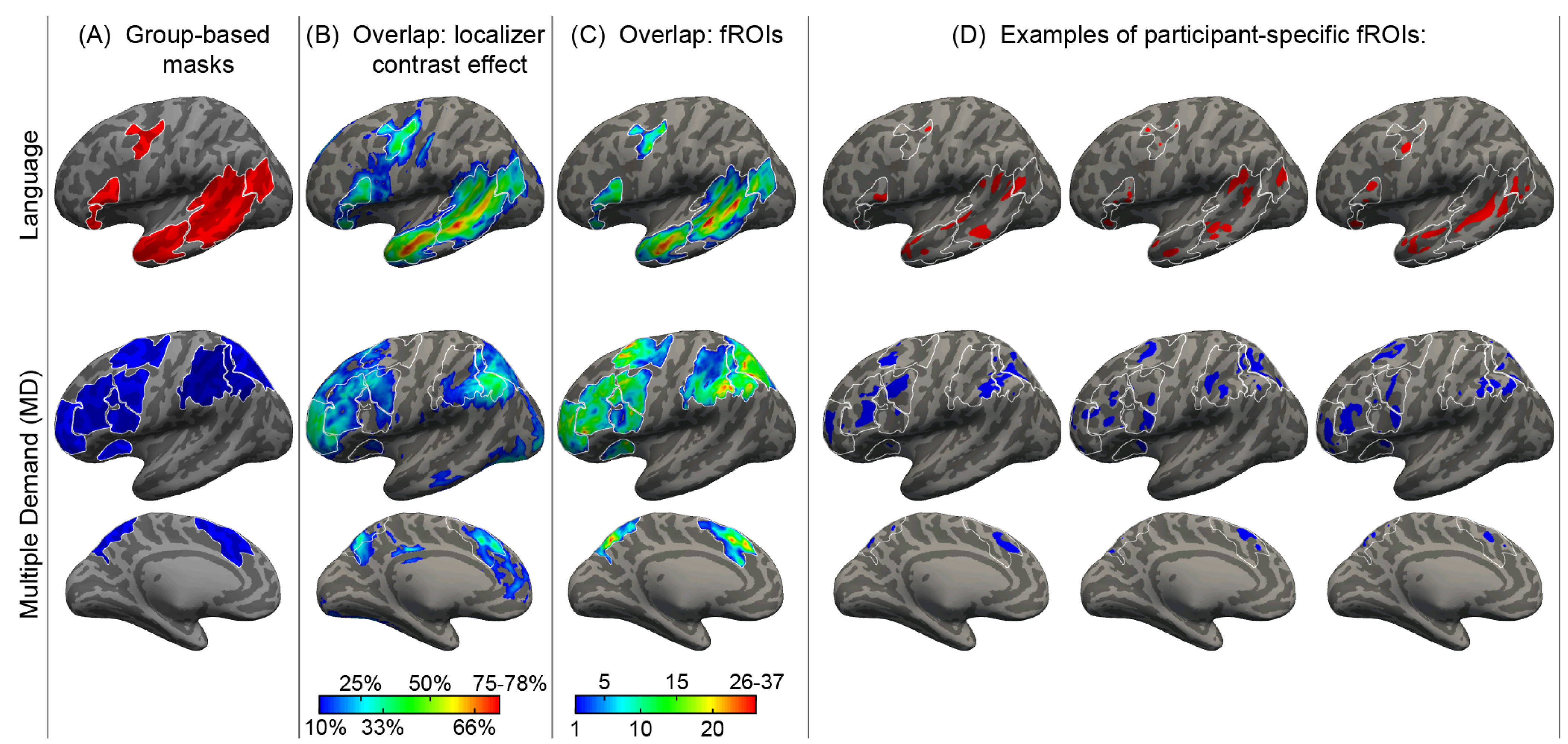
- 78 participants (30 male)
- Audio presentation of Natural Stories corpus [7]
- Functionally localized participant-specific regions of interest (fROI) in language network (**LANG**) and domain-general multiple-demand network (**MD**) [4]
- Data-driven HRF identification
  - Deconvolutional time series regression [23]
- Predictors: TR index, sound power, word rate, word frequency, 5-gram surprisal, network (LANG vs. MD), by-participant random intercepts
- Response: Blood oxygen level dependent contrast imaging (BOLD)
- 3 ablative out-of-sample hypothesis tests on 1/2 data:
  - Surprisal in LANG responses
  - Surprisal in MD responses
  - Surprisal:Network in LANG+MD



Mean HRF in LANG



Mean HRF in MD



Functionally localized ROIs. Localizer task: sentences vs. nonword lists. LANG contrast: sent > nonword. MD contrast: nonword > sent.

Results

Comparison	*p*	LL Improvement	Effect Estimate
Surprisal (LANG)	0.0001***	108.33	0.256
Surprisal (MD)	1.0	-3.23	-0.008
Surprisal by Network (LANG+MD)	0.0001***	86.69	0.231

Main result: There is a significant prediction effect in LANG but not MD, and a significant difference in prediction effect between LANG and MD.

	LANG		MD		LANG+MD	
	% Total	% Relative	% Total	% Relative	% Total	% Relative
Ceiling	6.18	100	1.34	100	2.63	100
Model (train)	3.21	51.9	0.68	50.7	1.06	40.3
Model (test)	1.66	26.9	0.00	0.00	0.52	19.8

LANG model explains 27% of theoretical variance on unseen data, indicating that prediction effect is large.

Conclusion

We find robust prediction effects in LANG (language-specific), no prediction effects in MD (domain-general), and significant differentiation in prediction effects between networks. Results support **Hypothesis 1**: linguistic prediction is primarily carried out by the language network rather than by domain-general executive control.

References

[1] Brennan, J., Stabler, E. P., Van Wagenen, S. E., Luh, W.-M., and Hale, J. T. *Brain and language*, 2016.
[2] Campbell, K. L. and Tyler, L. K. *Current opinion in behavioral sciences*, 2018.
[3] Federmeier, K. D., Kutas, M., and Schul, R. *Brain and language*, 2010.
[4] Fedorenko, E., Hsieh, P.-J., Nieto-Castañón, A., Whitfield-Gabrieli, S., and Kanwisher, N. *Journal of neurophysiology*, 2010.
[5] Frank, S. L. and Bod, R. *Psychological Science*, 6 2011.
[6] Frank, S. L., Otten, L. J., Galli, G., and Vigliocco, G. *Brain & Language*, 2015.
[7] Futrell, R., Gibson, E., Tily, H. J. ., Blank, I., Vishnevetsky, A., Piantadosi, S., and Fedorenko, E. In Calzolari, N., Choukri, K., Cieri, C., Declerck, T., Goggi, S., Hasida, K., Isahara, H., Maegaard, B., Mariani, J., Mazo, H., Moreno, A., Odijk, J., Piperidis, S., and Tokunaga, T., editors, *Proceedings of the Eleventh International Conference on Language Resources and Evaluation (LREC 2018)*, 5 2018.
[8] Gambi, C., Gorrie, F., Pickering, M. J., and Rabagliati, H. *Journal of Experimental Child Psychology*, 2018.
[9] Hasson, U. and Honey, C. J. *NeuroImage*, 2012.
[10] Kaan, E. and Swaab, T. Y. *Trends in cognitive sciences*, 2002.
[11] Keller, G. B. and Mrsic-Flogel, T. D. *Neuron*, 2018.
[12] Kuperberg, G. R., Holcomb, P. J., Sitnikova, T., Greve, D., Dale, A. M., and Caplan, D. *Journal of Cognitive Neuroscience*, 2003.
[13] Kuperberg, G. R. and Jaeger, T. F. *Language, cognition and neuroscience*, 2016.
[14] Kutas, M. and Hillyard, S. A. *Nature*, 1984.
[15] Lopopolo, A., Frank, S. L., den Bosch, A., and Willems, R. M. *PloS one*, 2017.
[16] MacDonald, M. C., Pearlmutter, N. J., and Seidenberg, M. S. *Psychological Review*, 1994.
[17] Martin, C. D., Thierry, G., Kuipers, J.-R., Boutonnet, B., Foucart, A., and Costa, A. *Journal of Memory and Language*, 2013.
[18] Nieuwland, M. S., Martin, A. E., and Carreiras, M. *Human brain mapping*, 2012.
[19] Novick, J. M., Trueswell, J. C., and Thompson-Schill, S. L. *Cognitive, Affective, \& Behavioral Neuroscience*, 2005.
[20] Peelle, J. E., Troiani, V., Wingfield, A., and Grossman, M. *Cerebral Cortex*, 2009.
[21] Rayner, K., Ashby, J., Pollatsek, A., and Reichle, E. D. *Journal of Experimental Psychology: Human Perception and Performance*, 2004.
[22] Schuster, S., Hawelka, S., Hutzler, F., Kronbichler, M., and Richlan, F. *Cerebral Cortex*, 2016.
[23] Shain, C. and Schuler, W. In *Proceedings of the 2018 Conference on Empirical Methods in Natural Language Processing*, 2018.
[24] Singer, Y., Teramoto, Y., Willmore, B. D. B., Schnupp, J. W. H., King, A. J., and Harper, N. S. *eLife*, 2018.
[25] Smith, N. J. and Levy, R. *Cognition*, 2013.
[26] Staub, A. and Benatar, A. *Psychonomic Bulletin \& Review*, 2013.
[27] Tanenhaus, M. K., Spivey-Knowlton, M. J., Eberhard, K. M., and Sedivy, J. C. E. *Science*, 1995.
[28] Willems, R. M., Frank, S. L., Nijhof, A. D., Hagoort, P., and den Bosch, A. *Cerebral Cortex*, 2015.