

Analogy Questions can be Solved with Addition and Subtraction of fMRI Patterns

Meng-Huan Wu¹, Andrew J. Anderson², Robert A. Jacobs¹ & Rajeev D.S. Raizada¹

¹Department of Brain and Cognitive Sciences, University of Rochester

²Department of Neuroscience, University of Rochester

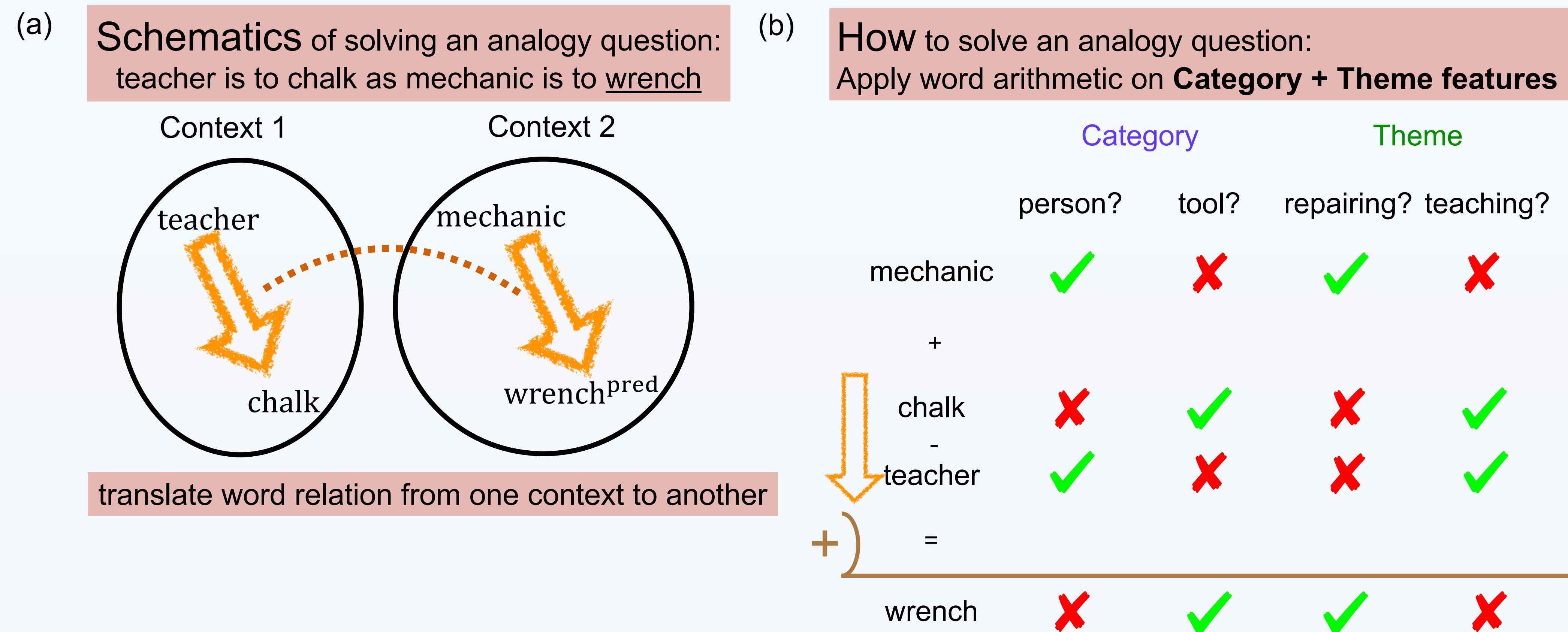


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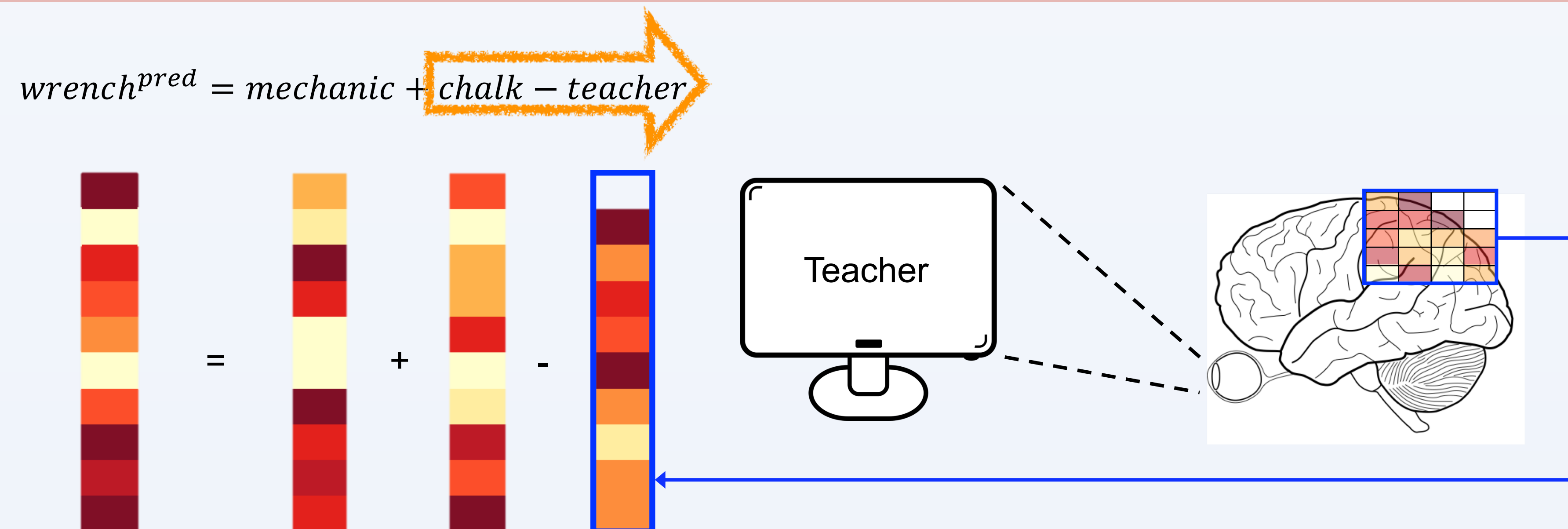
Introduction

- Analogical Reasoning is critical in our daily lives.
- However, how the human brain achieves such processes remains unclear.
- Computational models of word meaning (e.g., word2vec) solve analogical problems using word arithmetic.
- Are words represented in the brain in way that could enable analogical problems to be solved with similar arithmetic?

- **Question 1:** Can analogy questions be solved by adding and subtracting word fMRI patterns?
- **Question 2:** Can analogy questions be solved using word arithmetic within individual brain regions?



(c) **Question:** can analogy questions be solved by applying word arithmetic on **word fMRI patterns?**



- To solve the above analogy questions, it is necessary to integrate BOTH categorical information (person/tool) and thematic information (teaching/repairing).
- Some studies suggested that categorical and thematic information (Schwartz et al., 2011; Kalénine et al., 2009) is anatomically partitioned in the brain, represented in Anterior Temporal and Inferior Parietal regions respectively
- Other studies suggest that categorical and thematic information can also be represented within the same brain region (Anderson et al. 2014; Xu et al., 2018).
- If categorical and thematic information are anatomically partitioned then analogical problem solving will not be possible within the same brain region.

Methods

- (a)
1. ROI selection: language ROIs from Binder et al., 2009
 2. Voxel selection: for each ROI, select 100 voxels most consistently activated across runs
 3. **3 Ranking Metrics**

Predict-identity: Is it a wrench?

corr(wrench^{pred}, garage)
 corr(wrench^{pred}, school)
 corr(wrench^{pred}, wrench)
 corr(wrench^{pred}, chef)
 corr(wrench^{pred}, restaurant)
 corr(wrench^{pred}, skillet)

% rank

Predict-category: Is it a tool?

corr(wrench^{pred}, avg(tool words))
 corr(wrench^{pred}, avg(person words))
 corr(wrench^{pred}, avg(building words))

% rank

Predict-theme: Does it appear in a repairing theme?

corr(wrench^{pred}, garage)
 corr(wrench^{pred}, restaurant)
 corr(wrench^{pred}, gym)

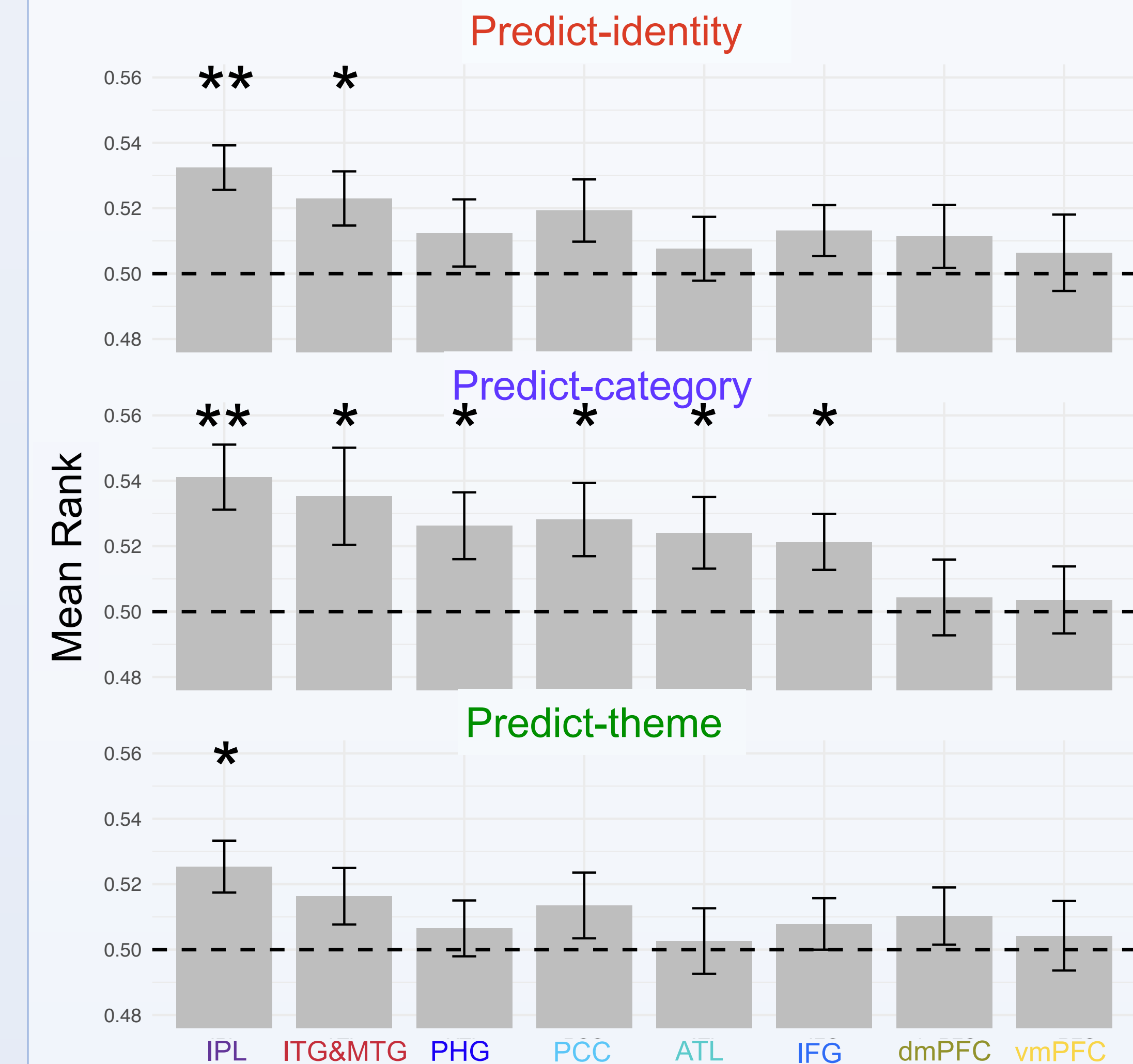
% rank

(b)

		3 Categories		
		Person	Tool	Building
15 Themes	Teach	teacher	chalk	school
	Repair	mechanic	wrench	garage
	Cooking	chef	skillet	restaurant
	...			

Word stimuli were organized into categories and themes

Results



IPL passed all three metrics.

The human brain can locally solve analogy questions with word arithmetic.

Conclusion

- Analogy questions can be solved by adding and subtracting word fMRI patterns. (Q1: ✓)
- Category was significantly predicted in 6/8 brain regions, while theme was predicted in 1/8.
- Word identity, category and theme were all predicted in Inferior Parietal Lobule (IPL), suggesting that the brain could locally solve analogical problems using word arithmetic within this region (Q2: ✓)
- This study contributes toward understanding how the human brain represents words, and leads to predictions for future work on which regions will be engaged in actual analogical reasoning, and what information may be compromised by brain lesions.

References

- Schwartz, M. F., Kimberg, D. Y., Walker, G. M., Brecher, A., Faseyitan, O. K., Dell, G. S., ... & Coslett, H. B. (2011). Neuroanatomical dissociation for taxonomic and thematic knowledge in the human brain. *Proceedings of the National Academy of Sciences*, 108(20), 8520-8524.
- Kalénine, S., Peyrin, C., Pichat, C., Segebarth, C., Bonthoux, F., & Baciu, M. (2009). The sensory-motor specificity of taxonomic and thematic conceptual relations: A behavioral and fMRI study. *Neuroimage*, 44(3), 1152-1162.
- Mikolov, T., Chen, K., Corrado, G., & Dean, J. (2013). Efficient estimation of word representations in vector space. *arXiv preprint arXiv:1301.3781*.