Looking into your mind through *Priming*

LING 348 / 748

Computational Psycholinguistics

Zhenghao Herbert Zhou, Apr 16th 2025

Please read the following words as quickly as you can.

lint

bin

squint

mint

hint

pin

flint

tin

stint

squint

pint

pint !!!

Please name a word that fits into the blanks.

_ a _ g u _ _ e

_ e _ u _ i _ _ l

o _ t _ p _ _

s _ p _ _ m e _

What have we learned…?

What have we learned…?

Priming — the role of Context in language use!

What have we learned…?

Priming — the role of Context in language use!

Origin

LATIN

primus — first → prime — fill, load

early 16th century

early 16th century (in the sense ‘fill, load’): origin uncertain; probably based on Latin *primus* ‘first’, since the sense expressed is a ‘first’ operation prior to something else.

Use over time for: priming

What have we learned…?

Priming — the role of Context in language use!

Collins

5. **transitive verb**

If you prime someone to do something, you prepare them to do it, for example, by giving them information about it beforehand.

Claire wished she'd primed Sarah beforehand.
Marianne had not known until Arnold primed her for her duties that she was to be the sole female.

Synonyms: inform, tell, train, coach More Synonyms of **prime**

6. **transitive verb**

If someone primes a bomb or a gun, they prepare it so that it is ready to explode or fire.

He was priming the bomb to go off in an hour's time.
He kept a primed shotgun in his office.

Synonyms: prepare, set up, load, equip More Synonyms of **prime**

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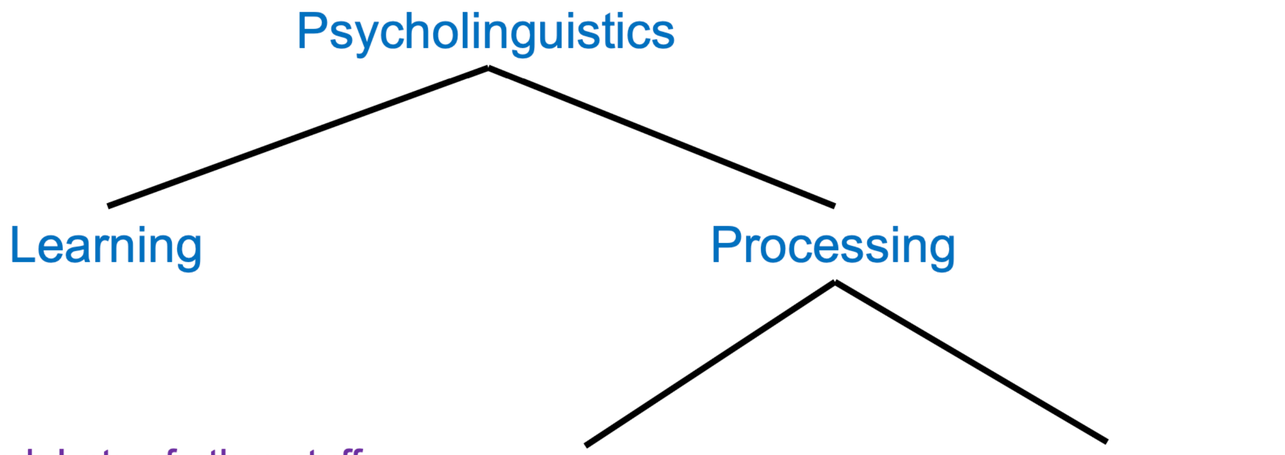
Priming (cognitive psychology): recent experience of a stimuli facilitates or inhibits later processing of the same or a similar stimulus.

Priming in psycholinguistics

Parts of psycholinguistics



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(e.g., interfaces with other
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But today I'll say just a tiny bit about production!

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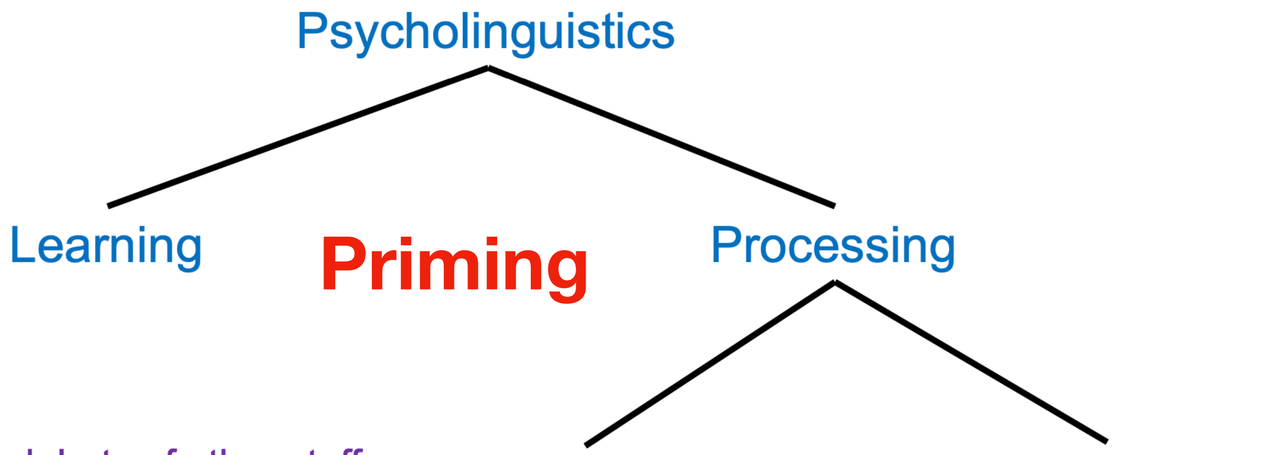

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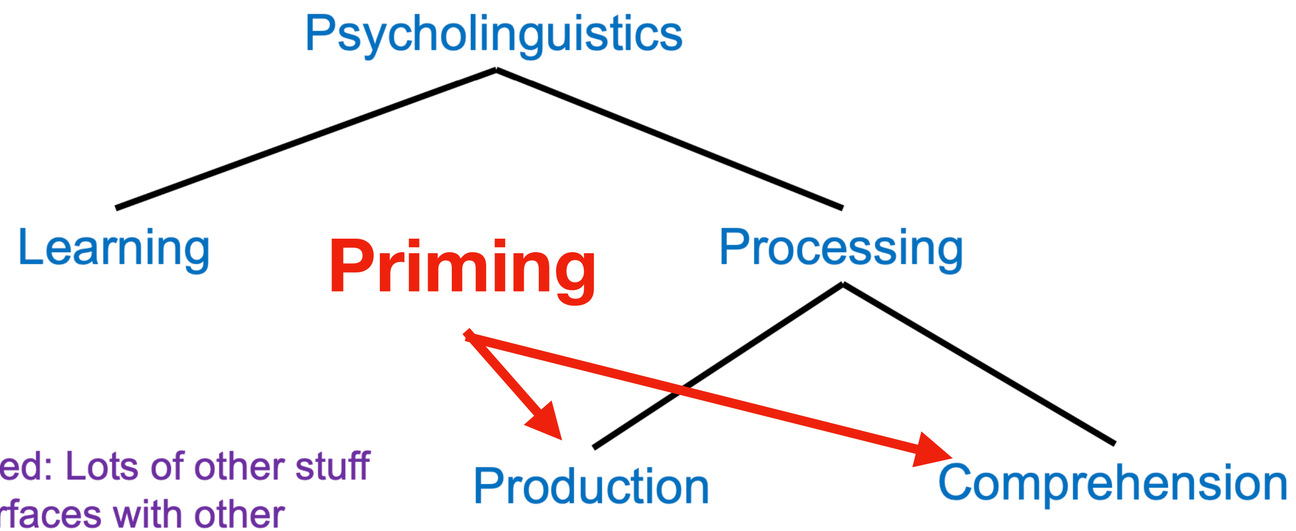

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  - Syntactic Priming

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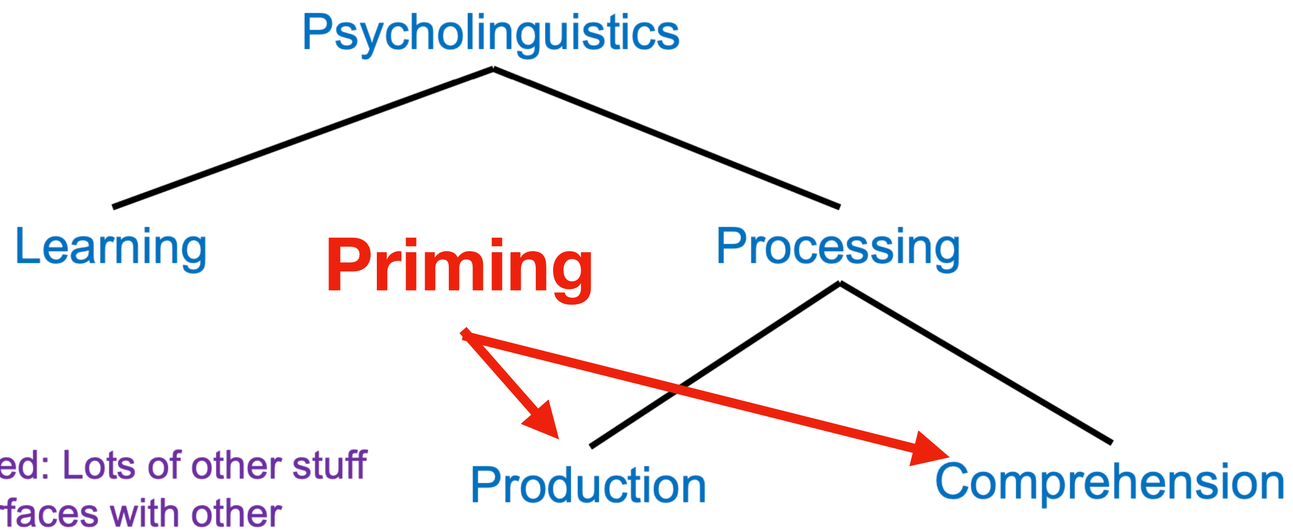

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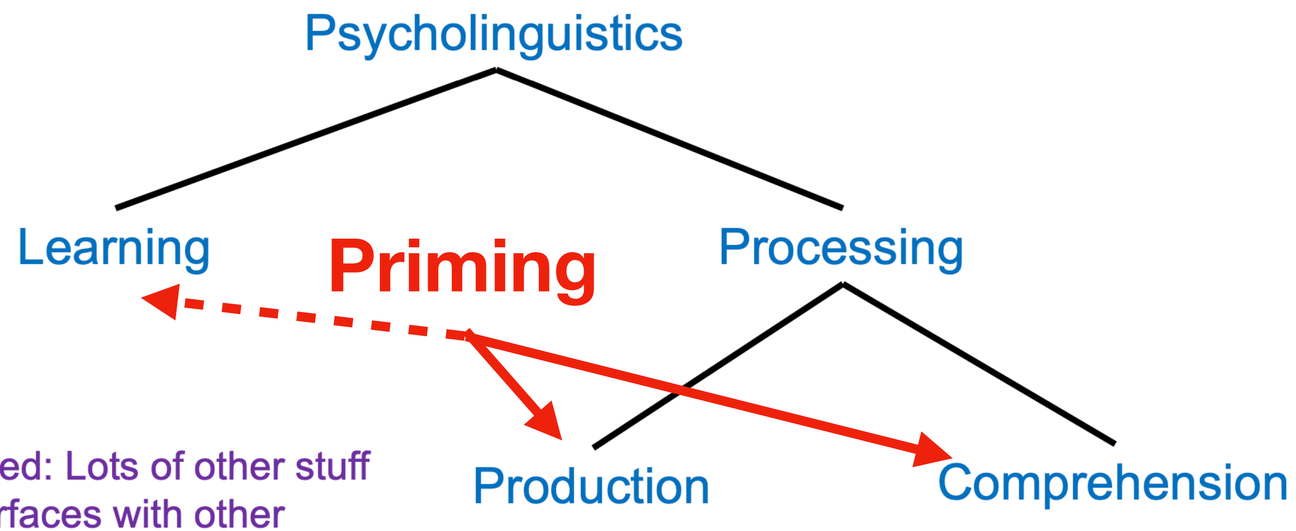

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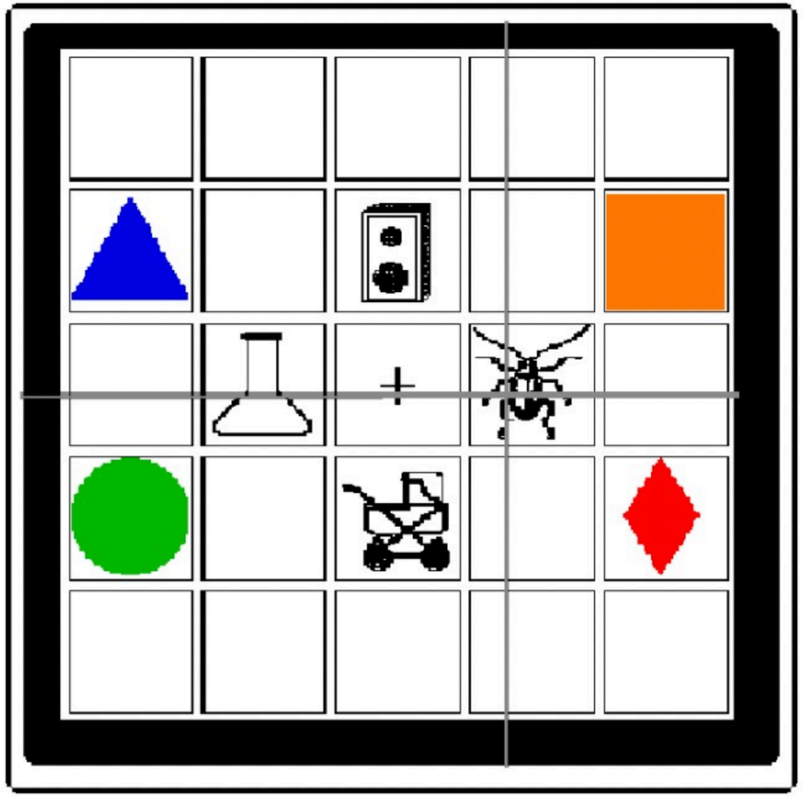
- Priming Language Models?
- To what extent is Priming a type of Learning?

Quick Recap

When we were talking about word recognition….

“Pick up the beaker”

- *Speaker;*
- *Beaker;*
- *Beetle;*
- *Carriage;*



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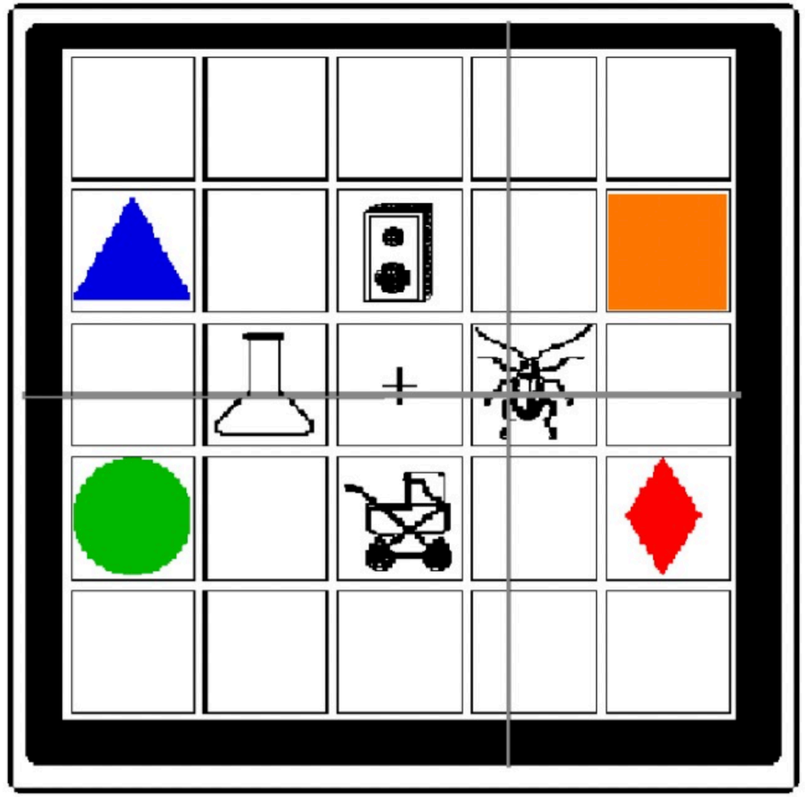

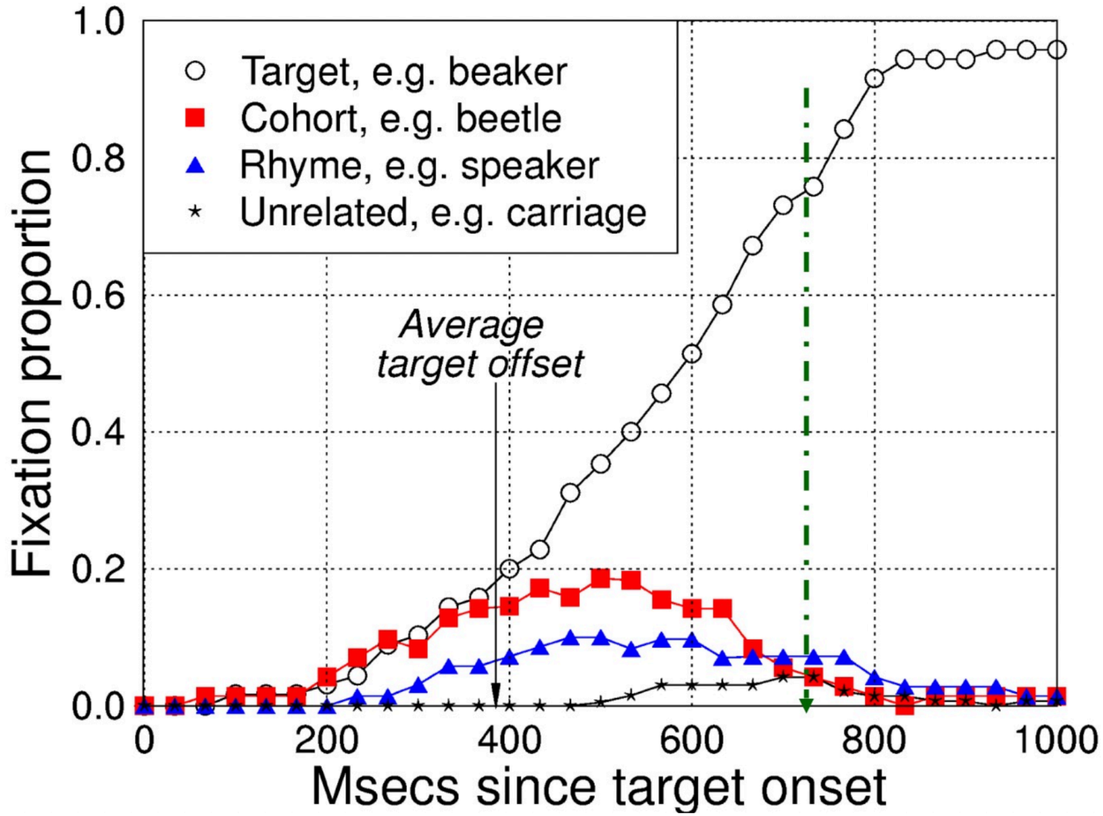

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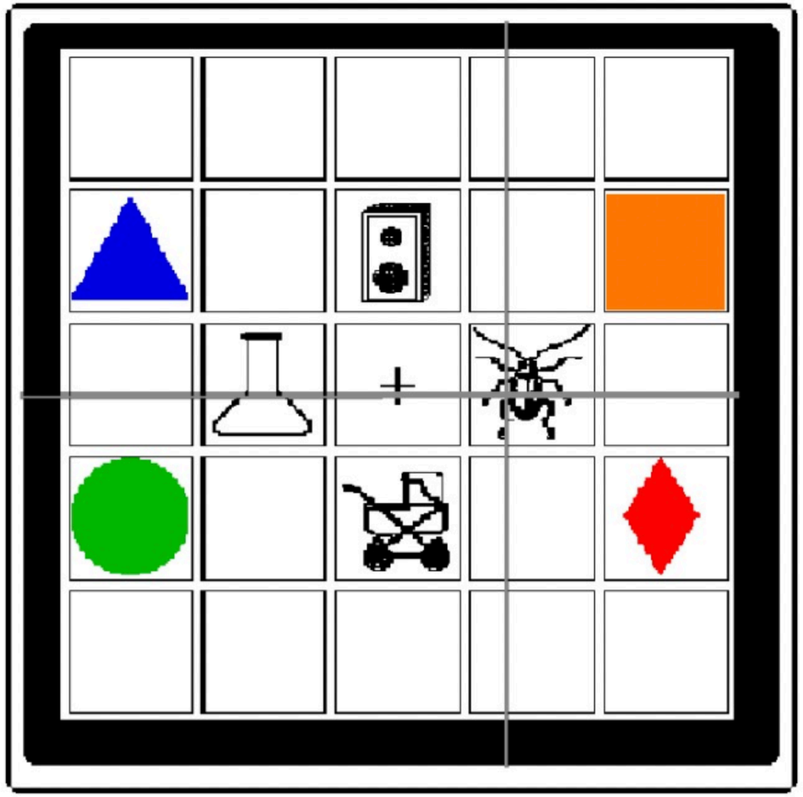

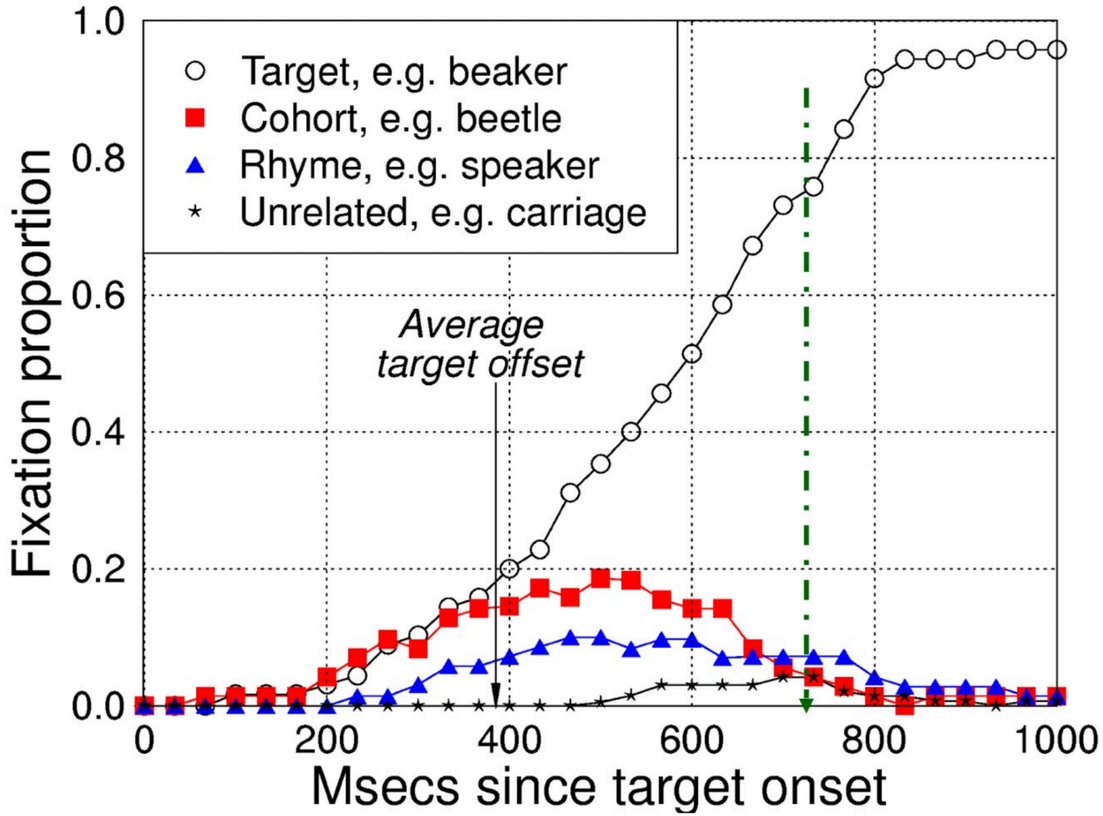

Parallel activations of multiple lexical items!

Semantic Priming

We have a highly interconnected Lexicon

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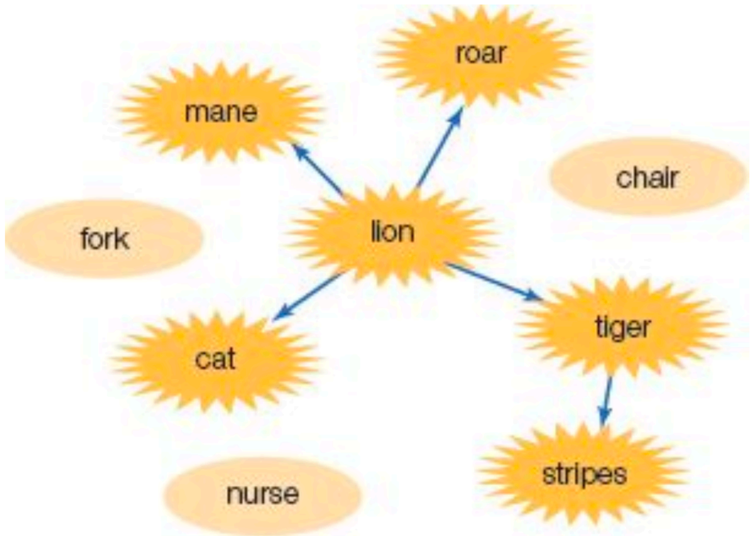

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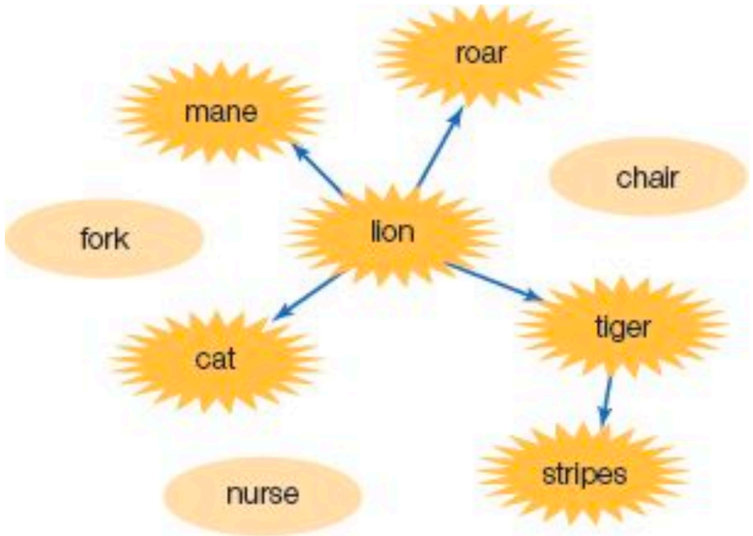
- **Related**: phonological priming, orthographical priming, etc.



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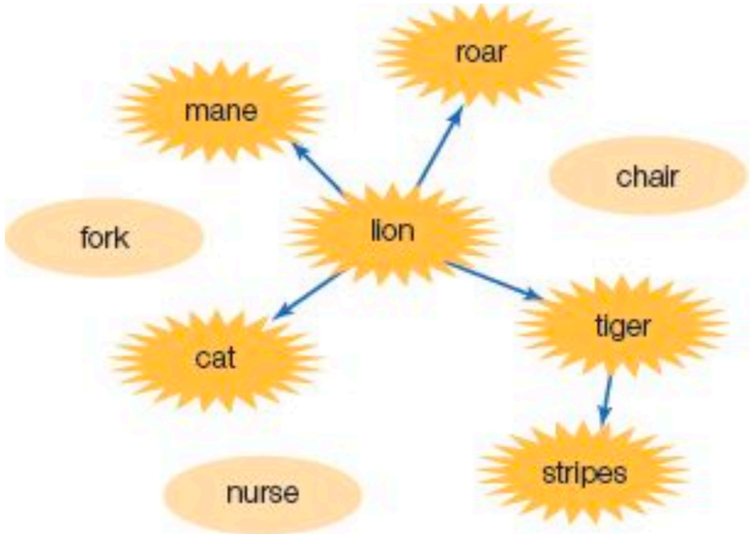

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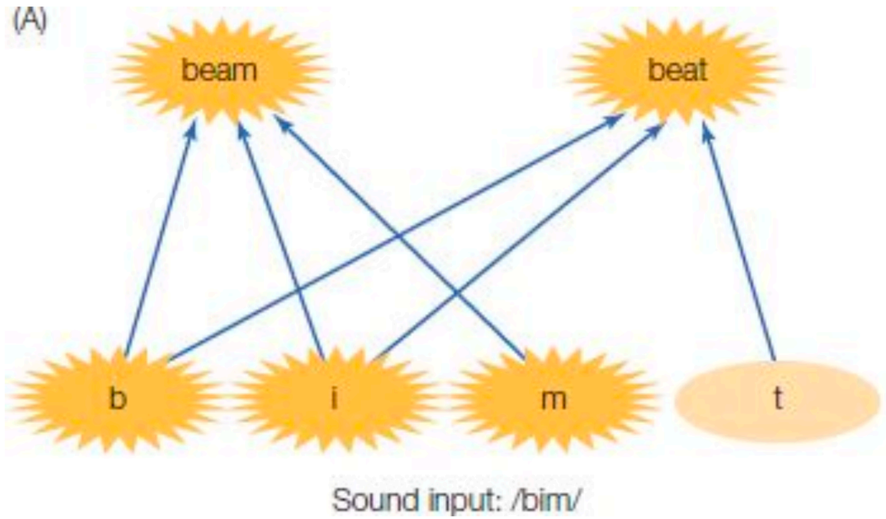

Phonological

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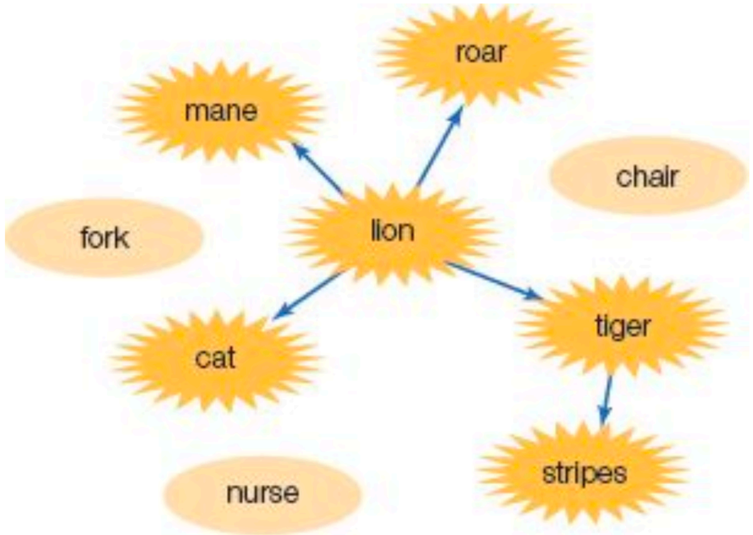

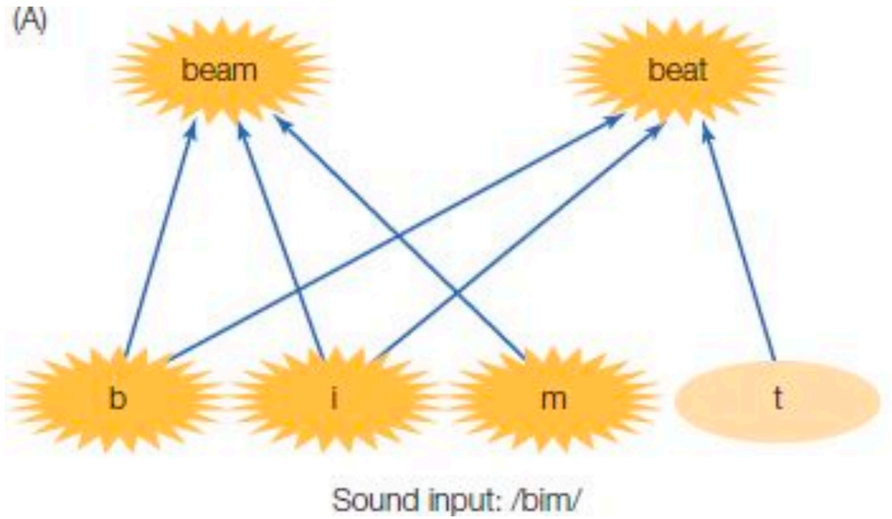

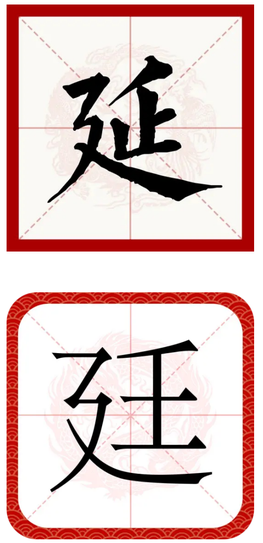

Semantic ***Phonological*** ***Orthographical***

Semantic Priming

Evidence from Myung et al. (2006)

Playing on the typewriter, typing on the piano: manipulation knowledge of objects

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Department of Cognitive and Linguistic Sciences, Box 1978, Brown University, Providence, RI 02912, USA

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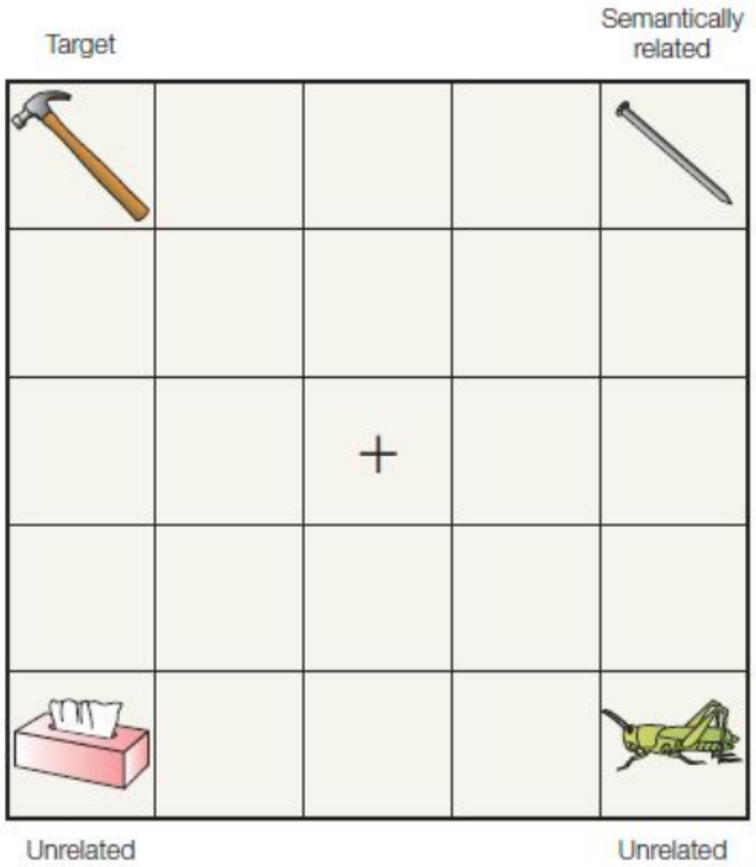

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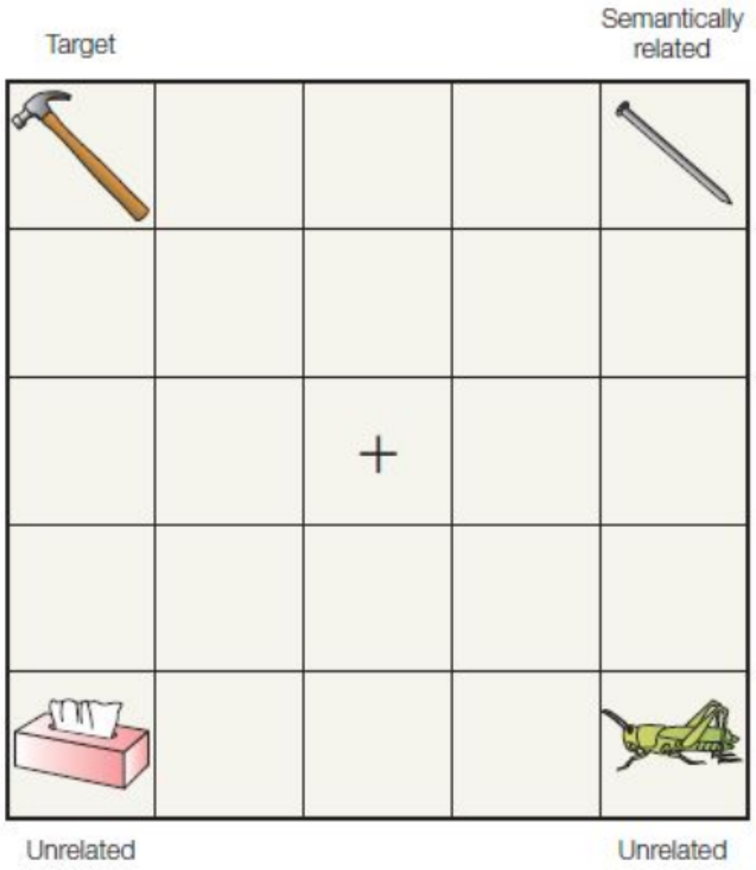

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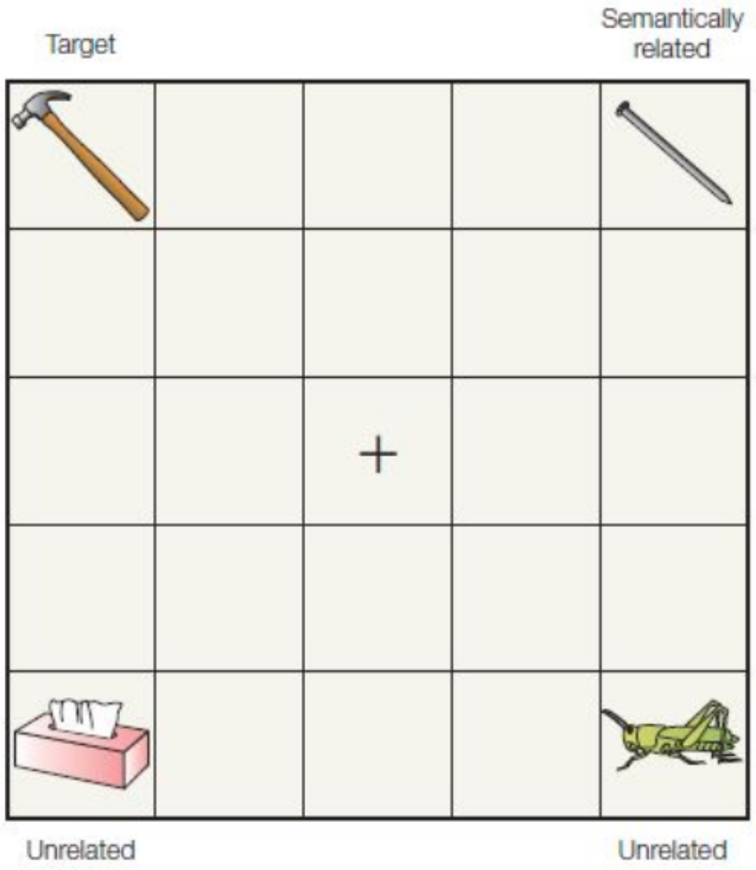

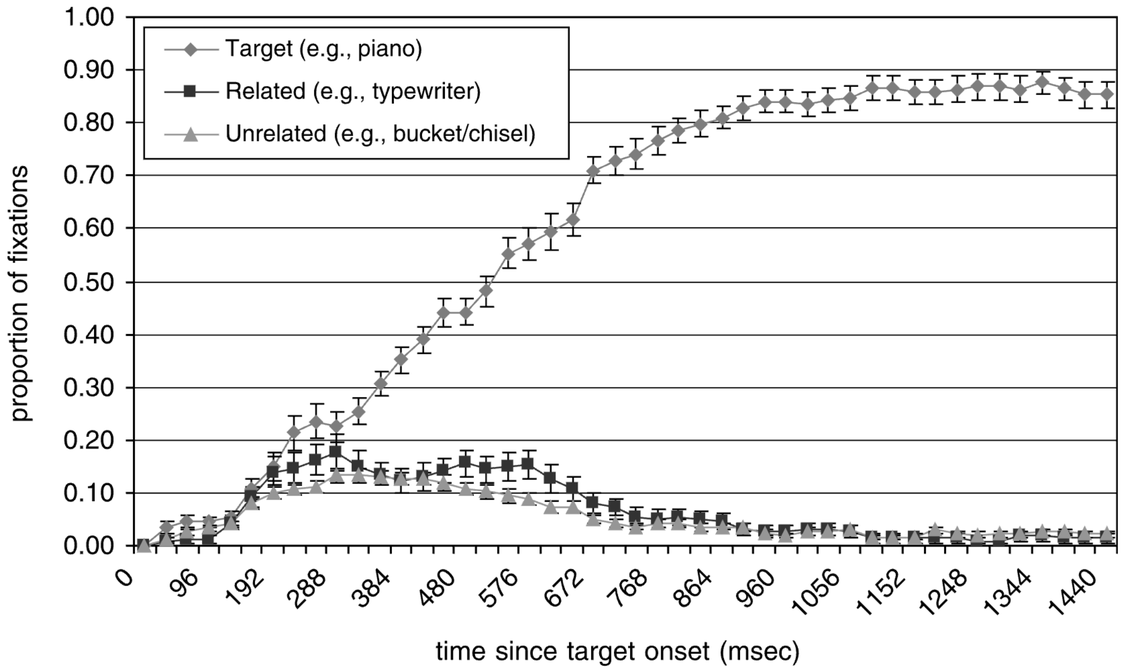

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Semantic Priming

Lexical Decision Task

Semantic Priming

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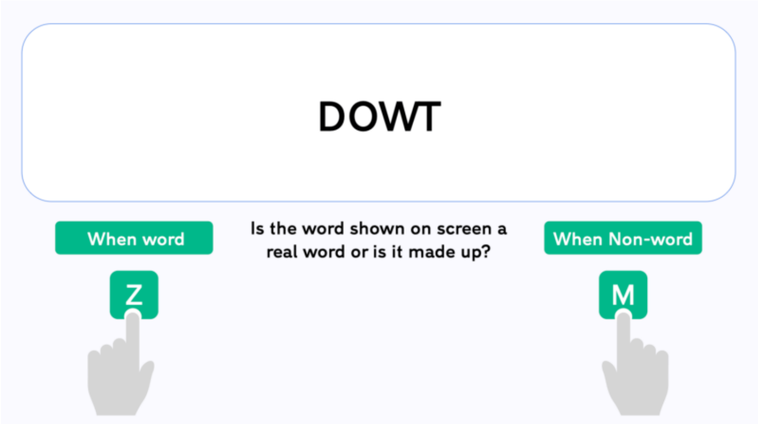

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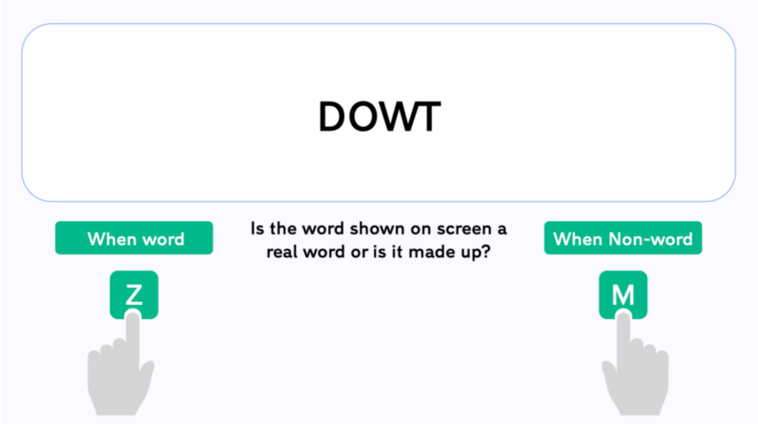

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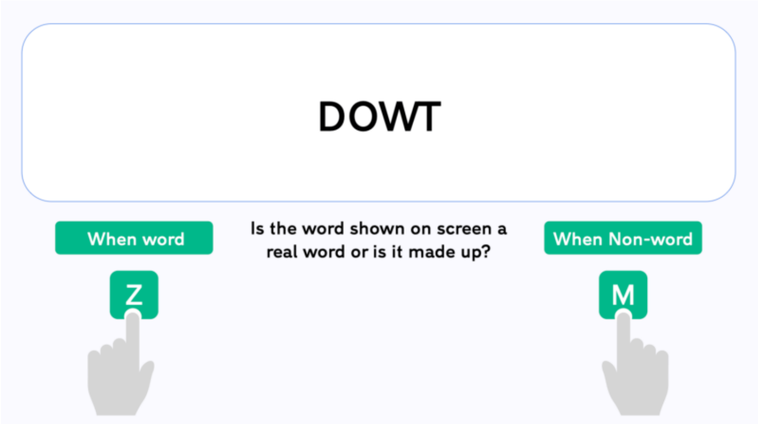

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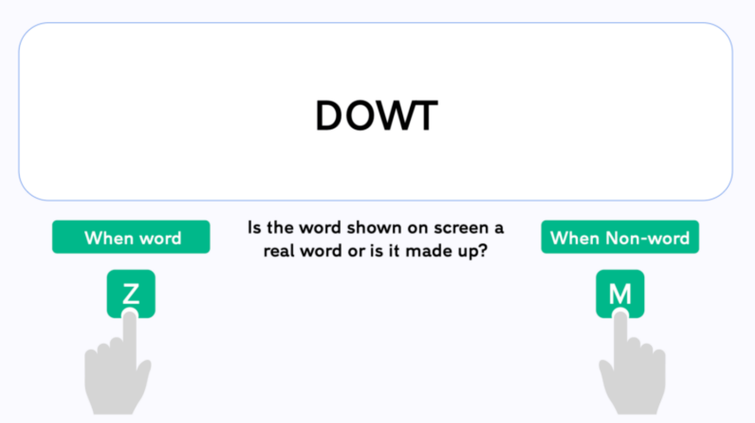

Related		Unrelated
WRENCH—HAMMER		WRENCH—BOOK
HANDLE—DOOR	*vs.*	HANDLE—SHOES
NURSE—DOCTOR		NURSE—DOCTOR
FLOWER—VASE		FLOWER—SCREEN

Semantic Priming

Cross-Modal Lexical Priming

Lexical Access during Sentence Comprehension: (Re)Consideration of Context Effects

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Semantic Priming

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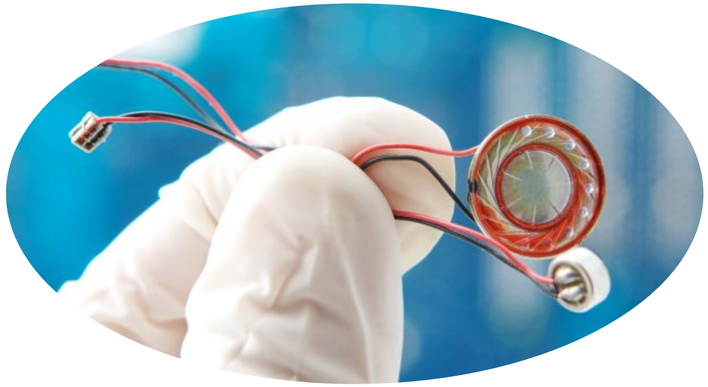
- **BUG**



Semantic Priming

Cross-Modal Lexical Priming, cont.

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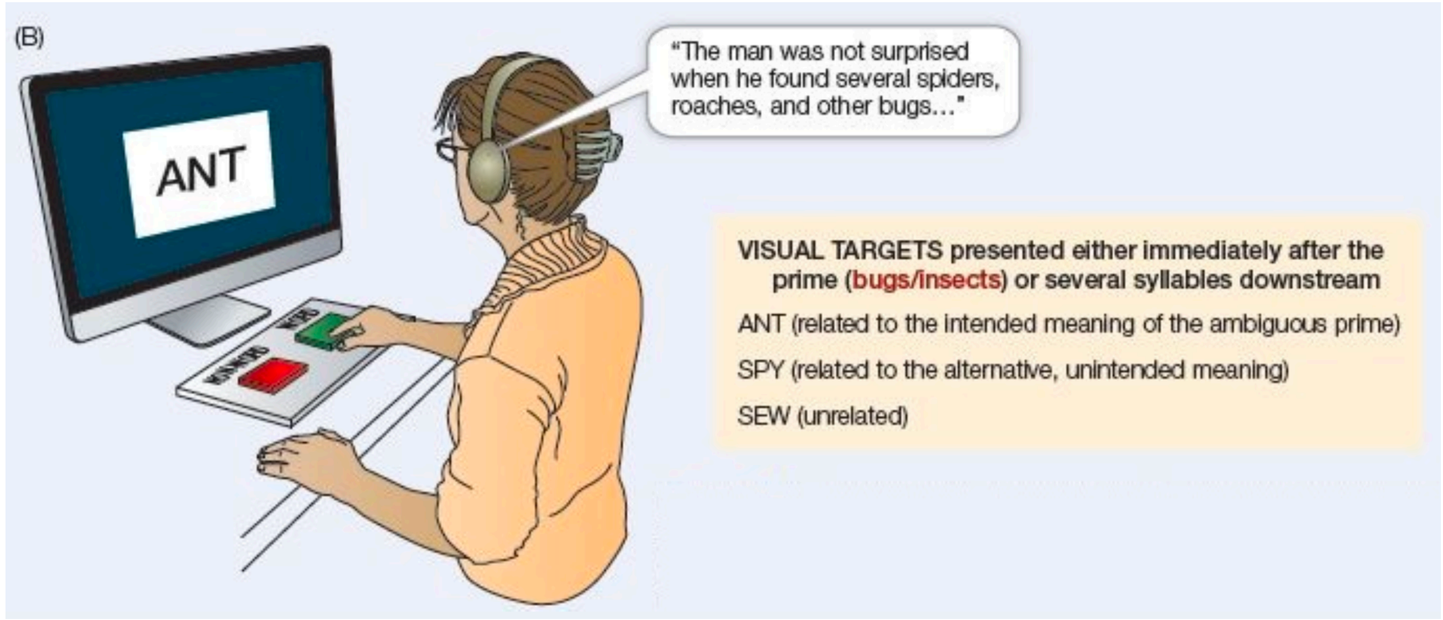

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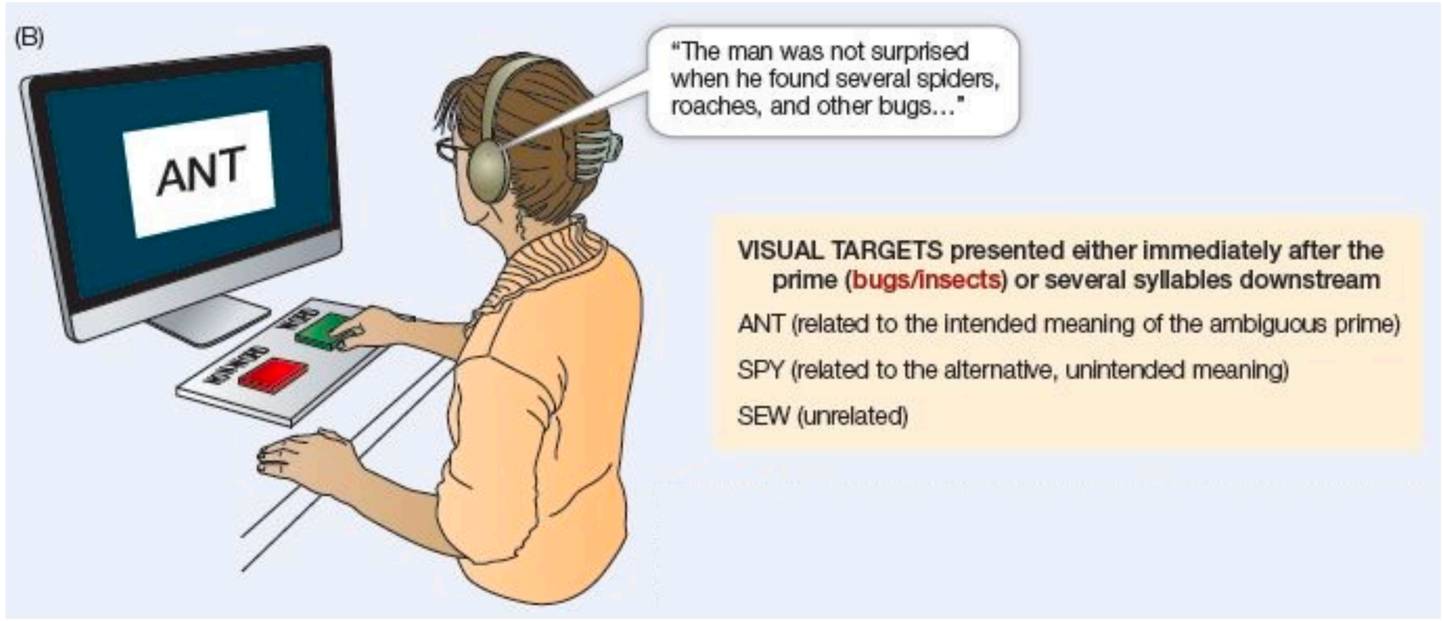

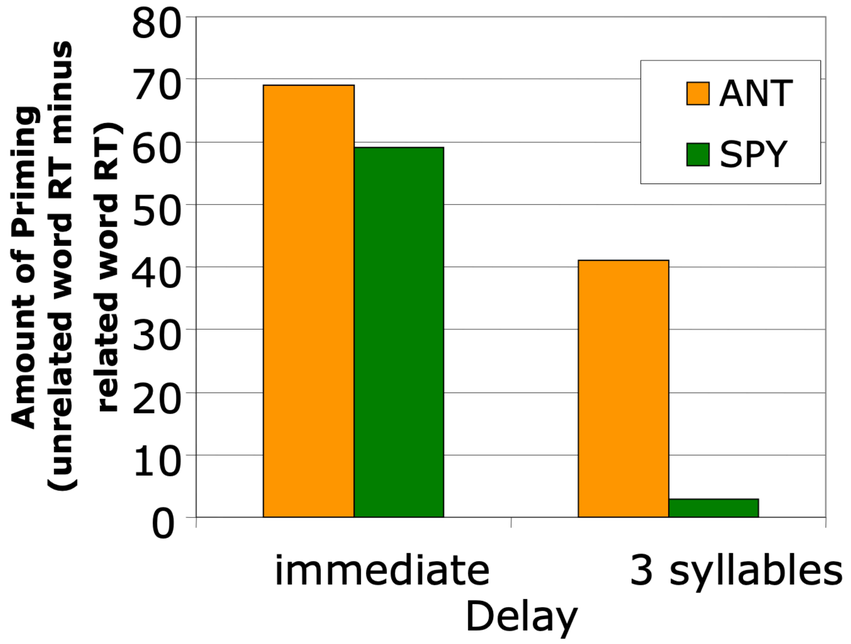

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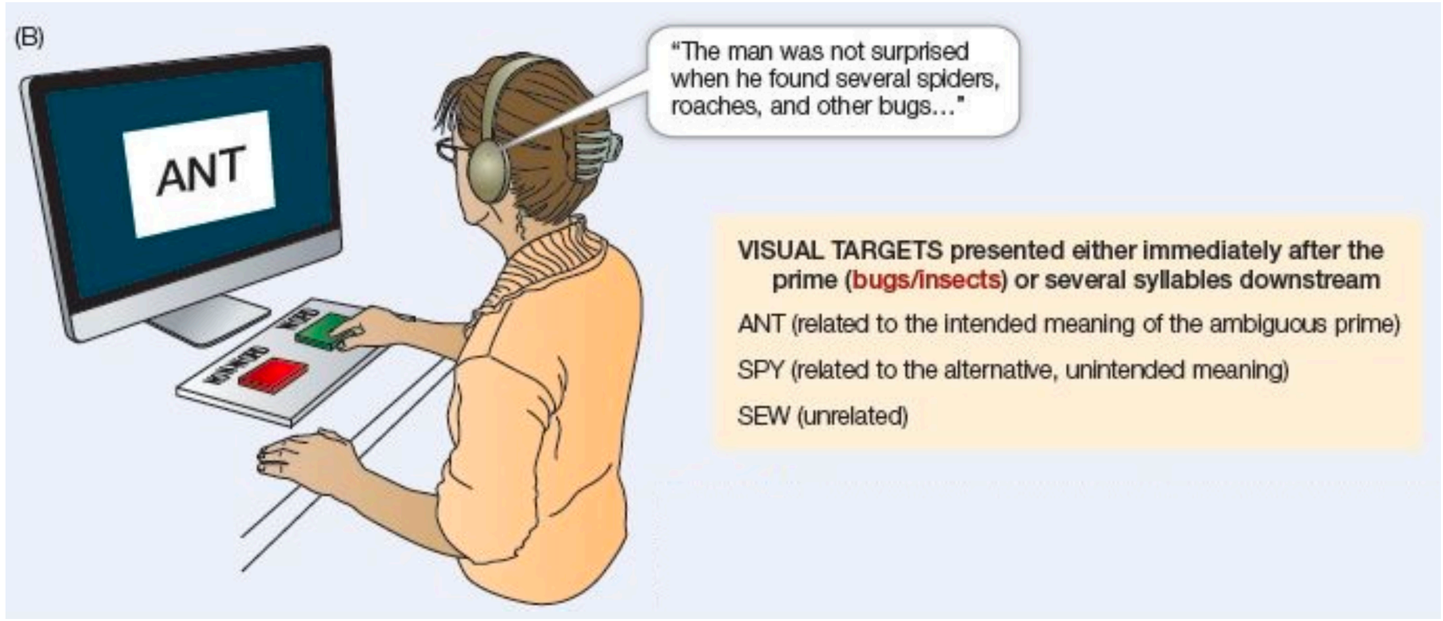

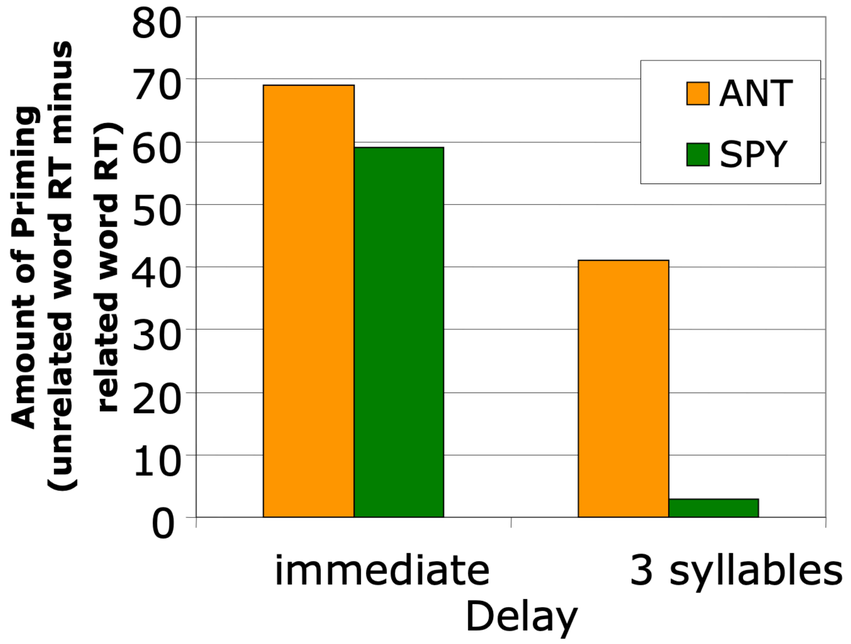

* CMLP has later been used to probe for activations in aphasic patients.

Semantic Priming

Another Version….

Semantic Priming

Another Version….

Nurse

Semantic Priming

A Subliminal Version

Replay it 20 times slower…

Semantic Priming

A Subliminal Version

Nurse

Replay it 20 times slower…

Subliminal Priming

From *Fight Club* (1999)

Subliminal Priming

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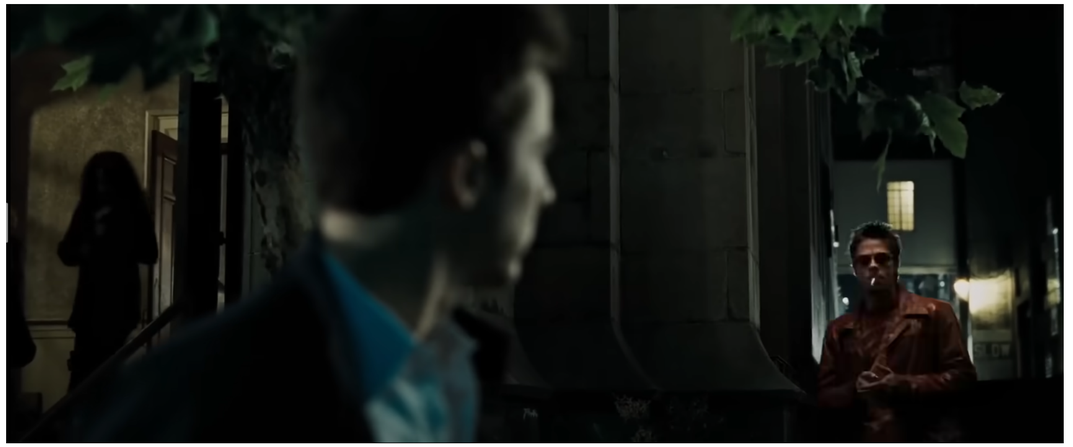

Subliminal Priming

Garden Path again…!

How to Prune a Garden Path by Nipping It in the Bud:
Fast Priming of Verb Argument Structure

John C. Trueswell and Albert E. Kim

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Subliminal Priming

Garden Path again…!

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Fast Priming of Verb Argument Structure

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Garden Path pruned!

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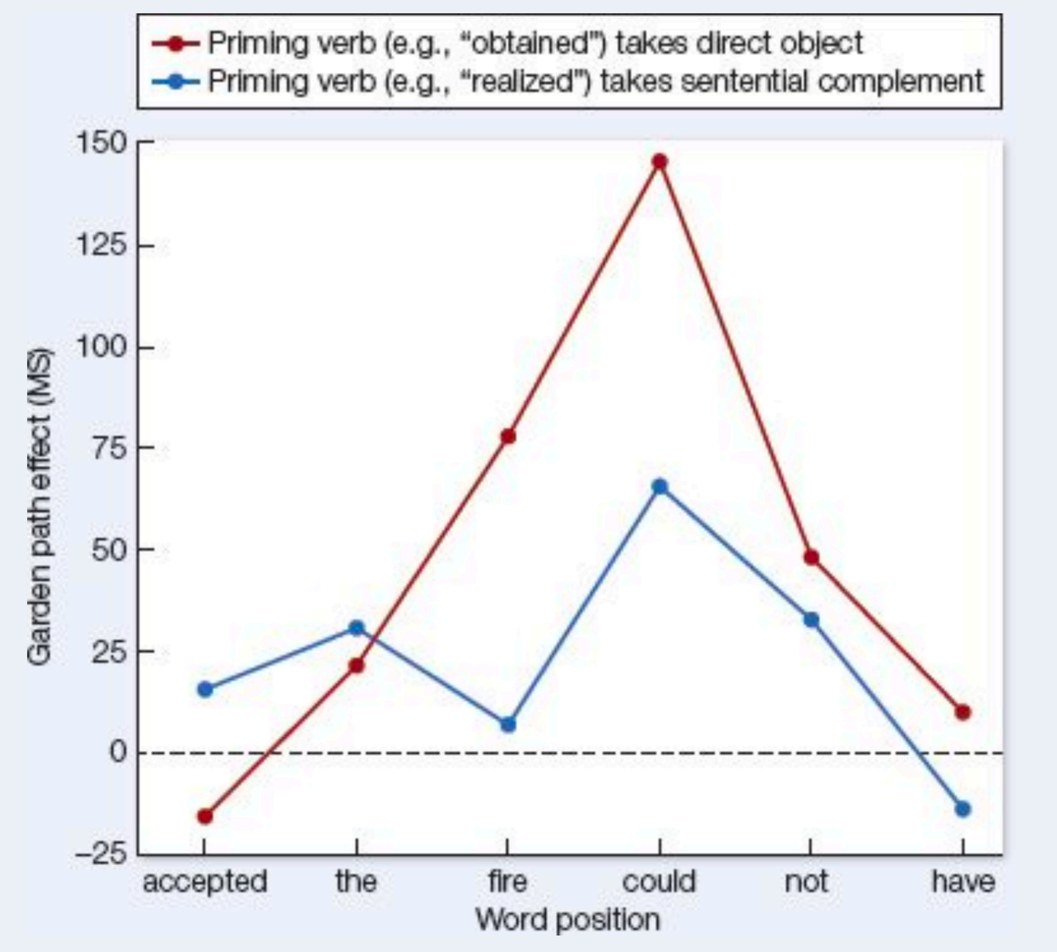

Syntactic / Structural Priming

Syntactic Priming

Can abstract structural representations be primed?

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How structural priming is measured in human studies?

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Prime

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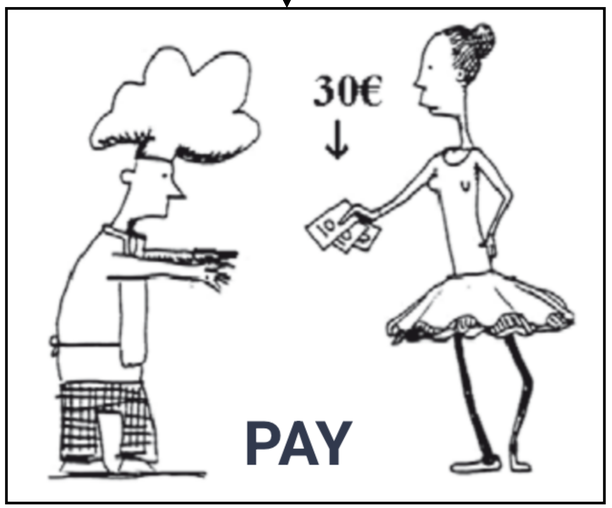

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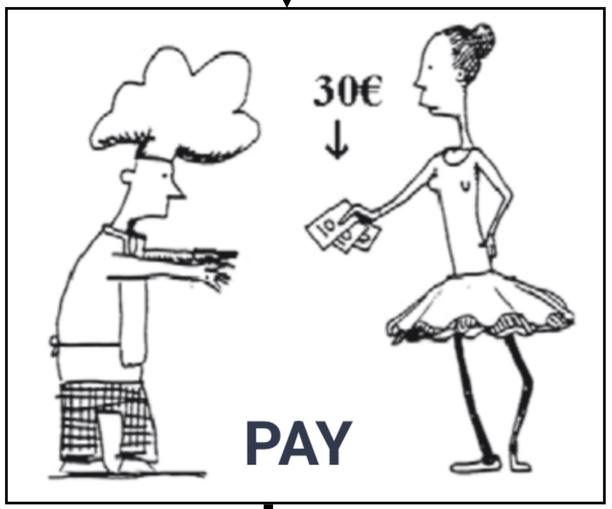

The dancer paid the cook 30 euros. [DO]

The dander paid 30 euros to the cook. [PD]

Prime

Picture + Preamble

Target

Production task with <u>Preamble Completion Paradigm</u>

Syntactic Priming - Lexical Boost

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Alice gave Bob a book

Prime

Target

Syntactic Priming - Inverse Frequency

One more property of structural priming

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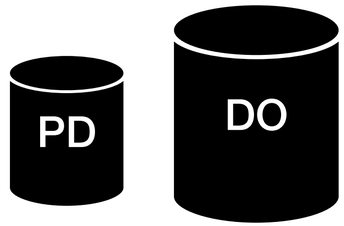

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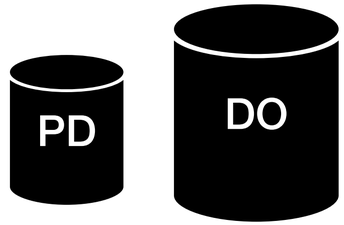

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A doctor bought a chief a plate.

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The secretary drew the card for the band.

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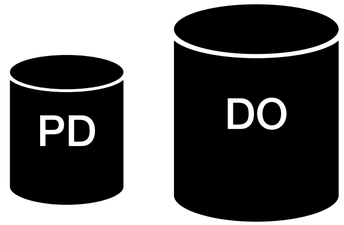

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The secretary drew the card for the band.

Greater priming effect!

Transient Activation

Pickering & Branigan (1998)

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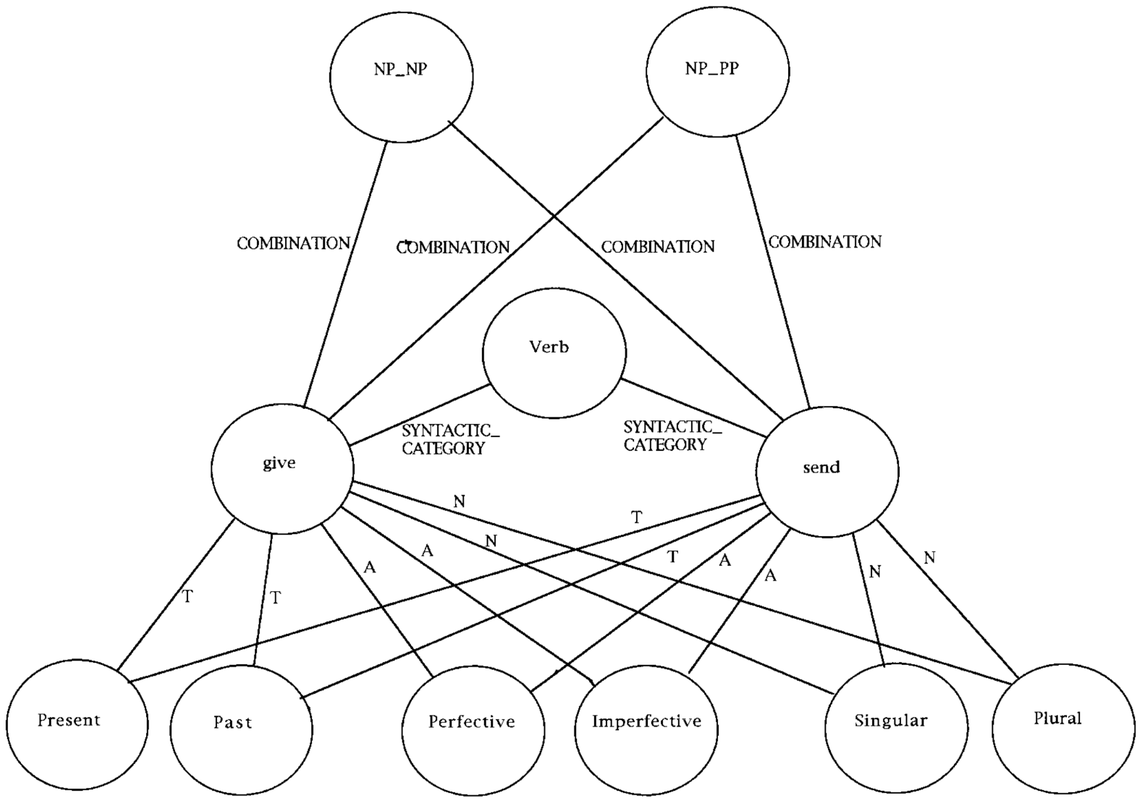

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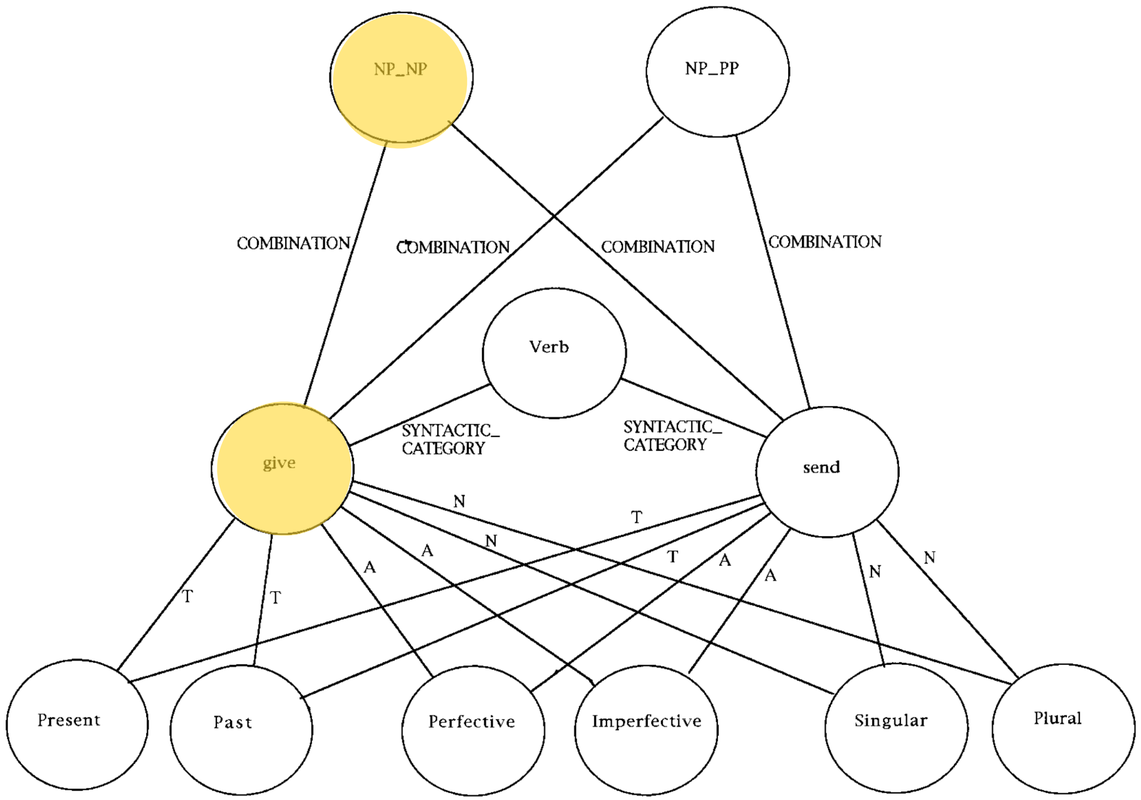

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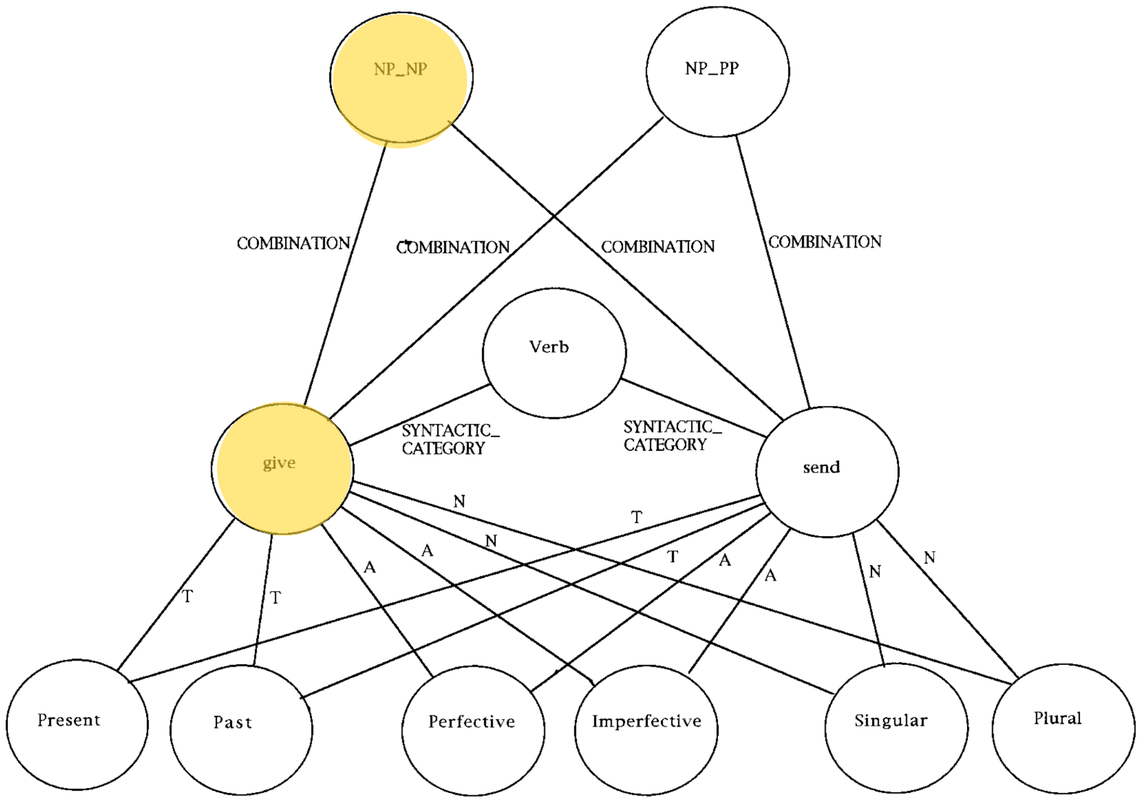

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Implicit Learning

Chang & Bock (2006)

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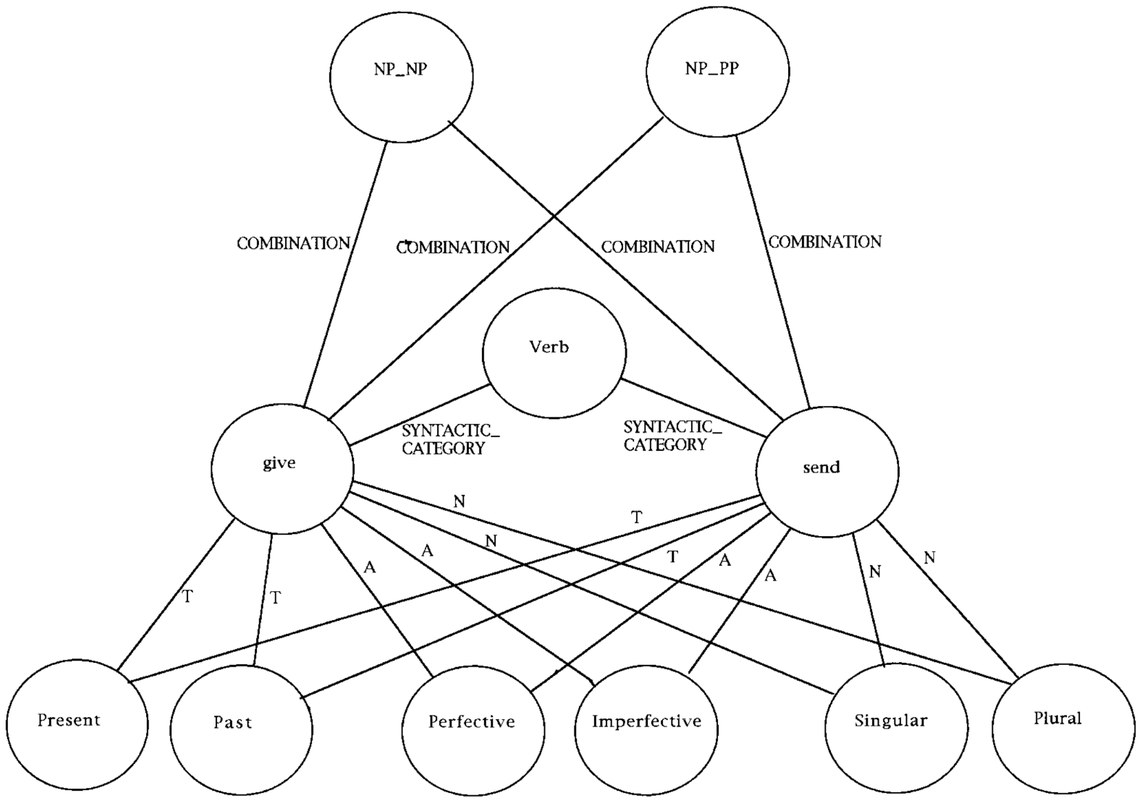

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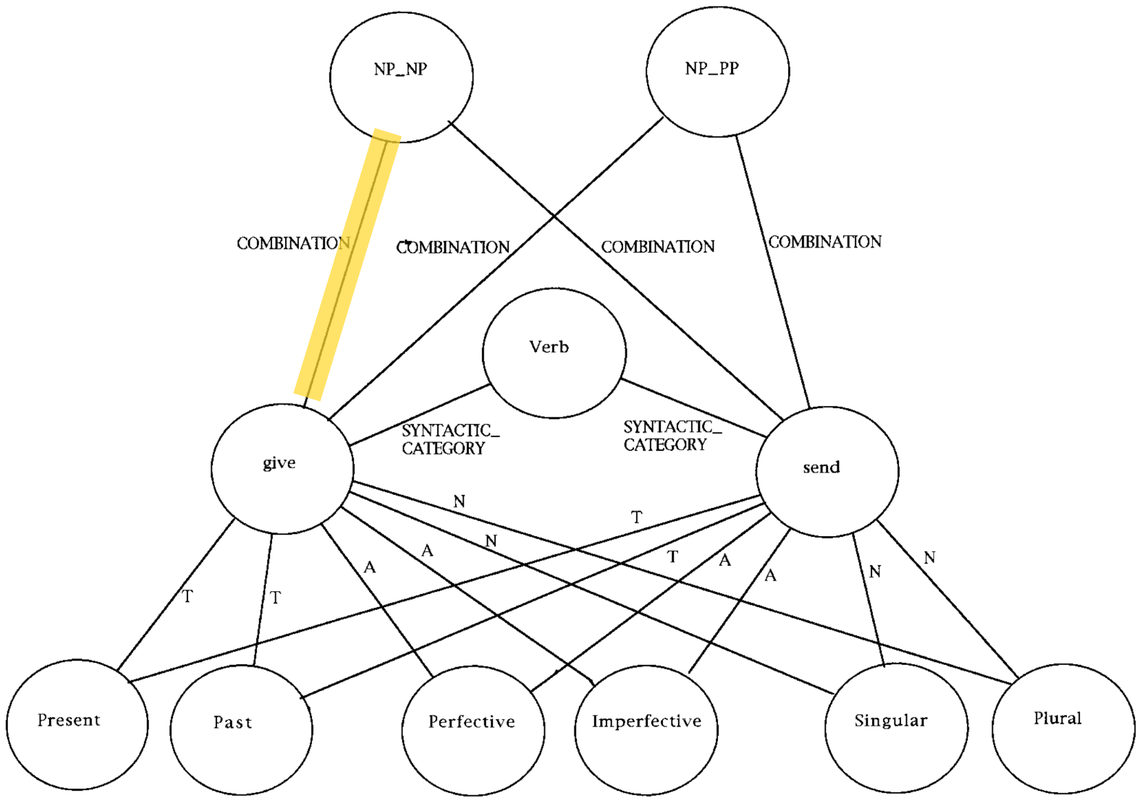

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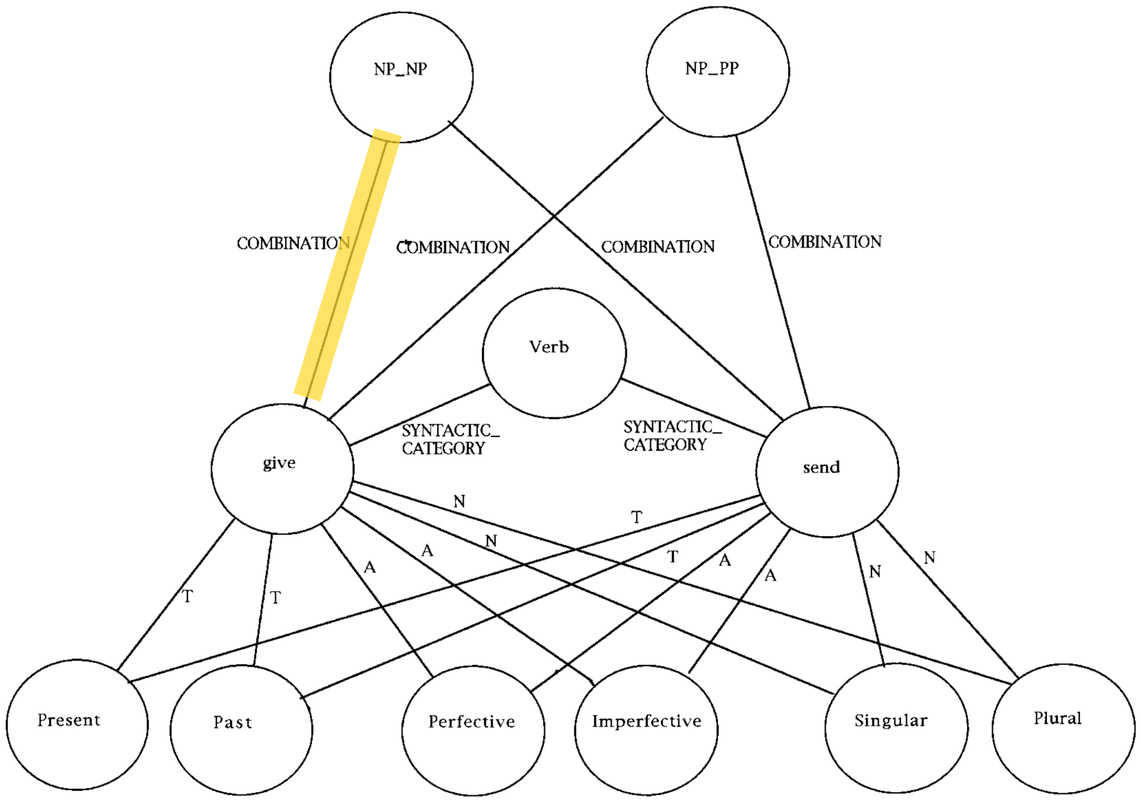

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What about Language Models?

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- **[*Inferring Internal Mechanisms*] How those structural representations inform us about the learning mechanisms in LMs?**

How to simulate priming in neural LMs?

Van Schijndel & Linzen (2018)

A Neural Model of Adaptation in Reading

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Van Schijndel & Linzen (2018), cont.

- **Test Dataset** = Natural Stories Corpus (Futrell et al. 2018)
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- **Result =** the adapted model subsumes the prediction of the non-adapted one;
  - $|t| > 2 \rightarrow$ significant
  - When adapted, the adaptive surprisal, but not the non-adaptive surprisal, is a significant predictor.

	$\hat{\beta}$	$\hat{\sigma}$	t
WITHOUT ADAPTIVE SURPRISAL:			
Sentence position	0.55	0.53	1.03
Word length	7.29	1.00	7.26
Non-adaptive surprisal	6.64	0.68	9.79
WITH ADAPTIVE SURPRISAL:			
Sentence position	0.29	0.53	0.55
Word length	6.42	1.00	6.40
Non-adaptive surprisal	-0.89	0.68	-1.31
Adaptive surprisal	8.45	0.63	13.42

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Van Schijndel & Linzen (2018), cont.

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- **Garden Path Minimal Pair**: compare surprisal / reading time on disambiguations:
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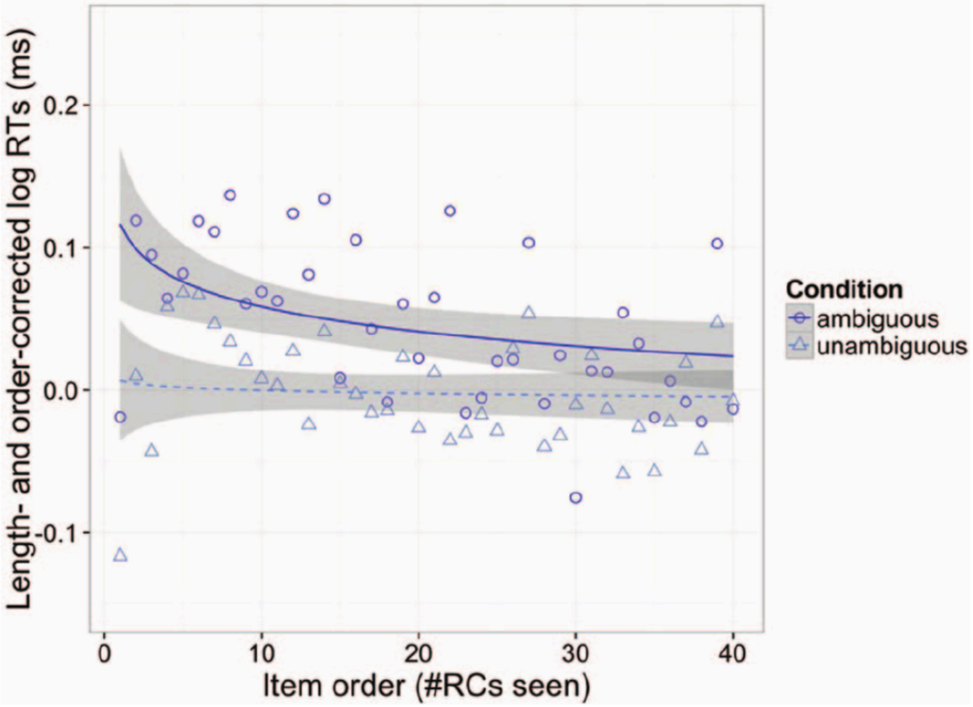
- **Compute**:

$$\text{MeanSurprisal}\left(\text{underline} \mid \text{ambiguous}\right) - \text{MeanSurprisal}\left(\text{underline} \mid \text{unambiguous}\right)$$

What are LMs adapting to?
Syntactic structure vs. Mere recent occurrence?

Van Schijndel & Linzen (2018), cont.



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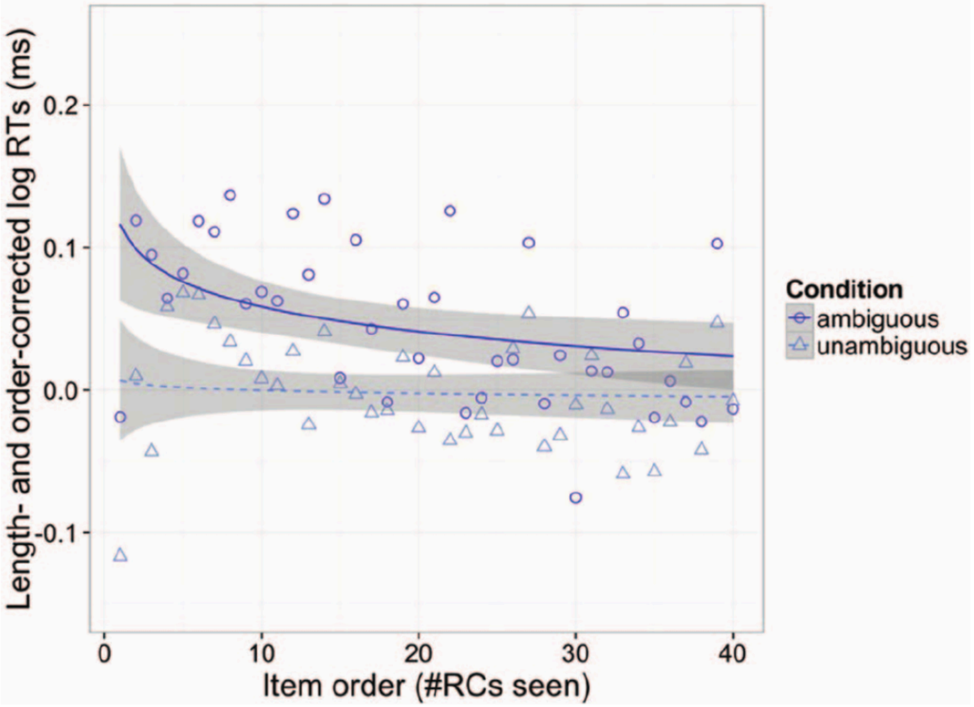

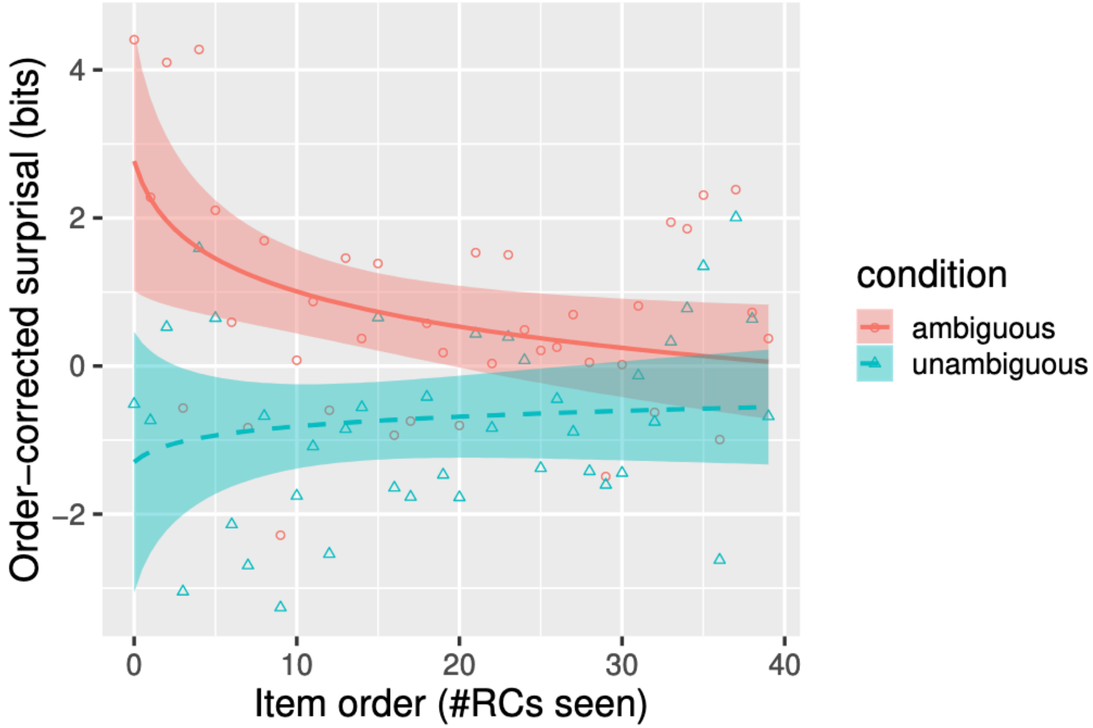

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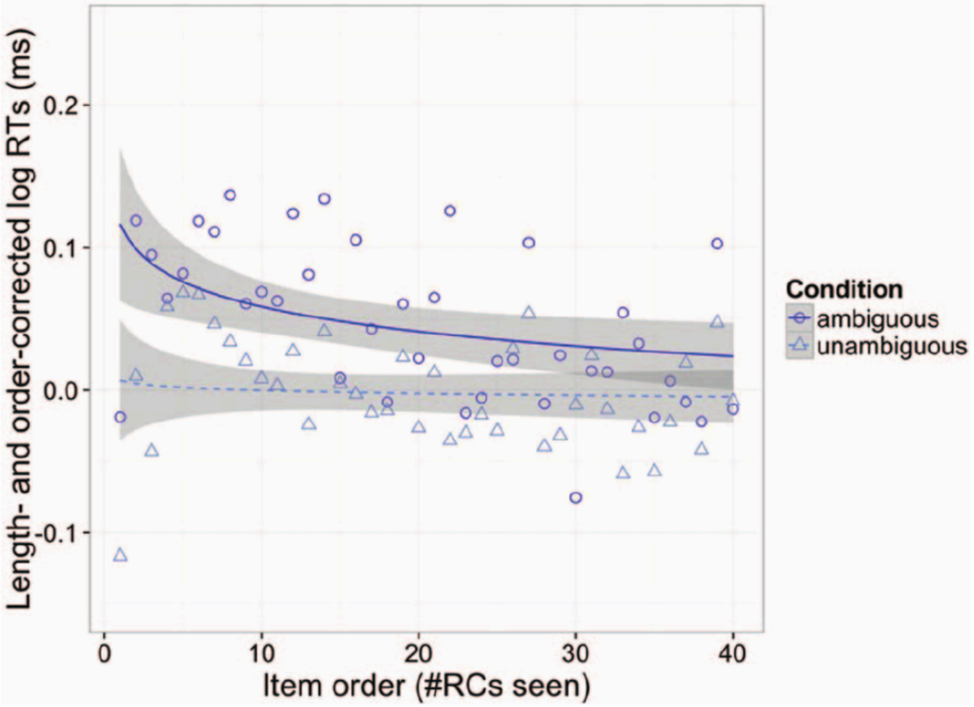

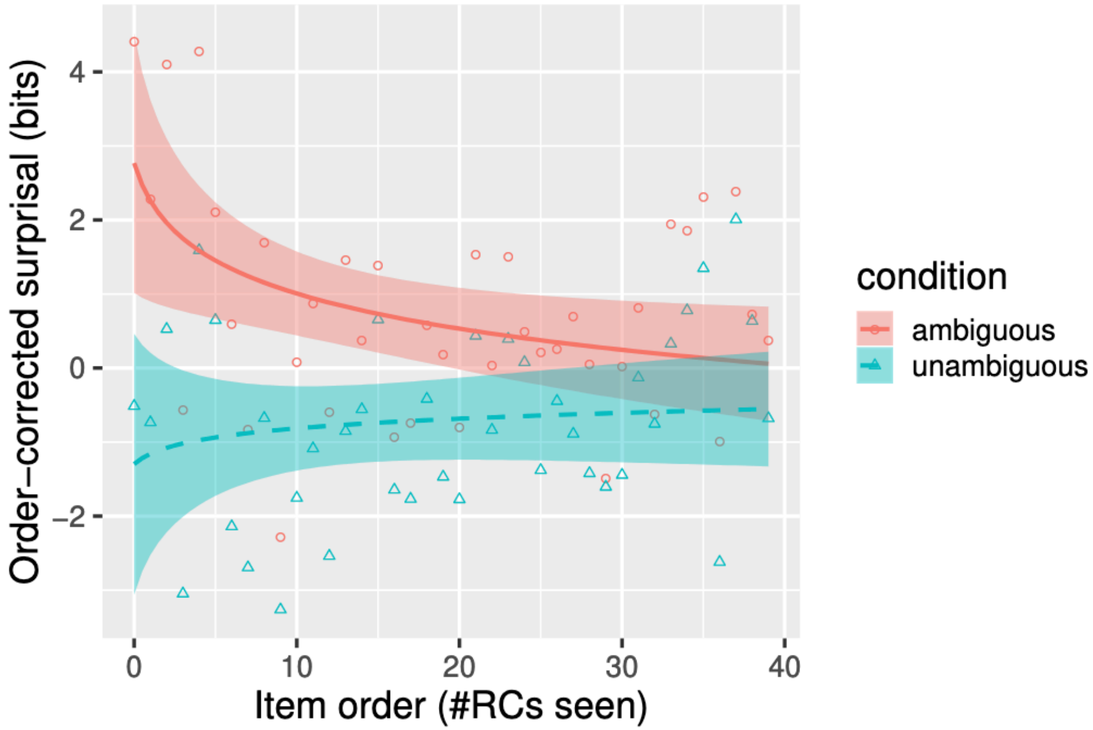

- **Result =** aligning with human pattern!
  - Initially large adaptation effect, followed by more gradual adaptation.

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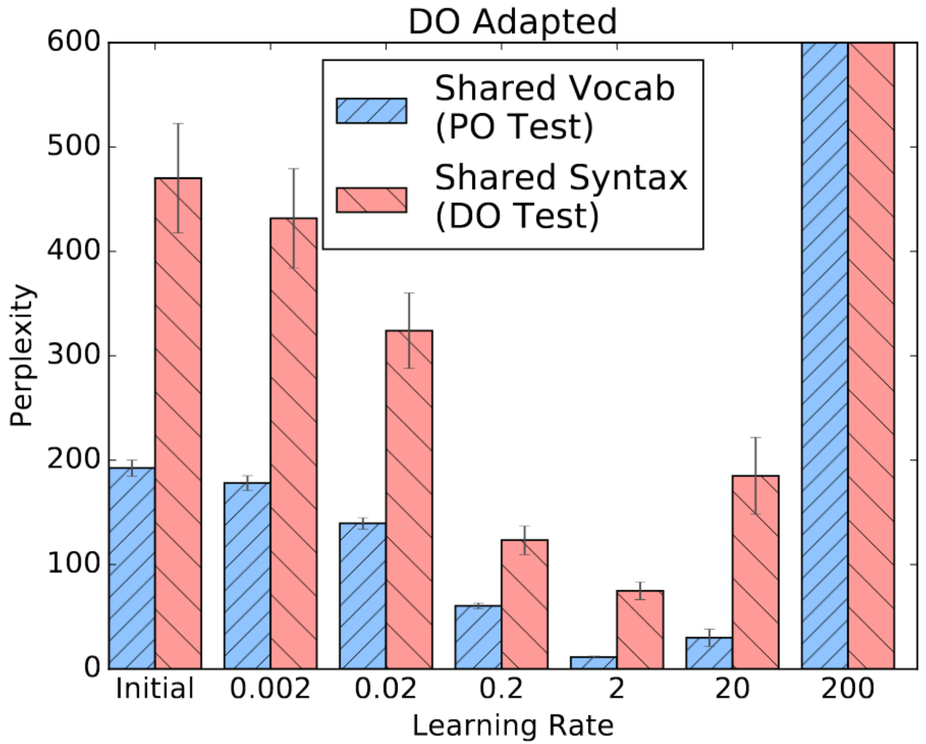

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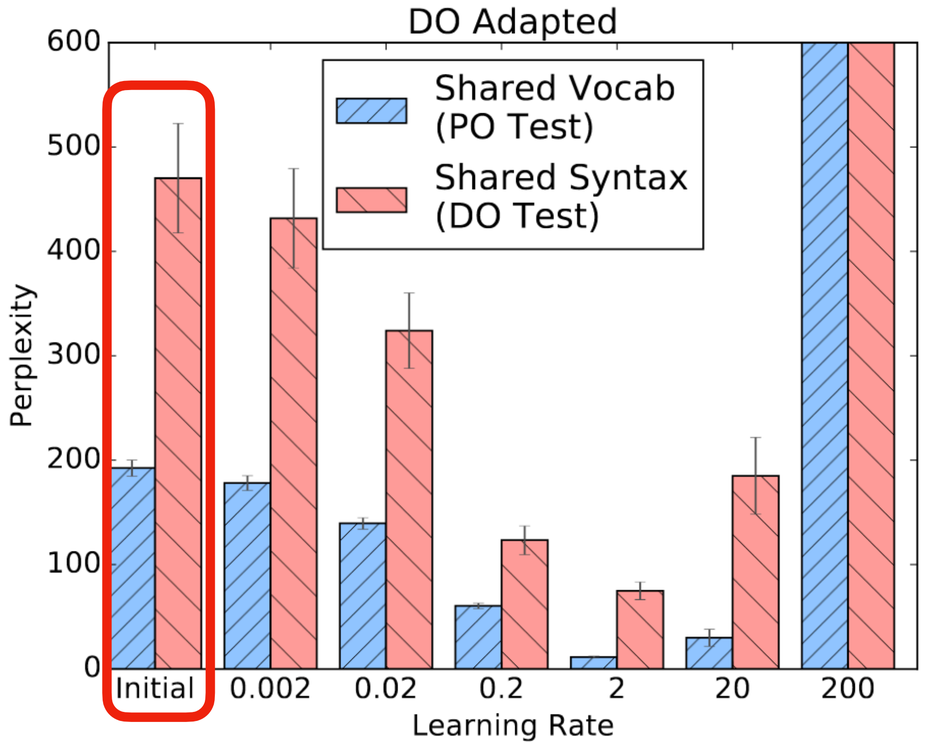

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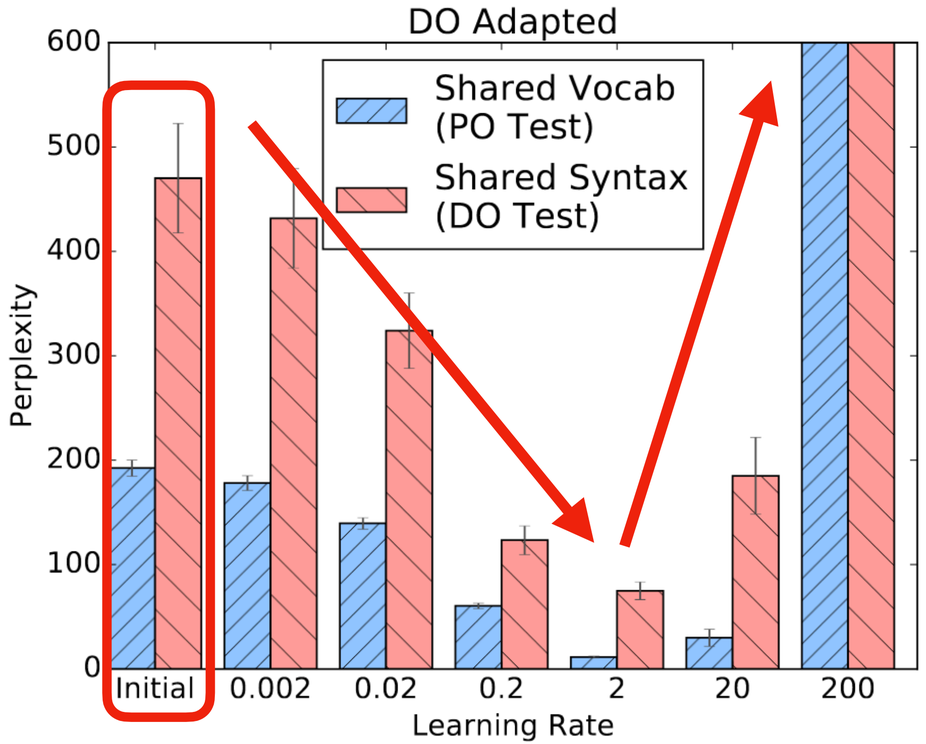

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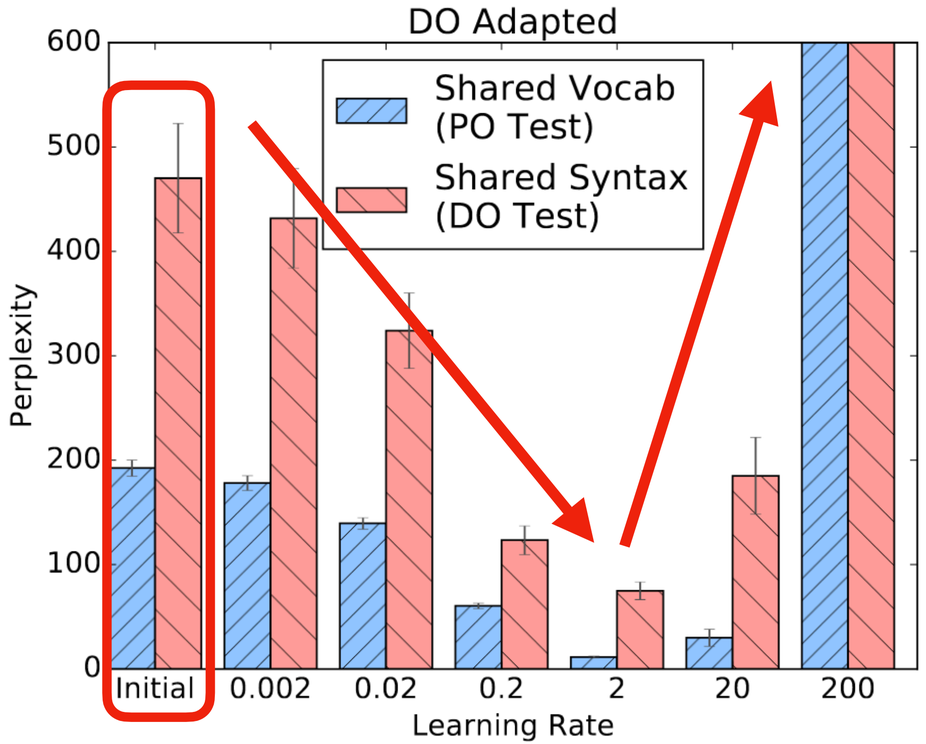
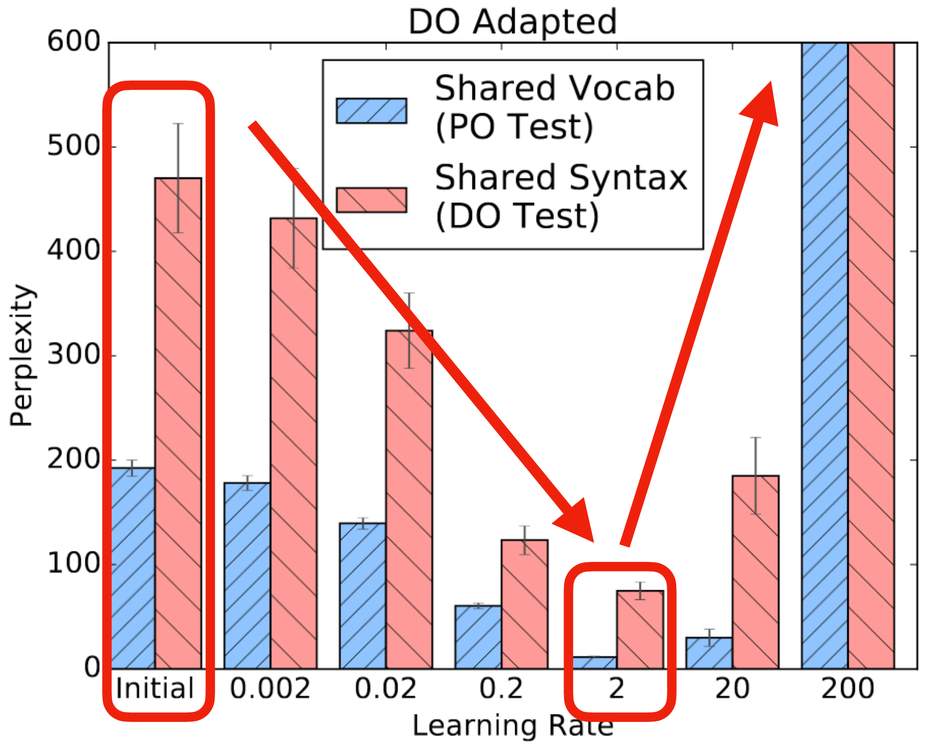


What are LMs adapting to? Syntactic structure vs. Mere recent occurrence?

Van Schijndel & Linzen (2018), cont.

- **Dative Alternation:** adapted to 100 DO sentence, and measure the perplexity on {100 other DO sentences, 100 PD counterpart};

- **Result**
  - Compare to the first bar: more decrease →larger adaptation;
  - Sharing **vocab** reduces perplexity more than sharing **syntax**!
  - Optimal learning rate = 2;



How to quantify similarity across syntactic structures?

Prasad et al. (2019)

Using Priming to Uncover the Organization of Syntactic Representations in Neural Language Models

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Tal Linzen
Johns Hopkins University
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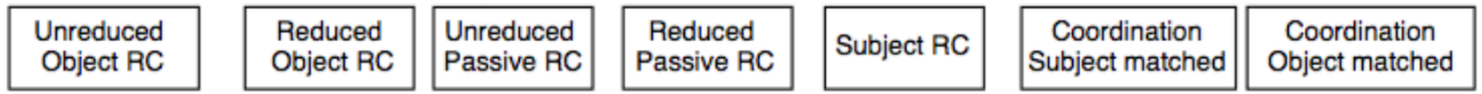
- **Method** = same as before — *fine-tuning* on LSTM;
- **Underlying Logic** = the degree to which one structure primes another → the similarity between the models' representations of those structures;

How to quantify similarity across syntactic structures?

Prasad et al. (2019)

$$\mathbb{D}(S_X, \neg S_X) = \frac{AE(X_2 \mid X_1)}{AE(\neg X_2 \mid X_1)}$$

- $\mathbb{D} > 1 \rightarrow$ within-class similarity is greater than inter-class similarity;
- $AE(X_2 \mid X_1)$ = adaptation effect on X_2 when primed by X_1;



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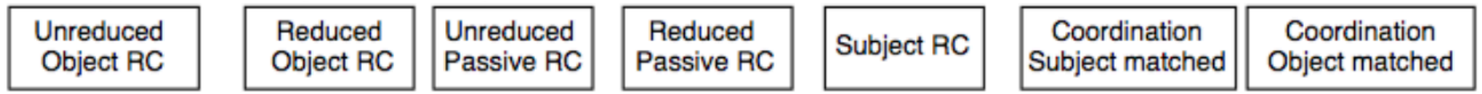

- **Lower level abstraction**: same type of relative clauses;
- **Intermediate abstraction**: RC classes {match, mismatch} w.r.t. reduction;
- **Highest abstraction**: classes {with, without} RC;

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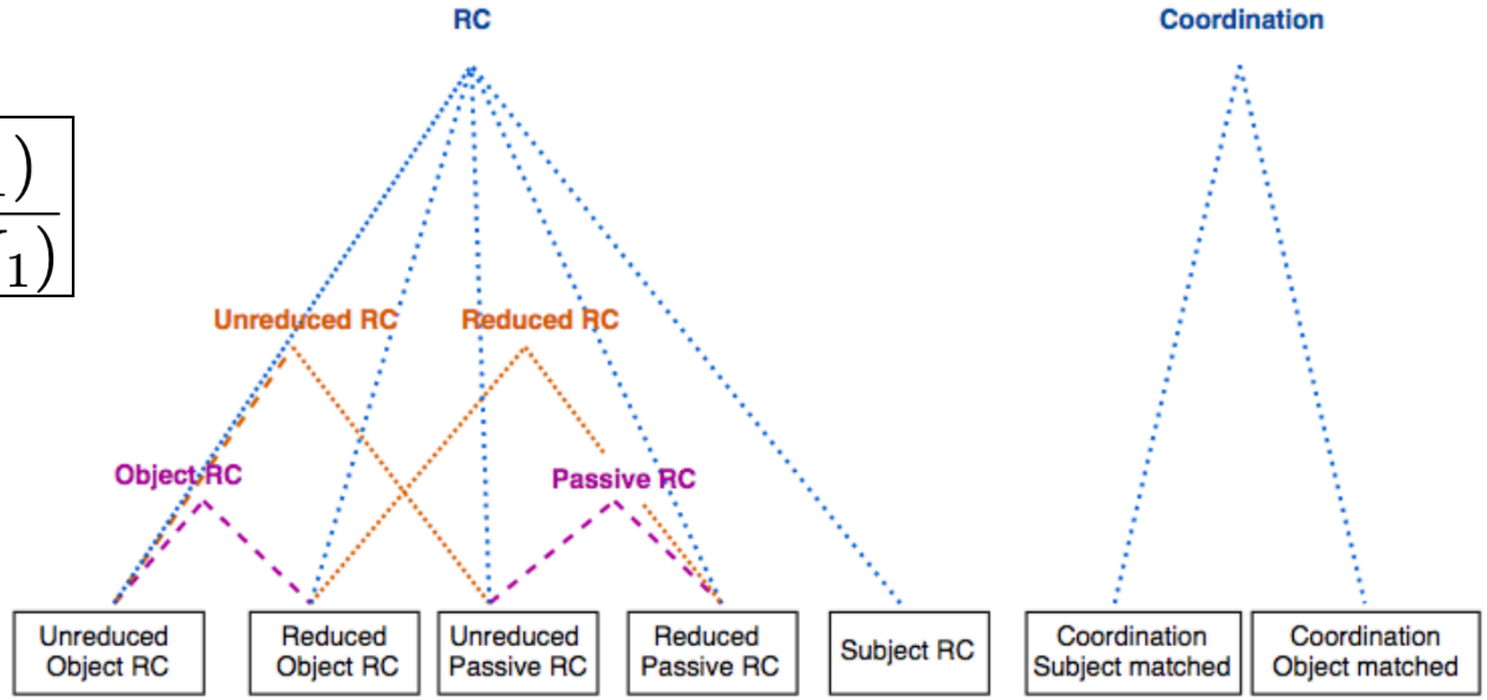

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Interim Summary

Fine-tuning as a method of priming

- Fine-tuning on prime sentences with LSTMs is a way of simulating priming!
  - It better simulates human reading time data.
- Mixed finding on keeping track of the abstract syntactic representations;
  - Lexical items does play a role;
- Can use priming to uncover internal organizations of structures.

Can you think of other ways of doing priming in LMs?

Concatenation as another way of priming!

Sinclair et al. (2022)

Structural Persistence in Language Models:
Priming as a Window into Abstract Language Representations

Arabella Sinclair[1,2*] **Jaap Jumelet**[2*] **Willem Zuidema**[2] **Raquel Fernández**[2]

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- **Concatenation:** concatenate the prime and target sentences directly — the prime sentence is now the *context* of the target sentence.

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$$PE_{\text{PO}} = \log P(T_{\text{PO}}|P_{\text{PO}}) - \log P(T_{\text{PO}}|P_{\text{DO}})$$
$$PE_{\text{DO}} = \log P(T_{\text{DO}}|P_{\text{DO}}) - \log P(T_{\text{DO}}|P_{\text{PO}})$$

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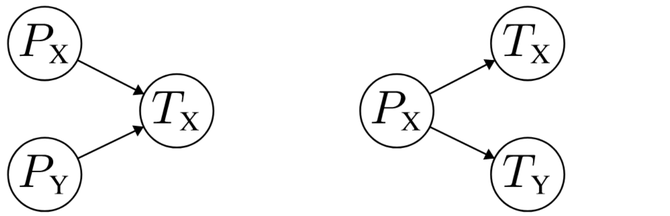


Priming Effect (Eq. 1) Prasad et al. (2019)

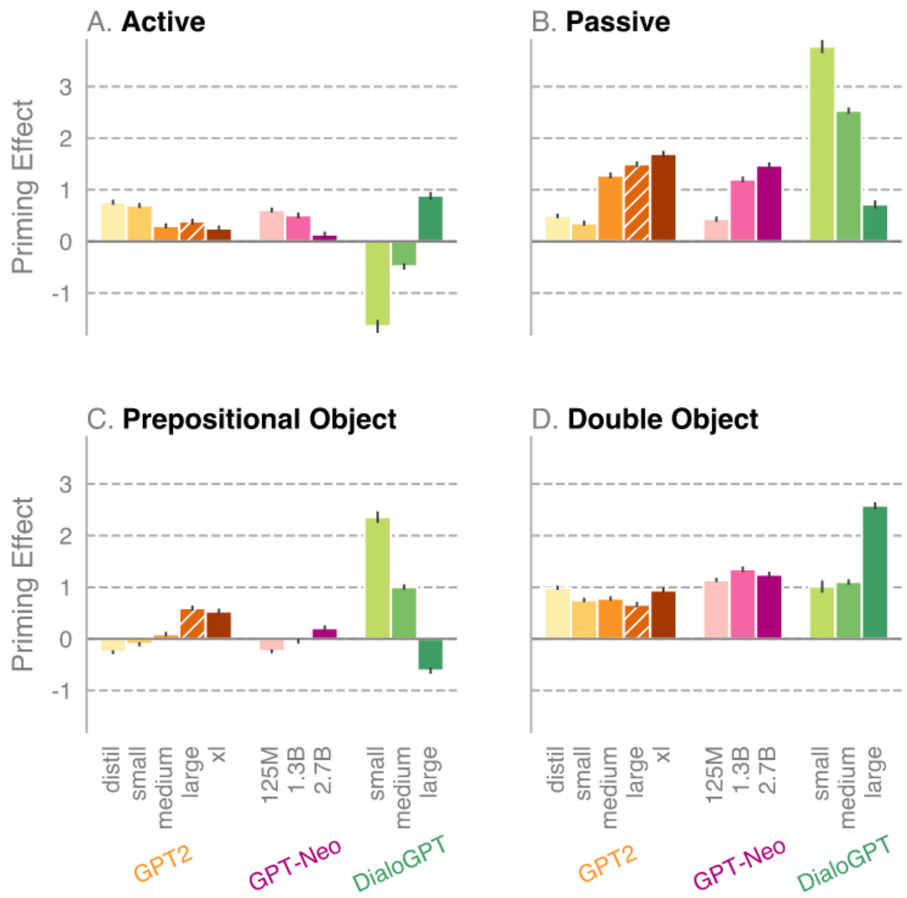
Does concatenation show standard priming?

Sinclair et al. (2022) cont.

- **Example Input:** *A professor promised a student a letter. The secretary drew the card for the boss.*
- **Model:** the GPT2 family and variants (we are finally in the modern realm!)

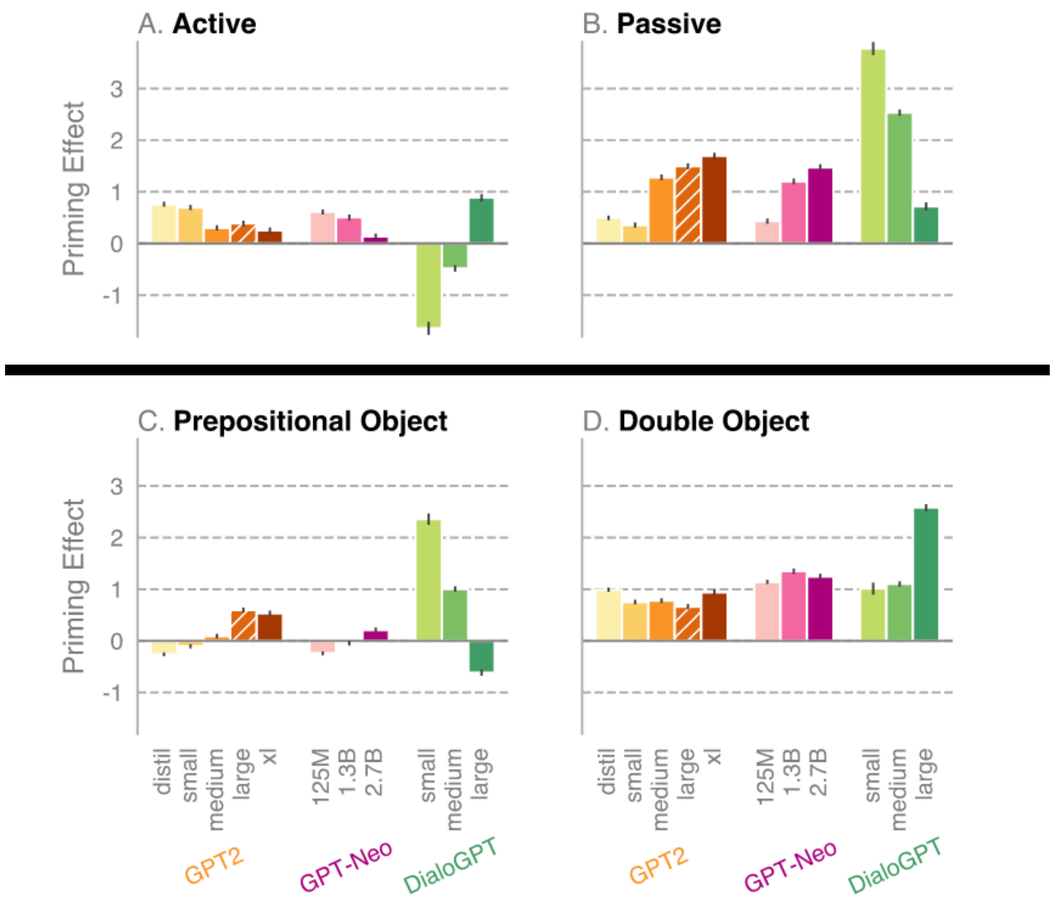
Does concatenation show standard priming?

Sinclair et al. (2022) cont.



Does concatenation show standard priming?

Sinclair et al. (2022) cont.



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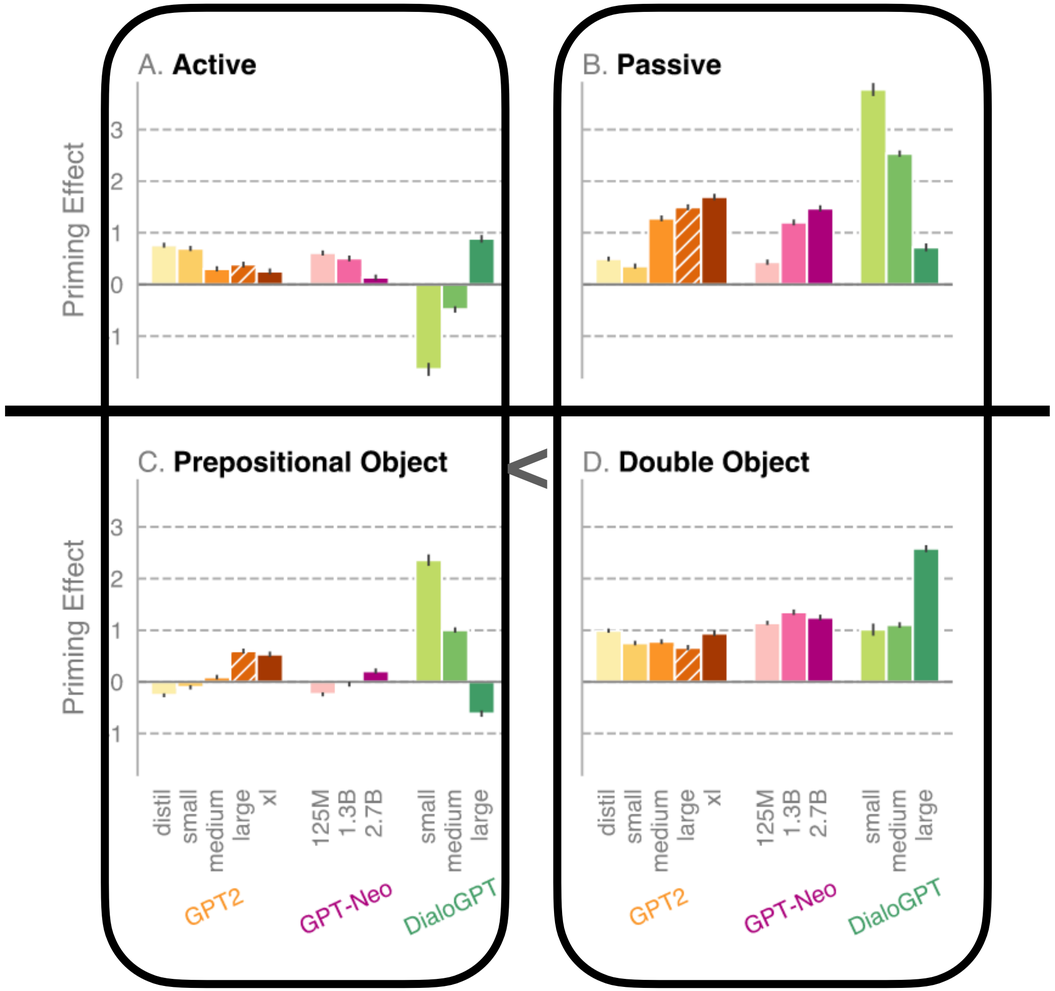
Sinclair et al. (2022) cont.



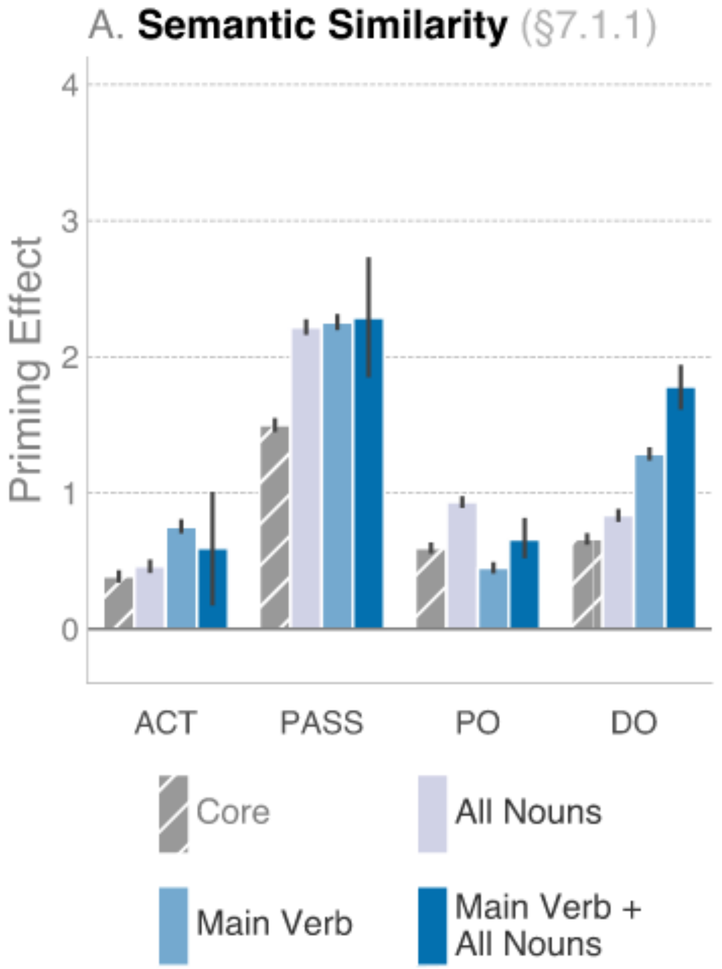
- **Results:**
  - Asymmetric priming effect:
    - PE(DO) > PE(PD)
    - PE(passive) > PE(active)
  - Increasing model size doesn't always increase priming effect.

What factors influence priming strength?

Sinclair et al. (2022) cont.

- **Semantics similarity?**
  - Cosine similarity from word embeddings;
  - Human free association data;

Corpus	Condition	Prime (ACT)	Target (PASS)
Semantic Similarity	Verb Only	*The chief **struck** the mayor.*	*A bishop was **beaten** by a hero.*
	All Nouns	*An **actor** broke a **glass**.*	*The **bottle** was wrapped by the **actress**.*
	All Words	*The **student drank** the **wine**.*	*A **beer** was **prepared** by a **professor**.*



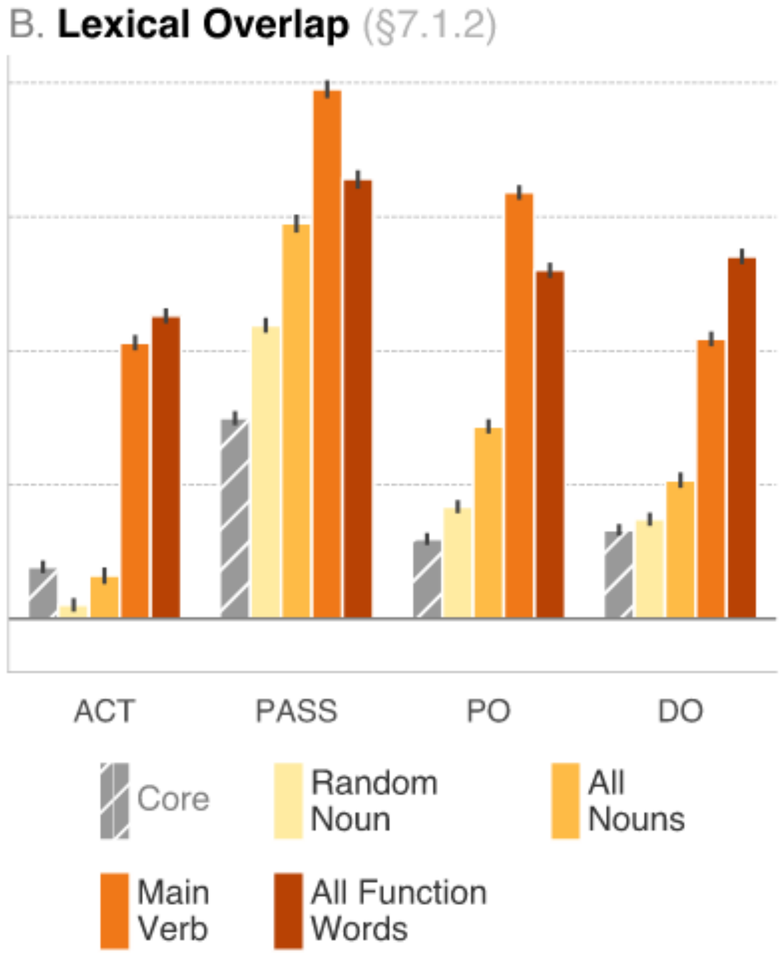
- **Superimposing semantic priming with syntactic priming!**

What factors influence priming strength?

Sinclair et al. (2022) cont.

- **Lexical overlap?**

Corpus	Condition	Prime (ACT)	Target (PASS)
Lexical Overlap	Random Noun	*The girl smelled the **chicken**.*	*A **chicken** was prepared by a pilot.*
	Main Verb	*A woman **used** a computer.*	*The iron was **used** by the father.*
	Function Words	***The** soldier wanted **the** pie.*	***The** book was carried by **the** manager.*
	All Nouns	*The **king** smelled the **wine**.*	*A **wine** was drunk by a **king**.*



- **Testing the lexical boost effect!**
  - Verbs (argument head) and function words have larger effect than content word — confirming the LBE.
  - **Syntactic priming modulates semantic priming!**

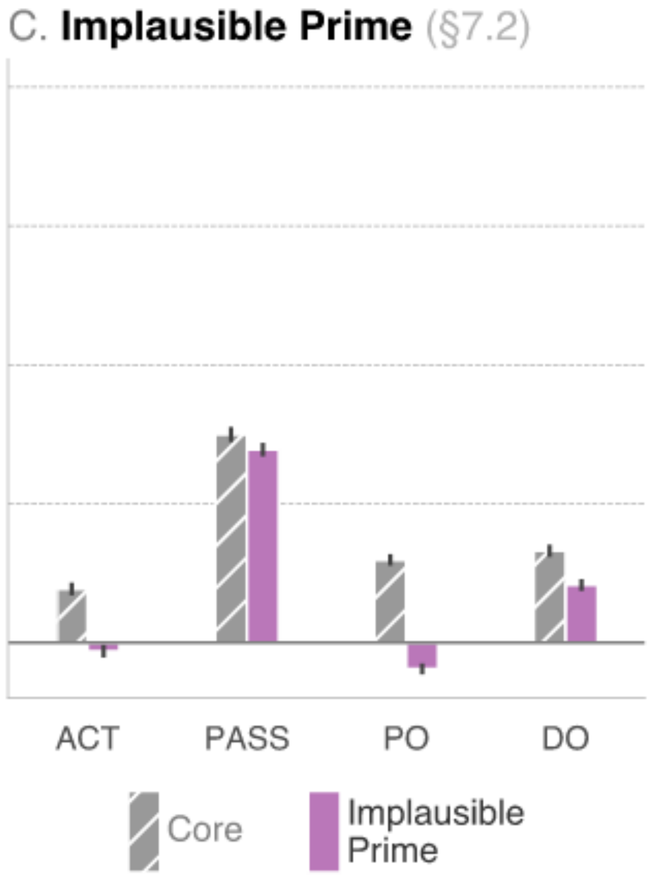
What factors influence priming strength?

Sinclair et al. (2022) cont.

- **Semantic plausibility?**

Corpus	Condition	Prime (ACT)	Target (PASS)
Implausible Prime	—	*The **newspaper grabbed** the **pot**.*	*A key is removed by an attorney.*

- **Is structural information autonomous from semantics?**
  - Asymmetry persists; negative priming!
  - **Structural encoding is not fully independent from semantics;**

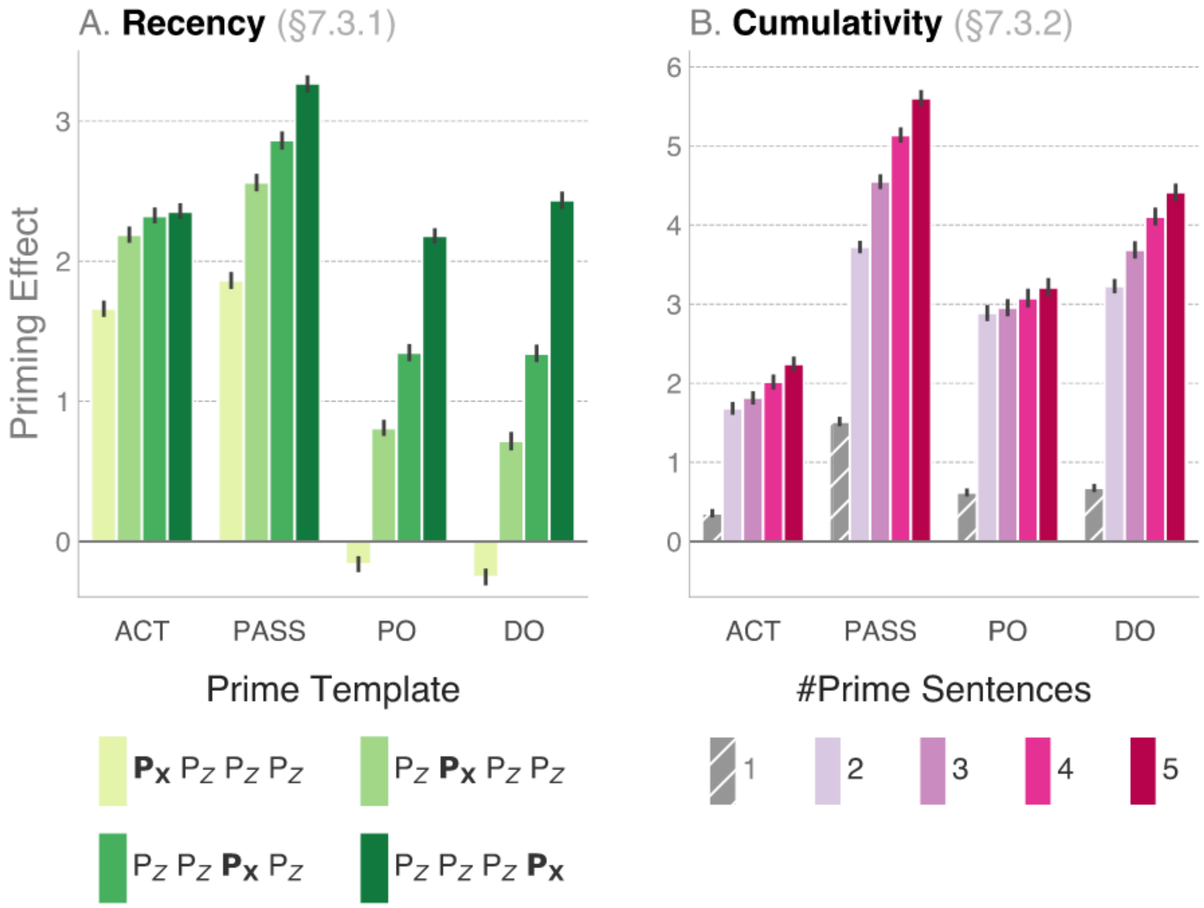


What factors influence priming strength?

Sinclair et al. (2022) cont.

- **Strength of Exposure?**
  - **Recency:** more recent, stronger PE
  - **Cumulativity:** more priming sentences, stronger PE

- **Indeed what we expect!**
  - Few-shot / In-context learning? — will come back to it….

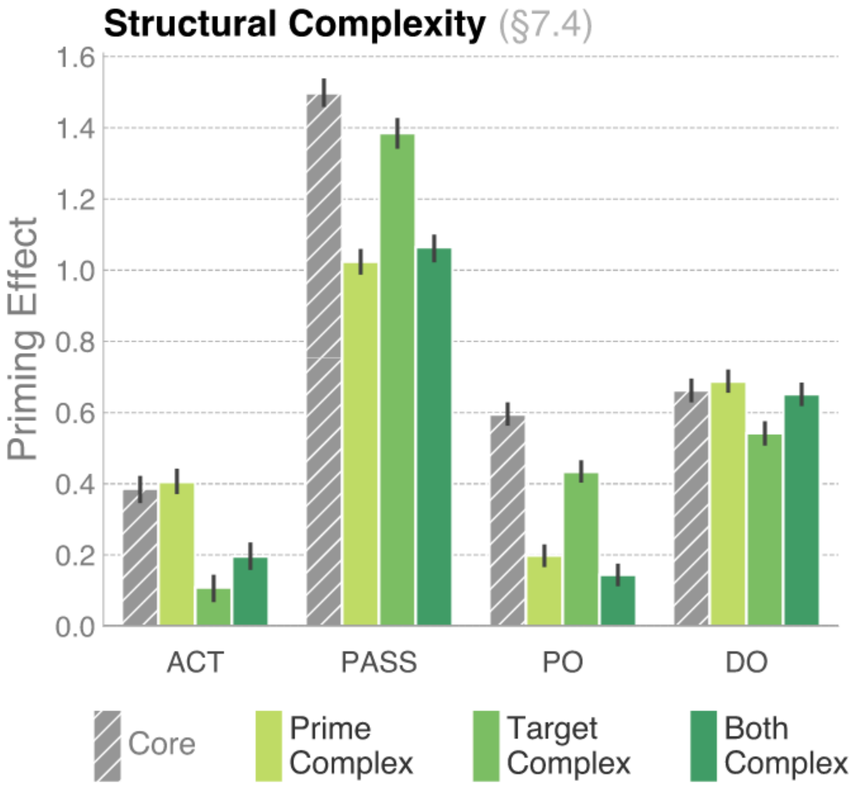


What factors influence priming strength?

Sinclair et al. (2022) cont.

- **Structural Complexity?**
  - **Sequential abstract structures: e.g. a sequence of part-of-speeches?**
  - **OR Hierarchical syntactic representation?**

Corpus	Condition	Prime (ACT)	Target (PASS)
Structural Complexity	Prime Complex	*A lady **with a red bag** chased a minister.*	*The juice was purchased by the child.*
	Target Complex	*The physician judged the leader.*	*A **rich** school was embraced by a business.*
	Both Complex	*The **bad** adult **with the hat** raised the knife.*	*A son was helped by an author **from Cuba**.*



- **Priming effect is a bit lower than Core;**
- **Some priming effect might be due to simple sequential structures, but some degree of hierarchical structures must also be encoded.**

Interim Summary

Concatenation as another method of priming

- Modern LLMs are susceptible to structural priming under the concatenation mode!
- A lot of factors modulates structural priming strength:
  - Semantic similarity & plausibility, lexical overlap;
  - Recency and cumulativity;
  - Structural complexity;
- Structural information is indeed encoded, though not fully autonomous from semantics;

How abstract structures are? Crosslingual Structural Priming!

Is the same structural representations shared across languages?

Michaelov et al. (2023)

Structural Priming Demonstrates Abstract Grammatical Representations in Multilingual Language Models

James A. Michaelov[a]* **Catherine Arnett**[b]* **Tyler A. Chang**[a] **Benjamin K. Bergen**[a]
[a]Department of Cognitive Science,
[b]Department of Linguistics,
University of California San Diego
{j1michae, ccarnett, tachang, bkbergen}@ucsd.edu

- Using **concatenate** mode for priming;
- Using the same data from 6 human experiments in English, Dutch, Spanish, German, Greek, Polish, Mandarin;
- **Model** = XGLM 4.5B (Lin et al. 2022) — pretrained on 134 languages!

Is the same structural representations shared across languages?

Michaelov et al. (2023). Cont.

- Some evidence for crosslingual structural priming in general;
- Crosslingual transfer can happen at the level of grammatical structures — beyond token level!
- Structural representations in LMs is abstract enough to generalize beyond sentences.

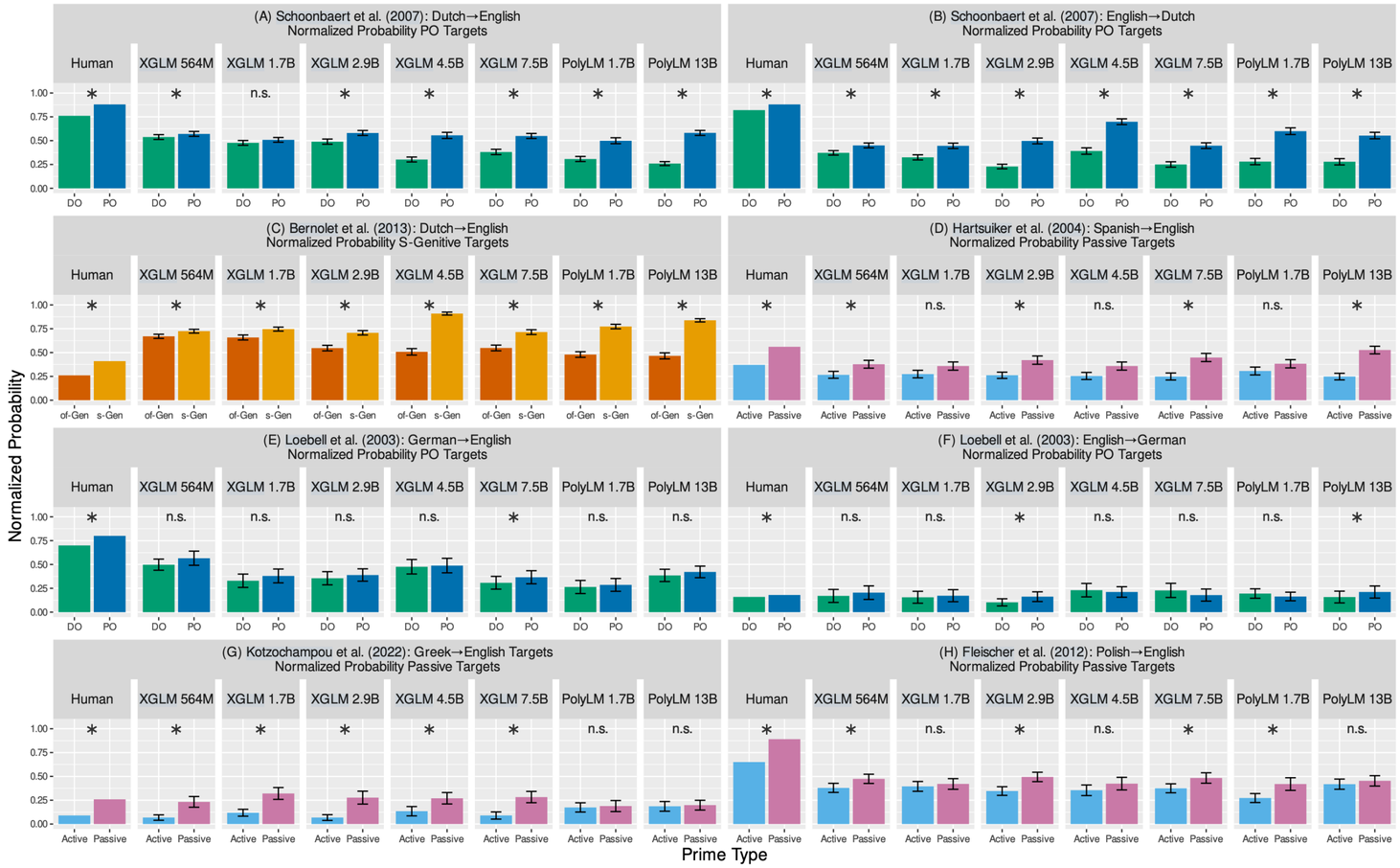


Figure 1: Human and language model results for crosslingual structural priming experiments.

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Figure 1: Human and language model results for crosslingual structural priming experiments.

One final tweak: what about Inverse Frequency Effect?

Structural Priming as a form of In-context Learning

Do LLMs show the Inverse Frequency Effect?

Jumelet et al. (2024) and Zhou et al. (2024)

Do Language Models Exhibit Human-like Structural Priming Effects?

Jaap Jumelet[1] **Willem Zuidema**[1] **Arabella Sinclair**[2]

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Is In-Context Learning a Type of Error-Driven Learning? Evidence from the Inverse Frequency Effect in Structural Priming

Zhenghao Zhou **Robert Frank** **R. Thomas McCoy**

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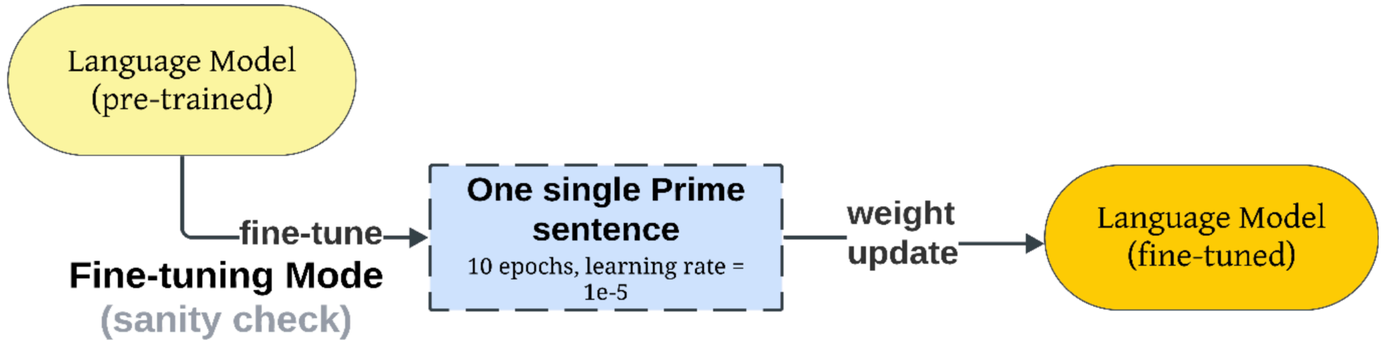
- **Assumption from Psycholinguists:** only some error-driven learning mechanism could lead to the IFE.
  - IF [LMs show the IFE without explicit gradient update (by fine-tuning)]
  - THEN [in-context learning must be some error-driven based mechanism in order to be sensitive to the verb bias information]

Is In-context Learning an Error-driven Mechanism?

Zhou et al. (2025) cont.



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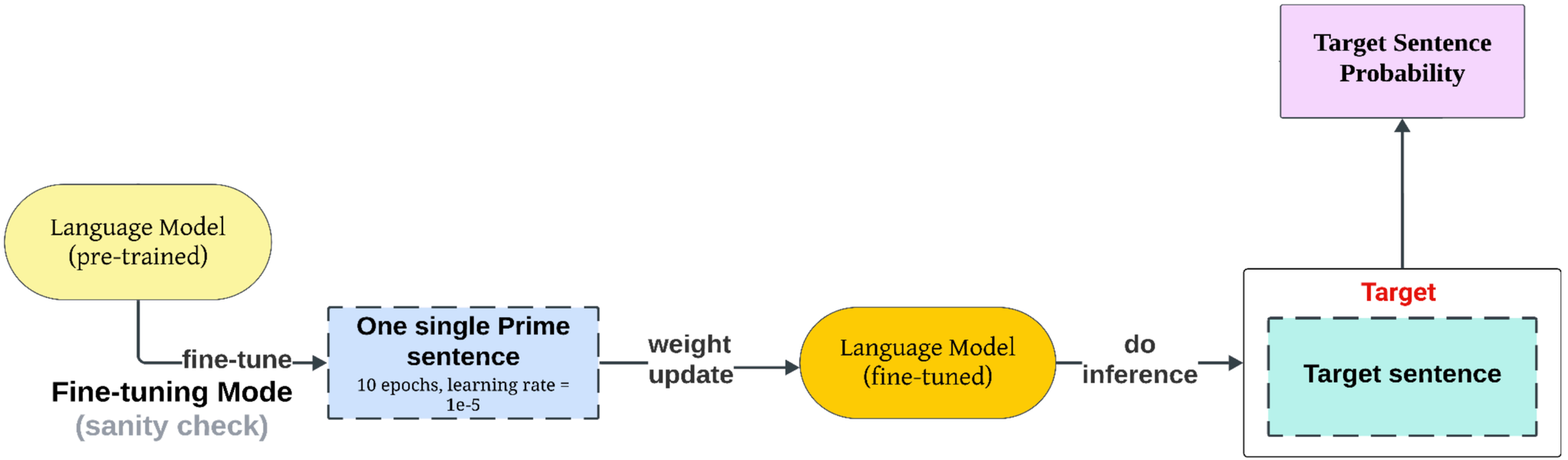
Zhou et al. (2025) cont.



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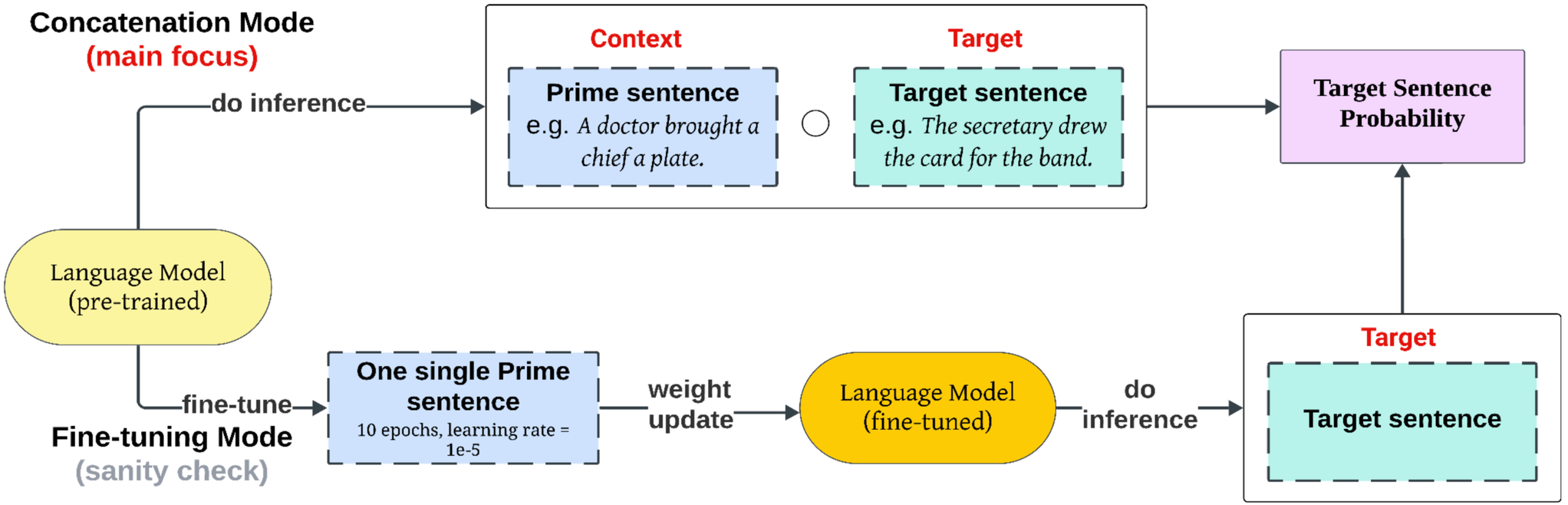
Zhou et al. (2025) cont.



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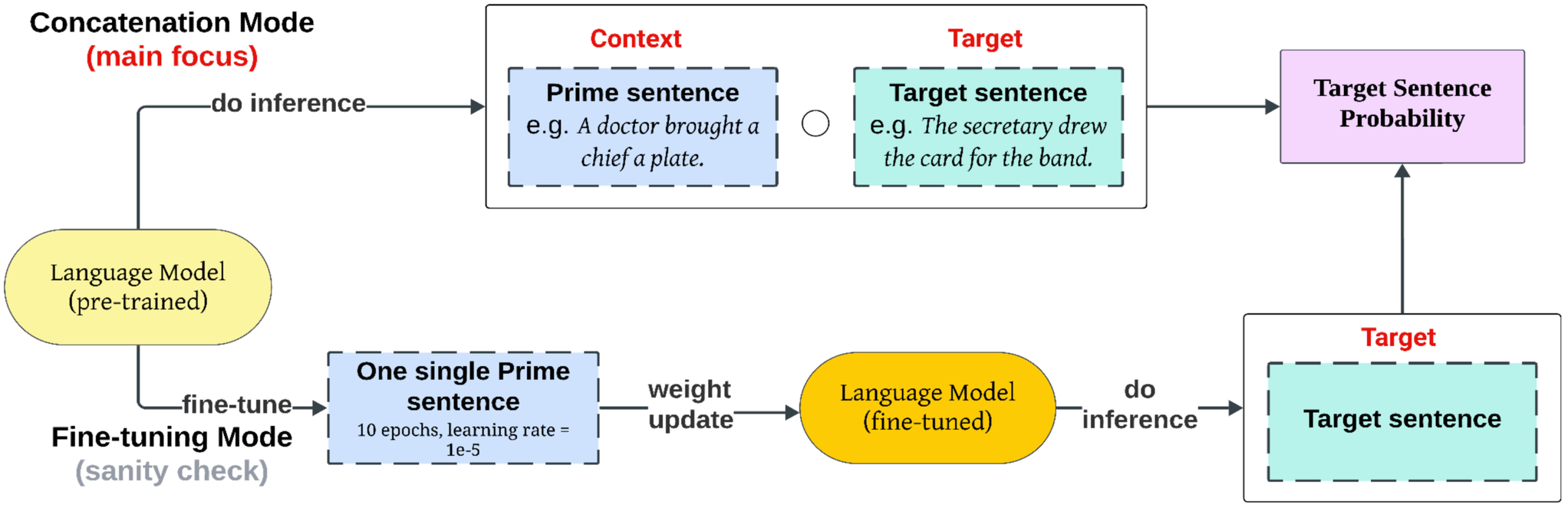
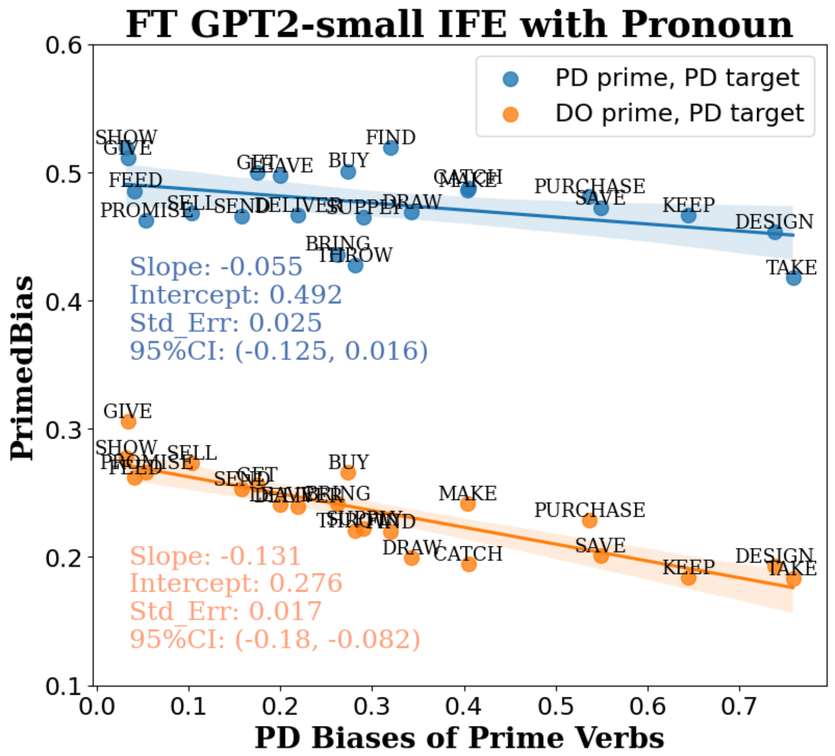
Zhou et al. (2025) cont.



- **Predictions**
  - **Fine-tuning Mode: (with explicit weight update) IFE ✅**
  - **Concatenation Mode: (no weight update) IFE ❓**

Is In-context Learning an Error-driven Mechanism?

Zhou et al. (2025) cont.



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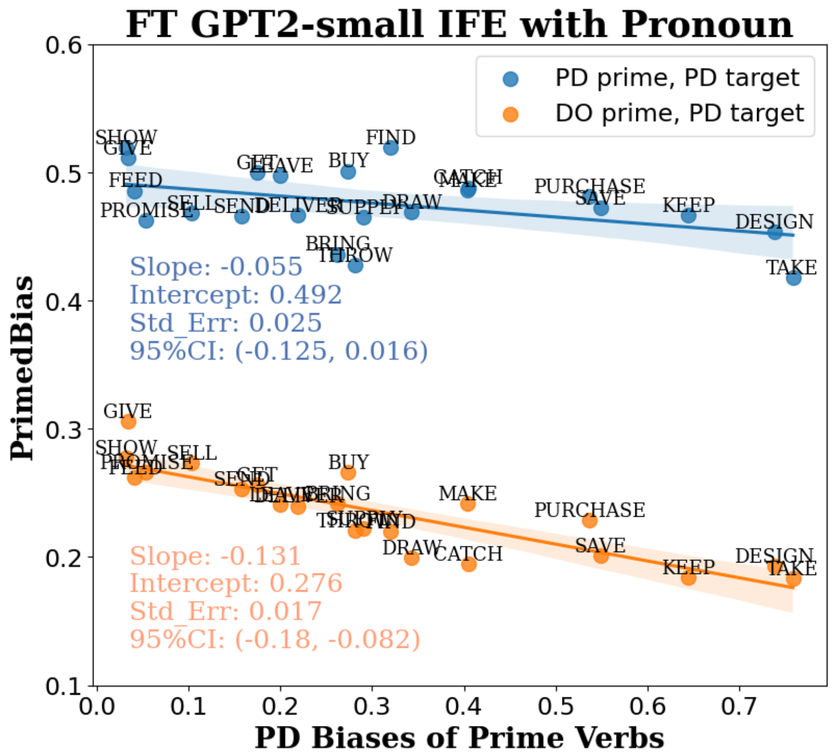
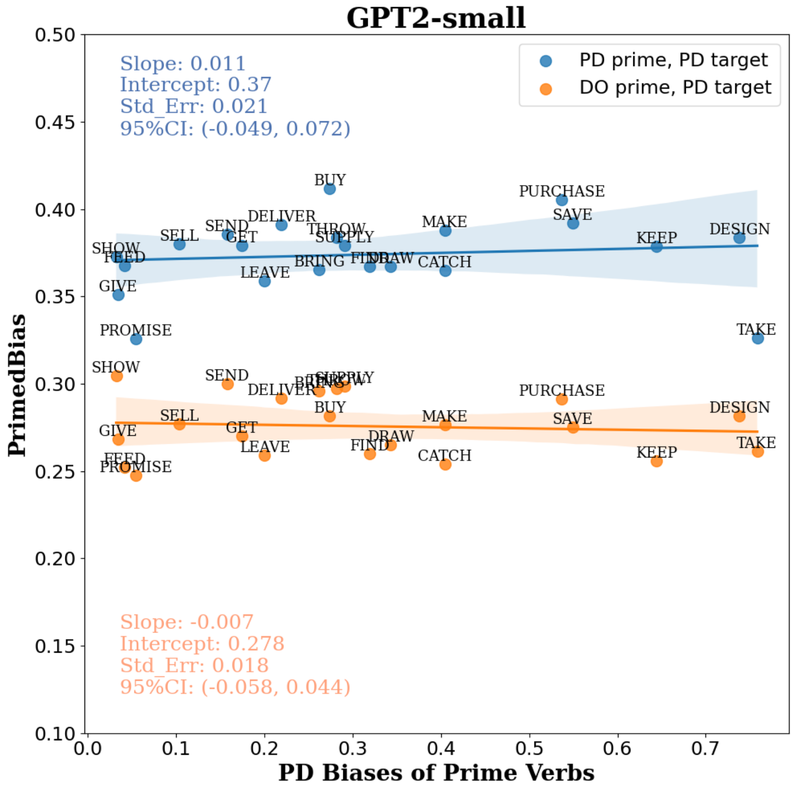


- **Standard priming:** blue has a higher intercept than orange
- **IFE:** double negative slopes

Is In-context Learning an Error-driven Mechanism?

Zhou et al. (2025) cont.



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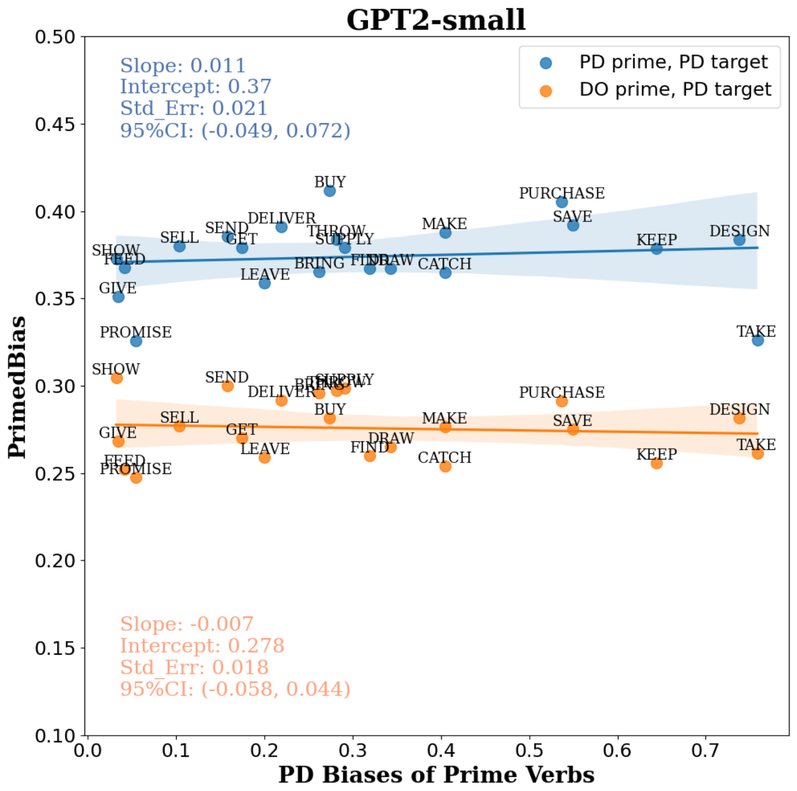

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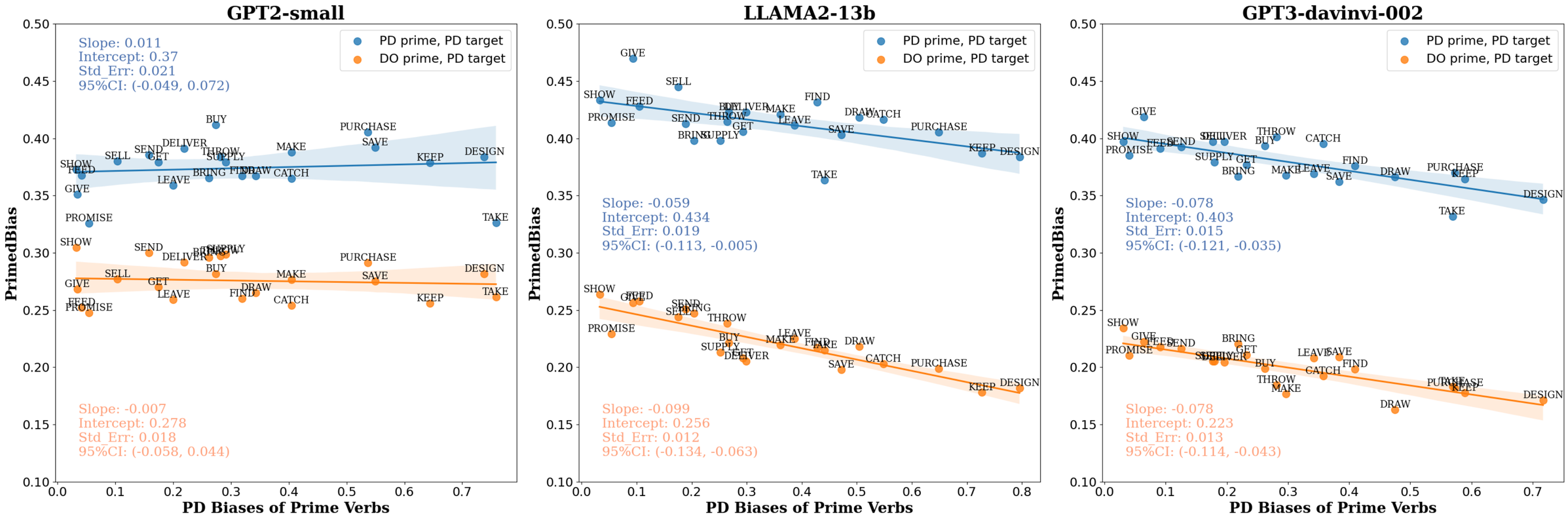

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What have we learned?

- **Human priming effects at multiple linguistic levels**
  - semantic, phonological, orthographical, and structural;
- **Two ways of simulating structural priming in LMs**
  - Fine-tuning, Concatenation (few-shot, in-context learning)
- **LMs show qualitatively human-like priming effect**
  - Lexical boost, inverse frequency;
  - Semantic similarity & plausibility, recency, cumulativity, etc.
  - Crosslingual structural priming;
- **Evidence for abstract structural representations, though not totally independent from semantic information.**

Thank you!

p.s. Octopus again….

Bender & Koller 2020: LMs cannot learn to understand meaning solely through form / syntax / statistical regularity…?

The Octopus Test from:

Climbing towards NLU:
On Meaning, Form, and Understanding in the Age of Data

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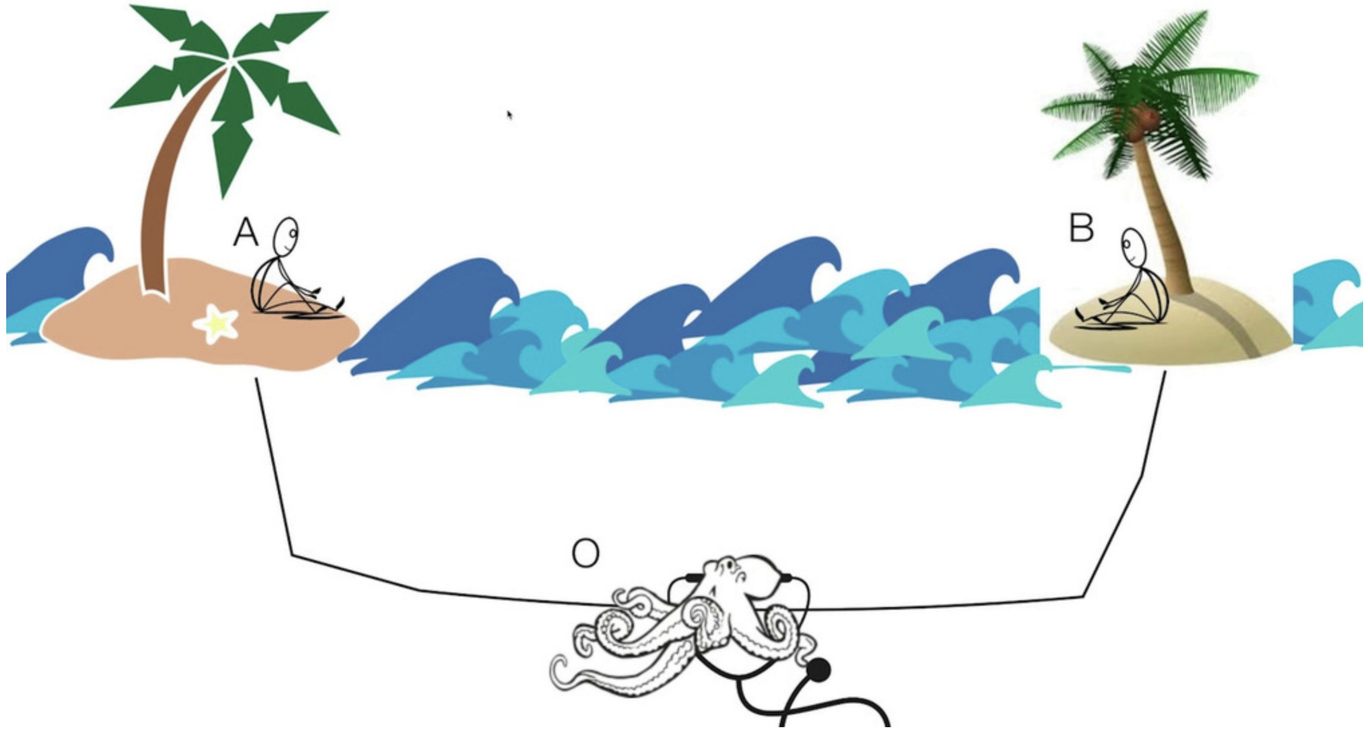

Opening Demonstrations:
credit to Sophie Hao and Bob Frank