Psycholinguistic methods, prediction in human language processing, and surprisal theory

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9.19: Computational Psycholinguistics

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Some psycholinguistic benchmarks

- What is our *cognitive state* at every moment of language understanding and language production?
- How do we manage uncertainty about the interpretation of past input, and about possible future input?
- What determines the difficulty of integrating a word into its context?
- What influences how we package our thoughts into utterances?

Psycholinguistic methodology

- Many workhorses of psycholinguistic experimentation involve *behavioral* measures
  - What choices do people make in various types of language-producing and language-comprehending situations?
    - What do we interpret an utterance to mean in a context?
    - What words do we choose to convey a meaning?
    - And, how long do they take to make these choices?
- *Offline* measures
  - rating sentences, completing sentences, …
- *Online* measures
  - tracking people's eye movements, having people read words aloud, reading under (implicit) time pressure…
- There are also non-behavioral, notably *neural*, methods for studying human language processing

Incrementality, structure, and surprise

The woman brought the sandwich from the kitchen tripped.

who was

The woman given the sandwich from the kitchen tripped.

The woman who was given the sandwich from the kitchen tripped.

who was

	Simple past	Past participle
bring	***brought***	***brought***
give	***gave***	***given***

Meaning can help us avoid surprise, too:

The evidence examined by the lawyer from the firm was unreliable.

Measuring human incremental processing state

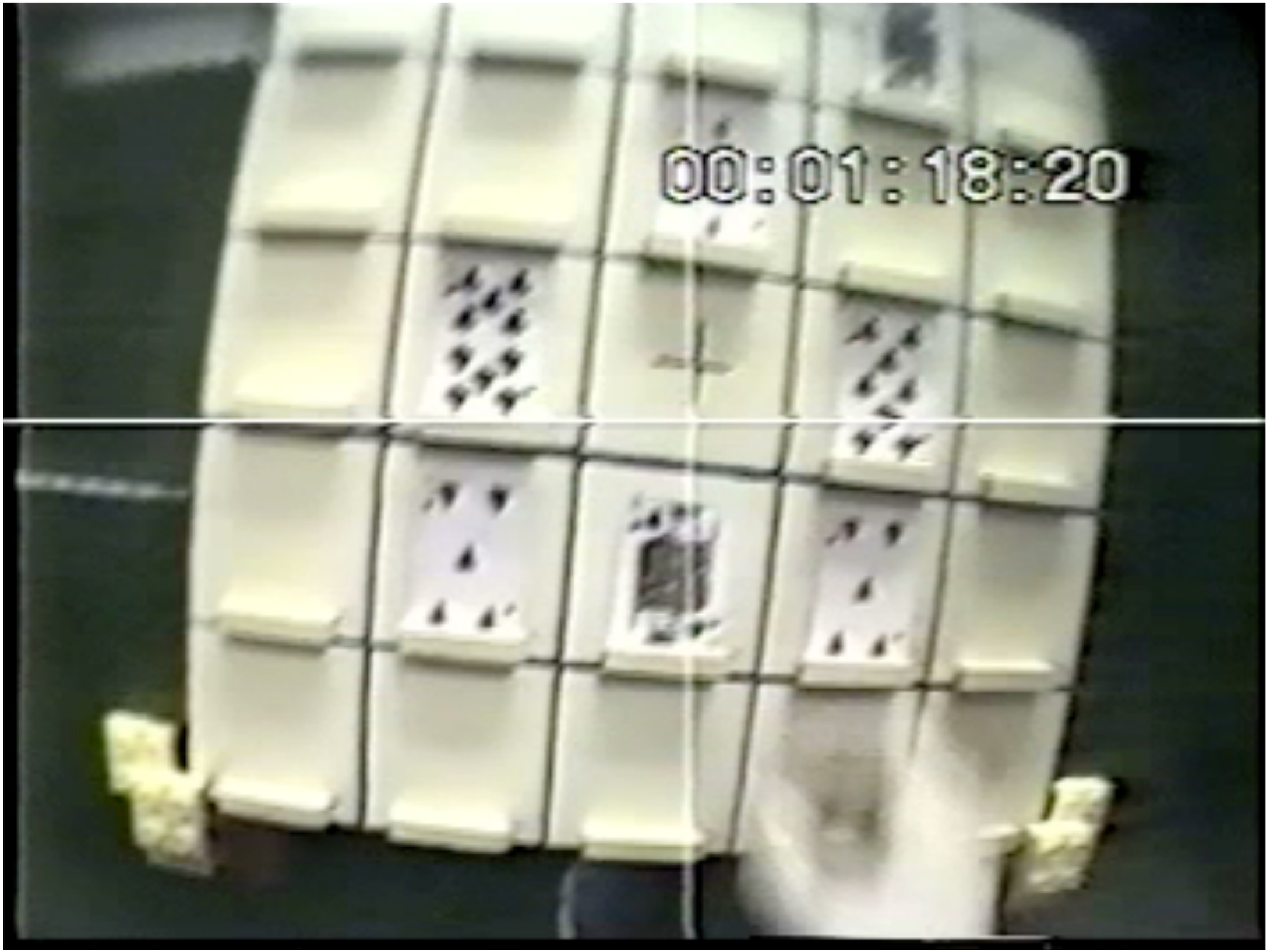
- Eye movements in the visual world
- Word-by-word reading times
  - Self-paced reading
  - Eye movements during natural reading

Behavioral

- Recordings of brain activity
  - Electrophysiological (EEG/ERP)
  - Magneto-encephalography (MEG)
  - Functional Magnetic Resonance Imaging (fMRI)
  - Electrocorticography (ECoG)

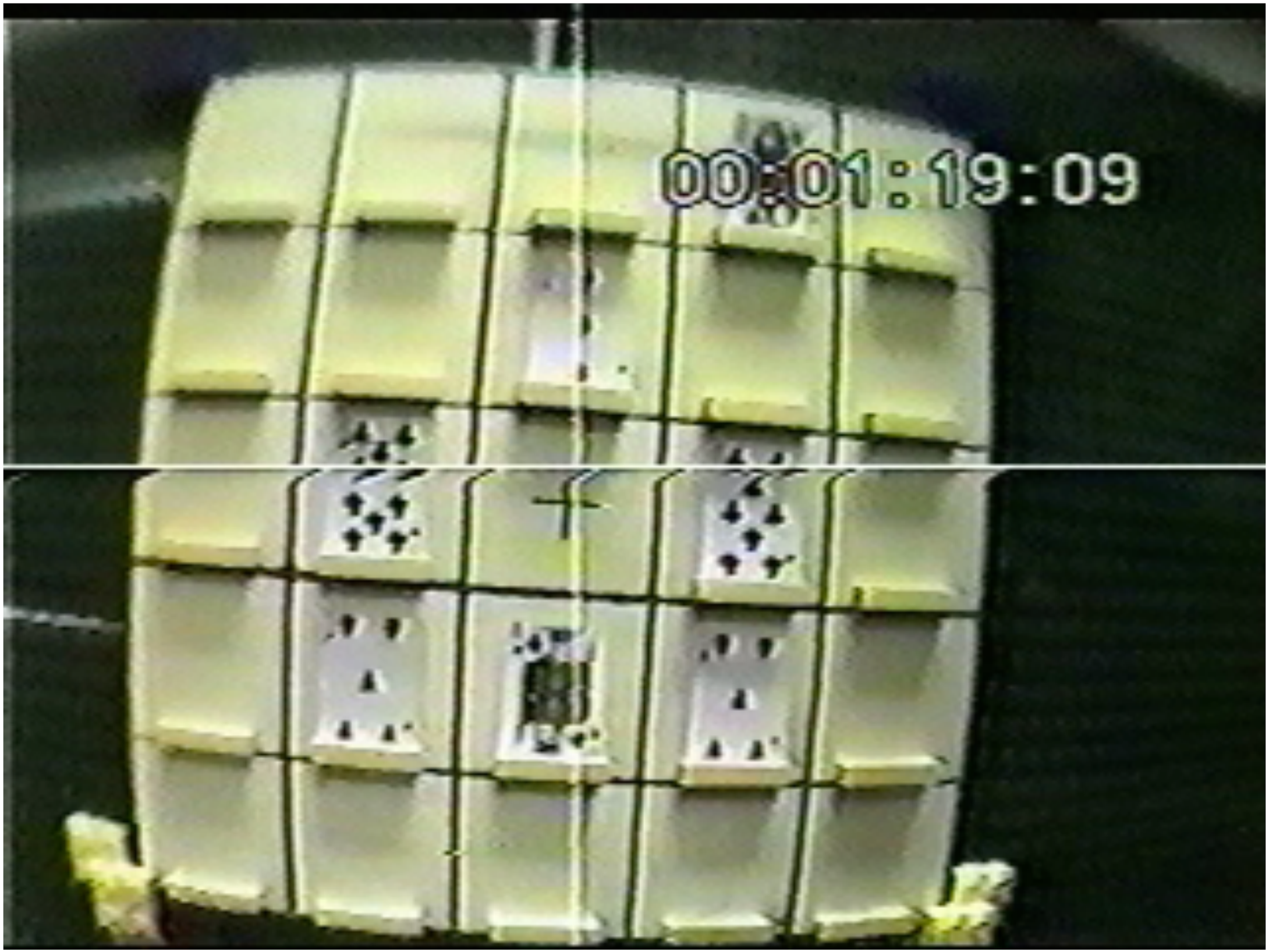
Neural

Eye movements in the visual world



(Video courtesy of Mike Tanenhaus)

Eye movements in the visual world (slow-motion)



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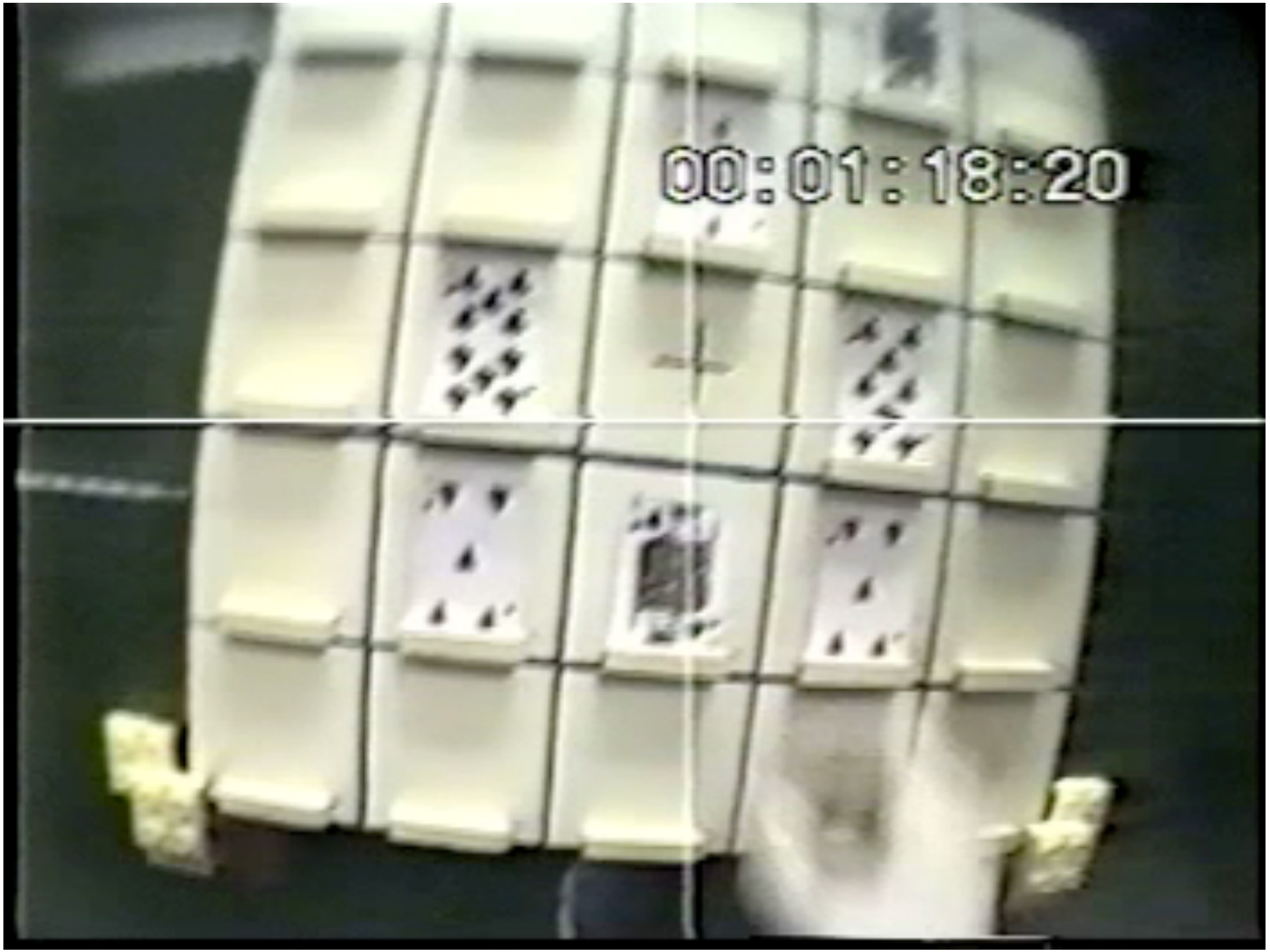
Eye movements in the visual world



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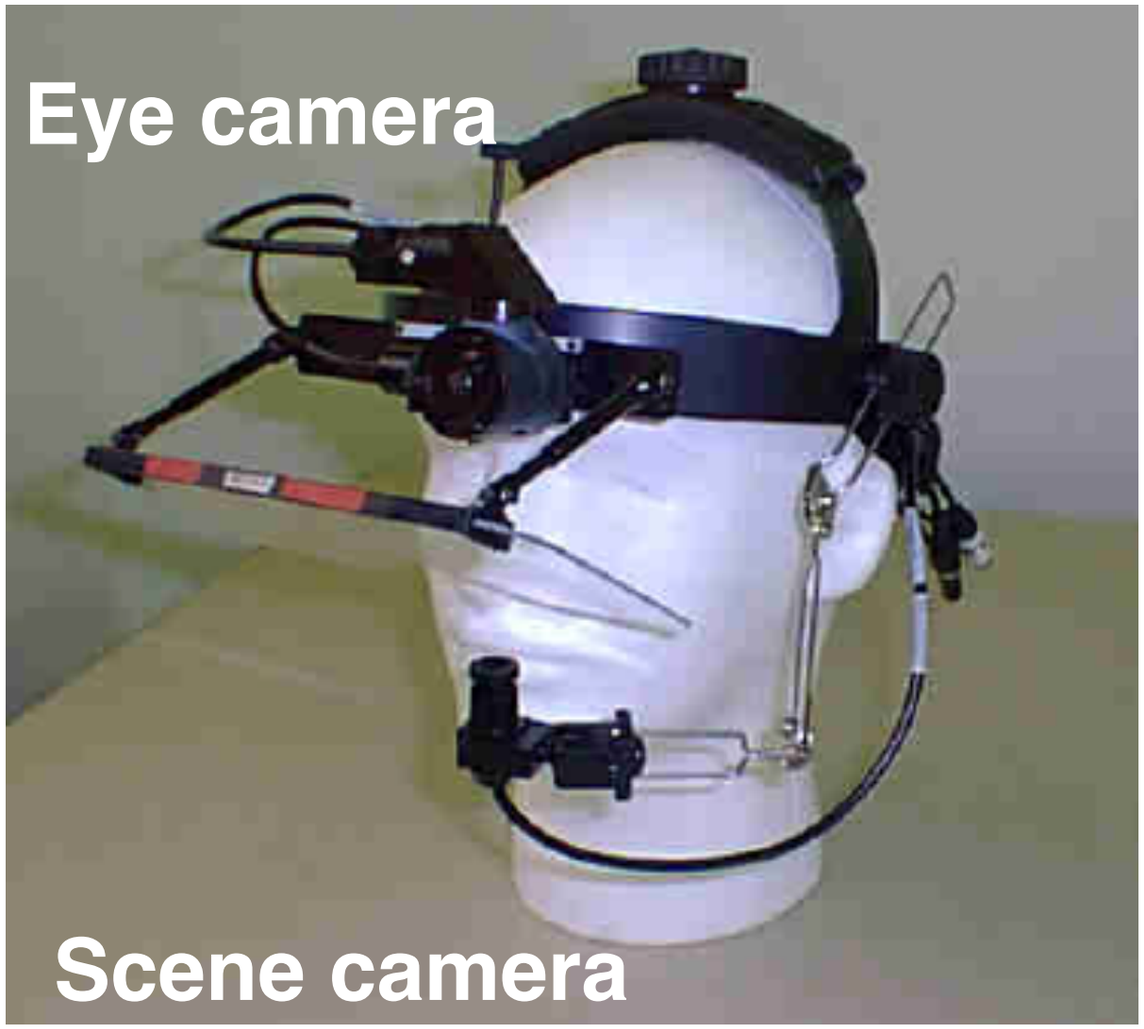
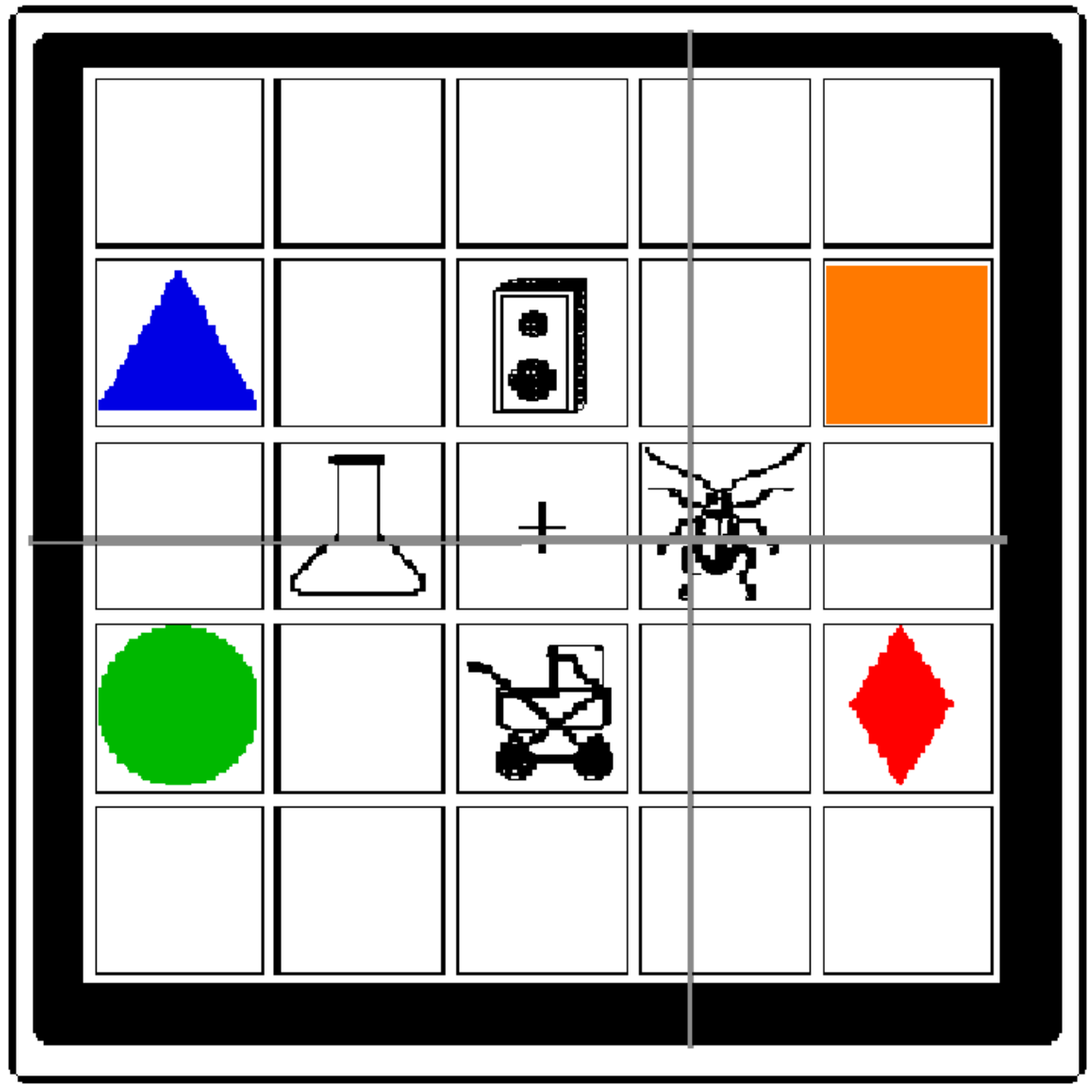
A visual world experiment





Instruction to experimental participant:

"Pick up the beaker"

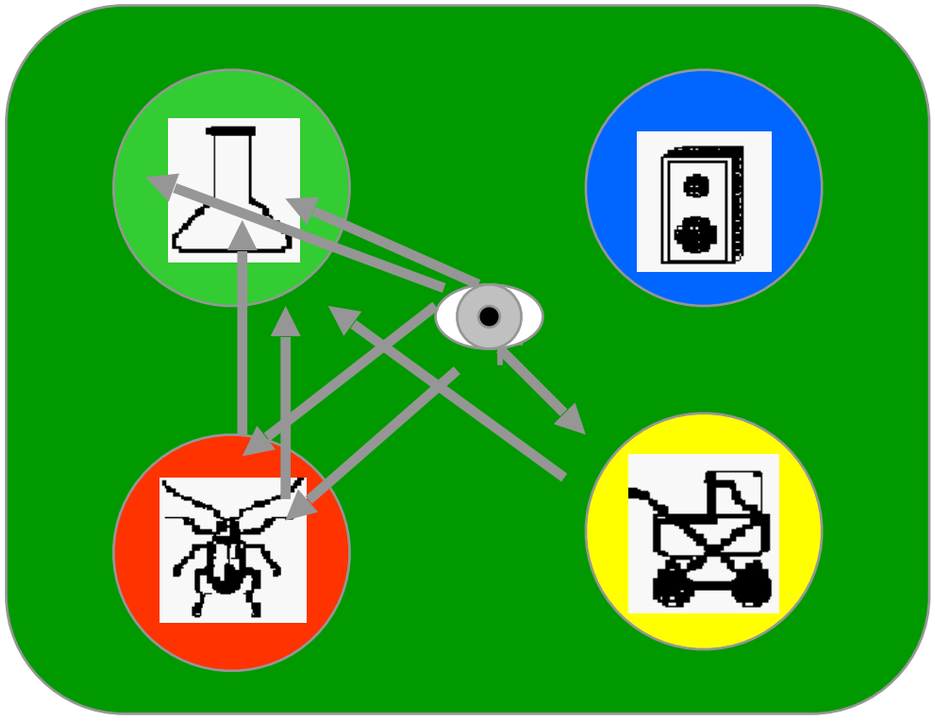
(Slide courtesy of Mike Tanenhaus)

Allopenna, Magnuson & Tanenhaus (1998)

Data from human eye movements

"Look at the cross."

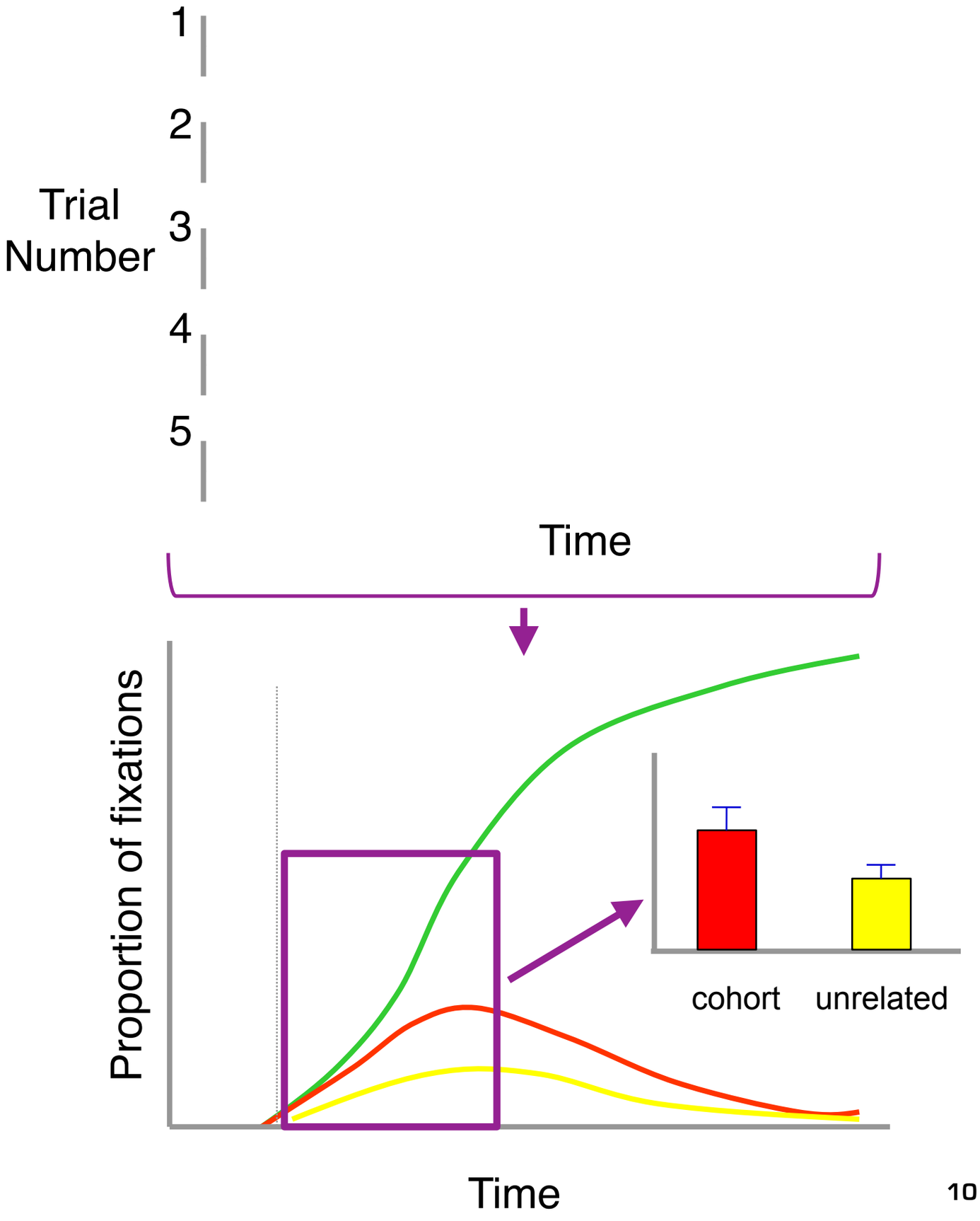
"Pick up the beaker."



Target = beaker

Cohort = beetle

Unrelated = carriage



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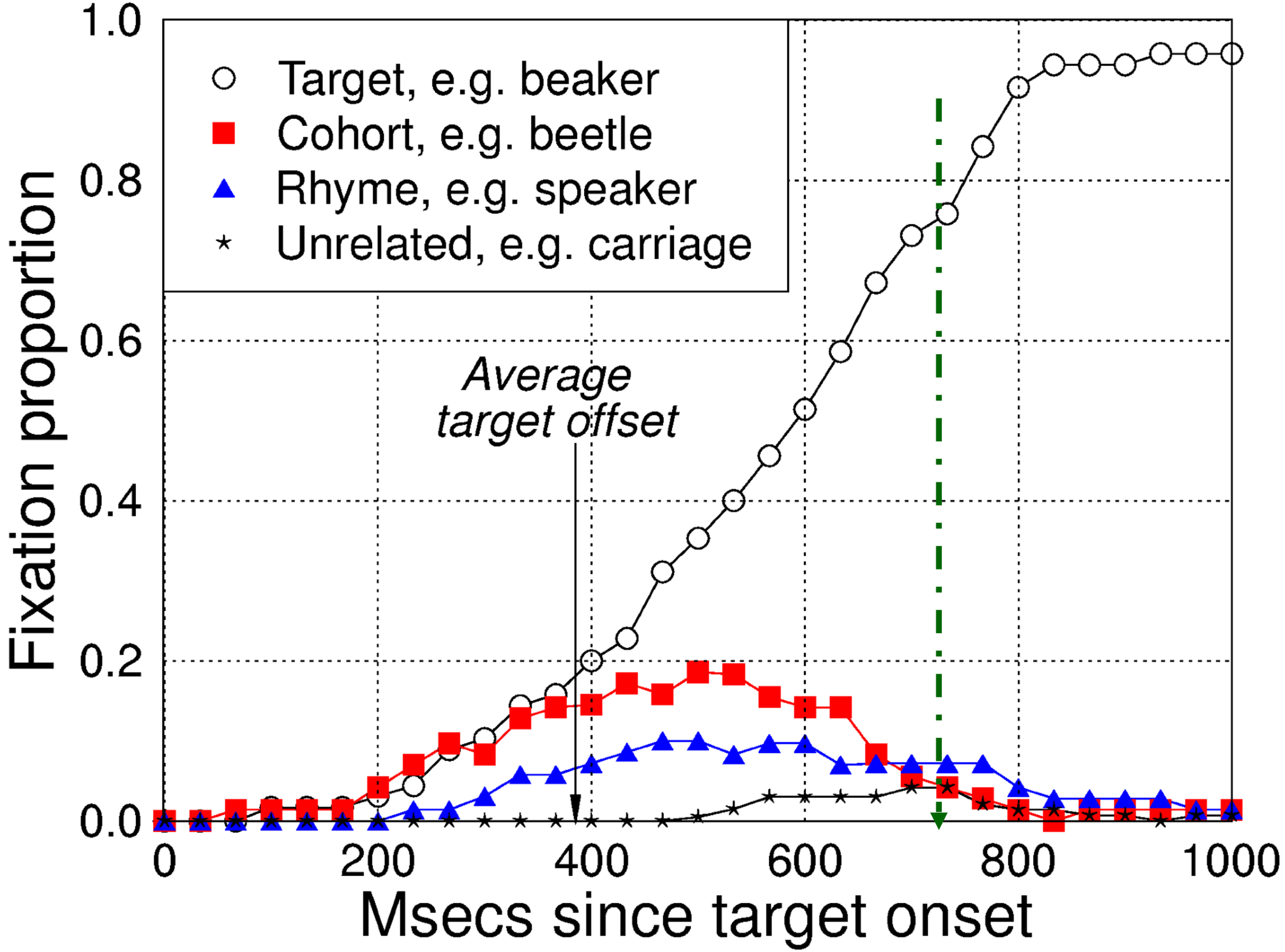
Allopenna, Magnuson & Tanenhaus (1998)



(Slide courtesy of Mike Tanenhaus)

How do people read?

CNN wants to change its viewers' habits.

(slide courtesy Yevgeni Berzak)

Eye movements in reading

(movie by Piers Cornelissen)

How do people read?

CNN wants to change its viewers' habits.

(slide courtesy Yevgeni Berzak)

How do people read?

Fixations

(slide courtesy Yevgeni Berzak)

How do people read?

Saccades

(slide courtesy Yevgeni Berzak)

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How do people read?

CNN wants to change its viewers' habits.

What do you see during a fixation?

(slide courtesy Yevgeni Berzak)

How do people read?

CNN wants to change its viewers' habits.

Perceptual span

What do you see during a fixation?

(slide courtesy Yevgeni Berzak)

How do people read?

CNN wants to change its viewers' habits.

What do you see during a saccade?

(slide courtesy Yevgeni Berzak)

How do people read?

What do you see during a saccade?

Nothing

(slide courtesy Yevgeni Berzak)

How do people read?

CNN wants to change its viewers' habits.

Forward

Saccade

(slide courtesy Yevgeni Berzak)

How do people read?

CNN wants to change its viewers' habits.

Forward

Saccade

(slide courtesy Yevgeni Berzak)

How do people read?

CNN wants to change its viewers' habits.

(slide courtesy Yevgeni Berzak)

How do people read?

CNN wants to change its viewers' habits.

Backward
Saccade
(Regression)

(slide courtesy Yevgeni Berzak)

How do people read?

(slide courtesy Yevgeni Berzak)

Eye movement measures

- Skips (also skip rate / fixation probability)
- First fixation duration
- First pass duration (or Gaze duration)
- First pass regression rate
- Go-past duration
- Total fixation duration

(slide courtesy Yevgeni Berzak)

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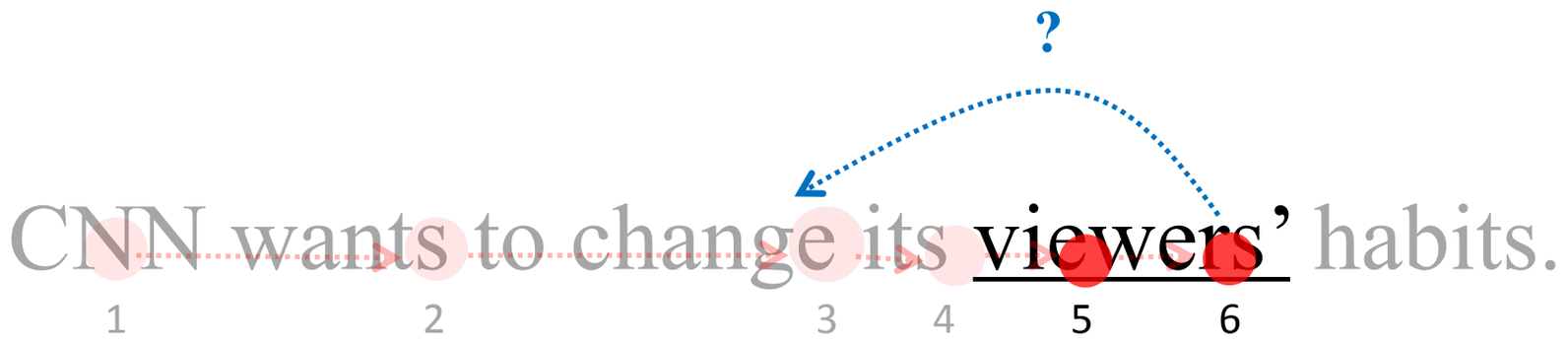

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(slide courtesy Yevgeni Berzak)

Linguistic Expectations

- Linguistic expectations can be studied with eye tracking for reading.
- Reading times (across different eye movement measures) reflect how contextual predictability affects linguistic processing.

(slide courtesy Yevgeni Berzak)

Generalizing incremental disambiguation

- Uncertainty in predictions about upcoming material

The old man stopped and stared at the statue? dog? view? woman?

The squirrel stored some nuts in the tree

- This is uncertainty about *what has not yet been said*
- Reading-time (Ehrlich & Rayner, 1981) and EEG (Kutas & Hillyard, 1980, 1984) evidence shows this affects processing rapidly
- A good model should account for expectations about how this uncertainty will be resolved

*(the **Cloze procedure**; Taylor, 1953)*

Rayner & Well 1996

The hikers slowly climbed up the _____

Equal word length & frequency

mountain (95%)

hillside (3%)

(slide courtesy Yevgeni Berzak)

Rayner & Well 1996

The hikers slowly climbed up the mountain to get a better view.

The hikers slowly climbed up the hillside to get a better view.

		Fixation Time		
Constraint	Fixation Probability	First Fixation	Gaze Duration	Total Time
High	0.78	239	261	294
Low	0.90	250	281	360

(slide courtesy Yevgeni Berzak)

Staub 2011

While the professor lectured the students walked across the quad.

(slide courtesy Yevgeni Berzak)

Staub 2011

???

While the professor lectured the students walked across the quad.

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Staub 2011

[While the professor [lectured the students]] walked across the quad.
Subj V Obj
???

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???

[While the professor lectured] [the students walked across the quad.]
Subj V Subj

(slide courtesy Yevgeni Berzak)

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While the professor lectured, the students walked across the quad.

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Staub 2011

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Subj V Obj

[While the professor lectured,] [the students walked across the quad.]

Subj V Subj

(slide courtesy Yevgeni Berzak)

Staub 2011: word frequency & predictability effects

While the professor lectured the students walked across the quad.
(ambiguous)

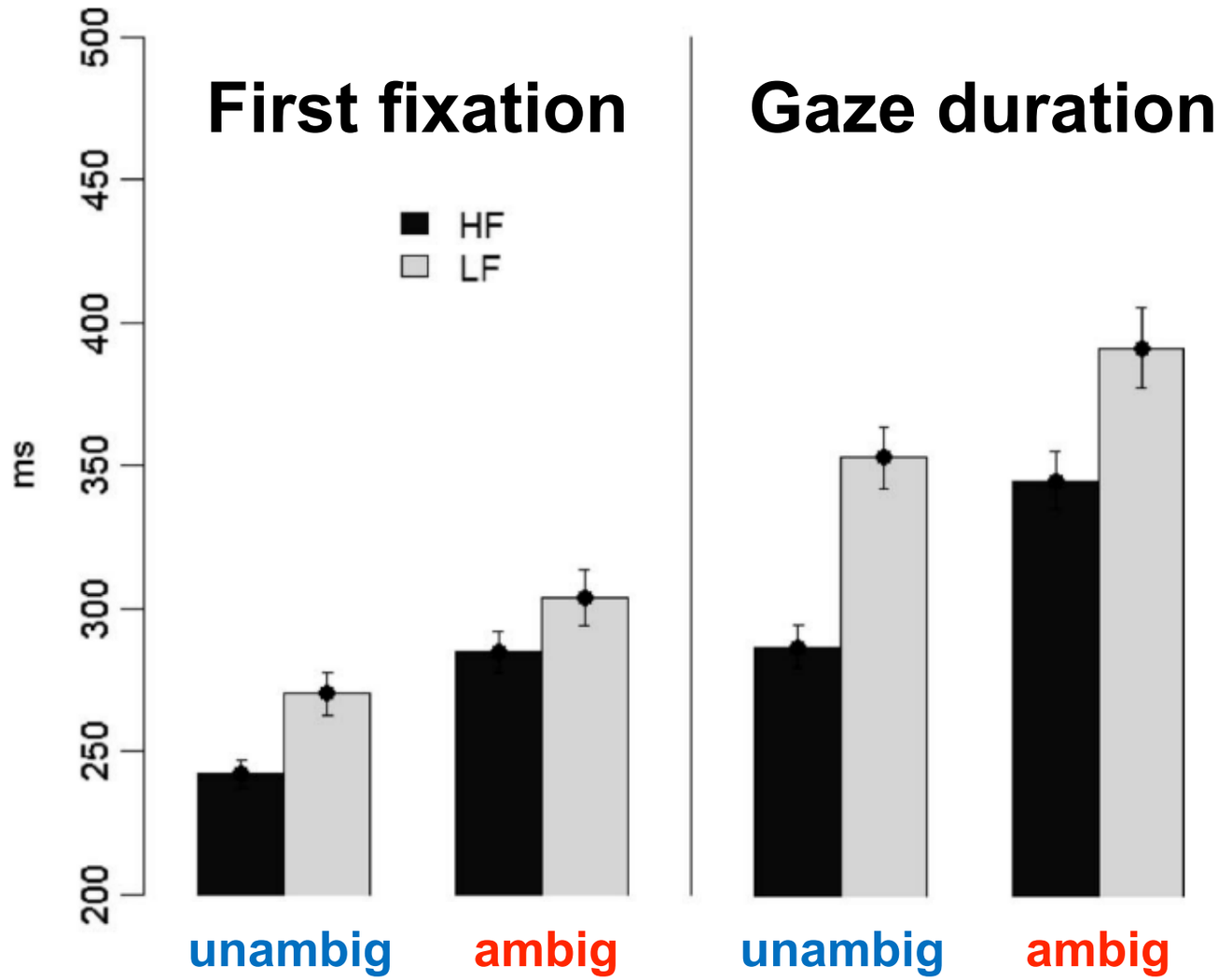
While the professor lectured, the students walked across the quad.
(unambiguous)

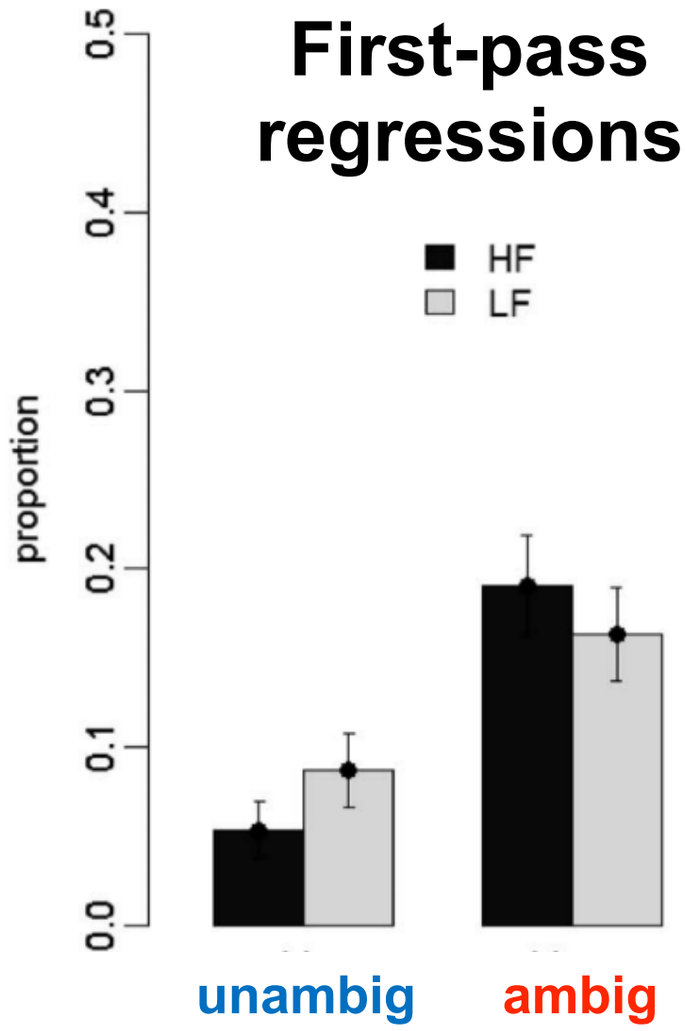
High **F**requency

ambled

ambled

Low **F**requency





(slide courtesy Yevgeni Berzak)

Psycholinguistic methodology (2)

- A lower-tech method: **self-paced reading** (SPR)
- Reveal each consecutive word with a button press

```
While the clouds crackled, above the glider soared--------------------
```

- Readers aren't allowed to backtrack
- We measure time between button presses and use it as a proxy for incremental processing difficulty

Psycholinguistic methodology (3)

- Another lower-tech method: **the maze**
- Choose the word that fits given the preceding context

(Forster et al., 2009; Boyce et al., 2020)

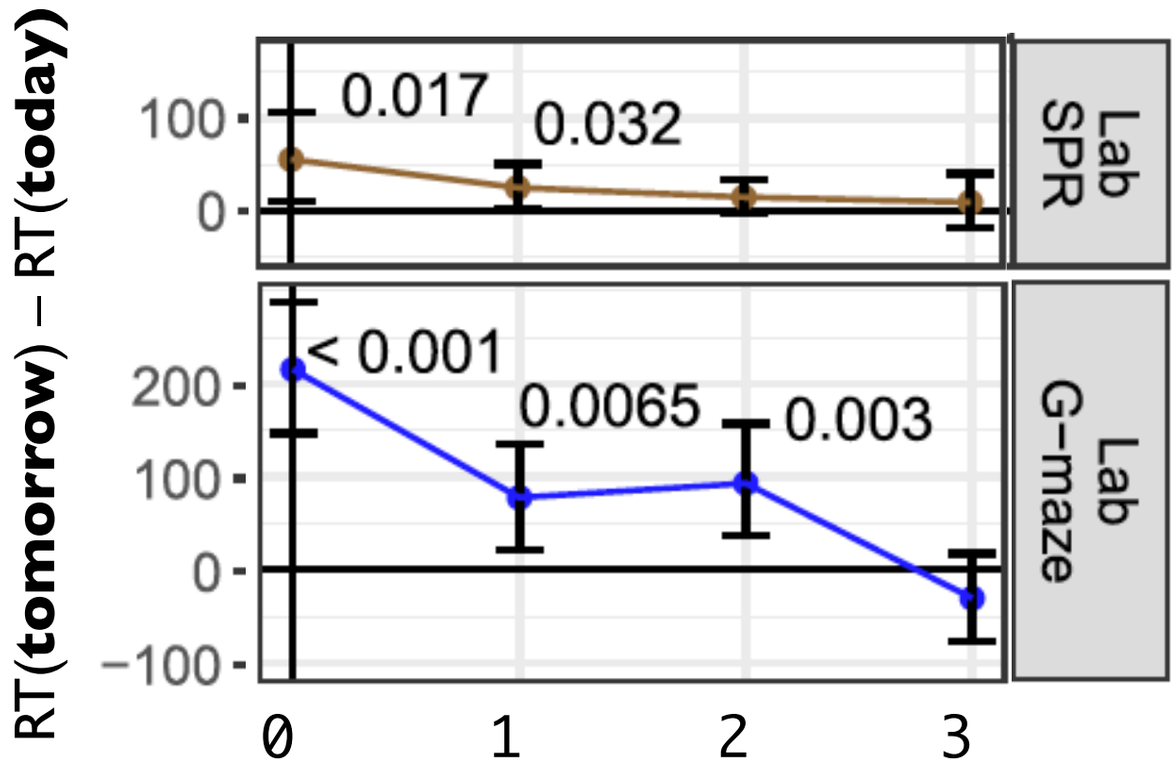
Example SPR and Maze results

James will fix the car he drove **today,** but he will need some help.

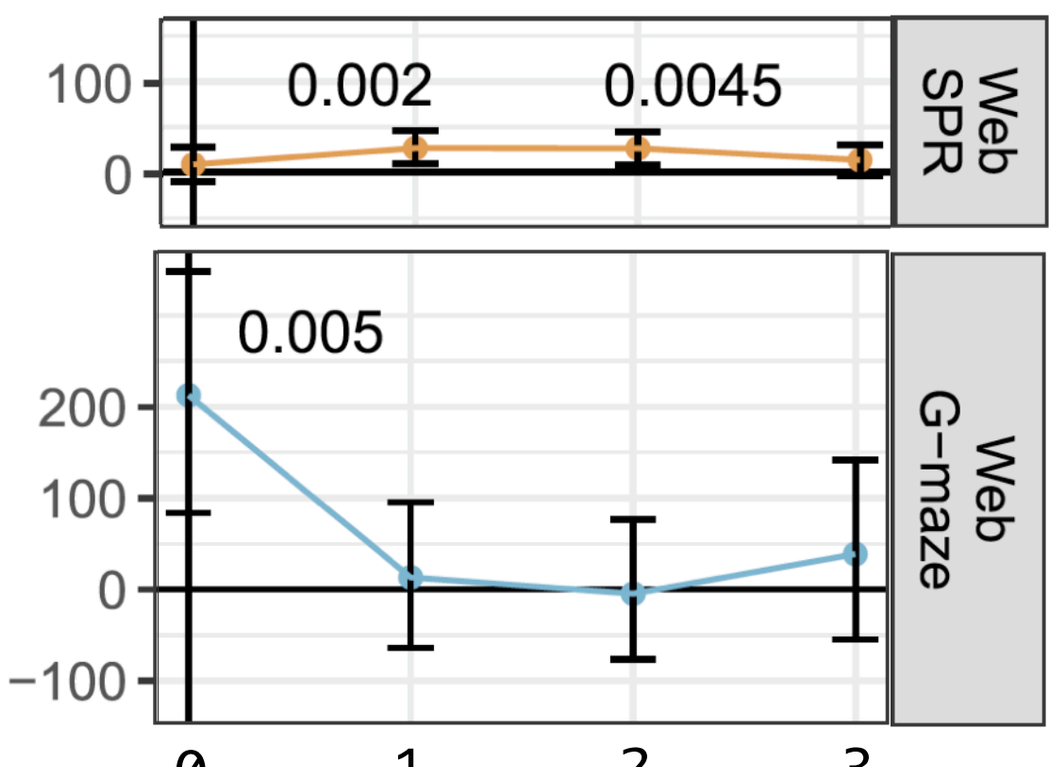
James will fix the car he drove **tomorrow,** but he will need some help.

Position: 0 1 2 3

Results in the lab



Results on the web (Mechanical Turk)

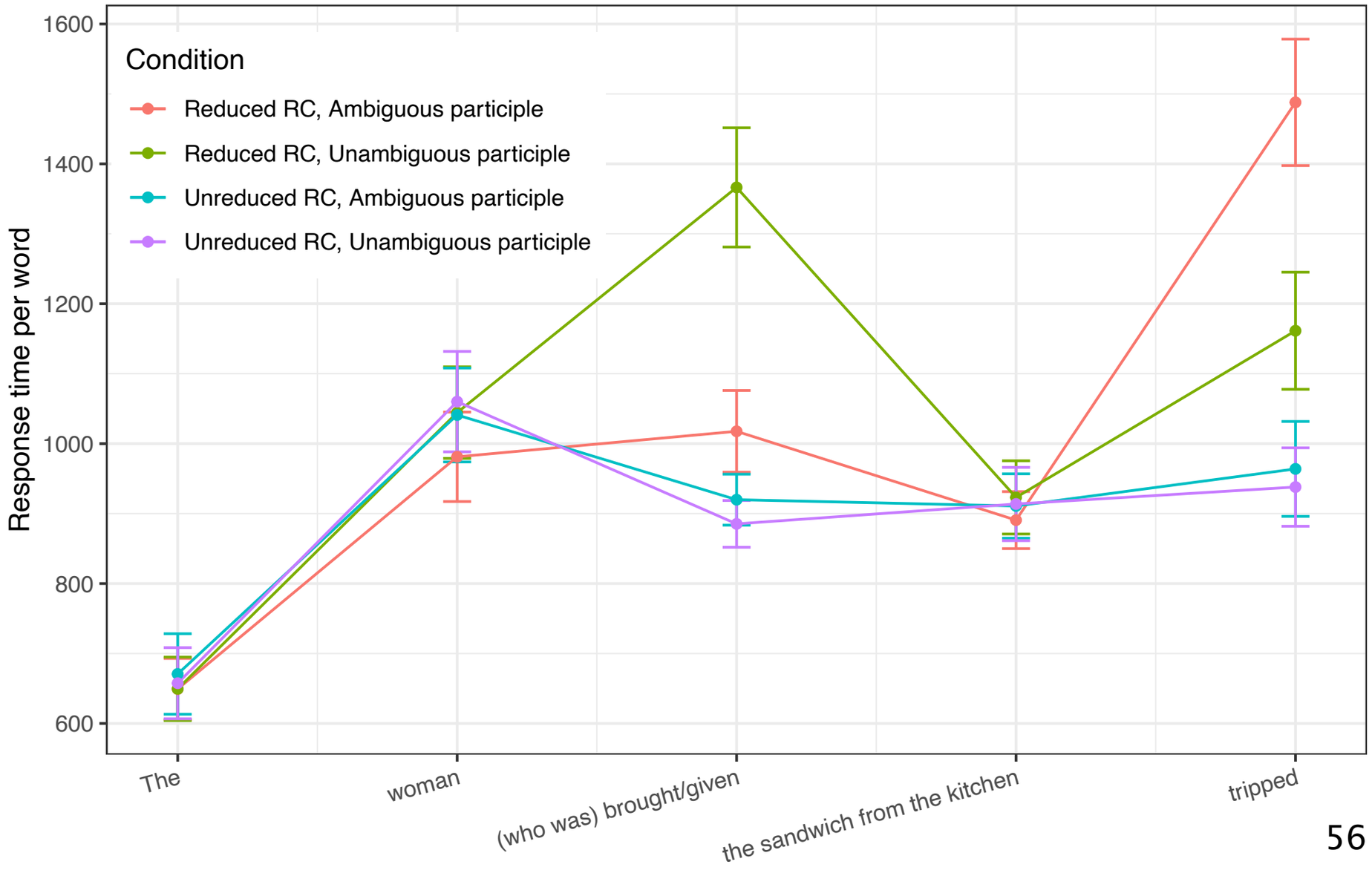


(Witzel et al., 2012; Boyce et al., 2020)

Incrementality, structure, and surprise

	Is the relative clause reduced?	Is the participle part-of-speech ambiguous?
The woman brought the sandwich from the kitchen tripped.	+	+
The woman given the sandwich from the kitchen tripped.	+	–
The woman who was brought the sandwich from the kitchen tripped.	–	+
The woman who was given the sandwich from the kitchen tripped.	–	–

	Simple past	Past participle
bring	***brought***	***brought***
give	***gave***	***given***



(Vani et al., in progress)

Psycholinguistic methodology (3)

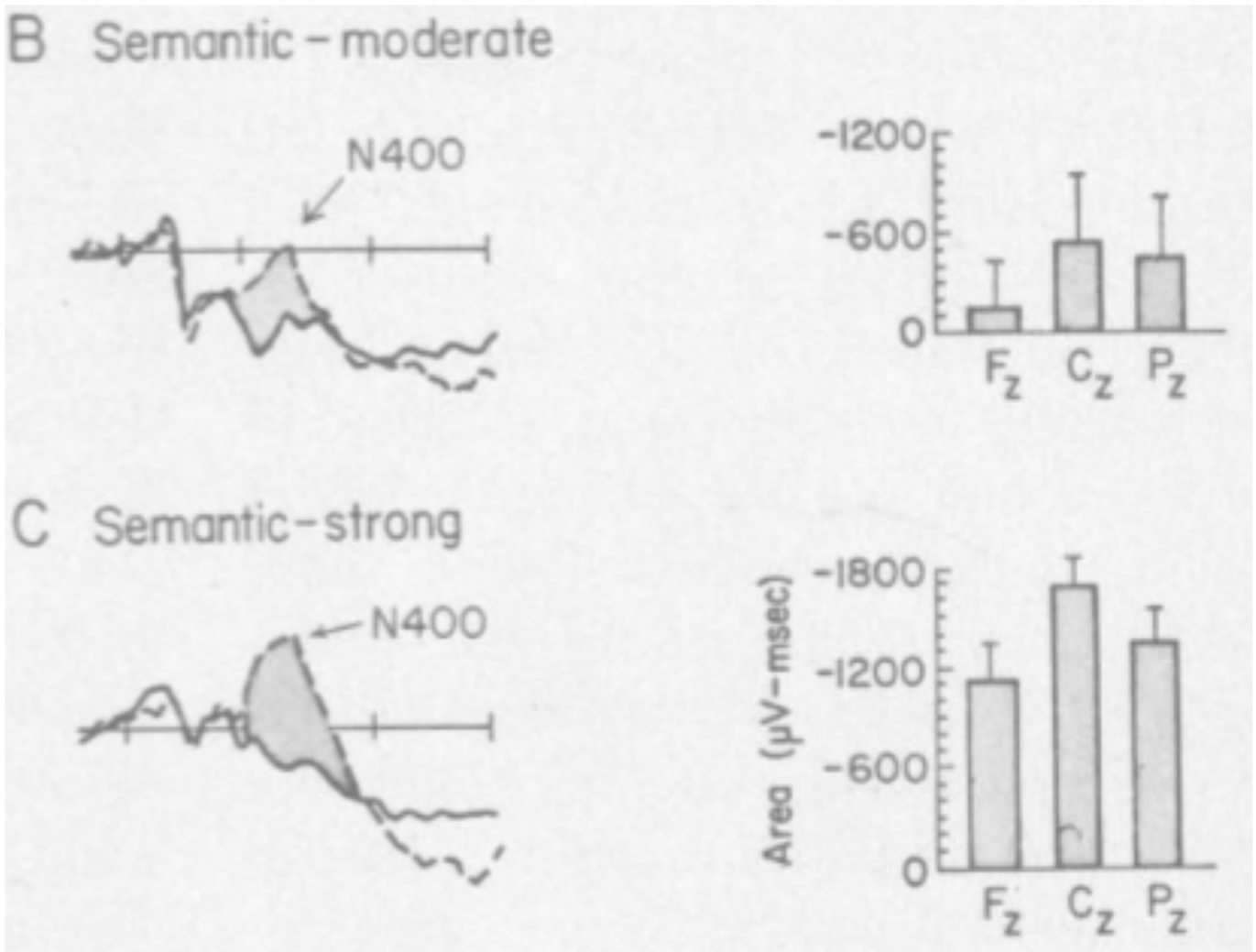
- *Neurolinguistic* experimentation is more and more widely used to study language comprehension
  - methods vary in temporal and spatial resolution
  - people are more passive in these experiments: sit back and listen to/read a sentence, word by word
  - strictly speaking *not* behavioral measures
  - the question of “what is difficult” becomes a little less straightforward

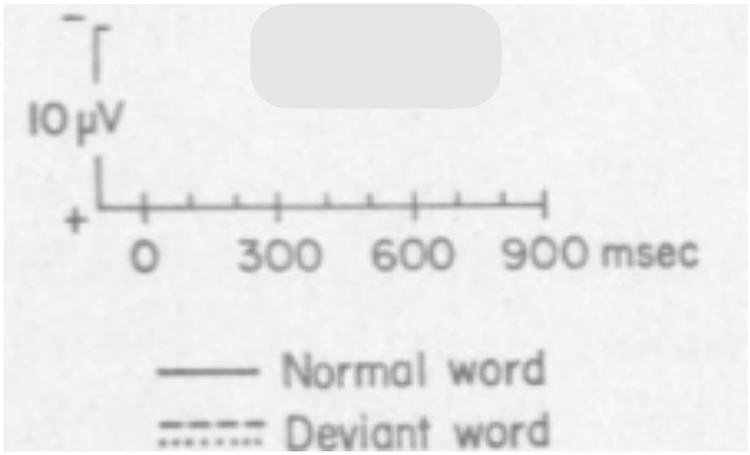
Electrophysiological responses

Rapid Serial Visual Presentation

The N400 in language comprehension

- Differing degrees of semantic congruity:
  - He took a sip from the *drink*. (normal)
  - He took a sip from the *waterfall*. (moderate incongruity)
  - He took a sip from the *transmitter*. (strong incongruity)



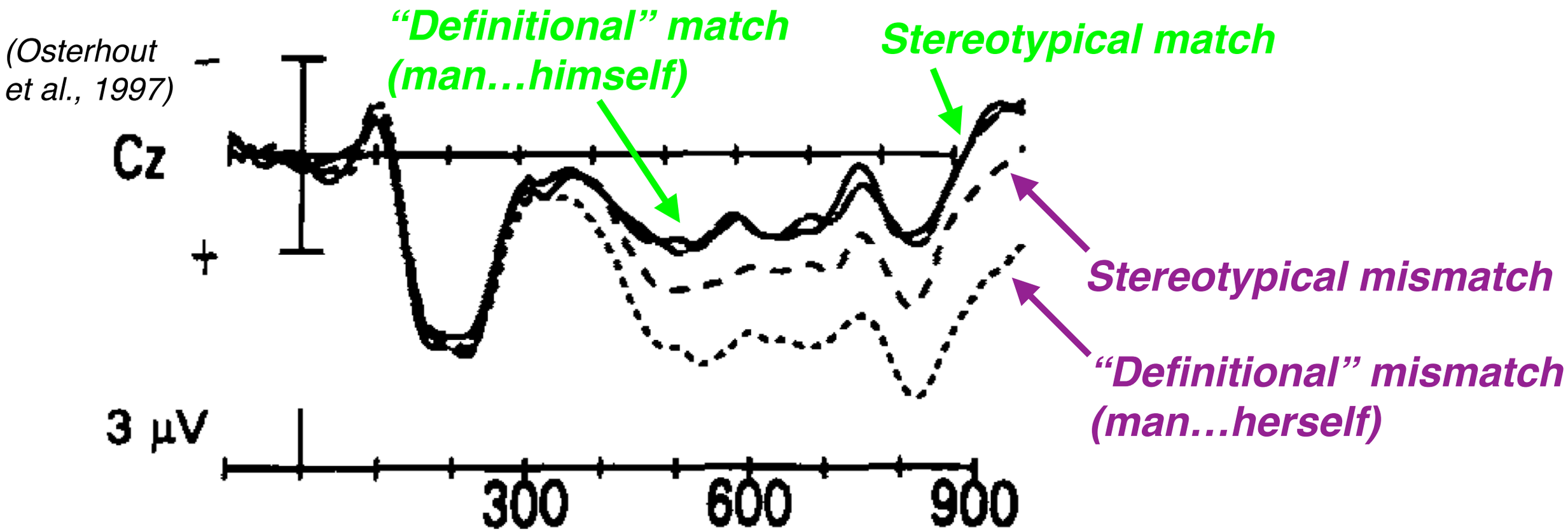


(Kutas & Hillyard, 1980, 1984)

The P600 ERP component in language comprehension

- Mismatches to lexically specified (*definitional**) semantic properties induce measurable expectation violations

  The man prepared herself for the interview.



- Mismatches to *stereotypical* semantic properties induce similar violations

  The nurse prepared himself for the operation.

(Osterhout et al., 1997; see also reading time studies by Sturt, 2003; Duffy & Keir, 2004, inter alia)

fMRI recordings during comprehension

- MRI measures changes in brain associated with blood flow
- Slow, but good *spatial resolution* for which parts of the brain are active in processing

Sentences condition

A	RUSTY	LOCK	WAS	FOUND	IN	THE	DRAWER	+	LOCK/ PEAR	+

Nonwords condition

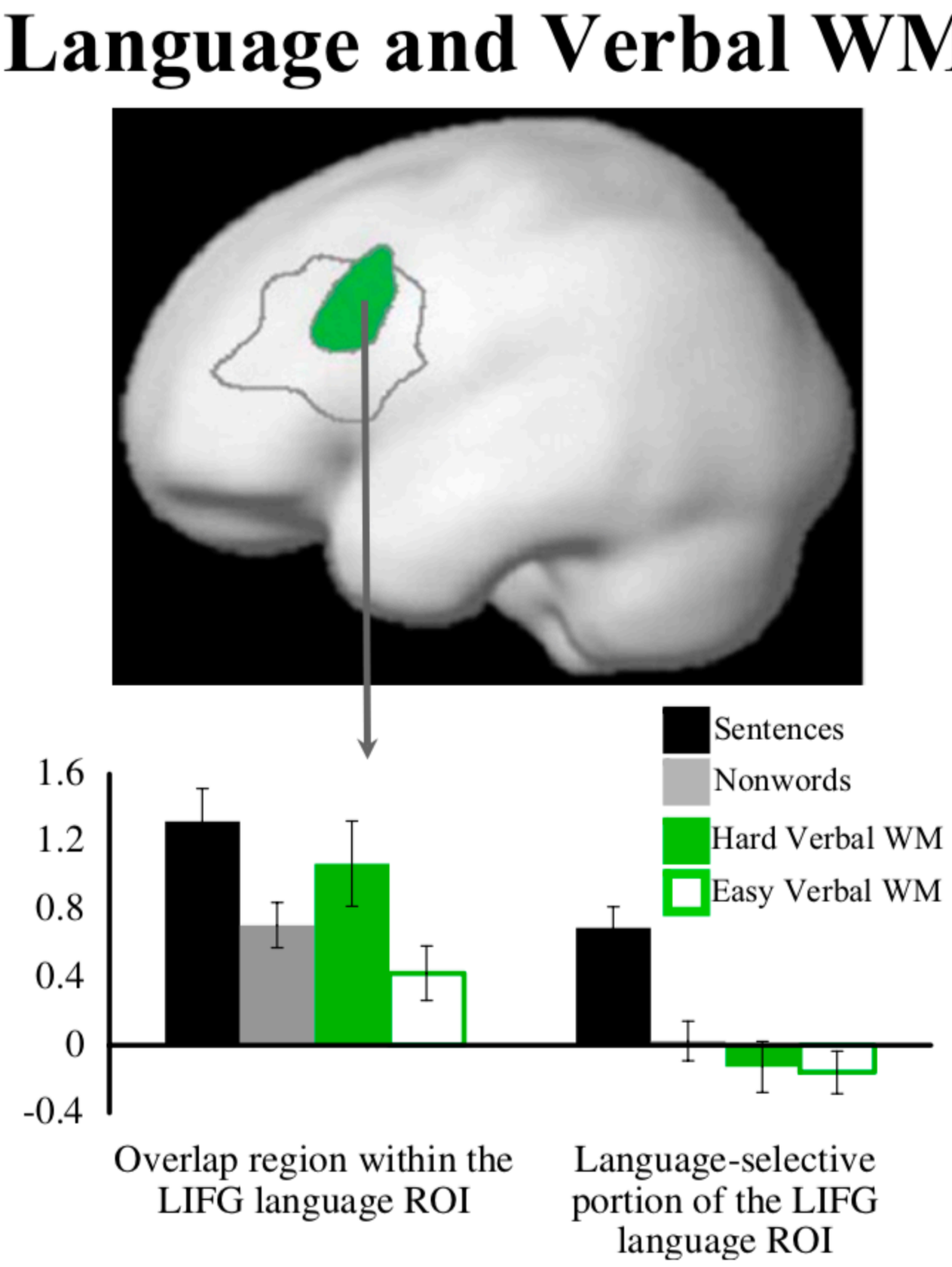
DAP	DRELLO	SMOP	UB	PLID	KAV	CRE	REPLODE	+	DRELLO/ NUZZ	+

Expt 3 (Verbal WM): Sample trial (hard condition)

+	three six	two four	one eight	five three	Response: 36241853 36248153	Feedback: ✓/✗	+

(Fedorenko et al., 2011)

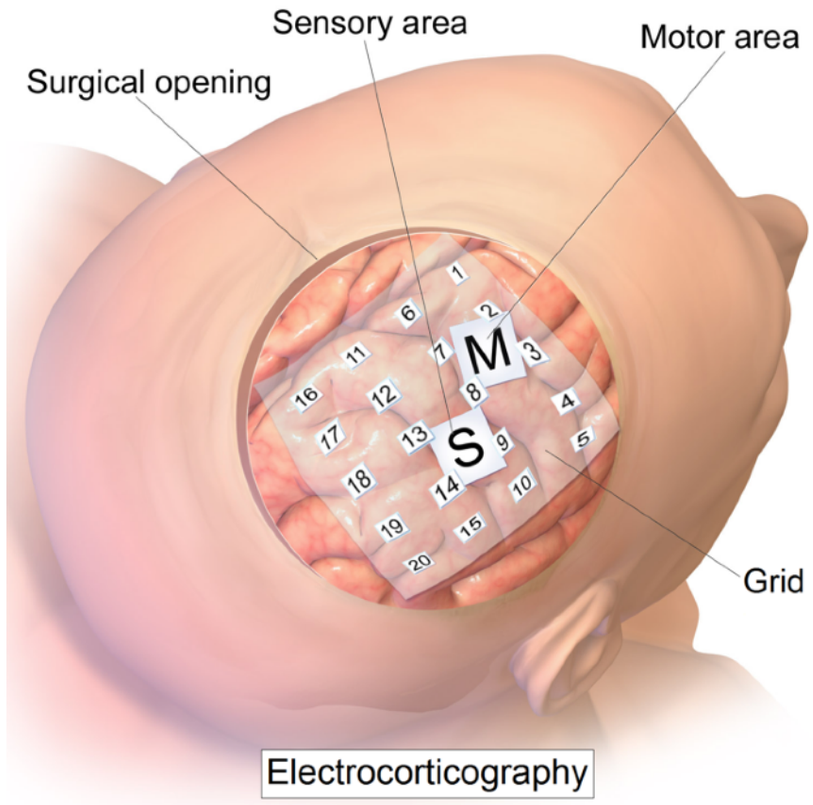
Functional brain specificity for language



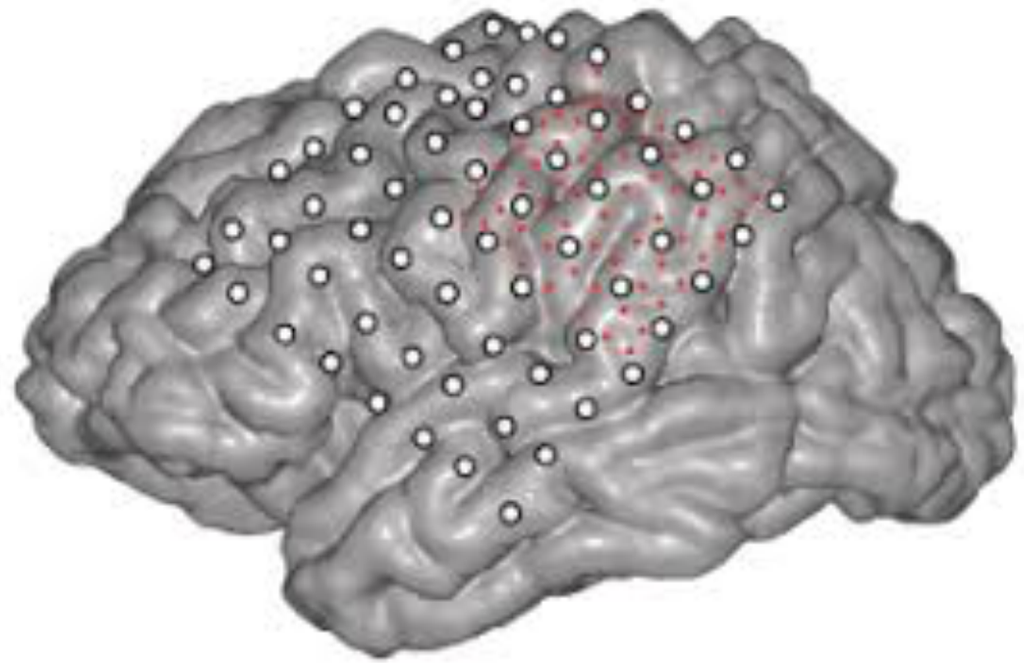
(Fedorenko et al., 2011)

Electrocorticography

- Pre-surgical epilepsy patients get electrode arrays directly implanted on the surface of the cortex



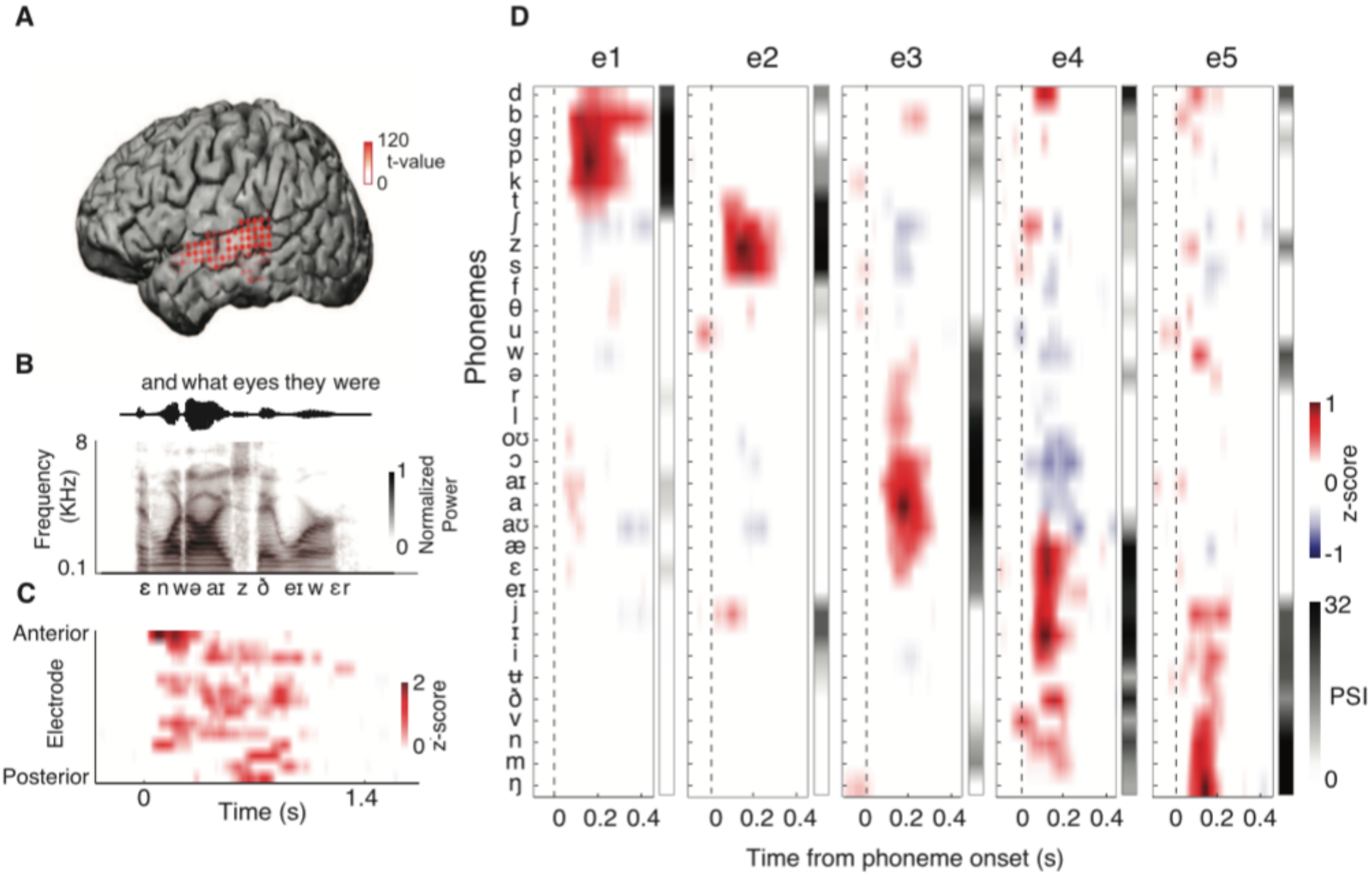
https://commons.wikimedia.org/wiki/File:Intracranial_electrode_grid_for_electrocorticography.png



http://med.stanford.edu/neurosurgery/research/NPTL/research2/_jcr_content/main/panel_builder/panel_0/text_image.img.620.high.png

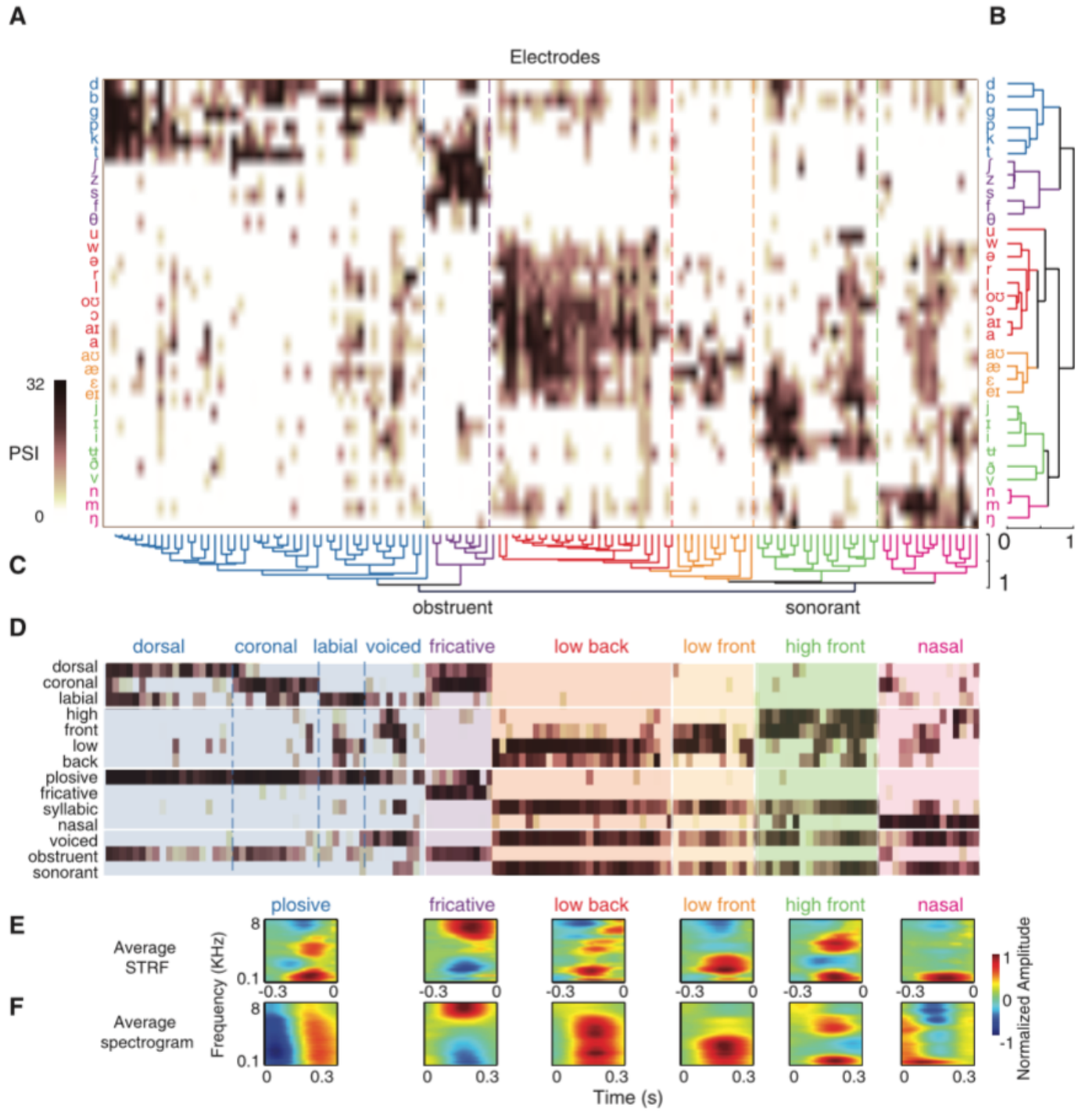
- During pre-surgical monitoring many patients generously donate their energy & attention for experiments

Neural phonemic representations



(Mesgarani et al., 2014, Science)

Neural consonant representations



(Mesgarani et al., 2014, Science)

Scientific opportunity:

Comprehensive theory to account for patterns of human language use & representation

Engineering opportunity:

Better prediction of human language understanding, and more human-like AI language-using agents

Quantifying probabilistic online processing difficulty

- Let a word's difficulty be its *surprisal* given its context:

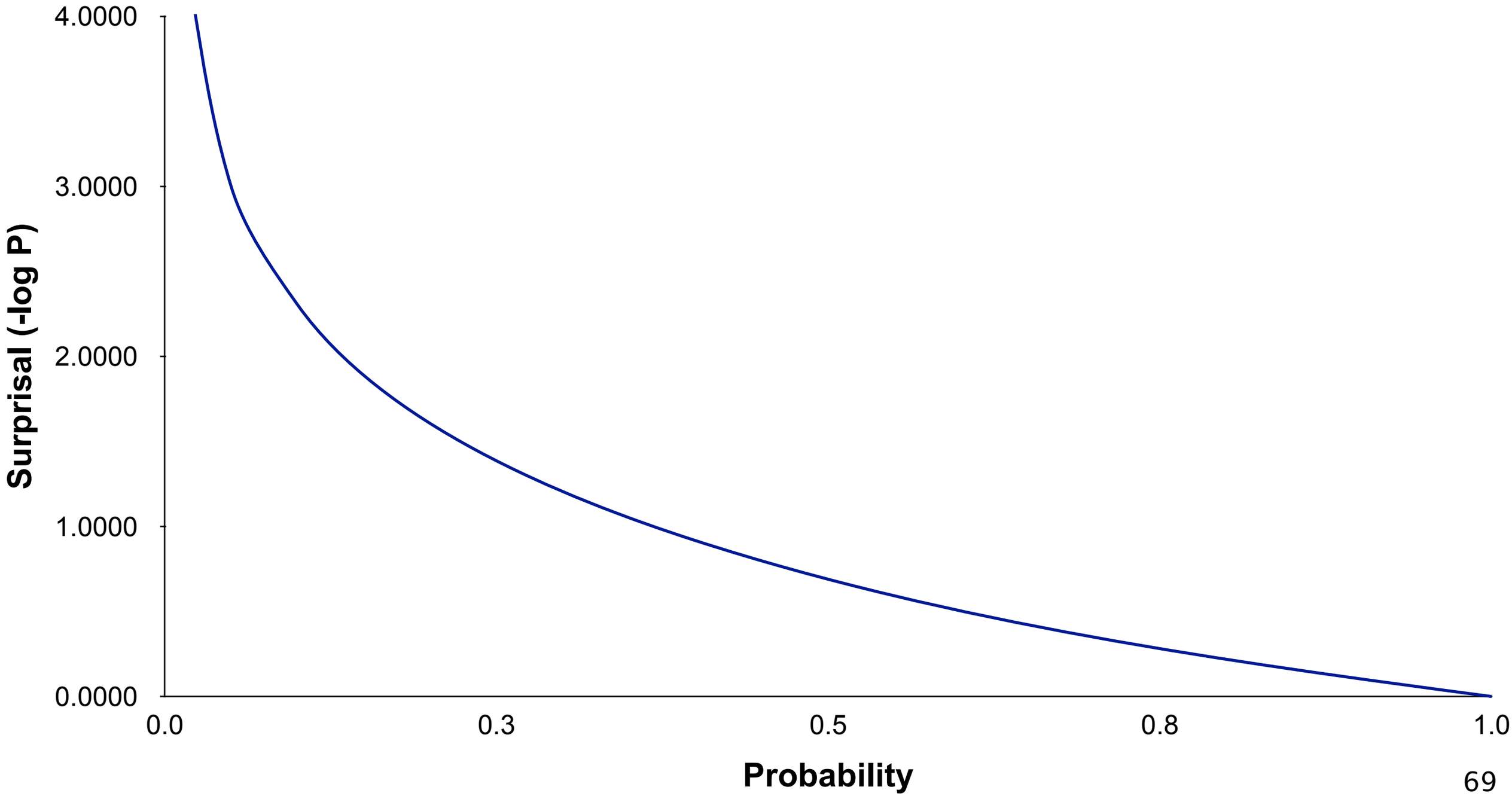
$$\text{Surprisal}(w_i) \equiv \log \frac{1}{P(w_i|\text{CONTEXT})}$$

$$\left[\approx \log \frac{1}{P(w_i|w_{1\ldots i-1})} \right]$$

- Captures the *expectation* intuition: the more we expect an event, the easier it is to process
  - Brains are prediction engines!
- Predictable words are read faster (Ehrlich & Rayner, 1981) and have distinctive EEG responses (Kutas & Hillyard 1980)
- Later on: combine with probabilistic grammars to give *grammatical expectations*

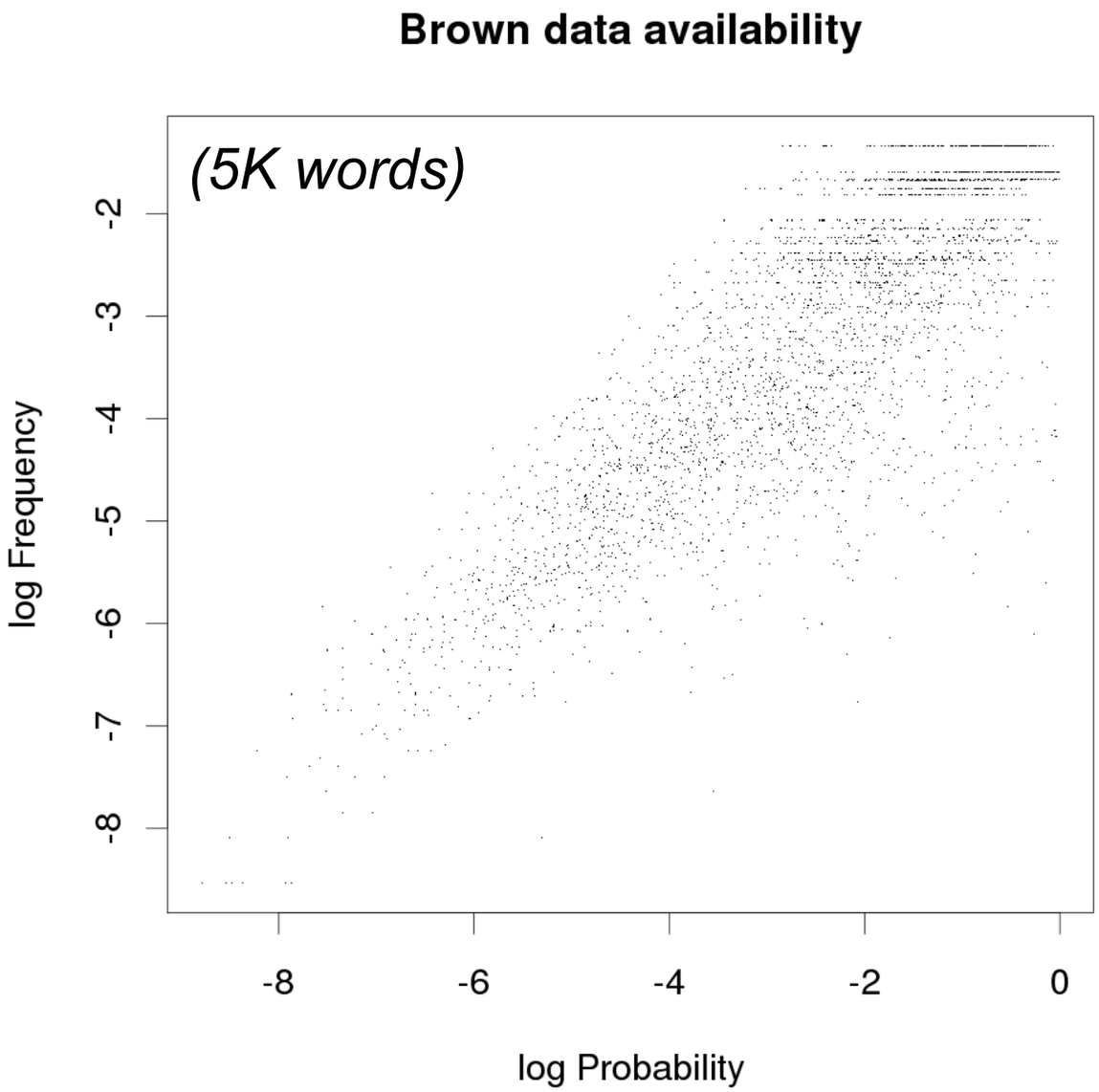
(Hale, 2001, NAACL; Levy, 2008, Cognition)

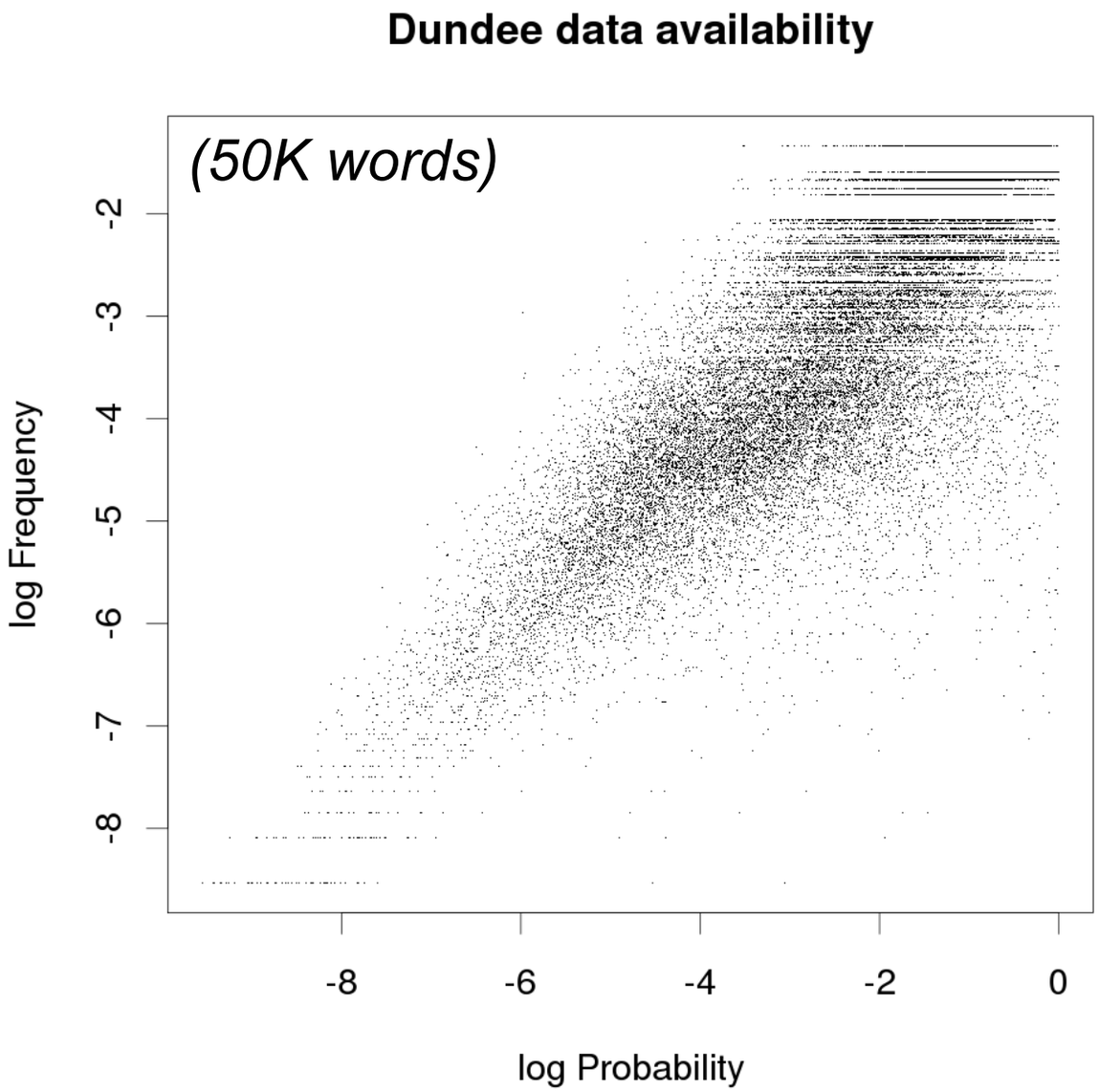
The surprisal graph



Estimating probability/time curve shape

- As a proxy for “processing difficulty,” reading time in two different methods: self-paced reading & eye-tracking
- Challenge: we need big data to estimate curve shape, but probability correlated with confounding variables

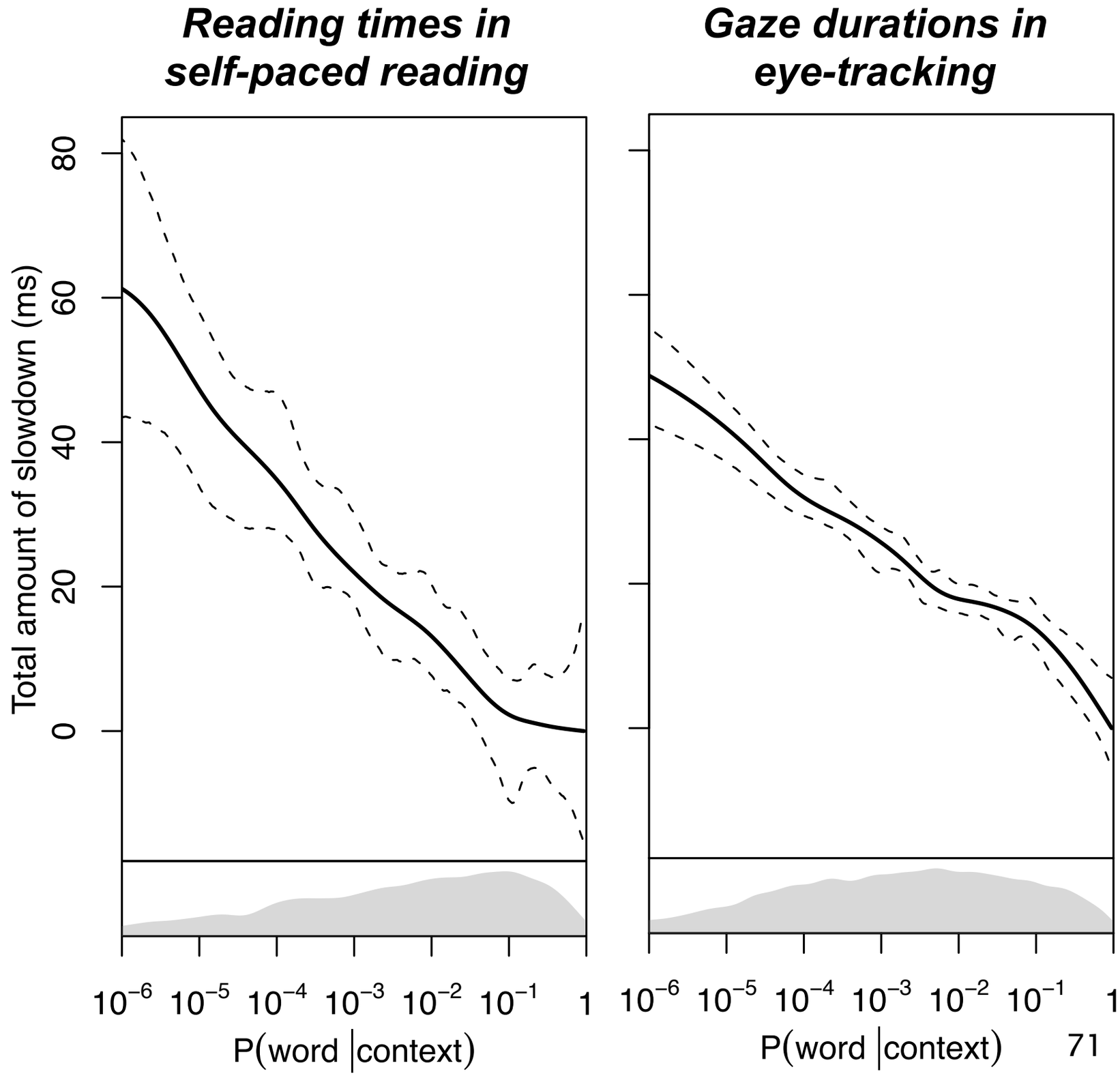




Estimating probability/time curve shape

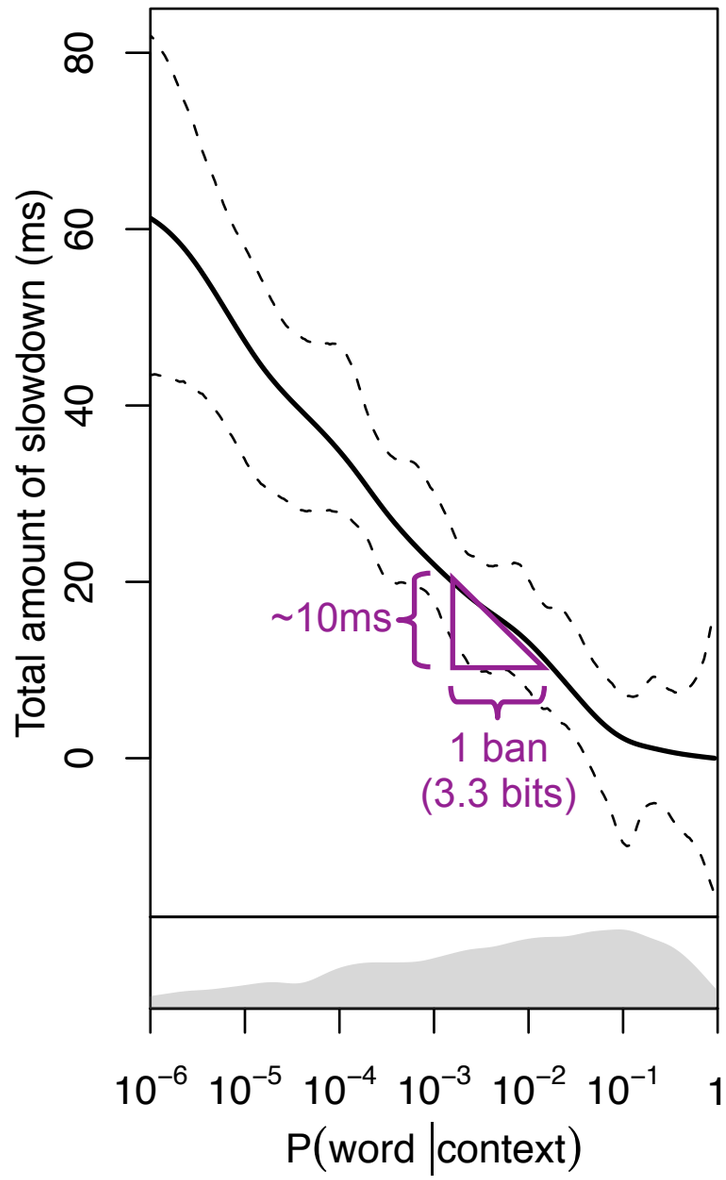
- Generalized additive model regression: total contribution of word (trigram) probability to RT near-linear over 6 orders of magnitude!

(Smith & Levy, 2013)



Take-away: how long to process a word in context?

- On average, time ***linear in the word's log-probability***
- Methodologically: reading puts control in the comprehender's hands (and eyes!), allowing us to study processing difficulty through reading time



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