

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

Incrementality, structure, and surprise

The

Incrementality, structure, and surprise

The woman

Incrementality, structure, and surprise

The woman brought

Incrementality, structure, and surprise

The woman brought the

Incrementality, structure, and surprise

The woman brought the sandwich

Incrementality, structure, and surprise

The woman brought the sandwich from

Incrementality, structure, and surprise

The woman brought the sandwich from the

Incrementality, structure, and surprise

The woman brought the sandwich from the kitchen

Incrementality, structure, and surprise

The woman brought the sandwich from the kitchen tripped.

Incrementality, structure, and surprise

Incrementality, structure, and surprise

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

Incrementality, structure, and surprise

The woman given the sandwich from the kitchen tripped.

who was

Incrementality, structure, and surprise

The woman given the sandwich from the kitchen tripped.

The woman given the sandwich from the kitchen tripped.

who was

Incrementality, structure, and surprise

The woman brought the sandwich from the kitchen tripped.



The woman given the sandwich from the kitchen tripped.

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Incrementality, structure, and surprise

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Incrementality, structure, and surprise

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who was

The woman given the sandwich from the kitchen tripped.

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who was

Simple past Past participle

bring **brought** **brought**

give **gave** **given**

Incrementality, structure, and surprise

The woman brought the sandwich from the kitchen tripped.

The woman brought the sandwich from the kitchen tripped.



The woman given the sandwich from the kitchen tripped.

The woman given the sandwich from the kitchen tripped.



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

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- Eye movements in the visual world

Measuring human incremental processing state

- Eye movements in the visual world
- Word-by-word reading times

Measuring human incremental processing state

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

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- Behavioral*
- Neural*

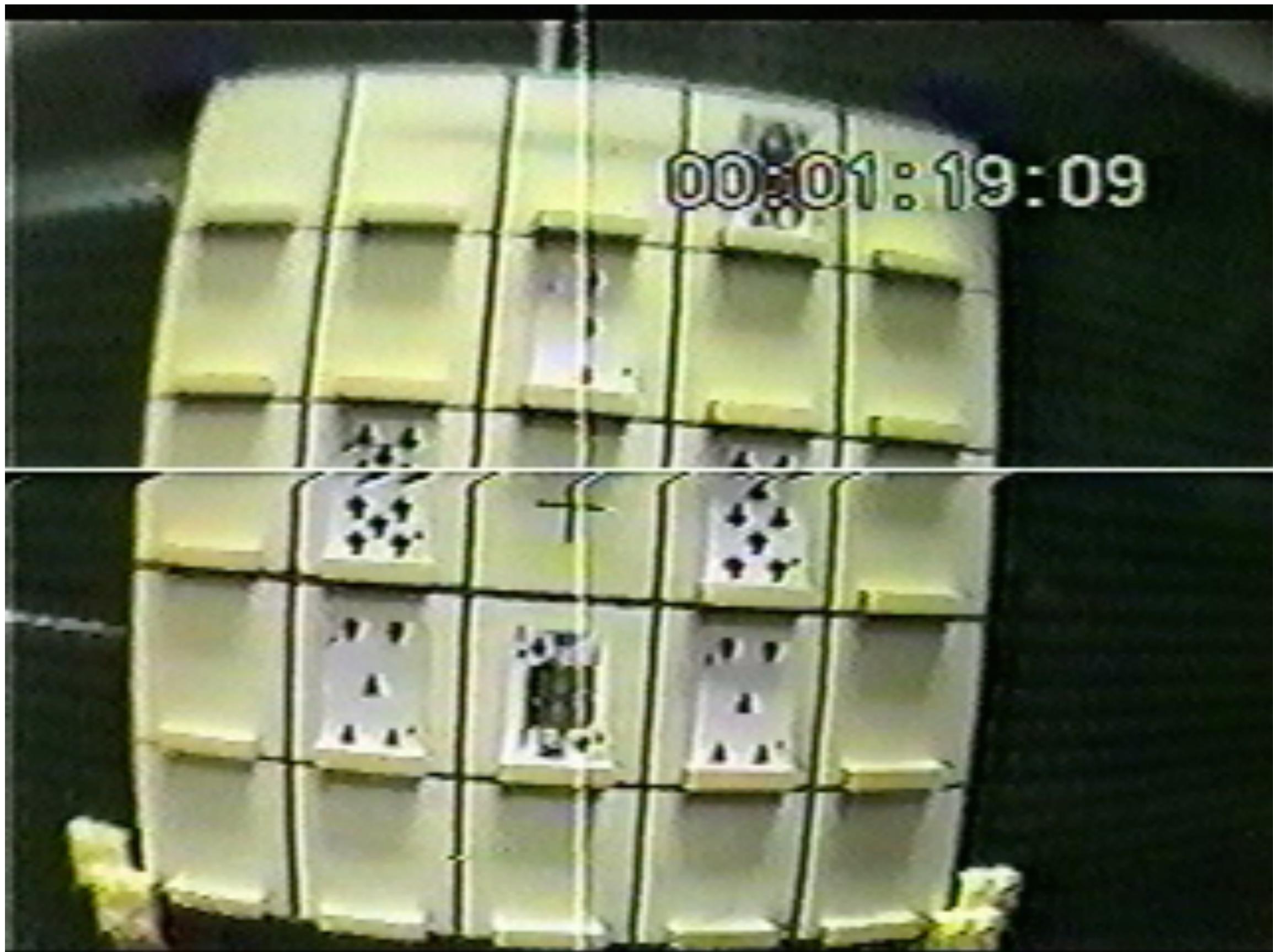
Eye movements in the visual world



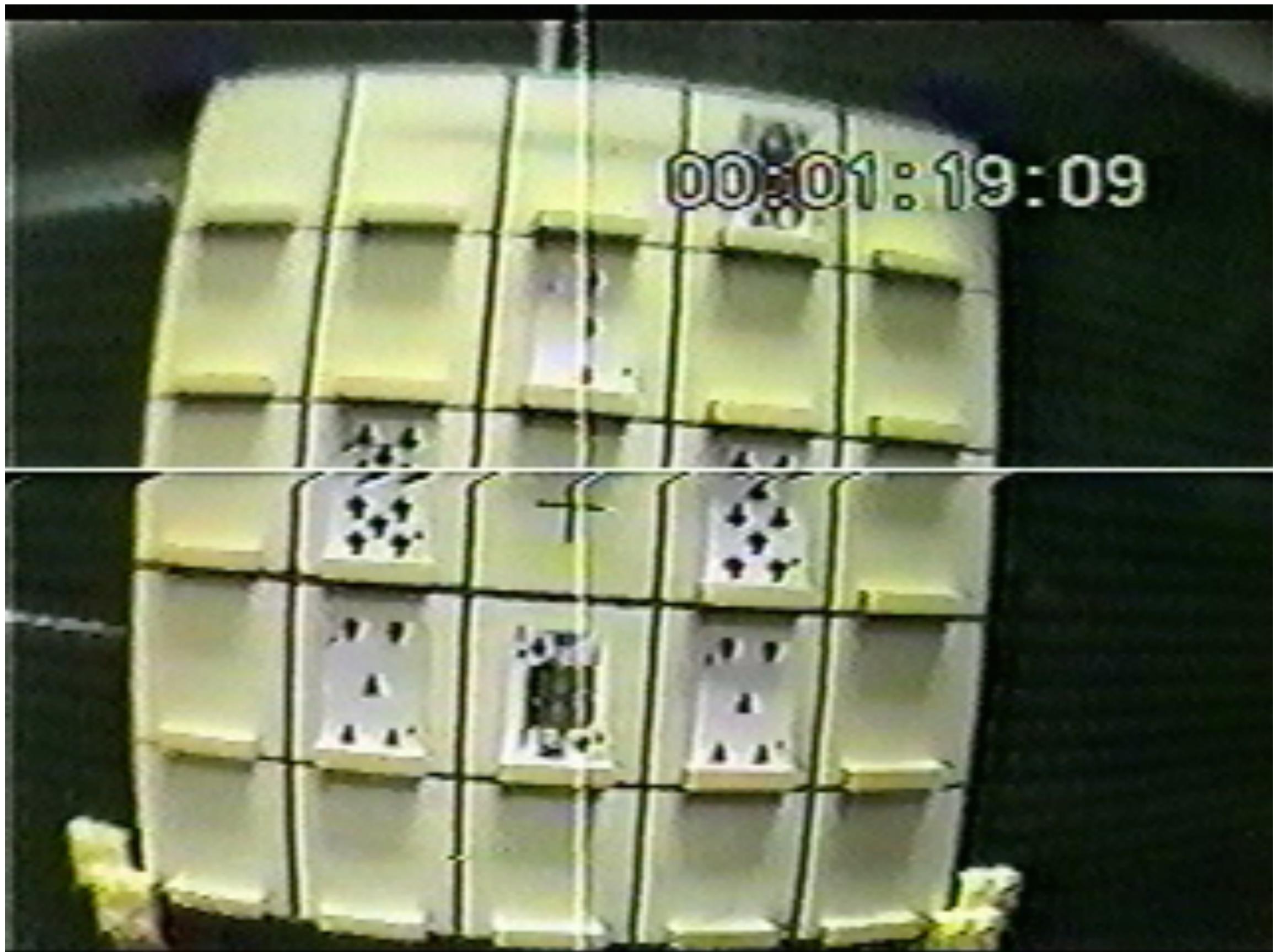
Eye movements in the visual world



Eye movements in the visual world (slow-motion)



Eye movements in the visual world (slow-motion)



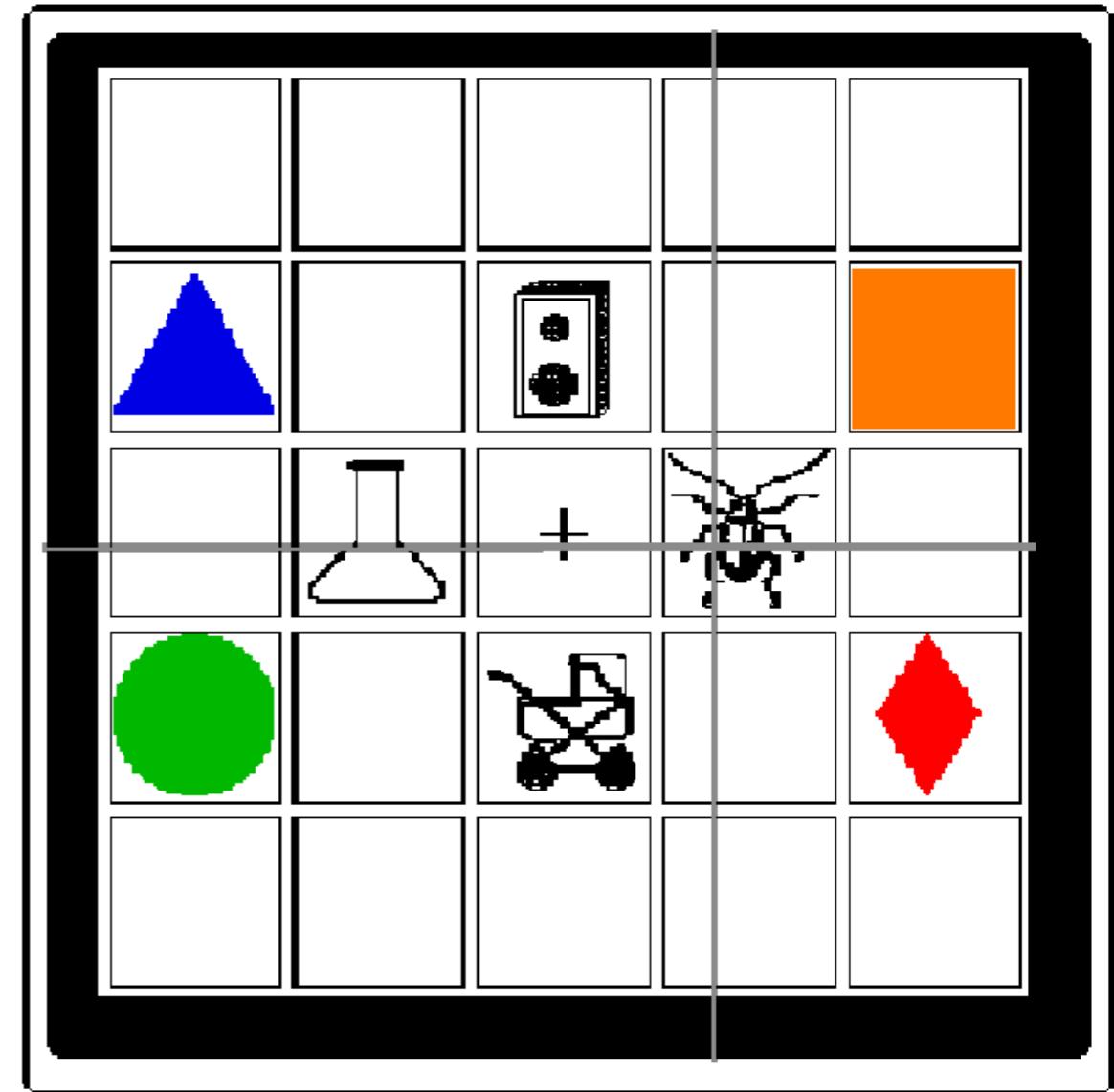
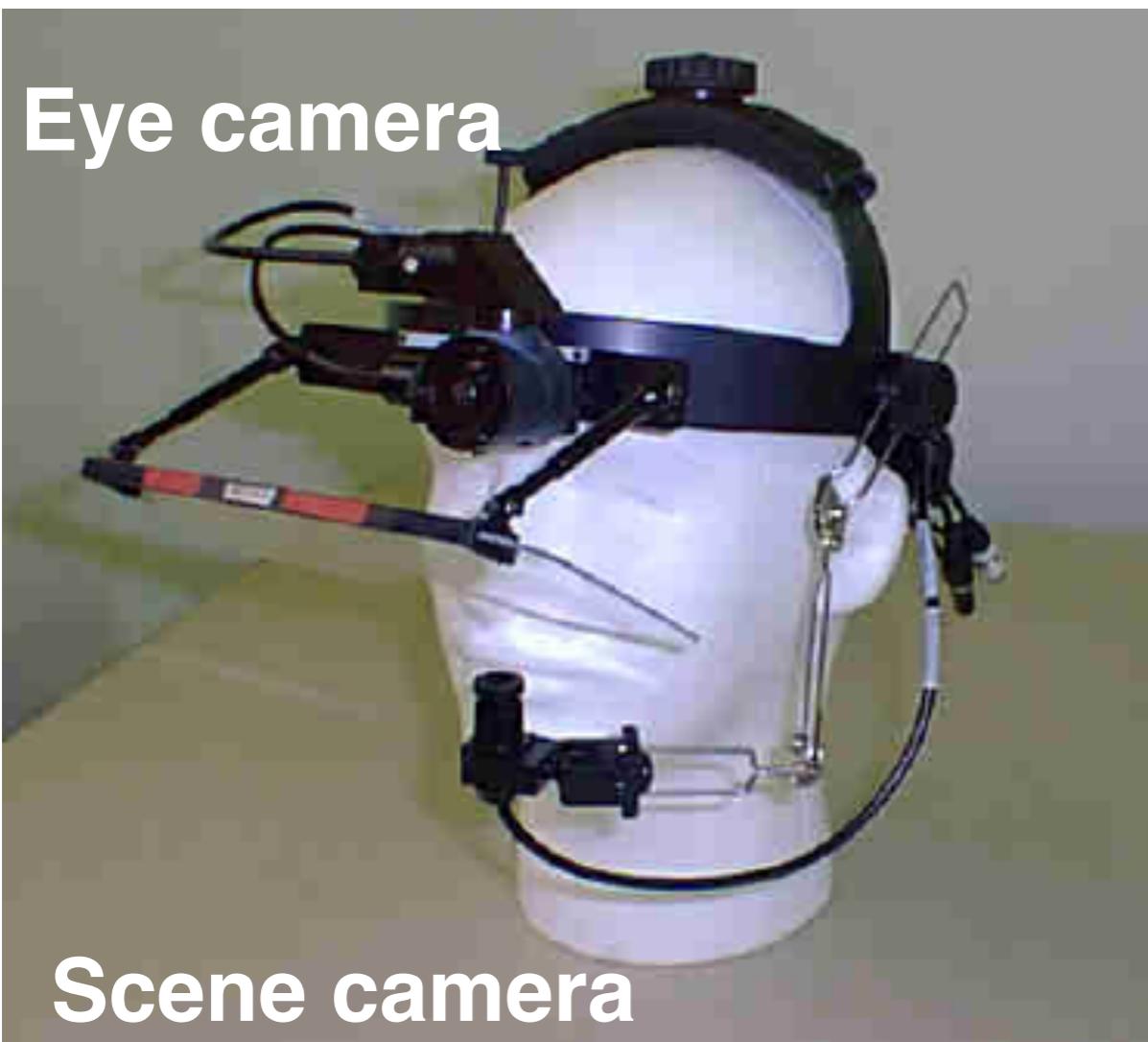
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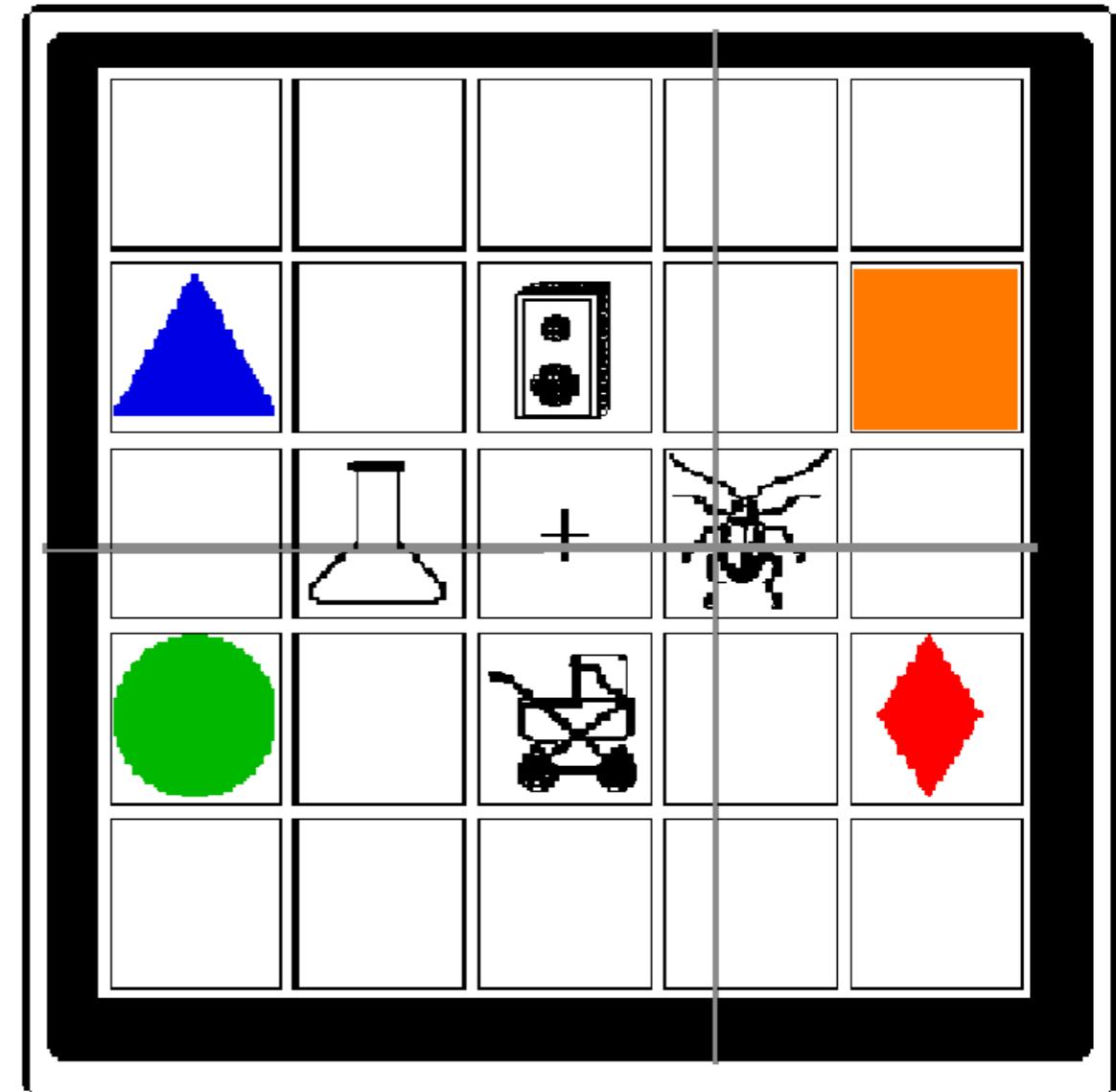
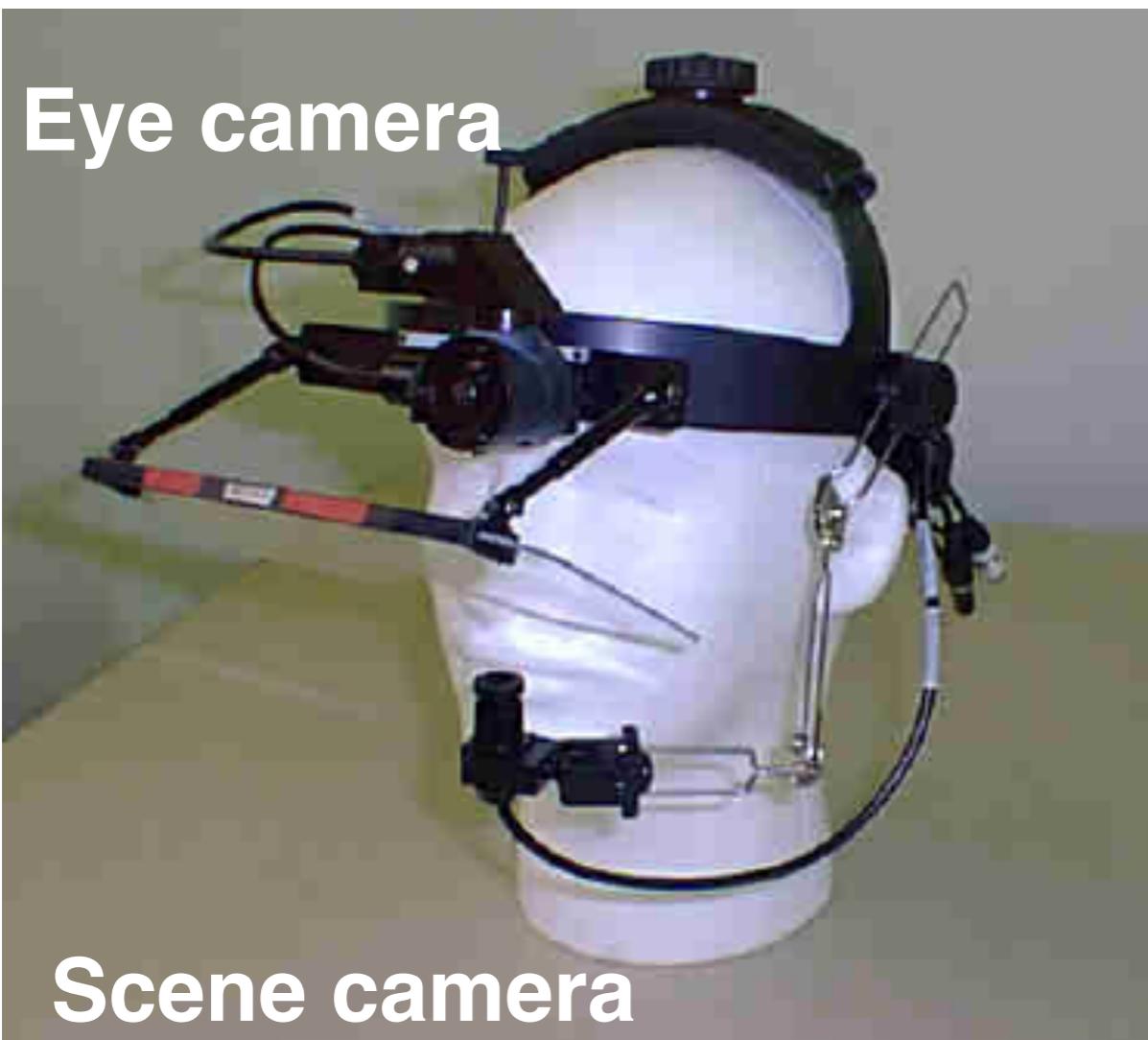
Eye movements in the visual world



A visual world experiment

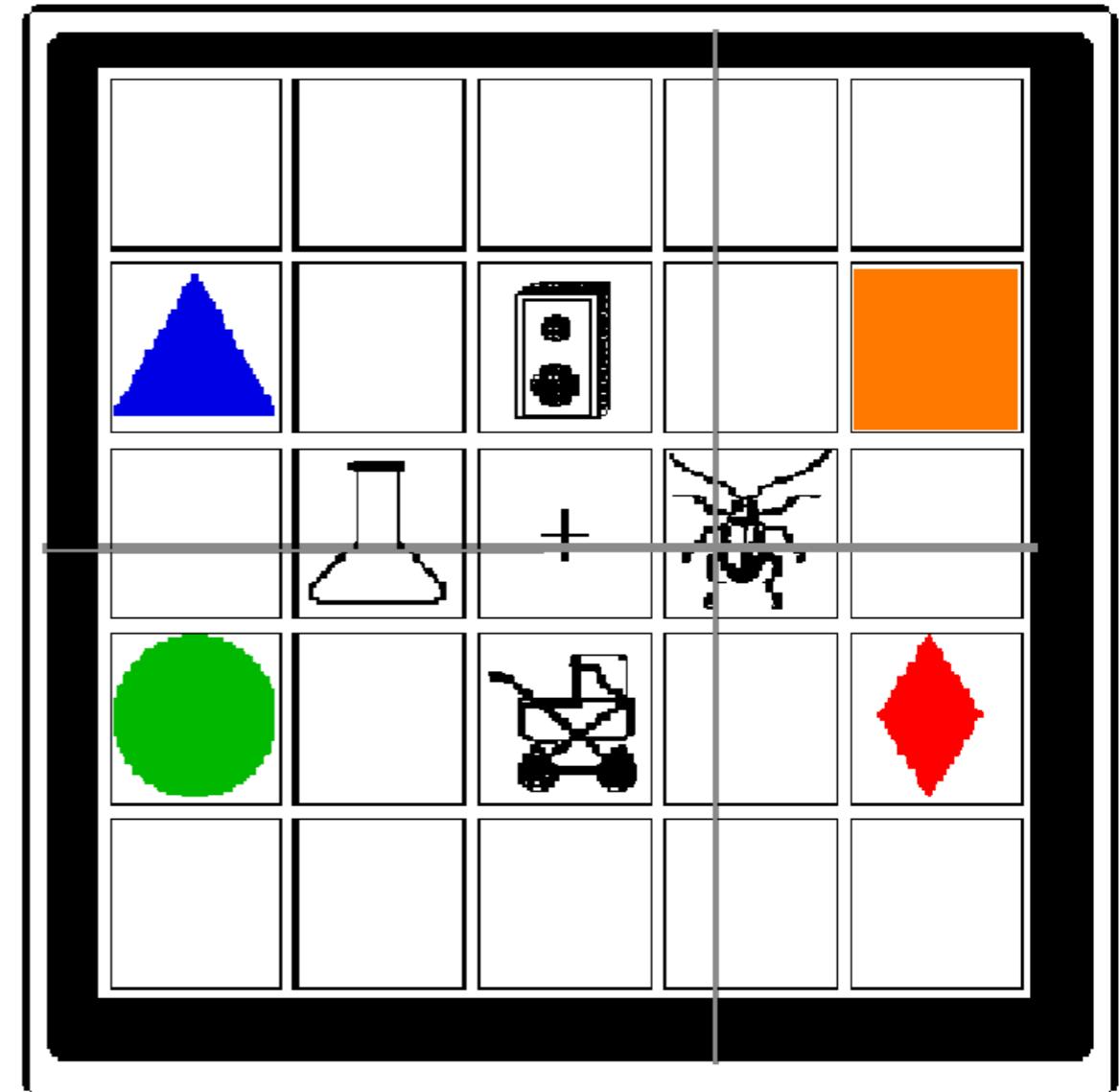
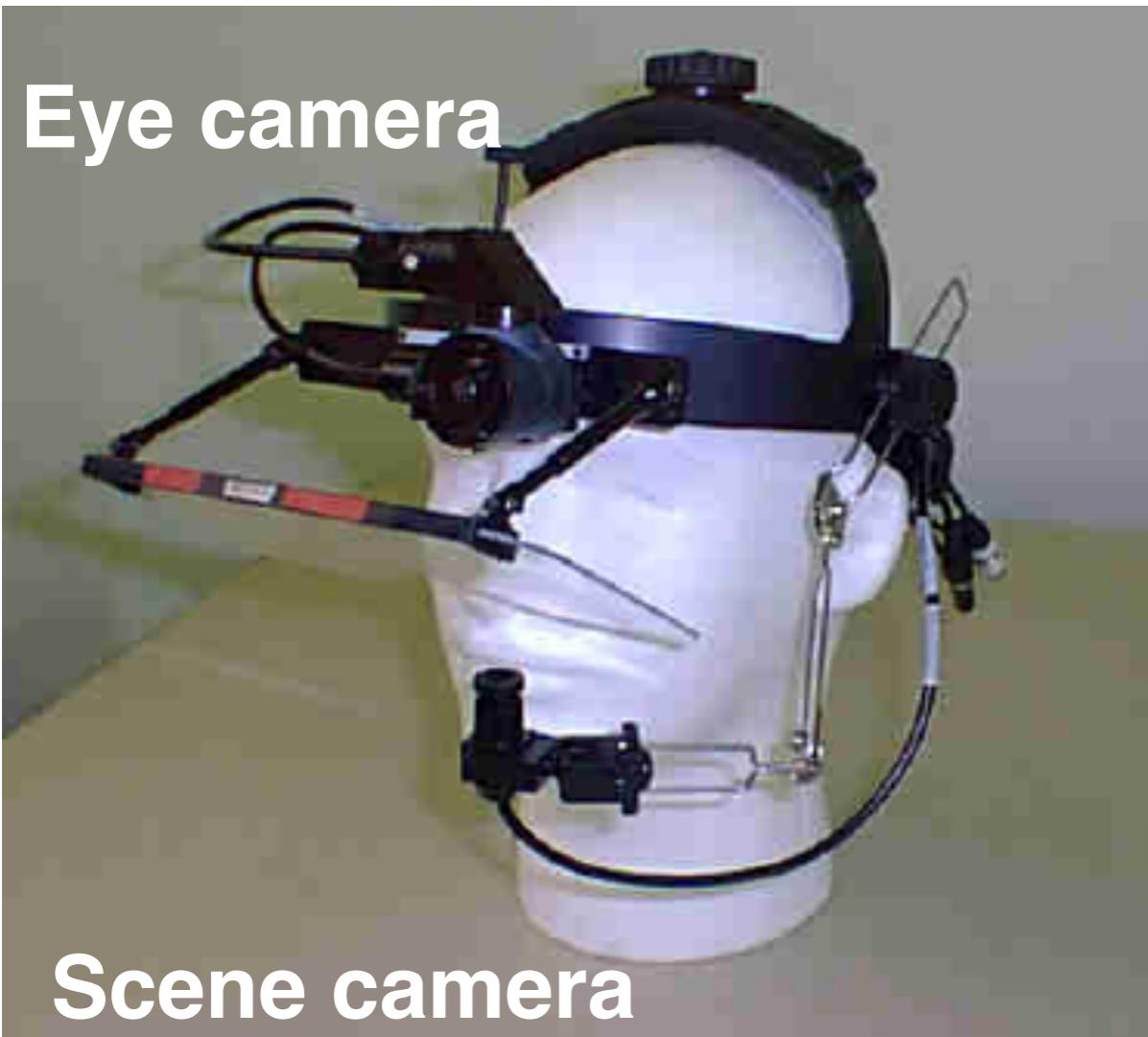


A visual world experiment



Instruction to experimental participant:

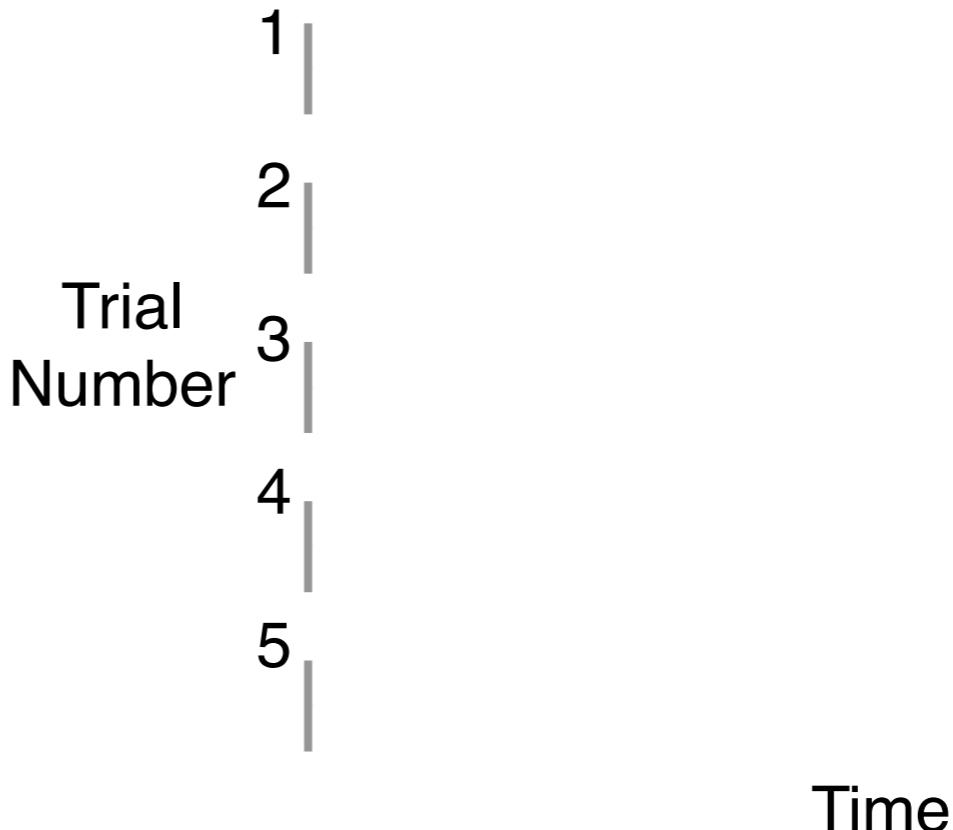
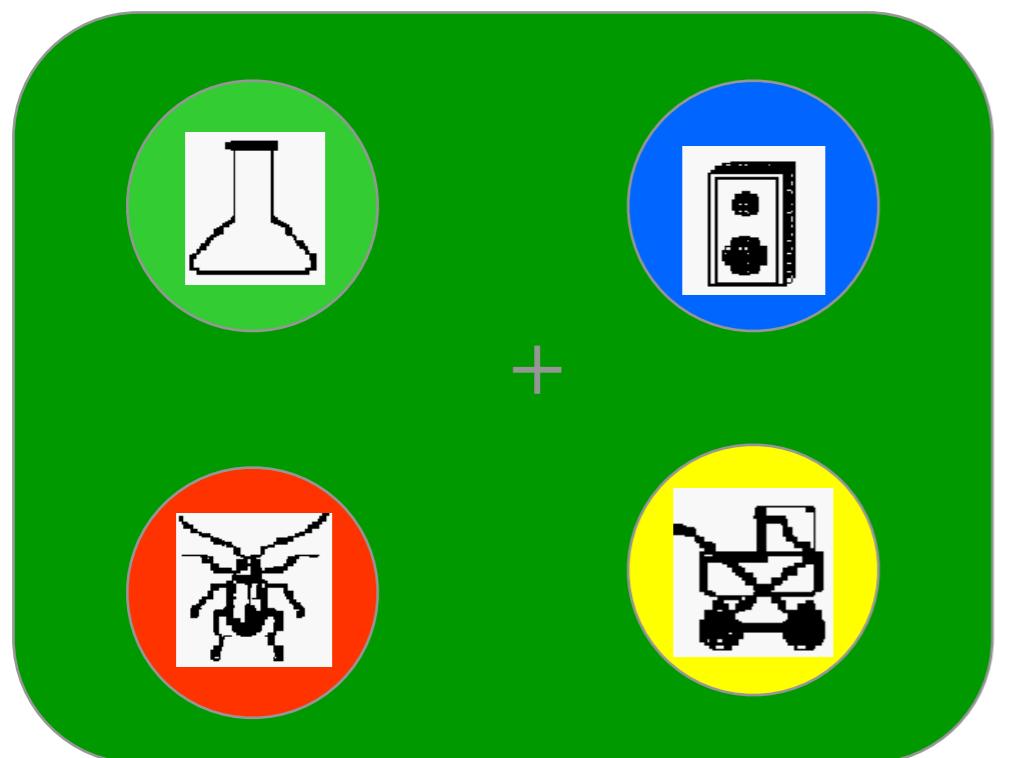
A visual world experiment



Instruction to experimental participant:

“Pick up the beaker”

Data from human eye movements



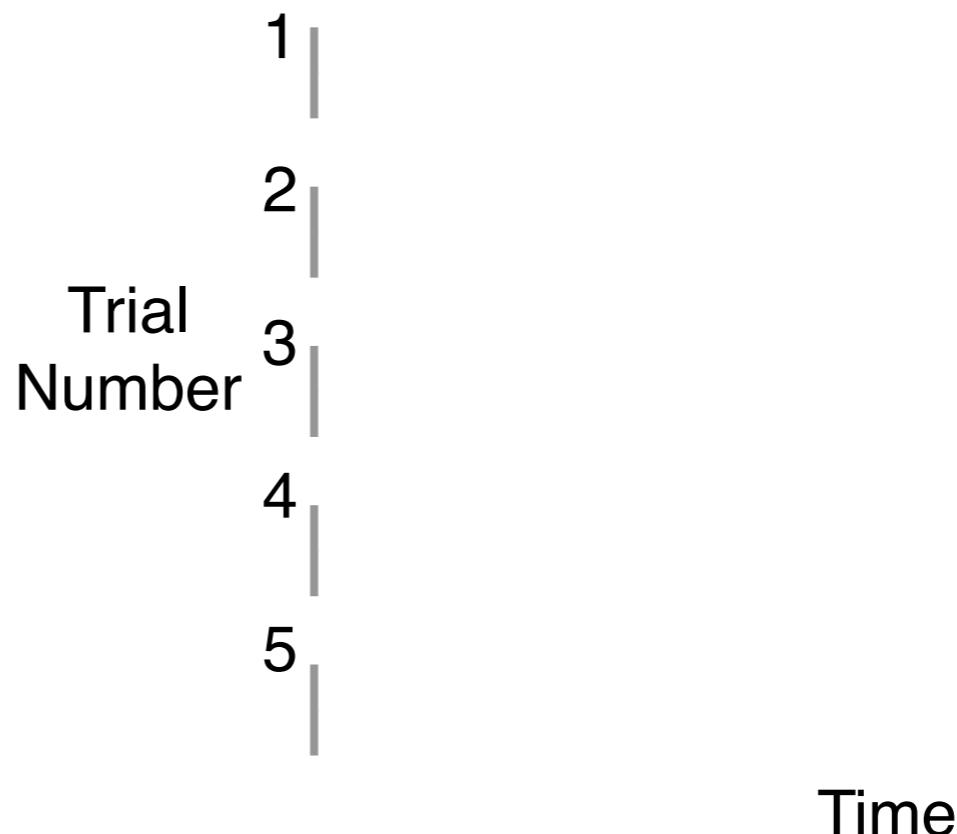
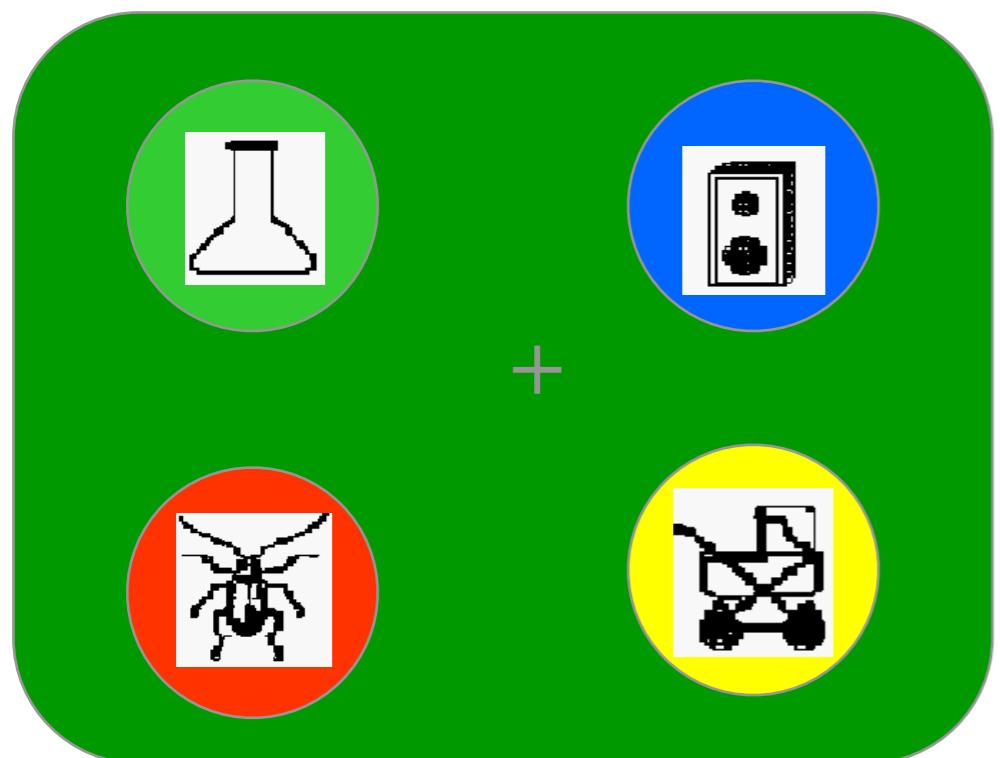
Target = beaker

Cohort = beetle

Unrelated = carriage

Data from human eye movements

“Look at the cross.”



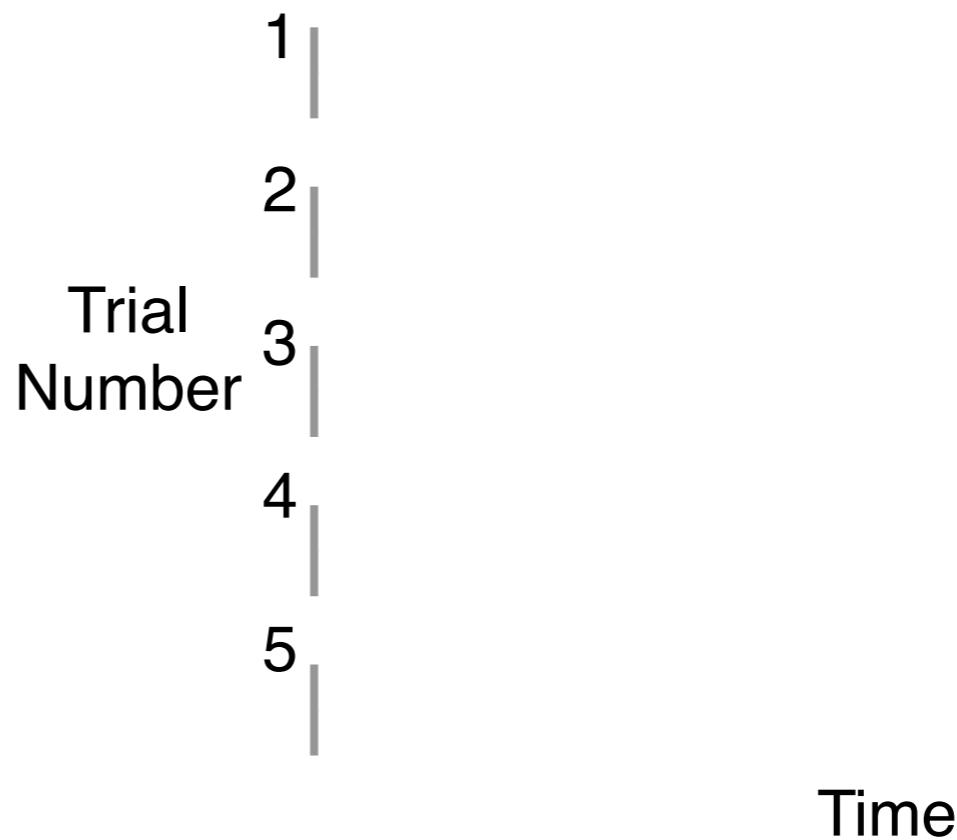
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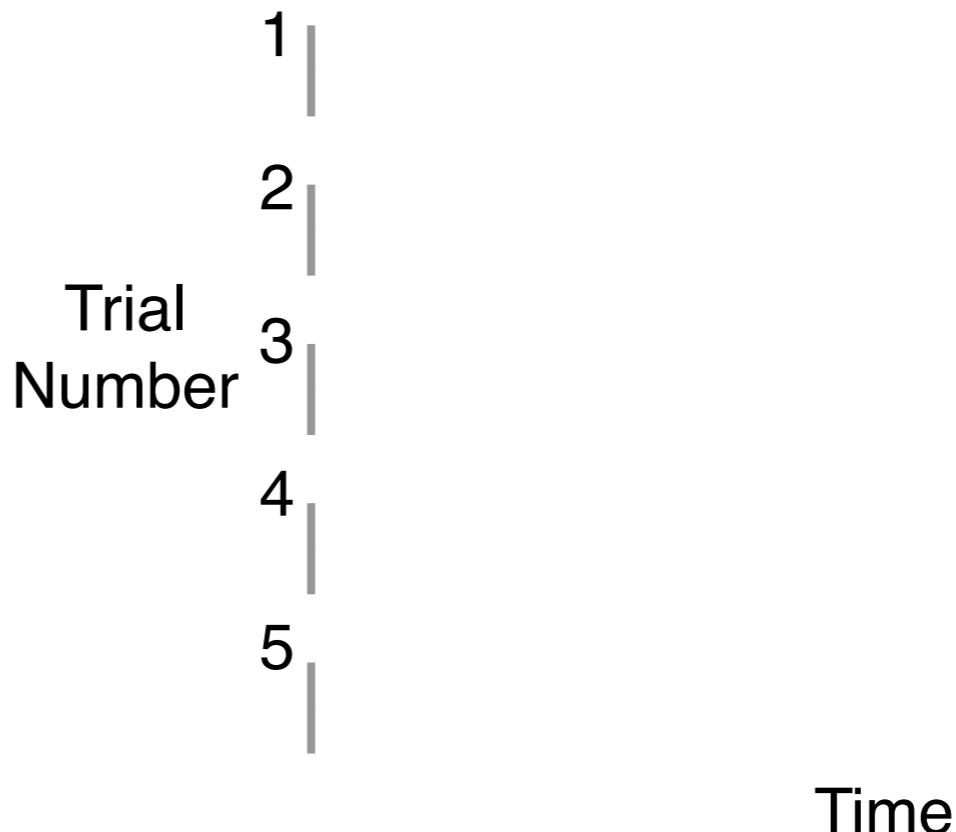
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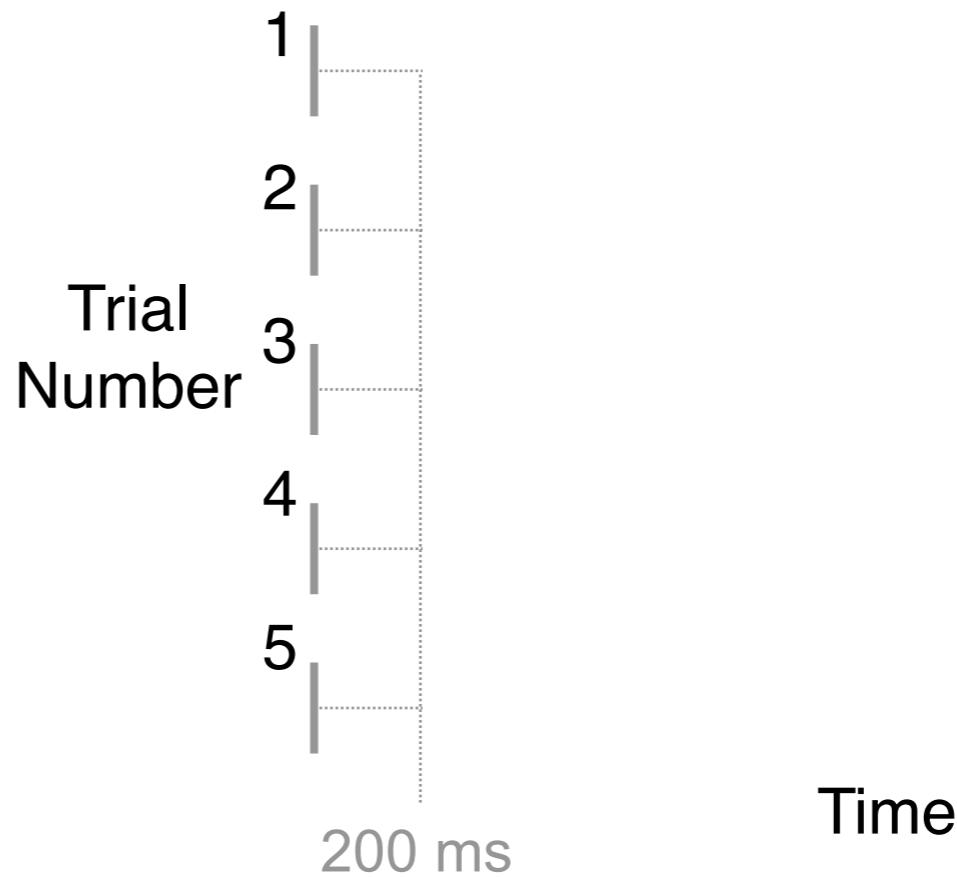
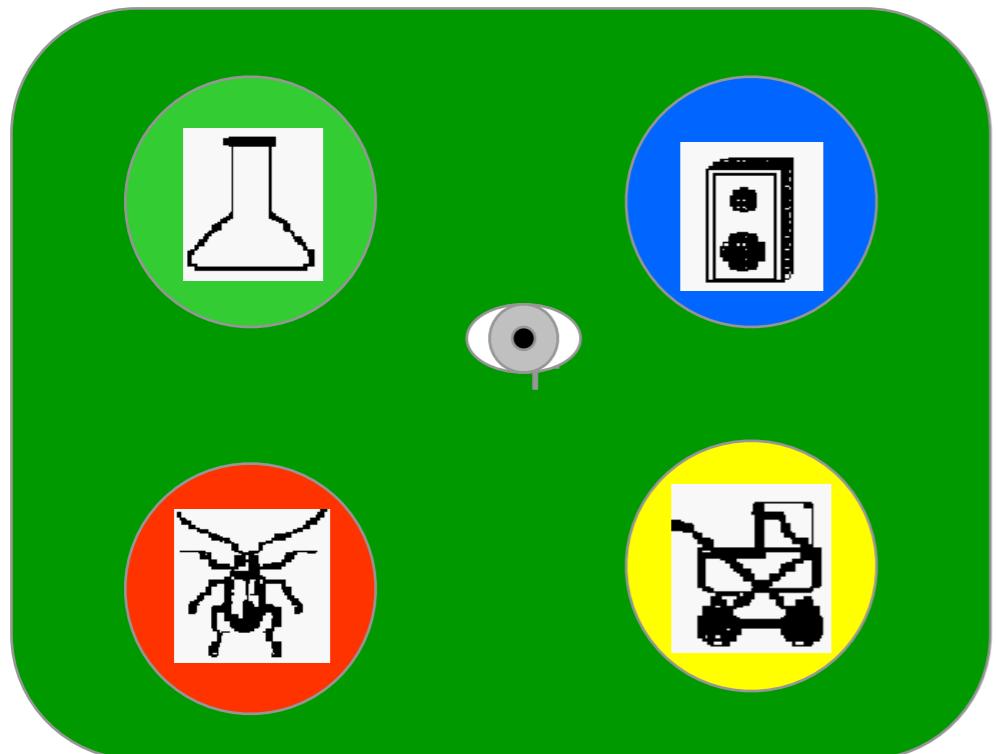
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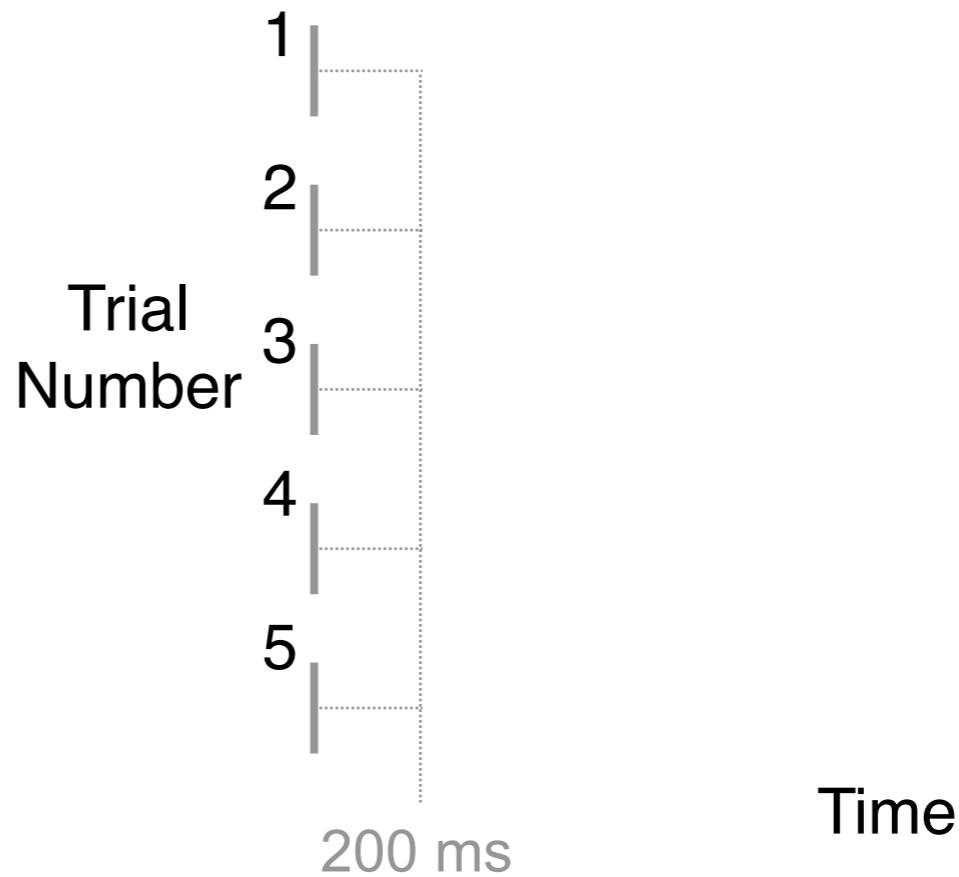
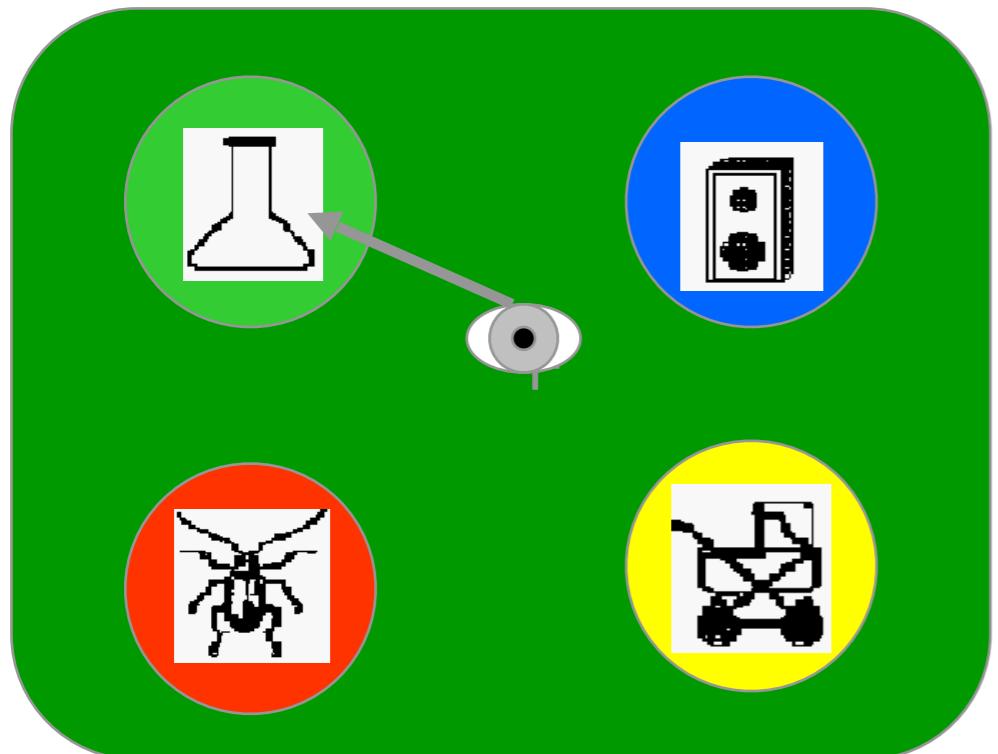
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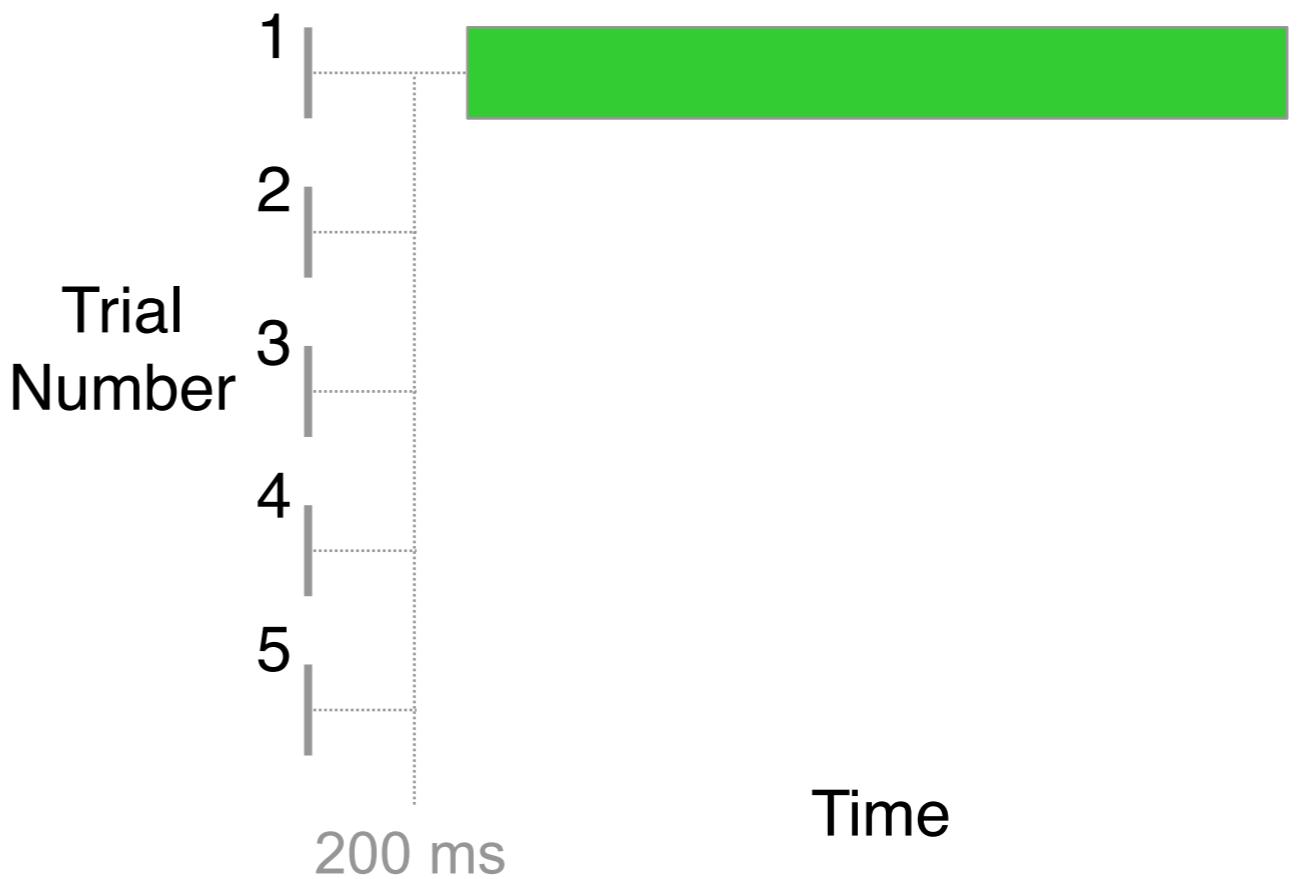
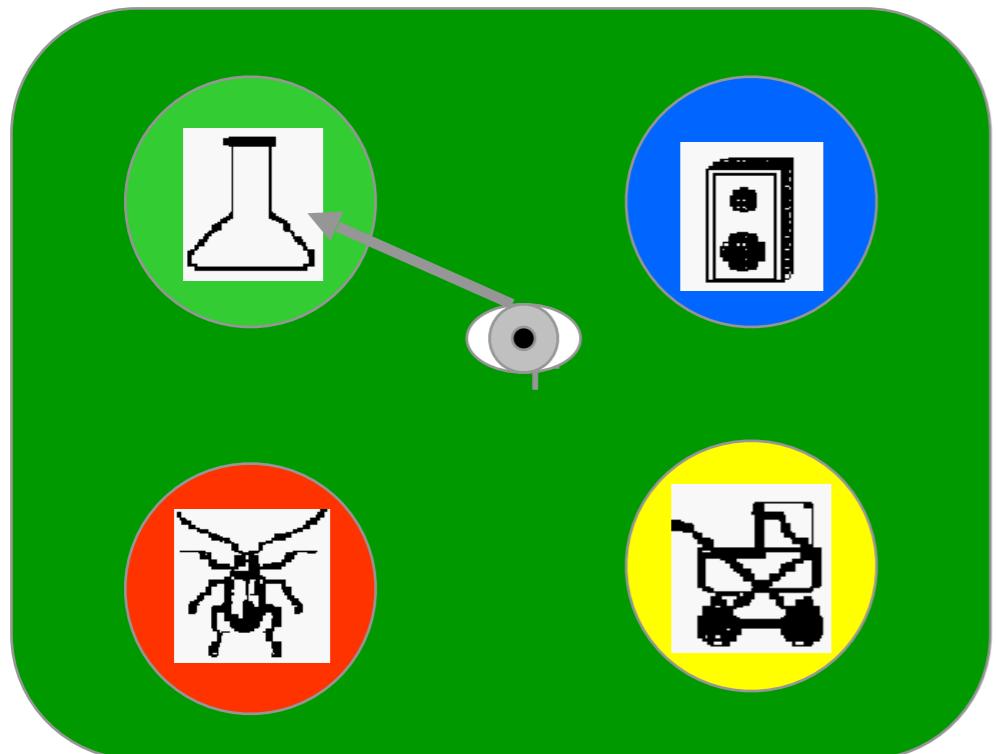
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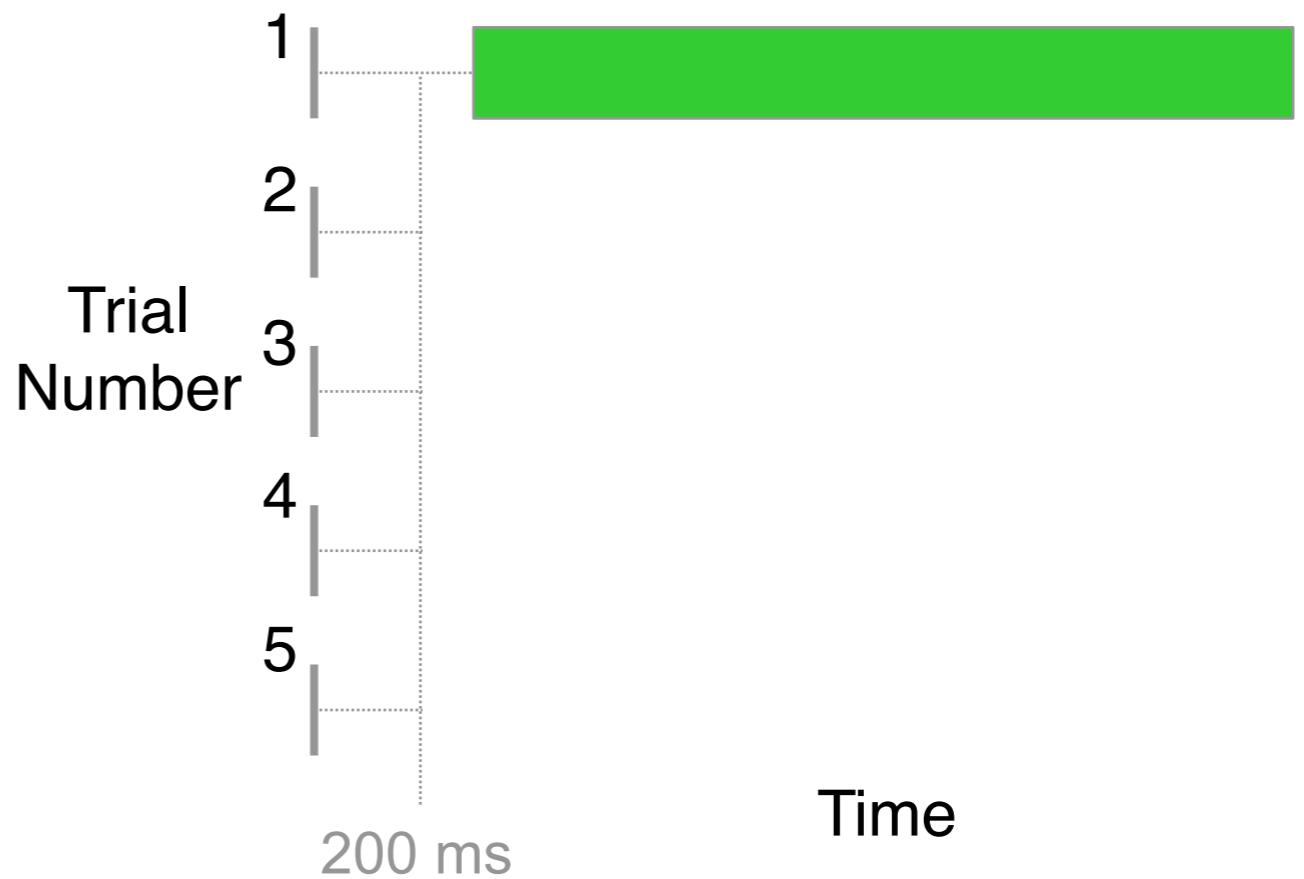
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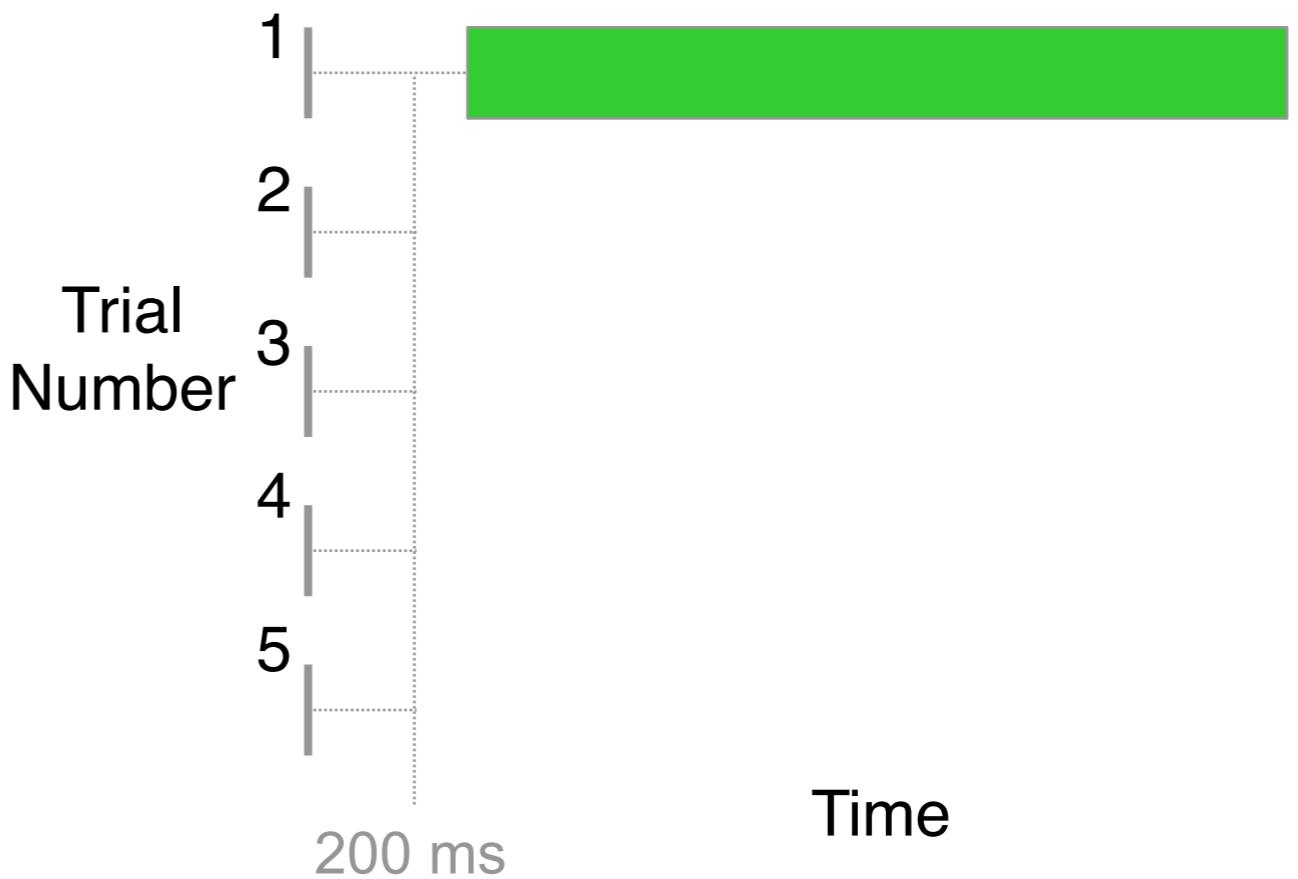
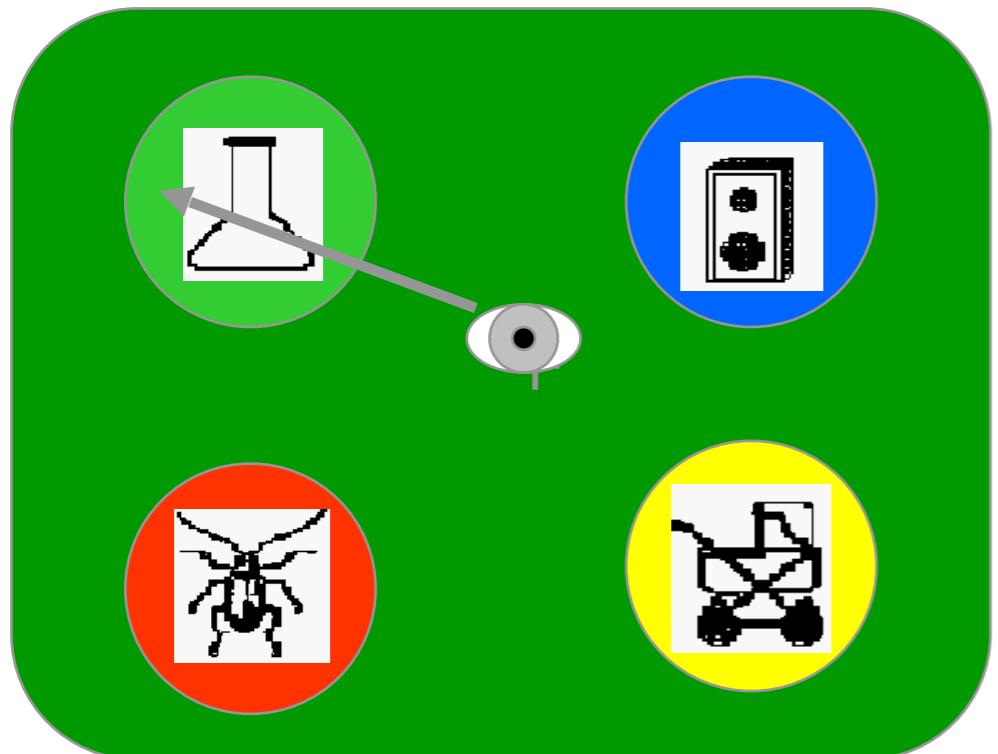
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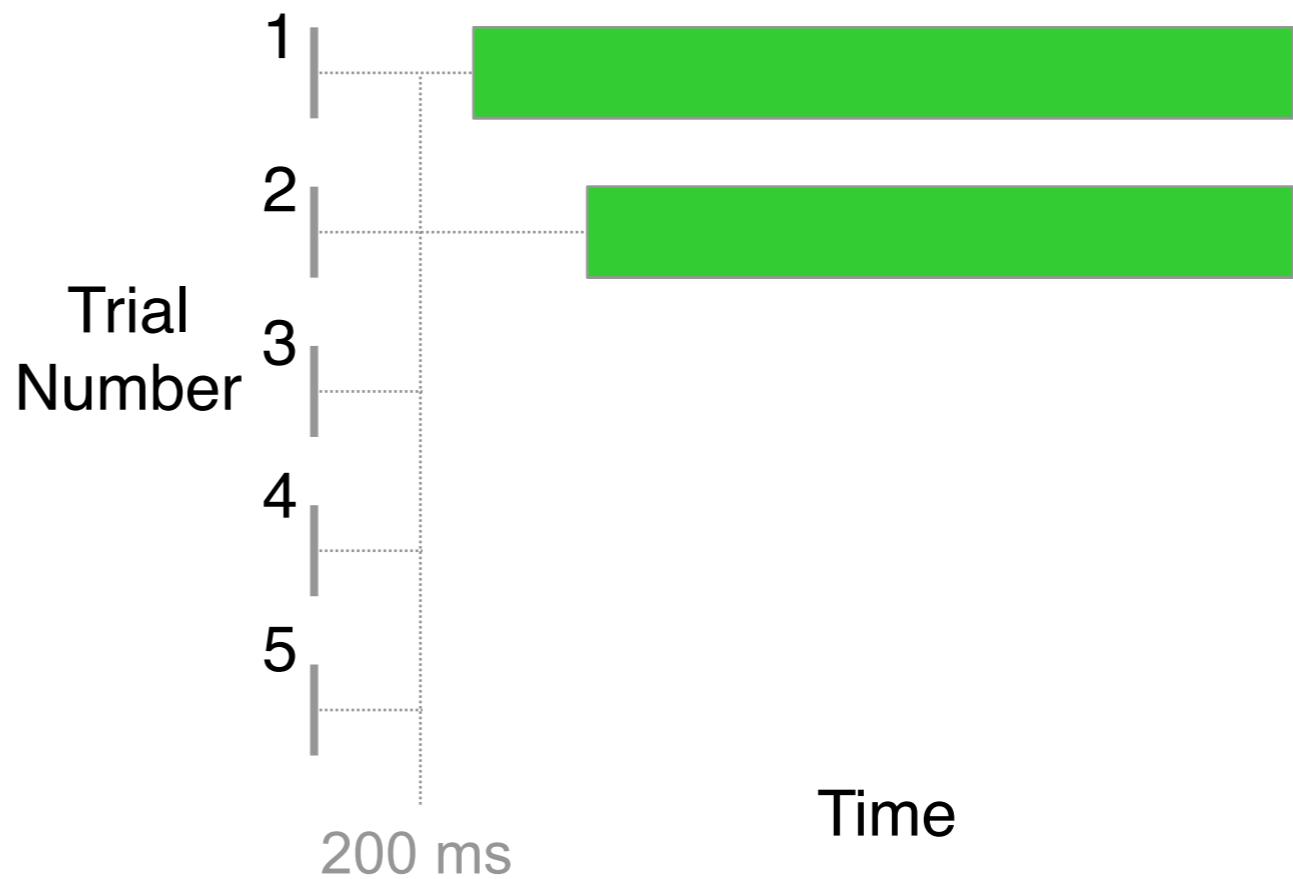
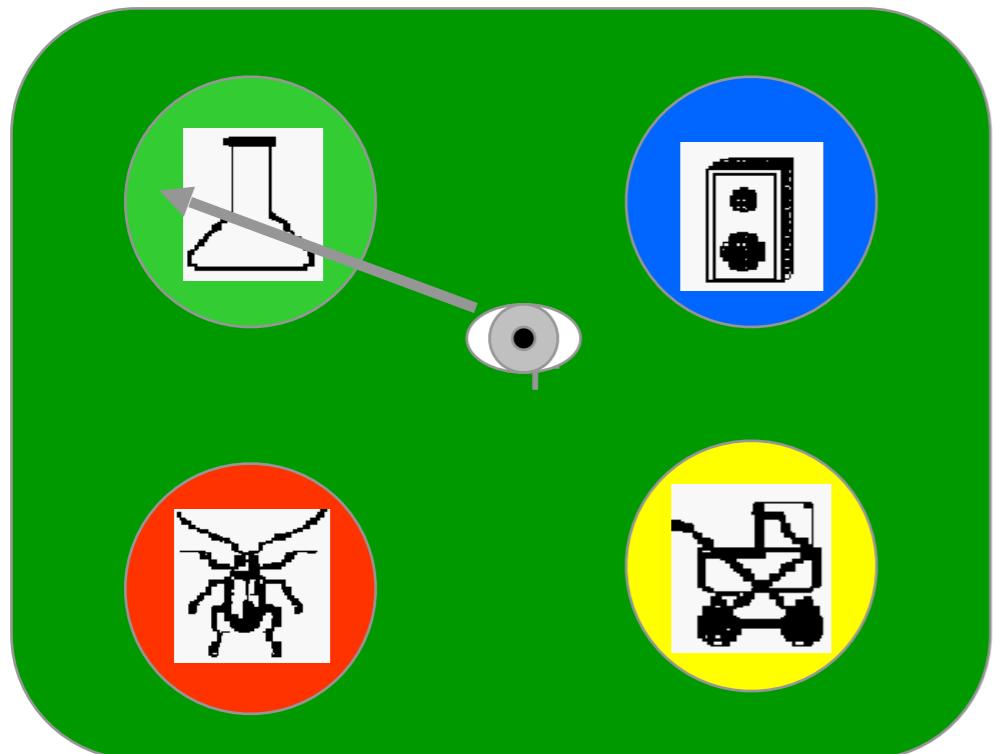
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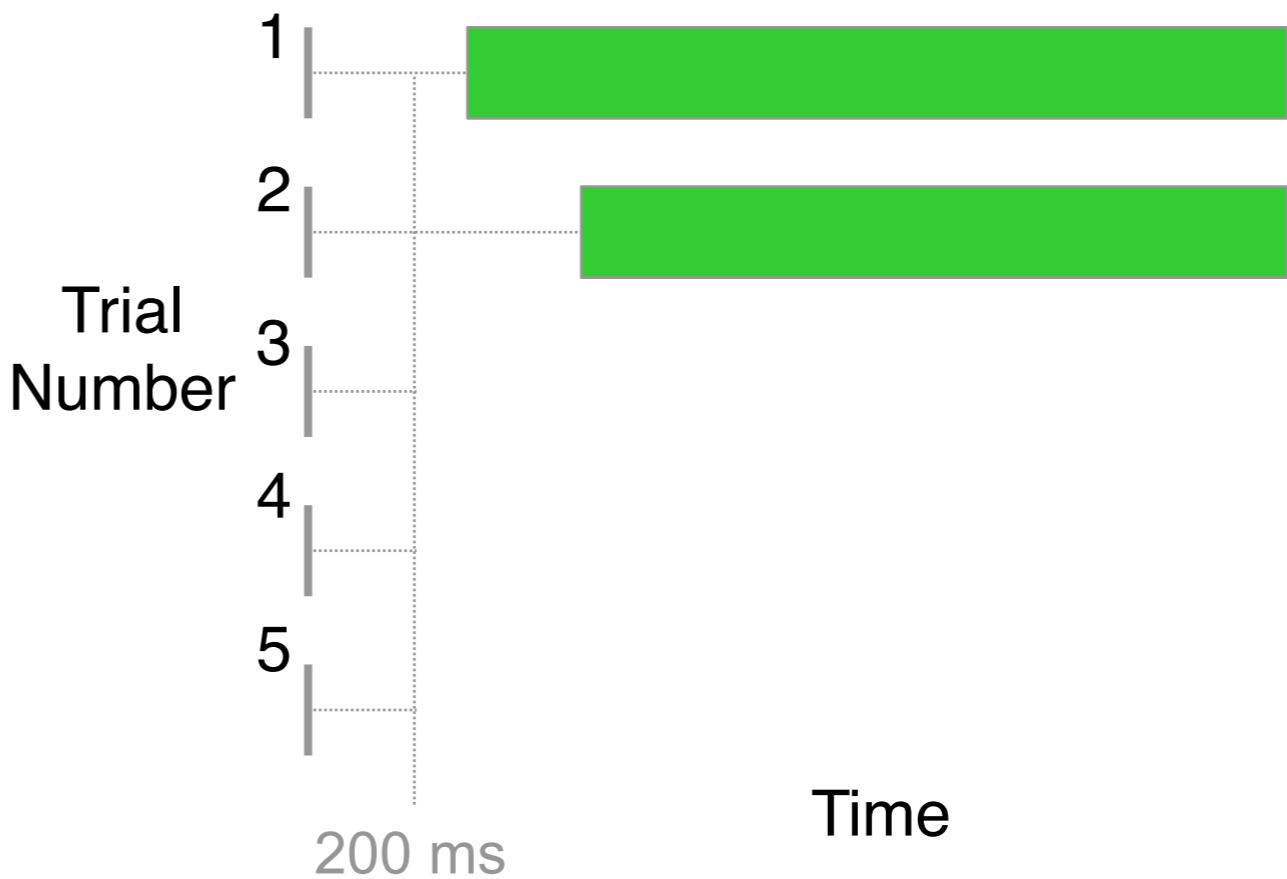
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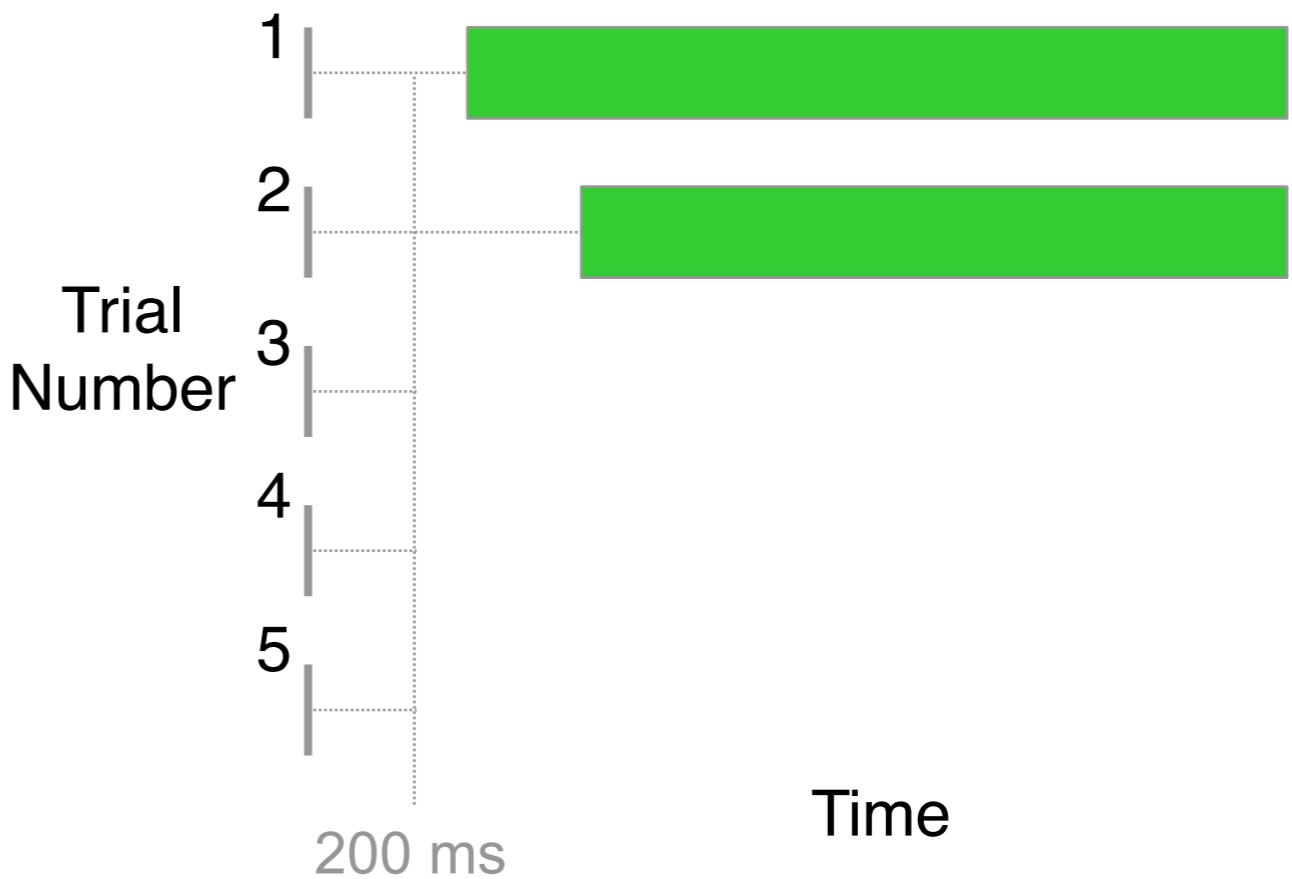
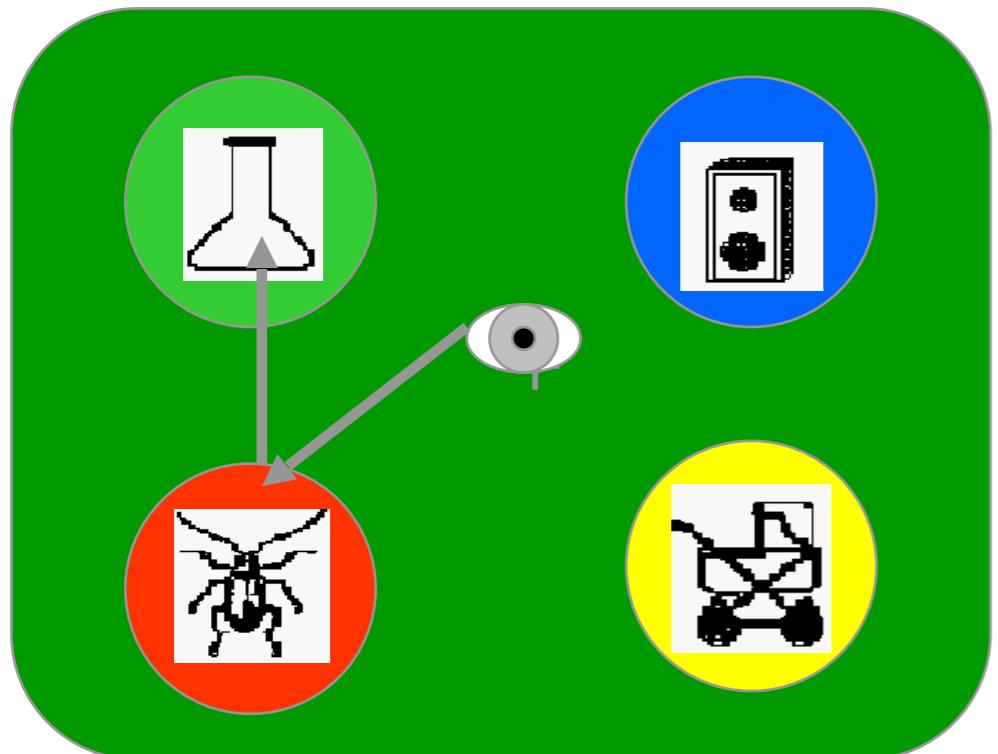
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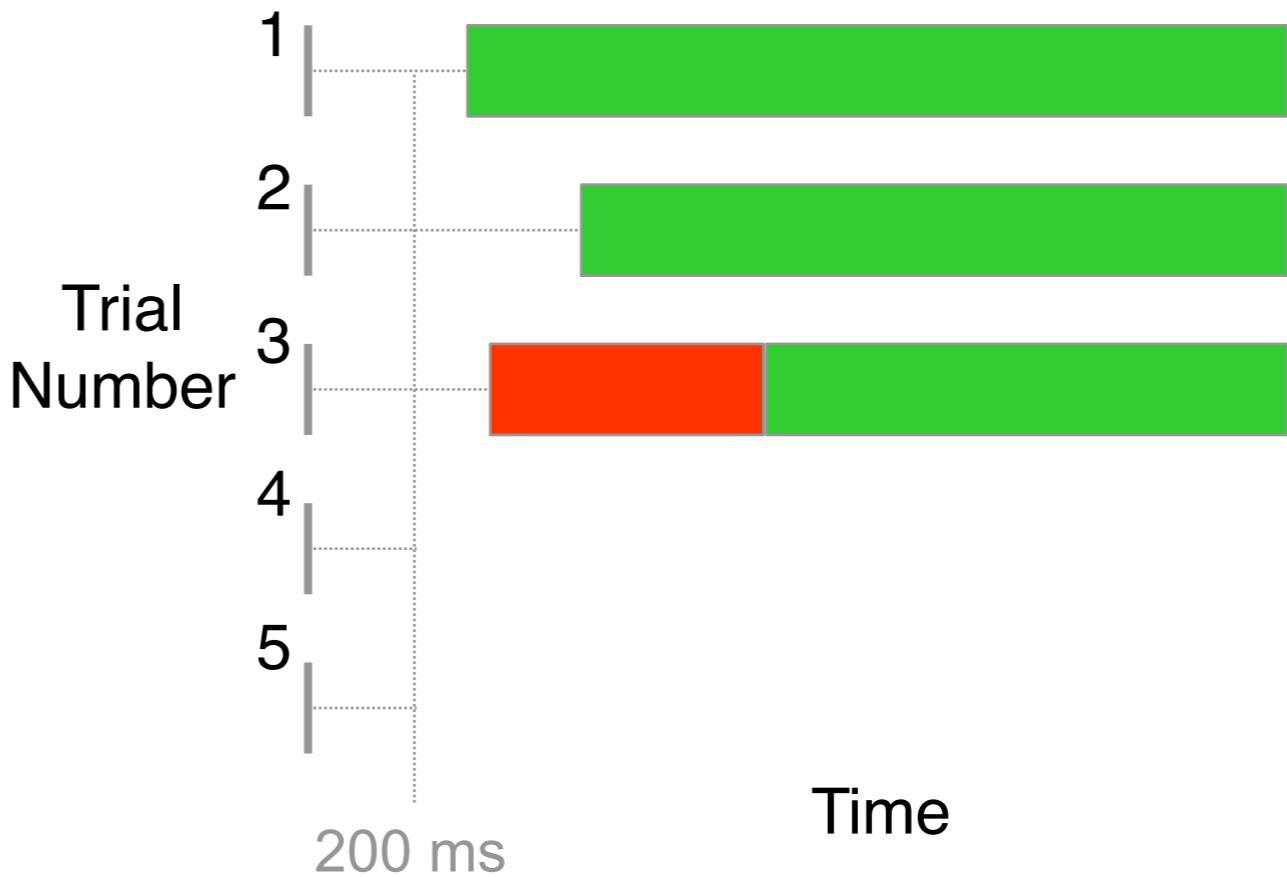
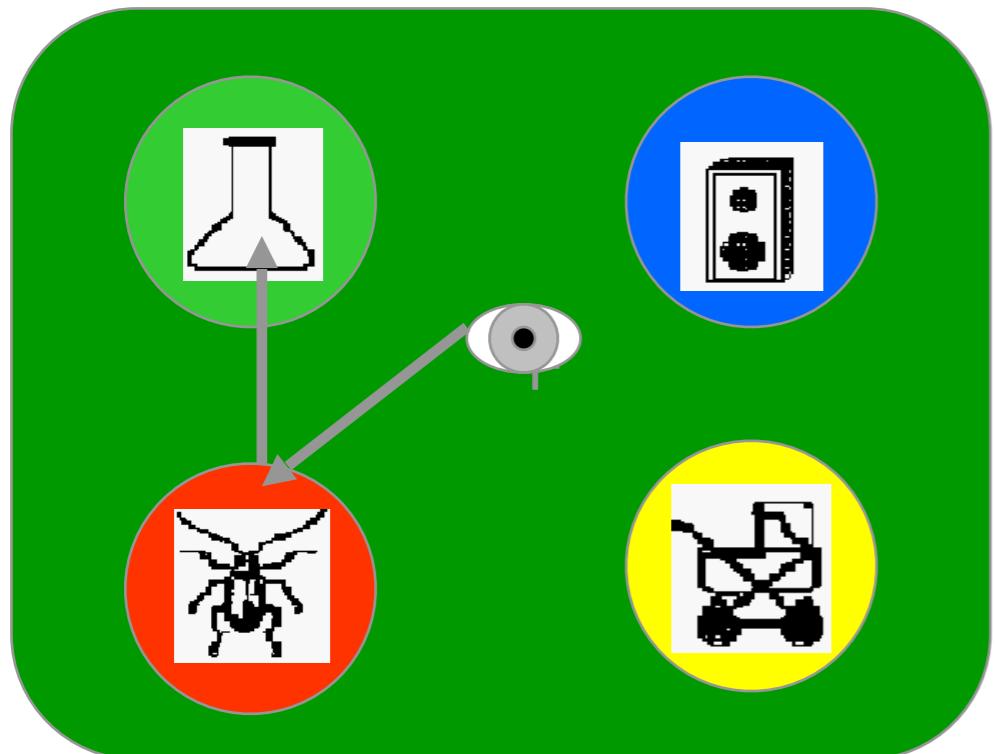
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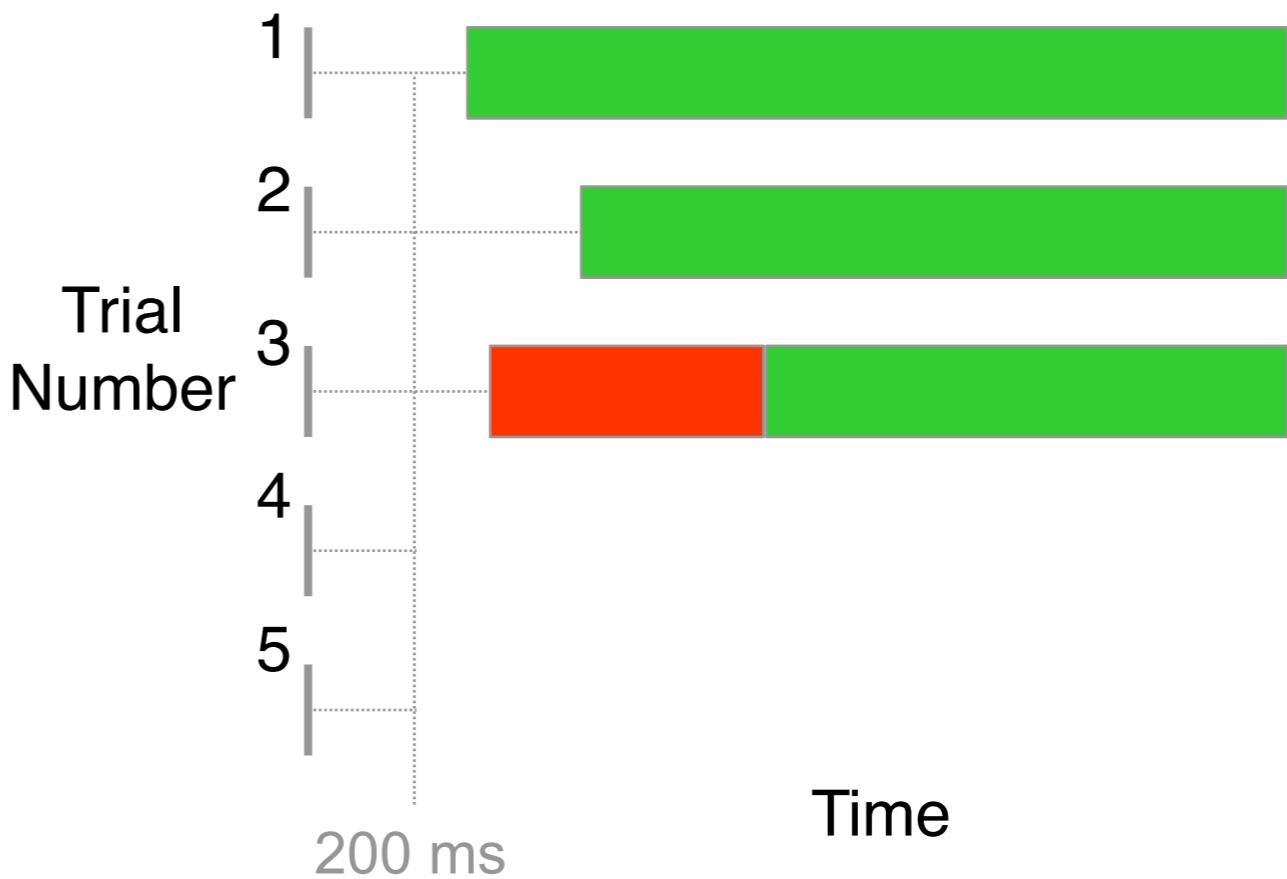
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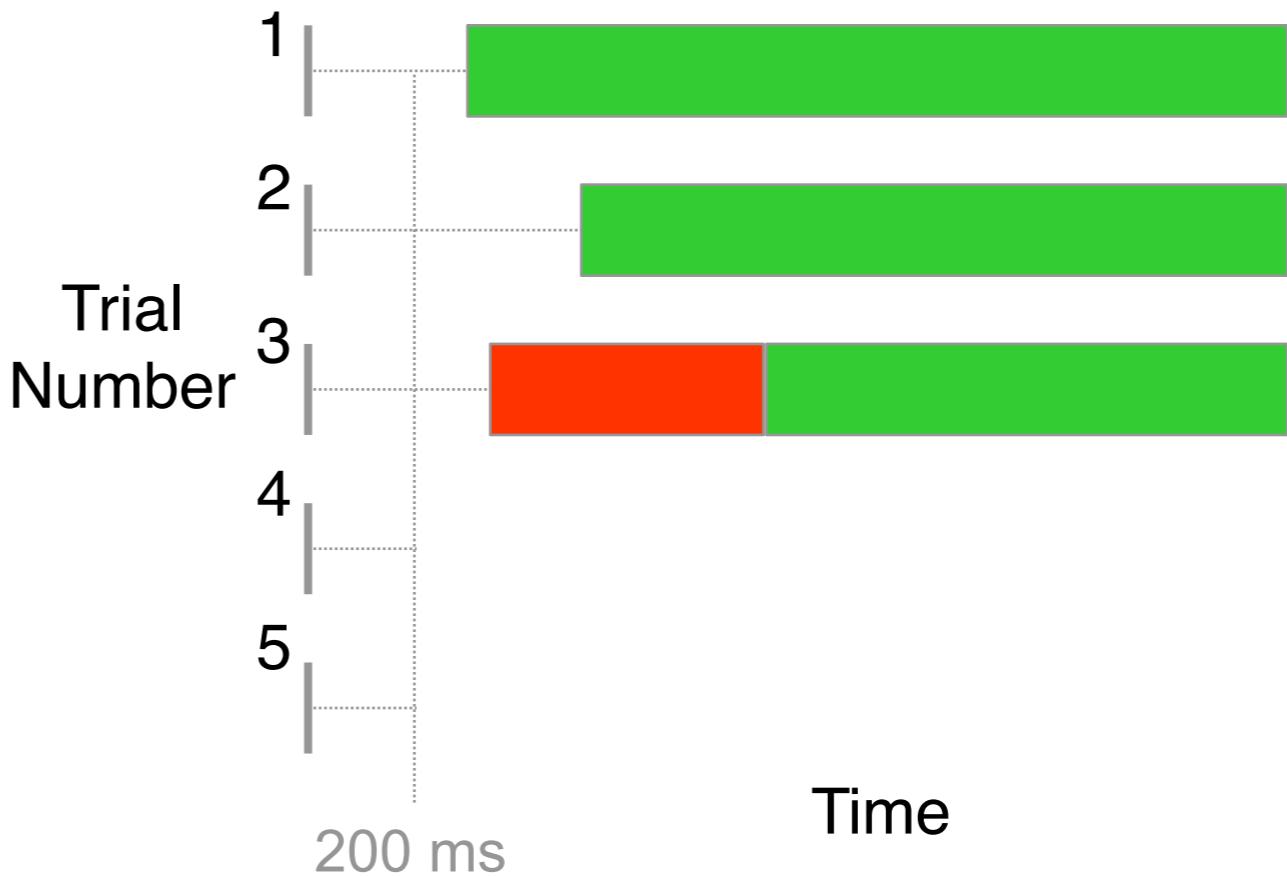
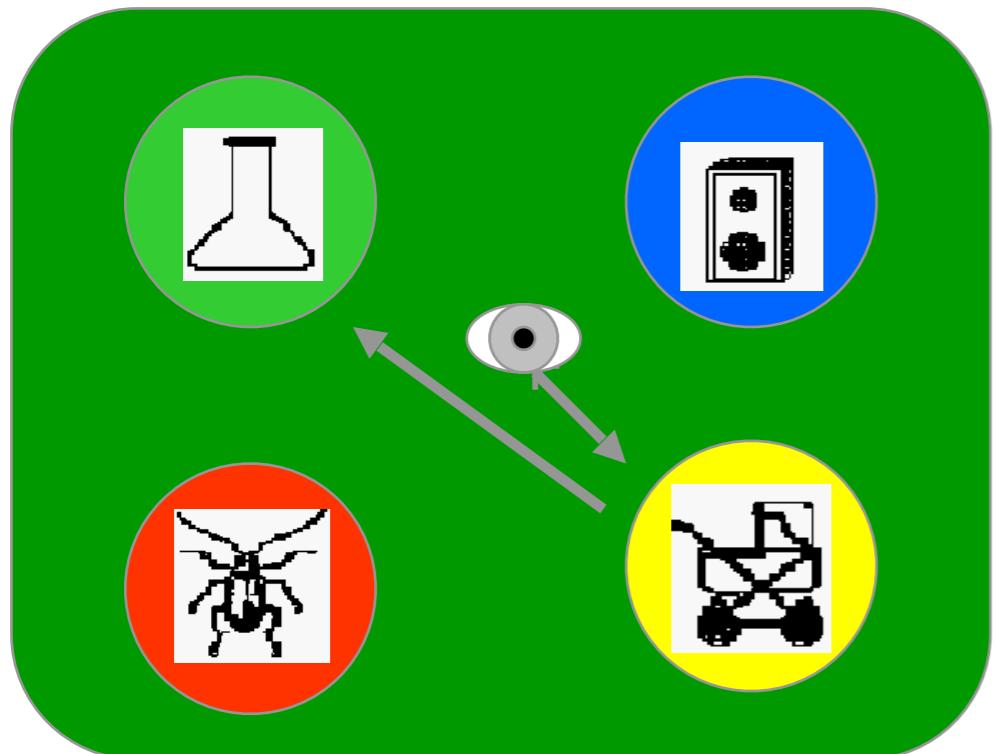
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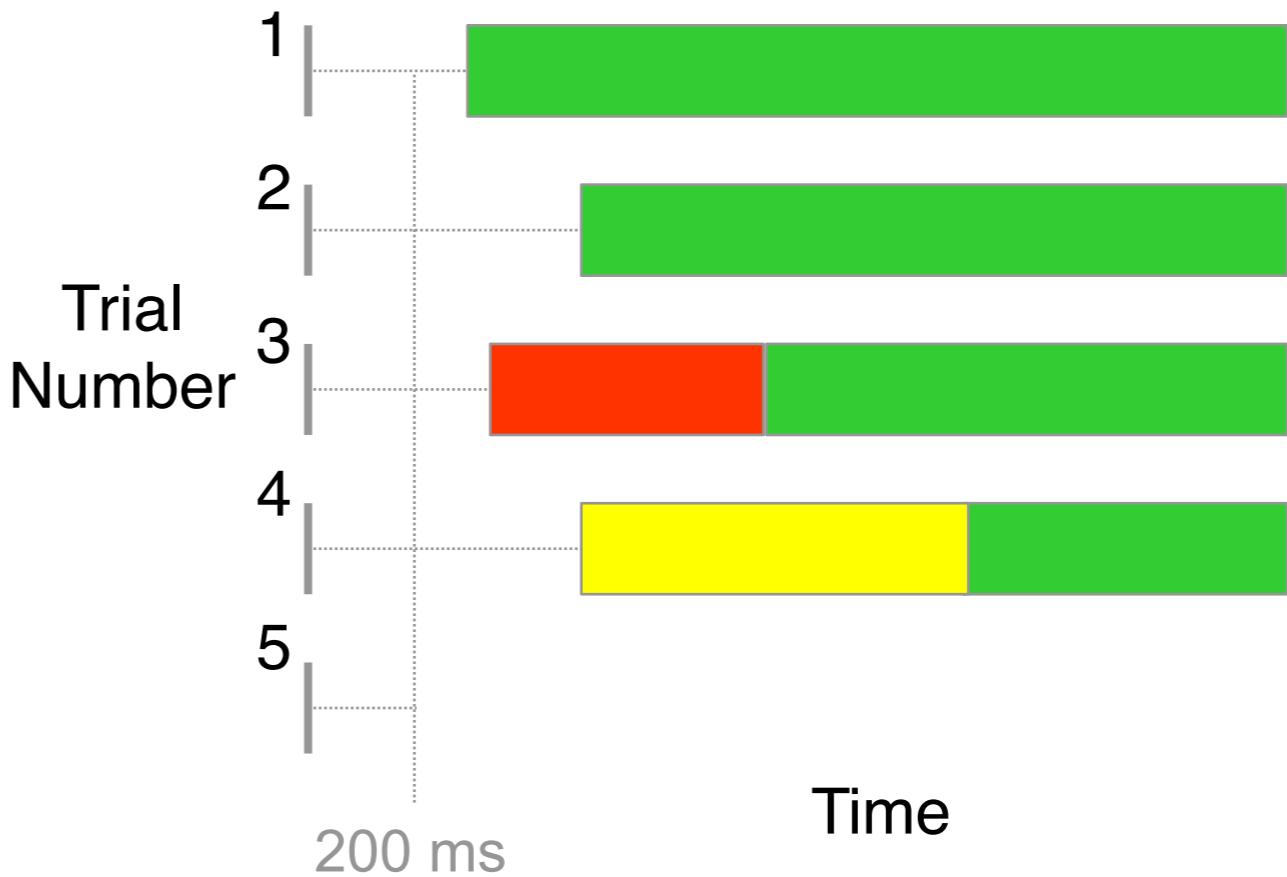
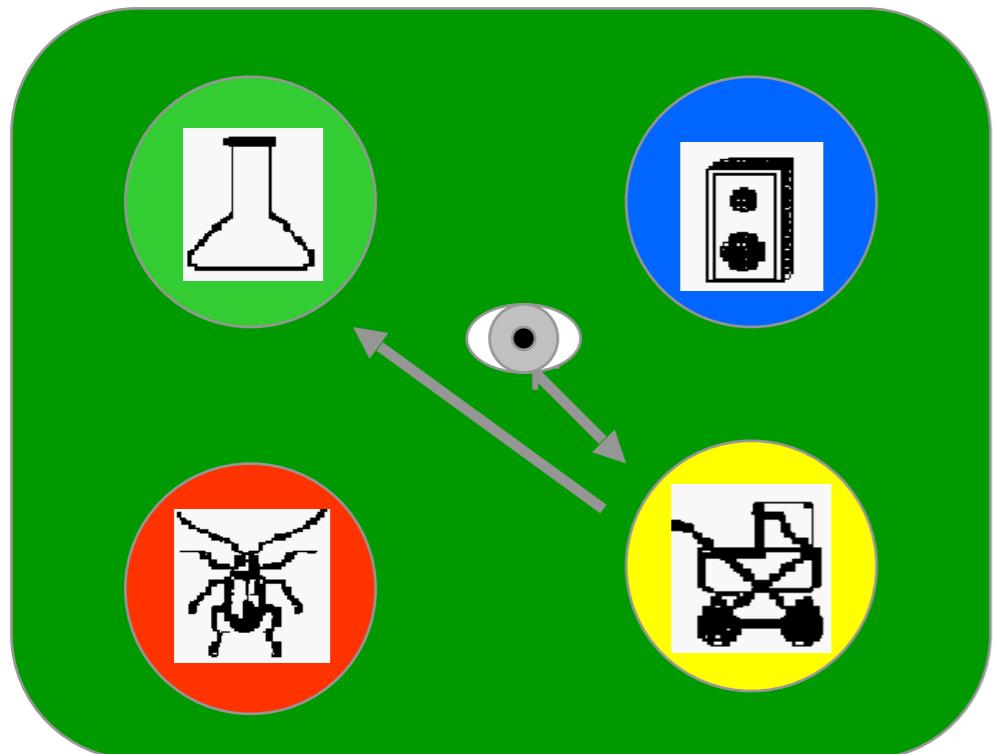
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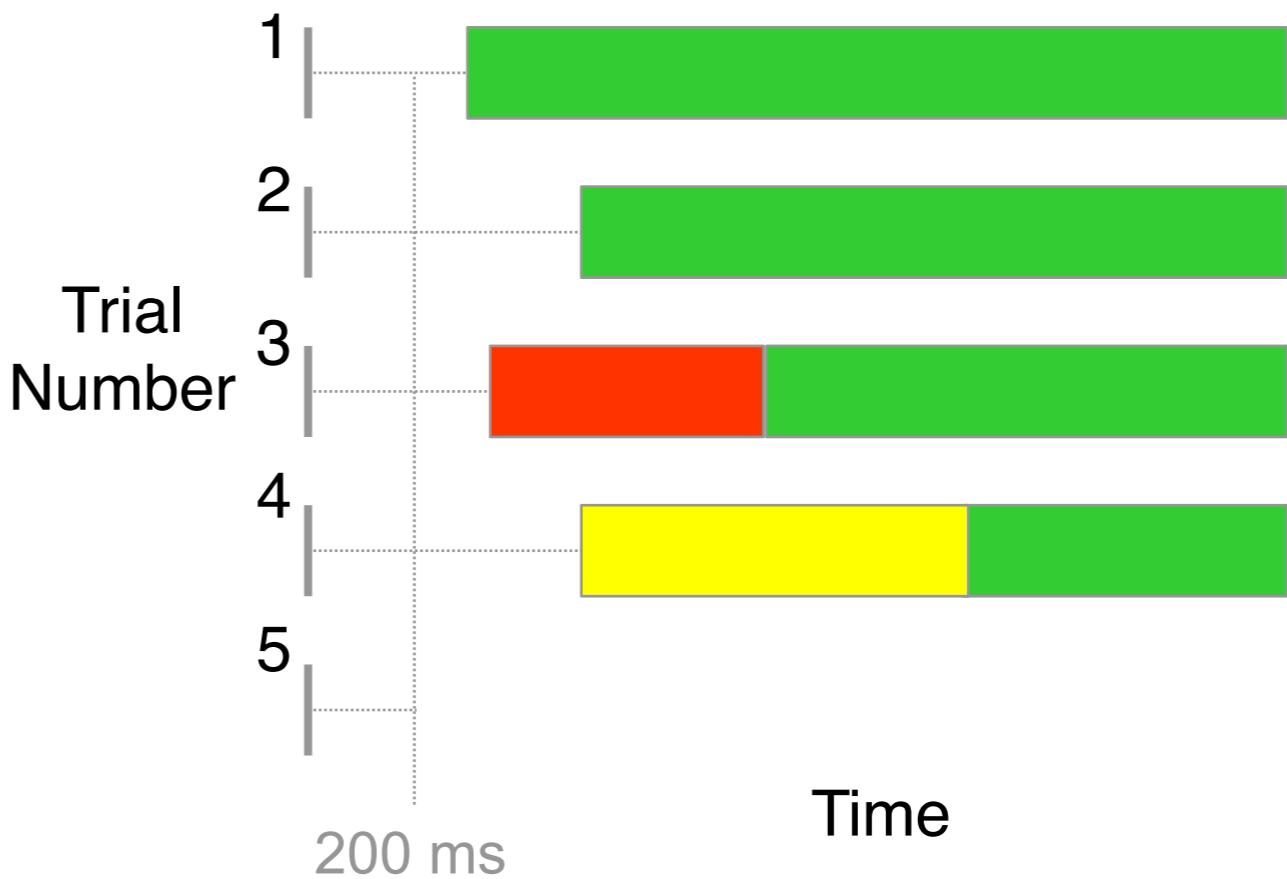
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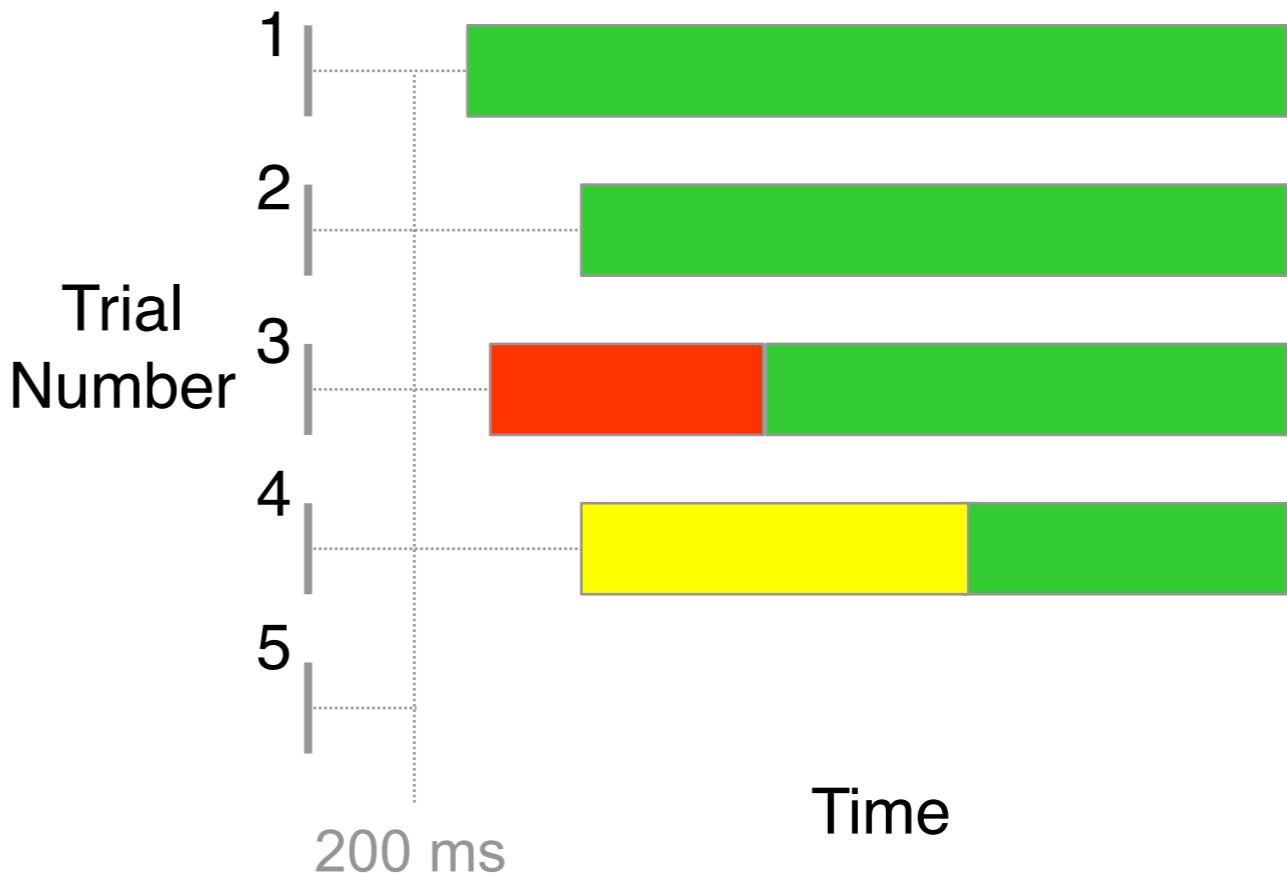
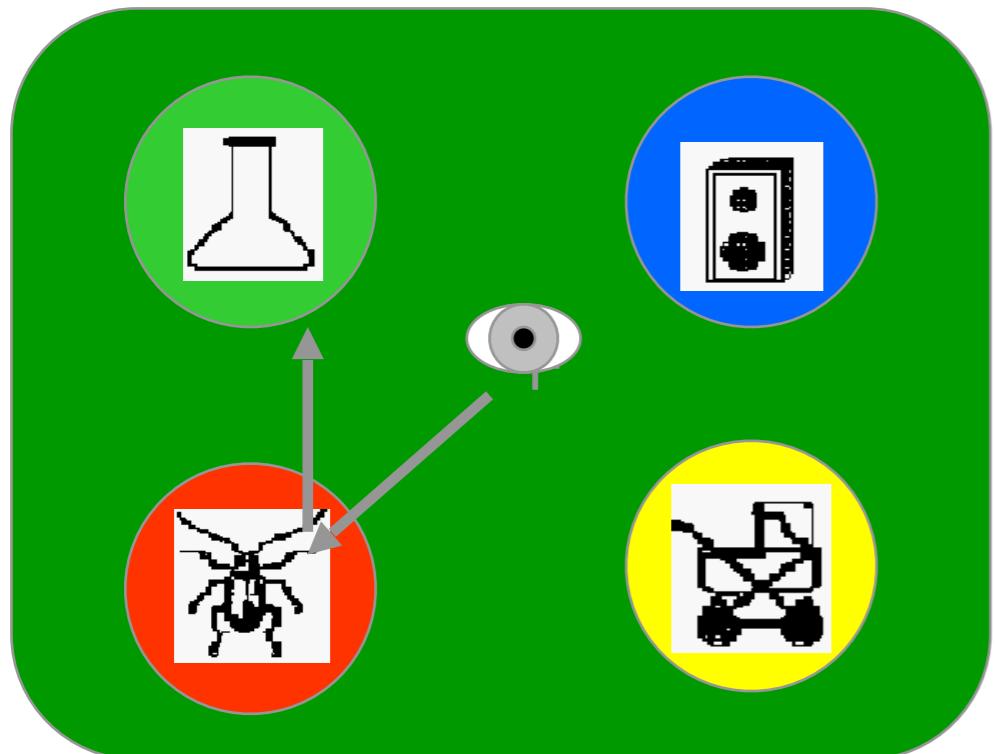
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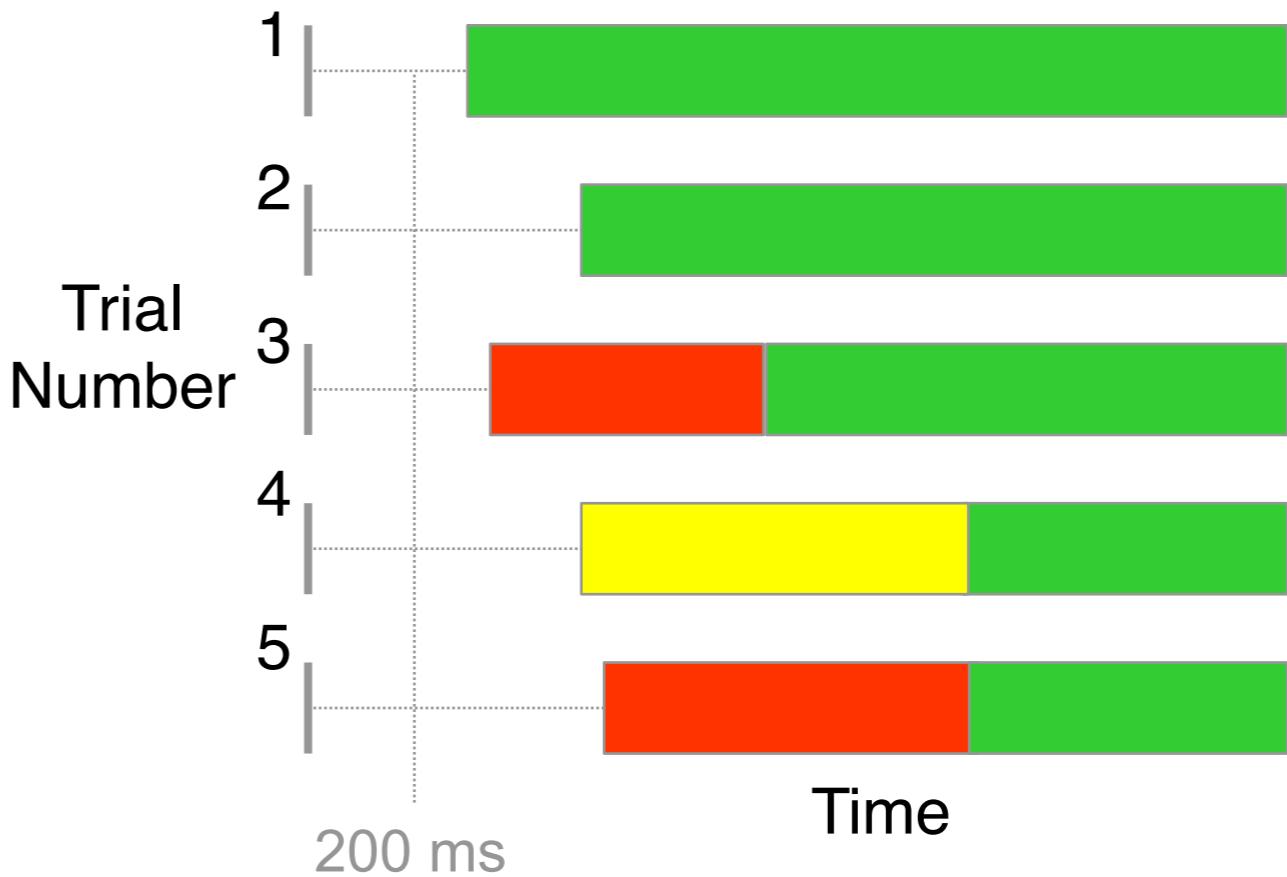
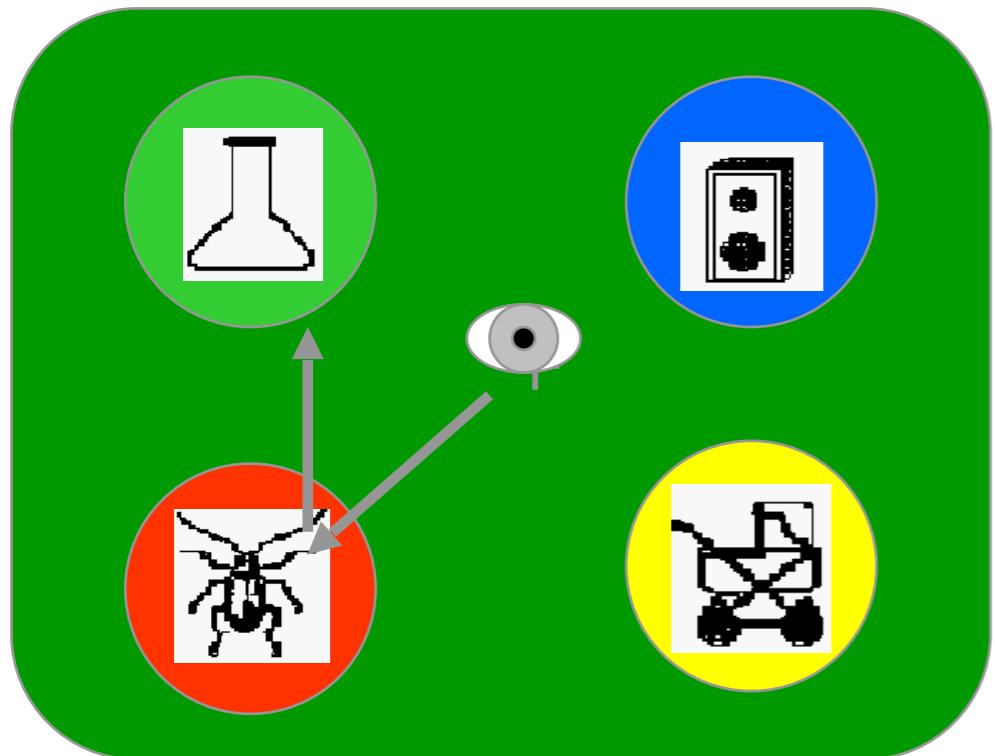
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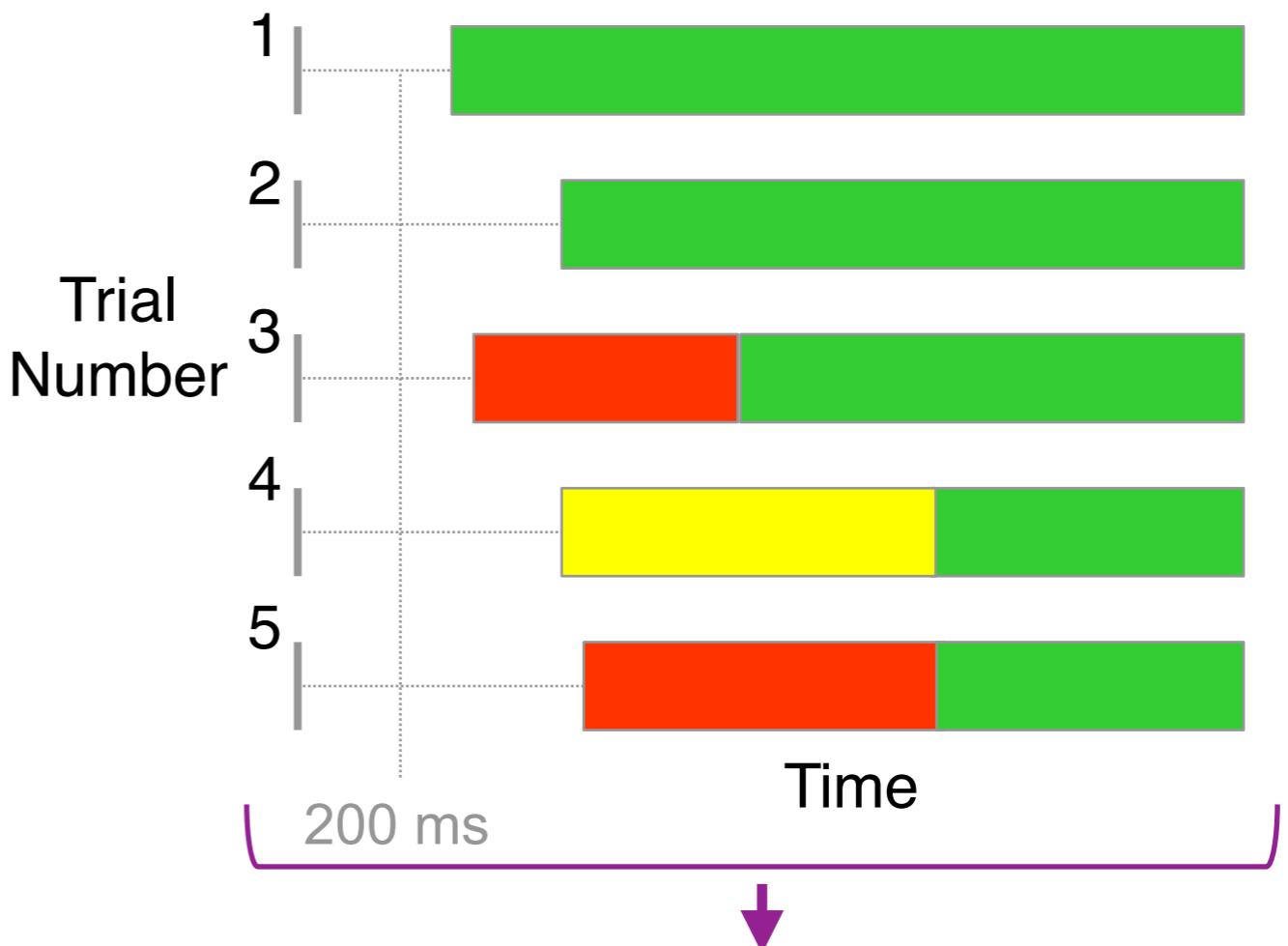
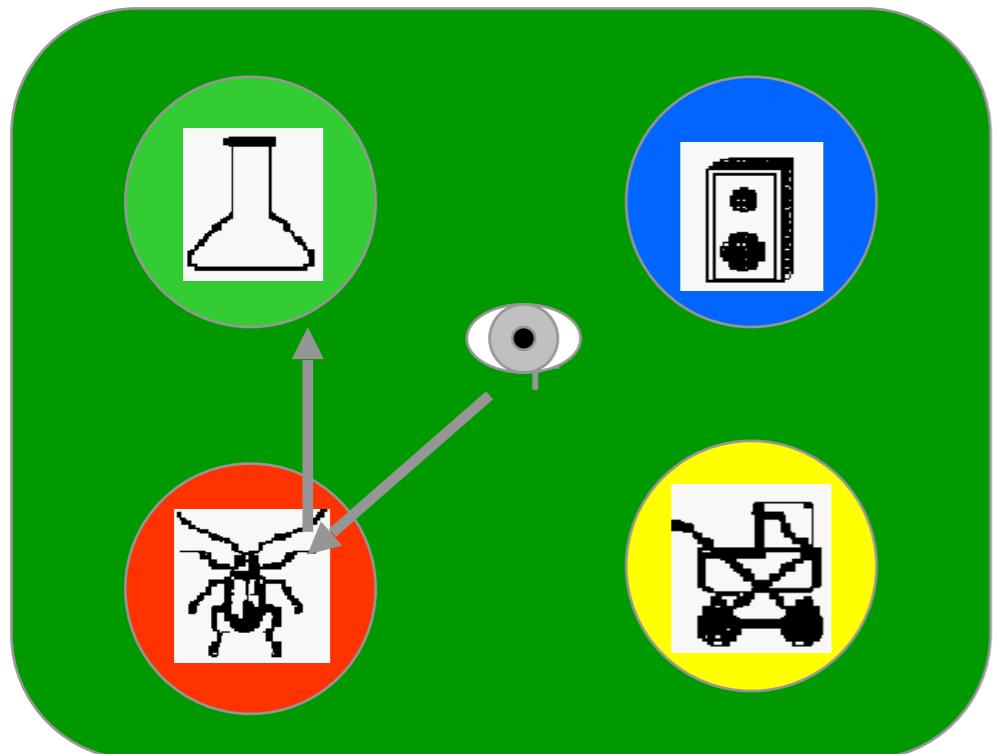
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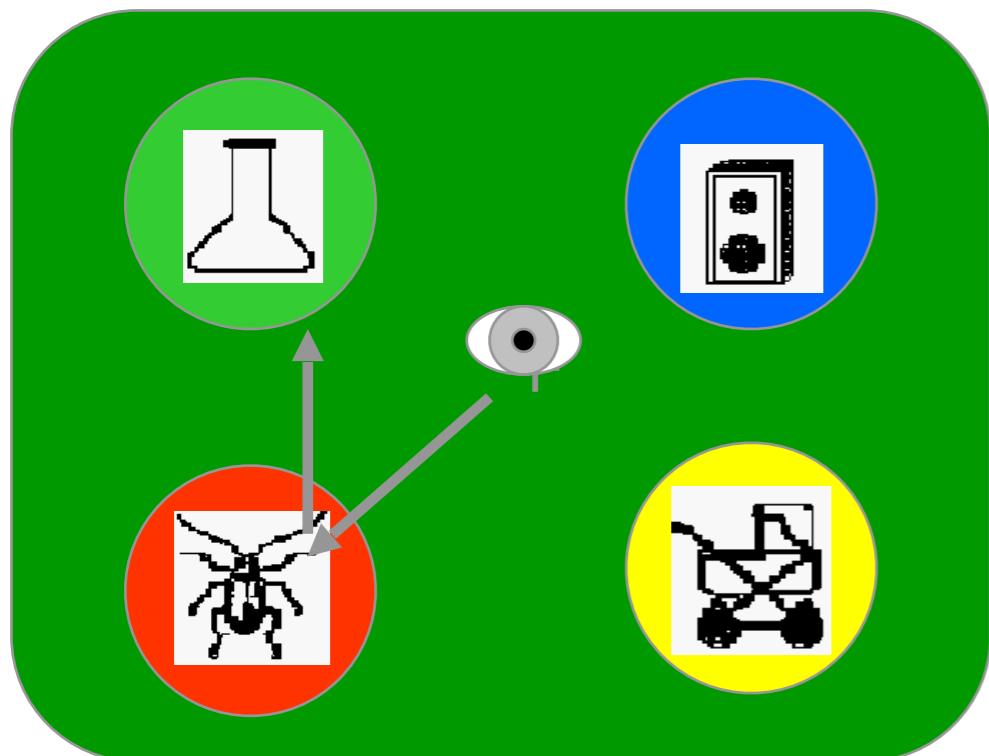
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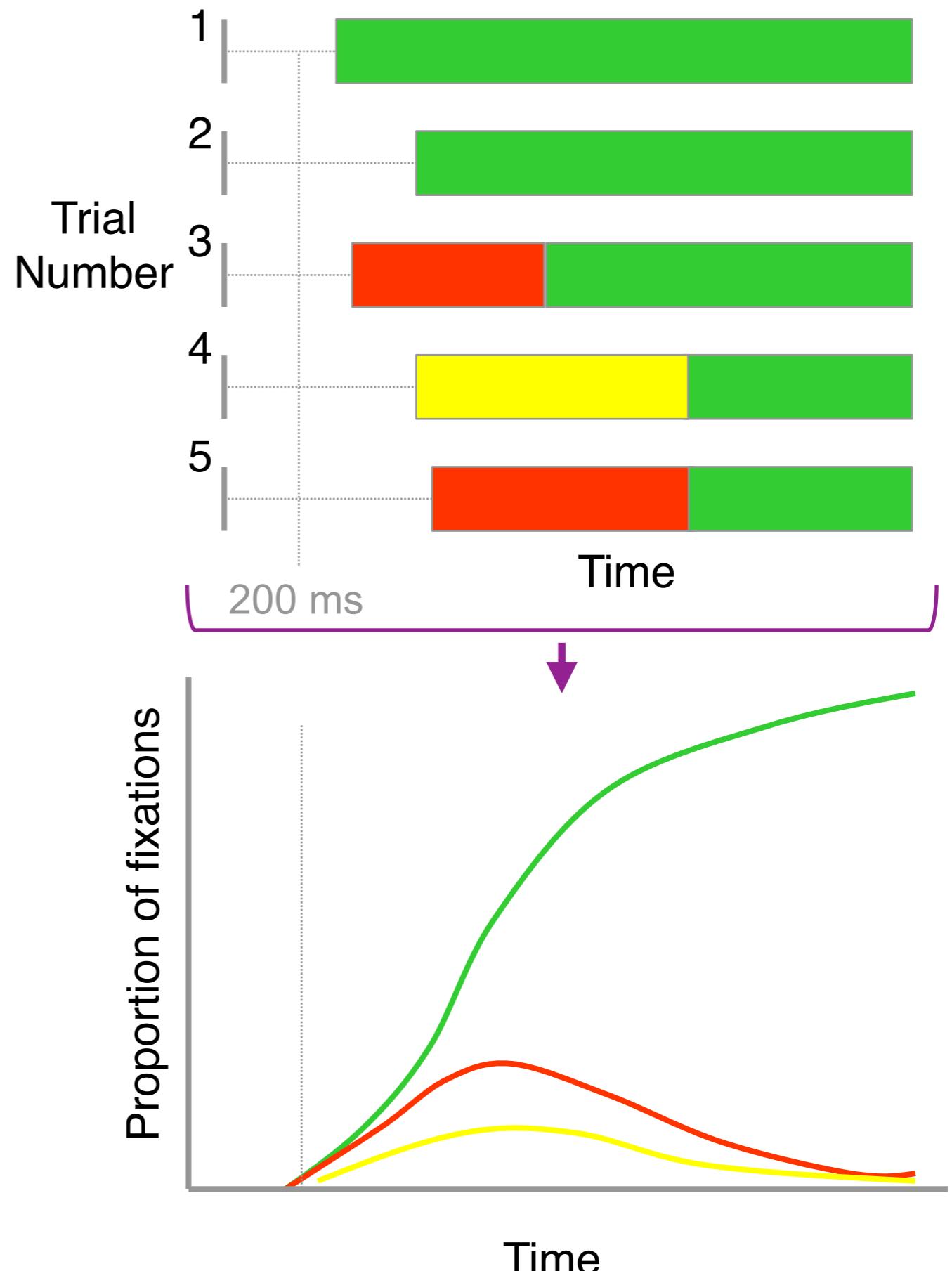
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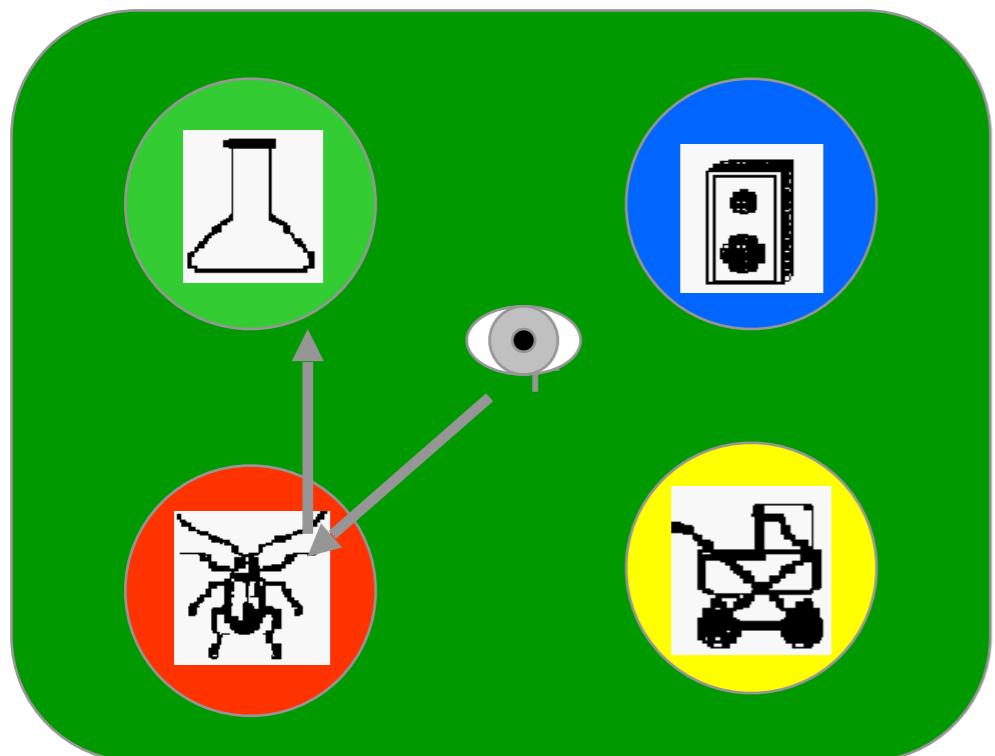
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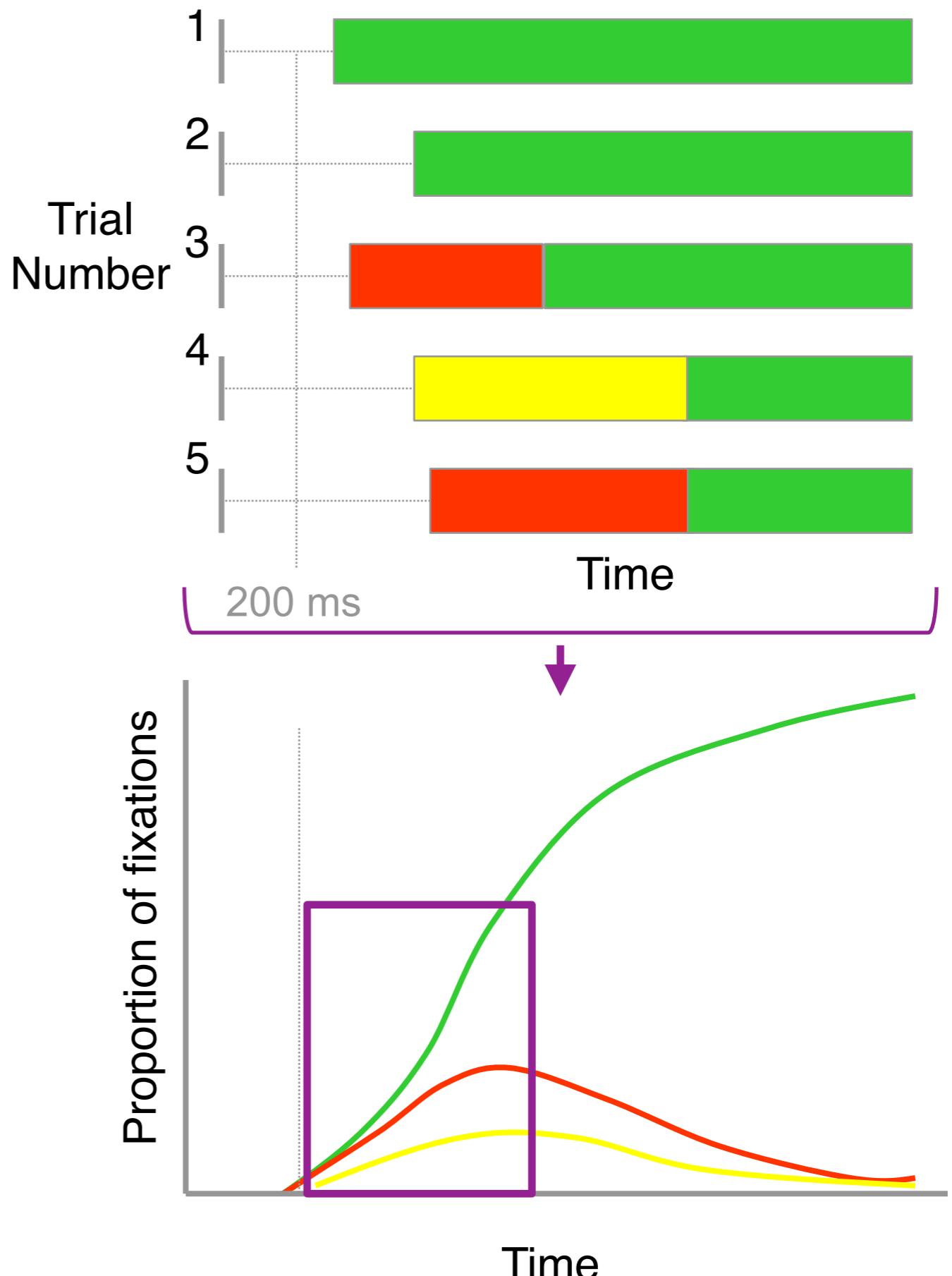
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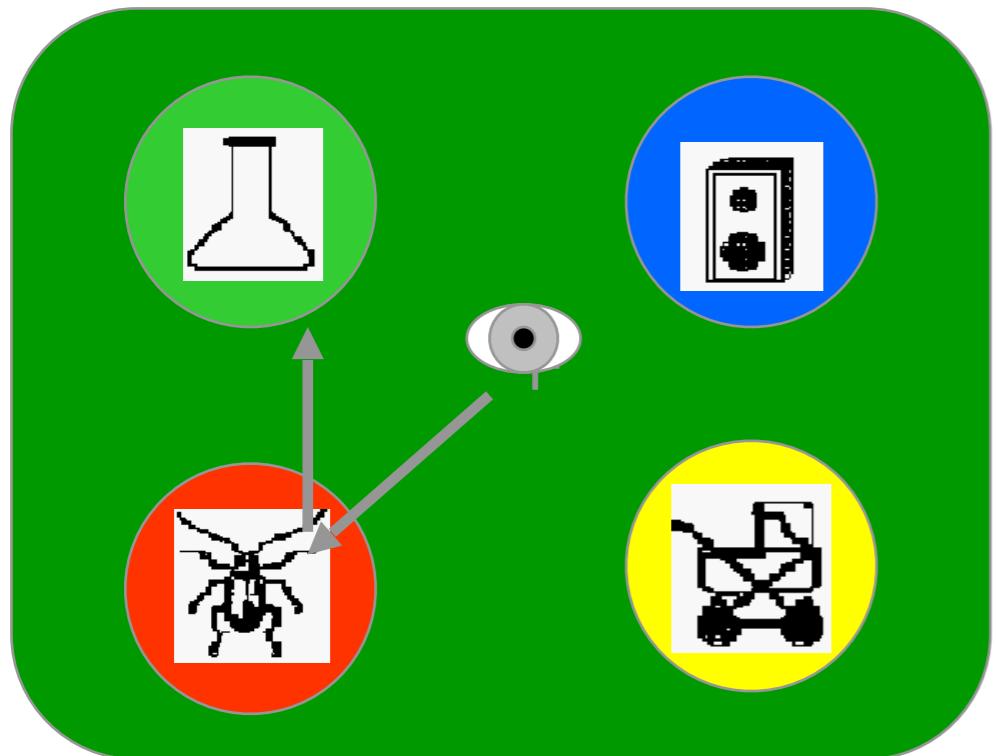
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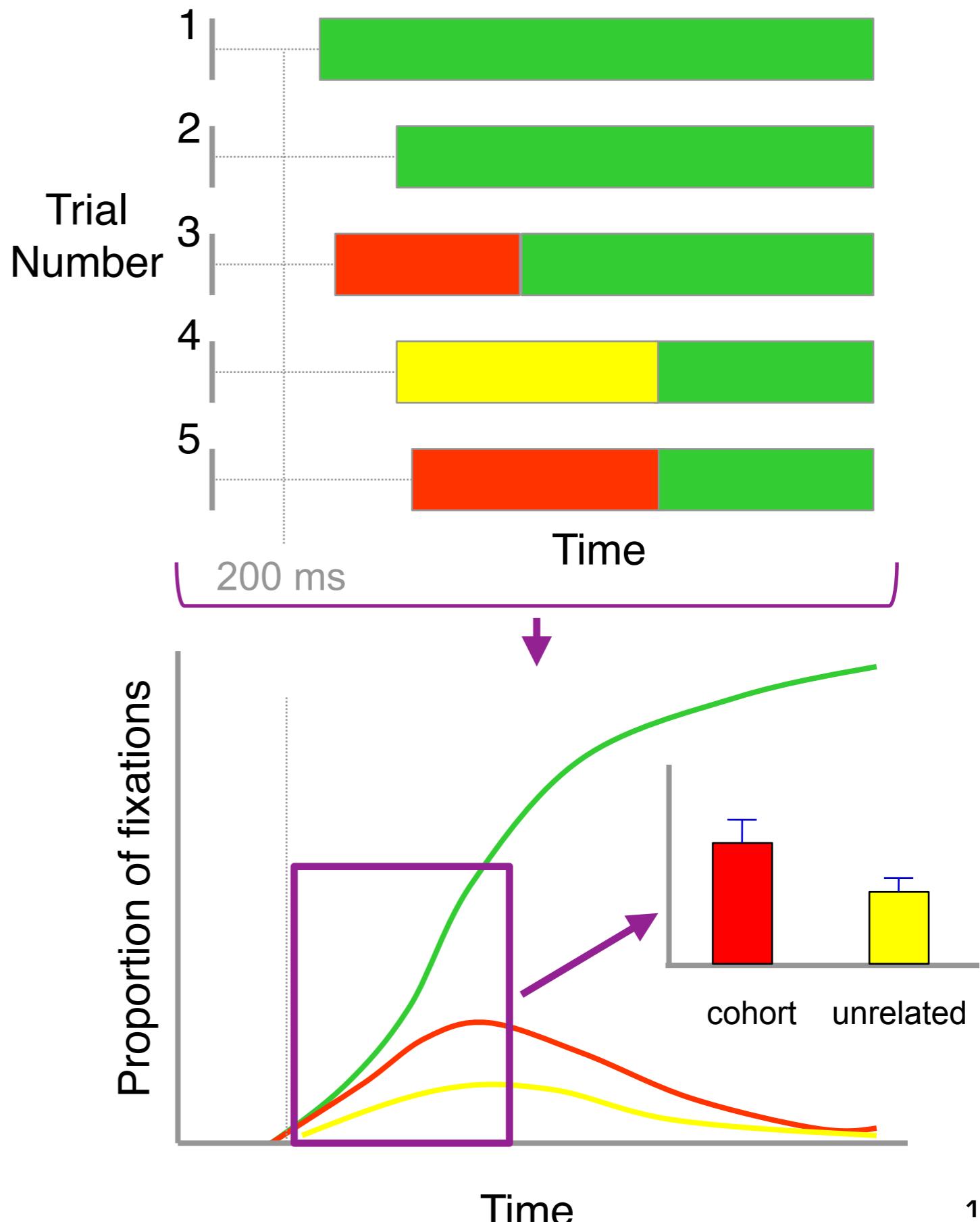
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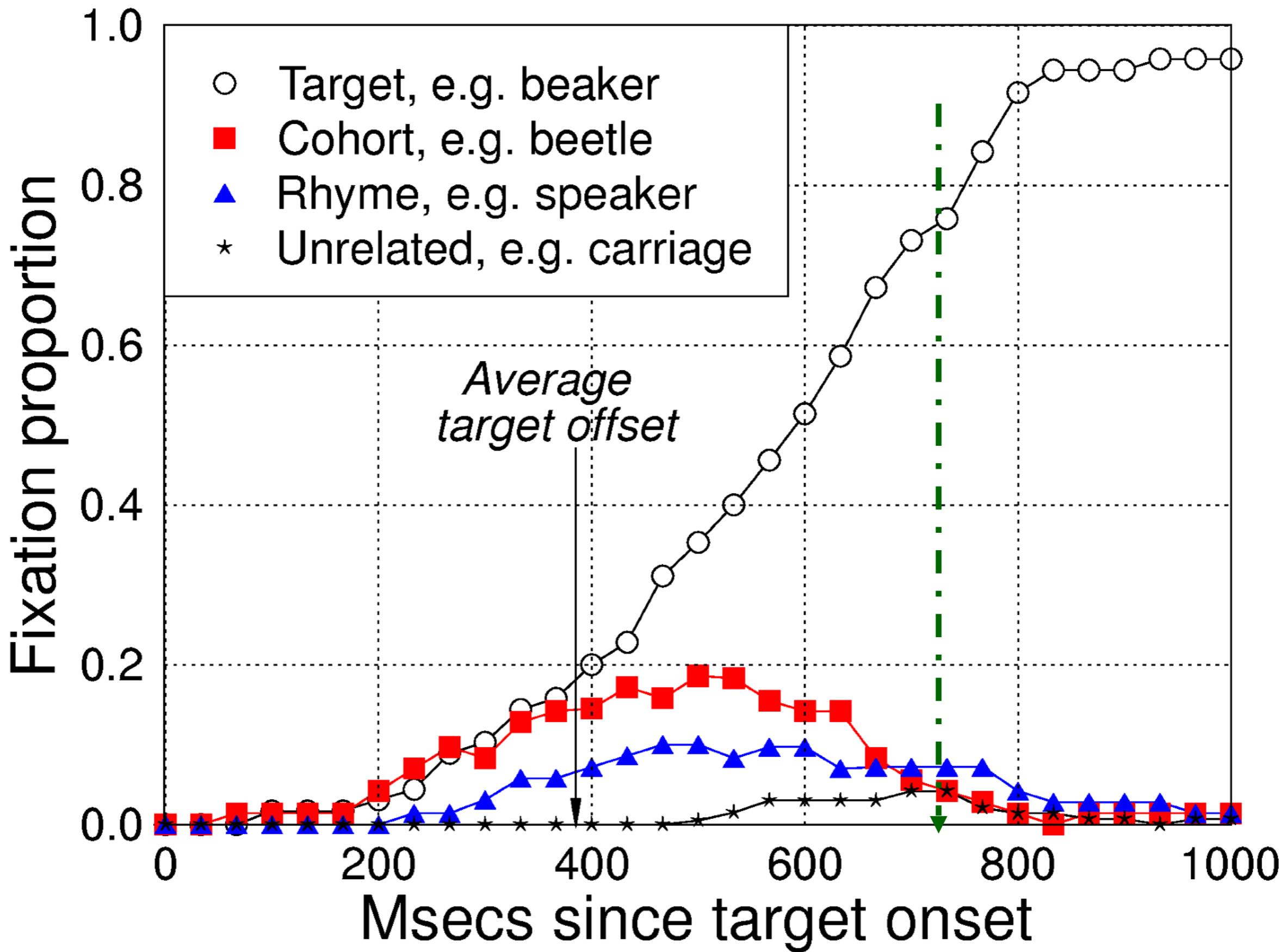
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Allopenna, Magnuson & Tanenhaus (1998)



How do people read?

How do people read?

CNN wants to change its viewers' habits.

Eye movements in reading

There are advantages and disadvantages of both electronic and hardcopy journals. Hardcopy journals are more easily browsed, more portable and, of course people are very much used to their format. Electronic journals save on paper and their format has improved considerably over the past few years, but there are still problems over managing copyright restrictions and persuading people to use electronic instead of hardcopy journals. There is also the problem of portability. More and more journals are now being published in electronic format, although some publishers will only let you subscribe to an electronic journal provided you also subscribe to the hardcopy (more money for the same thing). Some electronic journals cost over 100% more than their equivalent hardcopy. With all these factors in mind I have been discussing individual and shared-subscriptions with the Biochemistry Department, the RSL and Blackwell's. Whilst I feel that a move from hardcopy to electronic journals will be a very slow process in the ULP Library, electronic publishing is being carefully monitored and I would hope to introduce a few electronic texts into the Library alongside the journals which are already available for free over the Internet.

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How do people read?

CNN wants to change its viewers' habits.

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CNN wants to change its viewers' habits.

1 2 7 3 4 5 6 8

Fixations

How do people read?

CNN wants to change its viewers' habits.

The diagram consists of a horizontal dotted line with red arrows pointing right and left along its length. The text 'CNN wants to change its viewers' habits.' is written in a light gray font across the dotted line. Below the dotted line, there are numerical labels 1, 2, 3, 4, 5, 6, and 8, corresponding to the positions of the red arrows. The arrow at position 7 points left, while all other arrows point right, illustrating the direction of eye movements during reading.

Saccades

How do people read?

CNN wants to change its viewers' habits.

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CNN wants to change its viewers' habits.

How do people read?

 wants to change its viewers' habits.
225ms

How do people read?

CNN wants to change its viewers' habits.

225ms

How do people read?

CNN wants to change its viewers' habits.

225ms 30ms

How do people read?

CNN wants to change its viewers' habits.

What do you see during a fixation?

How do people read?

CNN wants to change its viewers' habits.

*Perceptual
span*

What do you see during a fixation?

How do people read?

CNN wants ~~to change~~ its viewers' habits.

What do you see during a saccade?

How do people read?



What do you see during a saccade?

Nothing

How do people read?

CNN wants to change its viewers' habits.

Forward
Saccade

How do people read?

CNN wants to change its viewers' habits.

Forward
Saccade

How do people read?

CNN wants to change its viewers' habits.

Forward
Saccade

How do people read?

CNN wants to change its viewers' habits.

Backward
Saccade
(Regression)

How do people read?

CNN wants to change its viewers' habits.

1

2

7

3

4

5

6

8

Eye movement measures

CNN wants to change its viewers' habits.

- 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

Eye movement measures

CNN wants to change its viewers' habits.

1 2 3 4 5

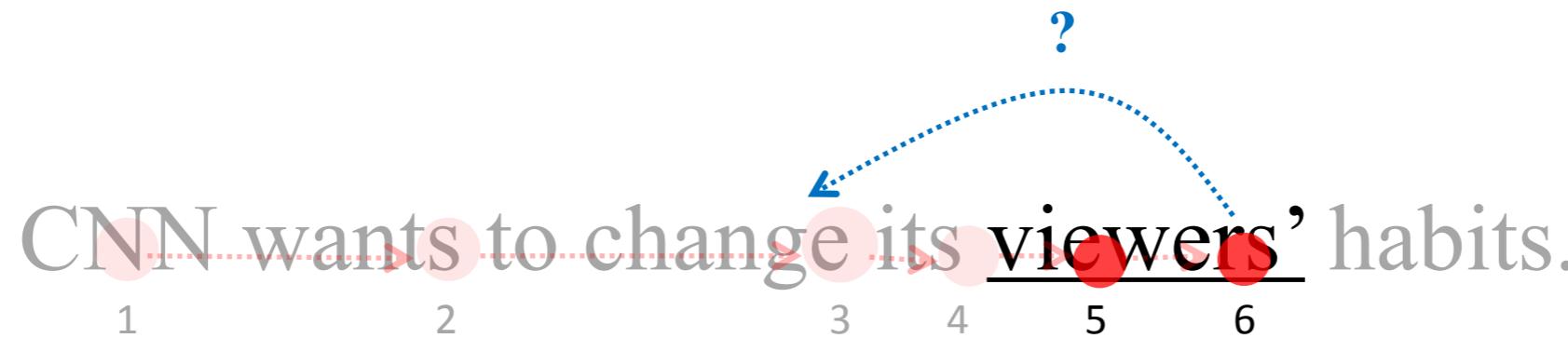
- Skips (also skip rate / fixation probability)
- First fixation duration
- First pass duration (or Gaze duration)
- First pass regression rate
- Go-past duration
- Total fixation duration

Eye movement measures

CNN wants to change its viewers' habits.

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Eye movement measures



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Eye movement measures

CNN wants to change its viewers' habits.

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- Go-past duration
- Total fixation duration

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.

Generalizing incremental disambiguation

Generalizing incremental disambiguation

- Uncertainty in predictions about upcoming material

Generalizing incremental disambiguation

- Uncertainty in predictions about upcoming material

The old man stopped and stared at the

Generalizing incremental disambiguation

- Uncertainty in predictions about upcoming material

The old man stopped and stared at the statue?

Generalizing incremental disambiguation

- Uncertainty in predictions about upcoming material

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

Generalizing incremental disambiguation

- Uncertainty in predictions about upcoming material

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

Generalizing incremental disambiguation

- Uncertainty in predictions about upcoming material

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

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

Generalizing incremental disambiguation

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*The old man stopped and stared at the statue? dog?
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Generalizing incremental disambiguation

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- This is uncertainty about *what has not yet been said*

Generalizing incremental disambiguation

- Uncertainty in predictions about upcoming material

*The old man stopped and stared at the statue? dog?
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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

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

Rayner & Well 1996

The hikers slowly climbed up the _____

Rayner & Well 1996

*The hikers slowly climbed up the _____
mountain (95%)*

Rayner & Well 1996

The hikers slowly climbed up the _____

mountain (95%)

hillside (3%)

Rayner & Well 1996

The hikers slowly climbed up the _____

Equal word length
& frequency

mountain (95%)
hillside (3%)

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 <u>Probability</u>	First Fixation	Gaze Duration	Total Time
High	0.78	239	261	294
Low	0.90	250	281	360

Staub 2011

While the professor lectured the students walked across the quad.

Staub 2011

???

While the professor lectured the students walked across the quad.

Staub 2011

Staub 2011

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

Subj V Obj

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

Subj V Subj

Staub 2011

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

Subj V Obj

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

Subj V Subj

???

Staub 2011

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

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

Staub 2011

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

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

Staub 2011: word frequency & predictability effects

While the professor lectured the students walked across the quad.

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

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.

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)

Staub 2011: word frequency & predictability effects

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

ambled

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

ambled

Staub 2011: word frequency & predictability effects

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

High Frequency
walked

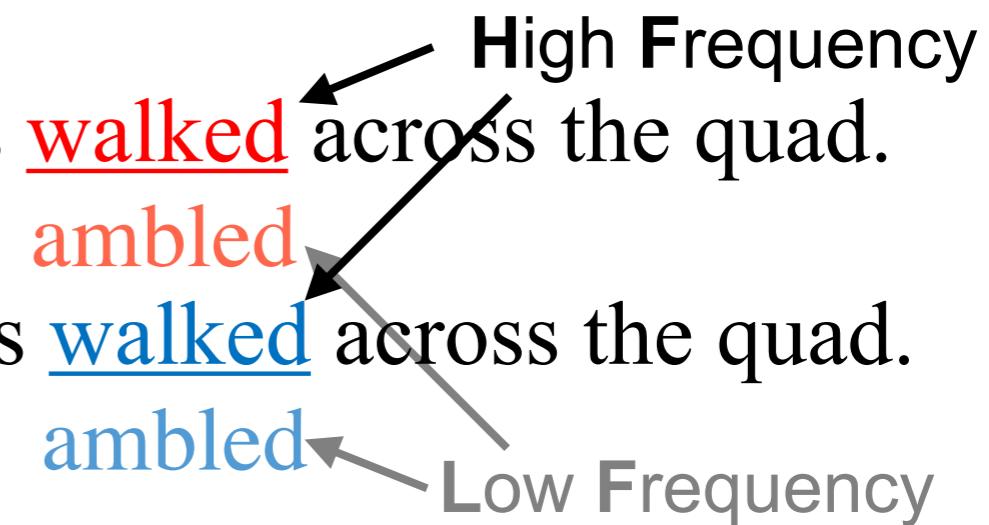
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ambled

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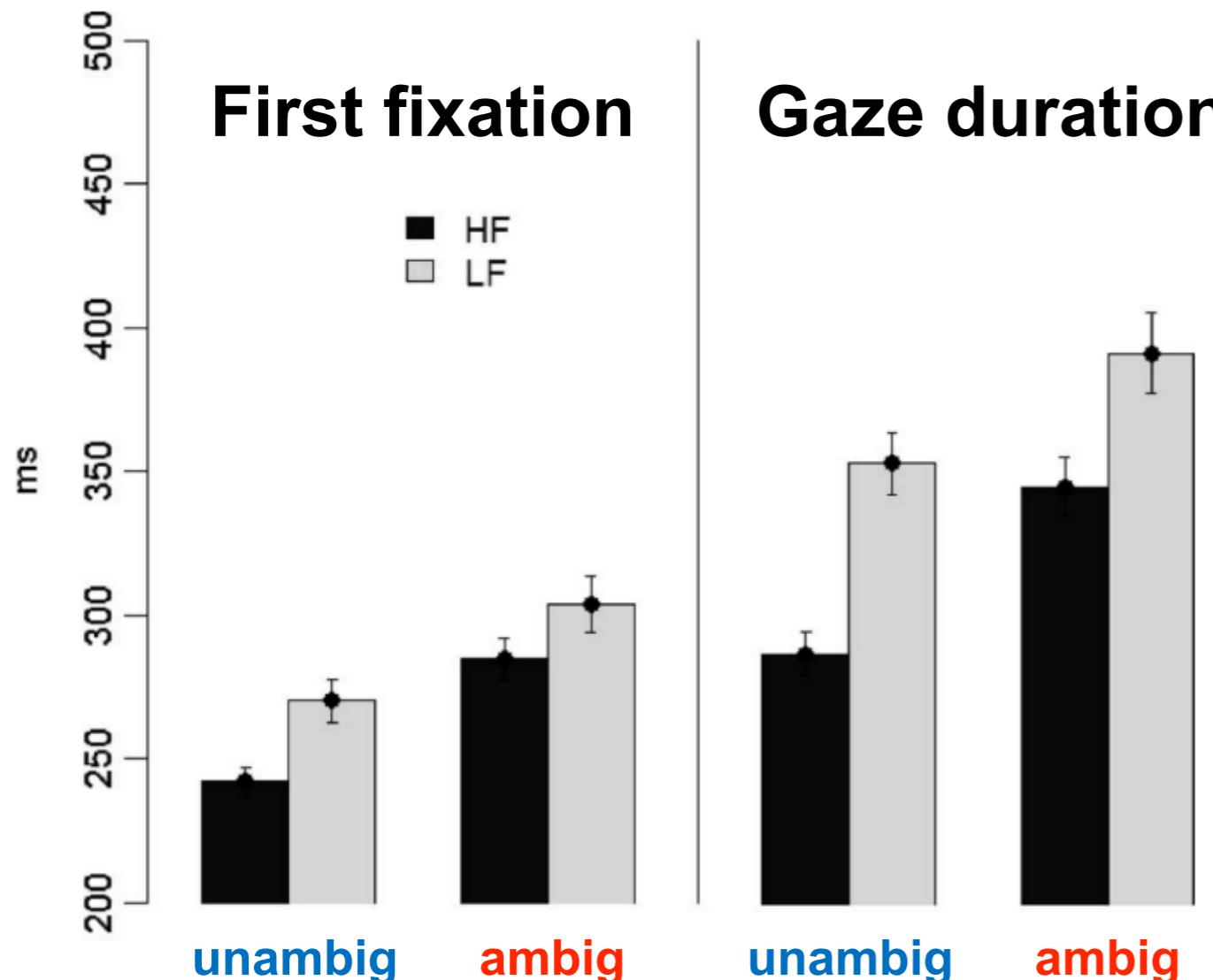


Staub 2011: word frequency & predictability effects

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

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

High Frequency
walked
ambled
ambled
Low Frequency

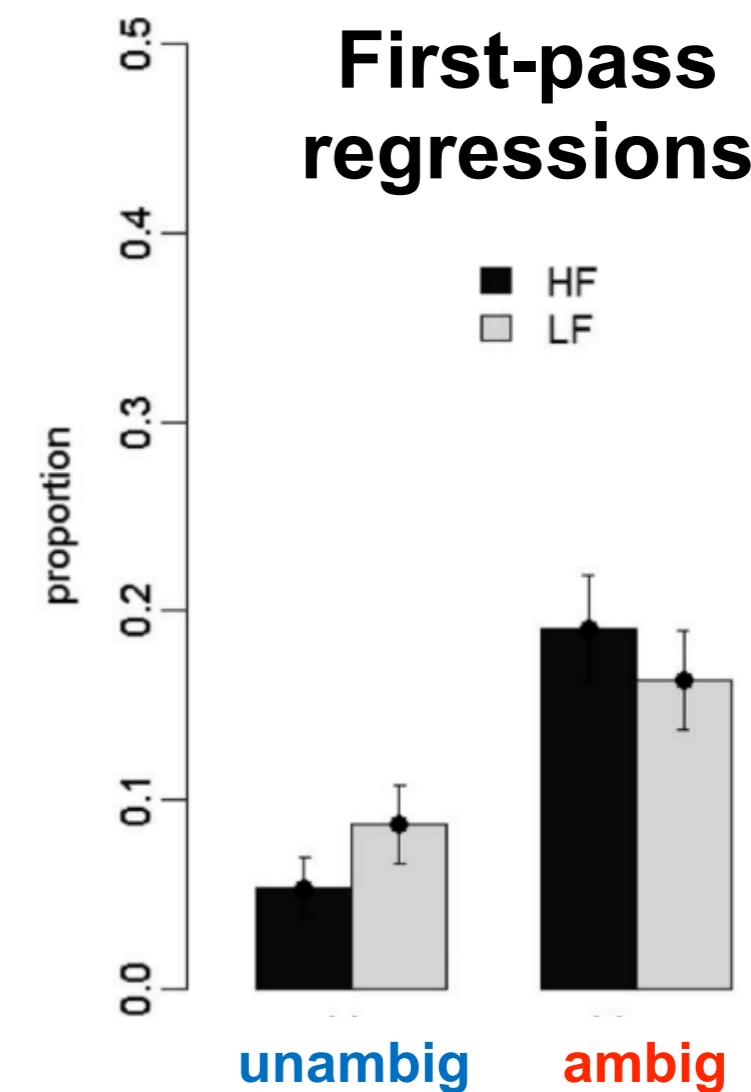
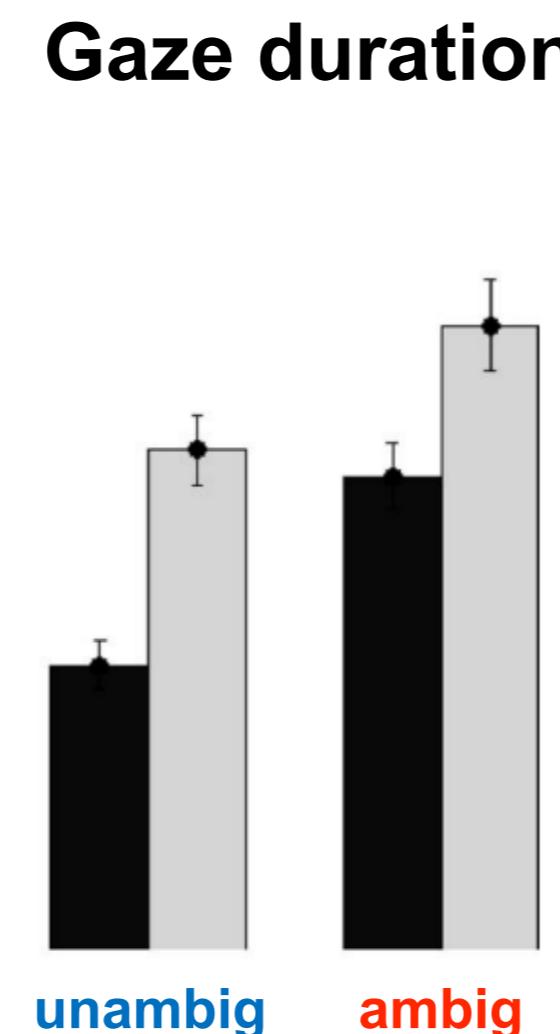
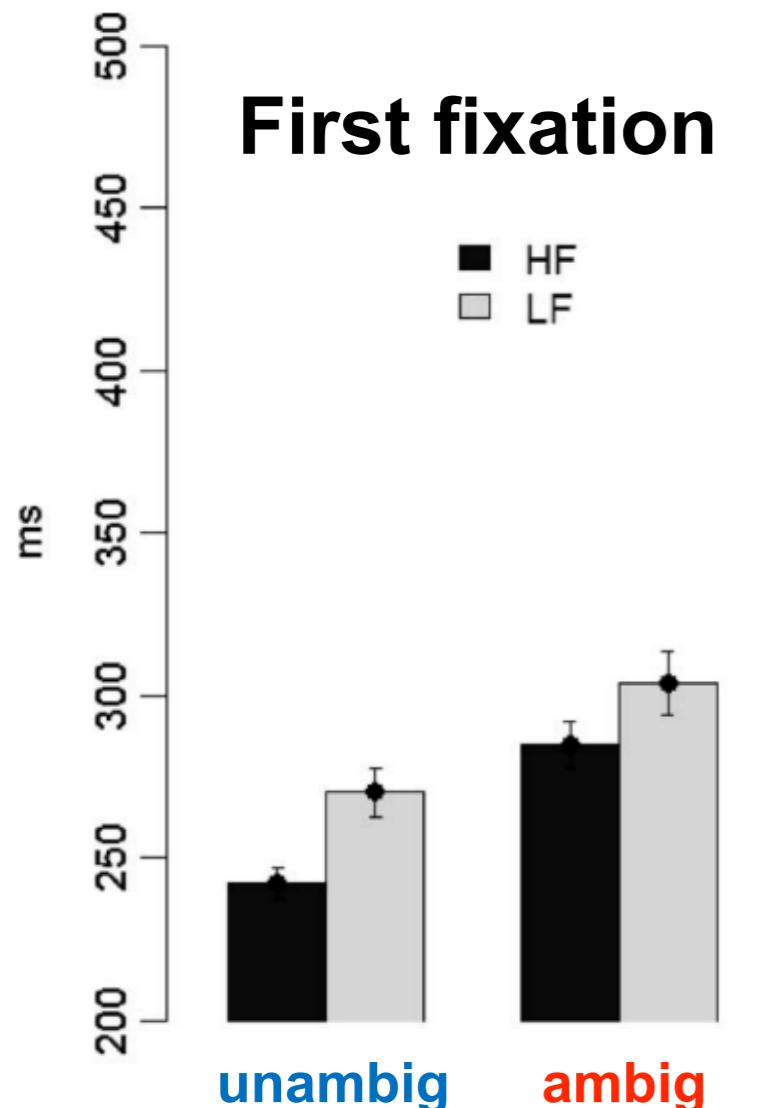


Staub 2011: word frequency & predictability effects

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(unambiguous)

High Frequency
ambled
walked
ambled
Low Frequency



Psycholinguistic methodology (2)

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- A lower-tech method: **self-paced reading** (SPR)

Psycholinguistic methodology (2)

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

Psycholinguistic methodology (2)

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Psycholinguistic methodology (2)

- A lower-tech method: **self-paced reading** (SPR)
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while -----

Psycholinguistic methodology (2)

- A lower-tech method: **self-paced reading** (SPR)
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----- the -----

Psycholinguistic methodology (2)

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

----- clouds -----

Psycholinguistic methodology (2)

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

----- crackled, -----

Psycholinguistic methodology (2)

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

----- above -----

Psycholinguistic methodology (2)

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

----- the -----

Psycholinguistic methodology (2)

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

----- glider -----

Psycholinguistic methodology (2)

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

----- soared -----

Psycholinguistic methodology (2)

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

----- soared -----

- Readers aren't allowed to backtrack

Psycholinguistic methodology (2)

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

----- 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)

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- Another lower-tech method: **the maze**

Psycholinguistic methodology (3)

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

Psycholinguistic methodology (3)

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

F

J

Psycholinguistic methodology (3)

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

The

X-X-X

F

J

Psycholinguistic methodology (3)

- Another lower-tech method: **the maze**
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The

X-X-X

F

J

Psycholinguistic methodology (3)

- Another lower-tech method: **the maze**
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of

dog

F

J

Psycholinguistic methodology (3)

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

of

dog

F

J

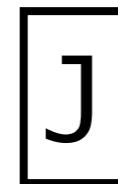
Psycholinguistic methodology (3)

- Another lower-tech method: **the maze**
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pretty



chased



Psycholinguistic methodology (3)

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

pretty

chased

F

J

Psycholinguistic methodology (3)

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

the

F

eat

J

Psycholinguistic methodology (3)

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

the

eat

F

J

Psycholinguistic methodology (3)

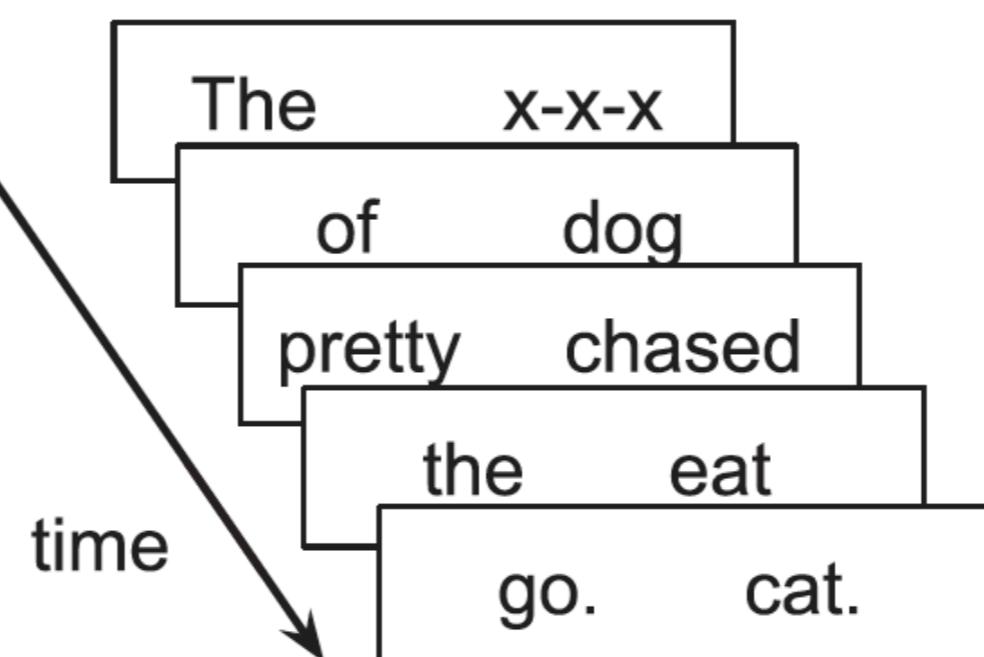
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the

eat

F

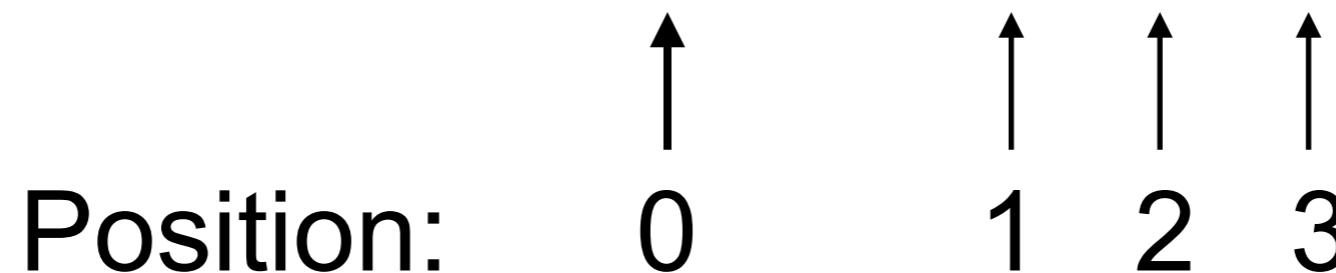
J



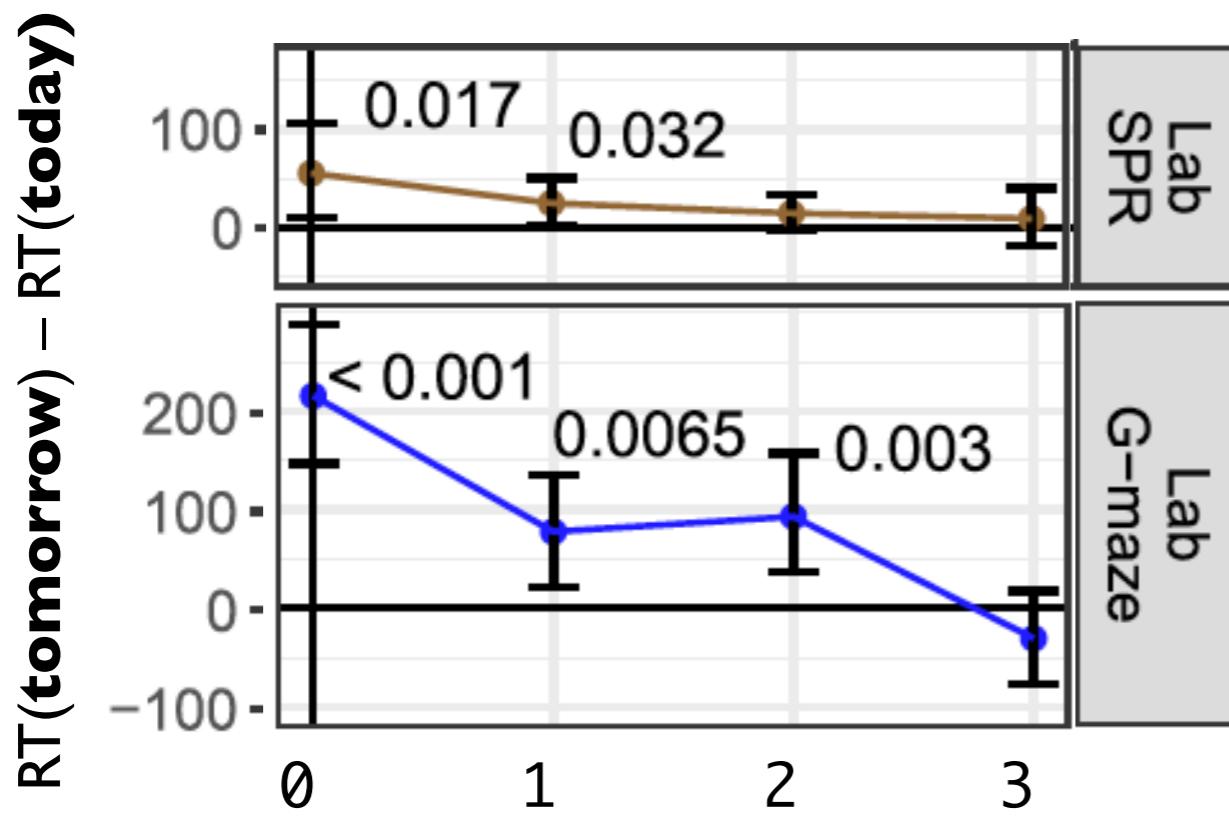
Example SPR and Maze results

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

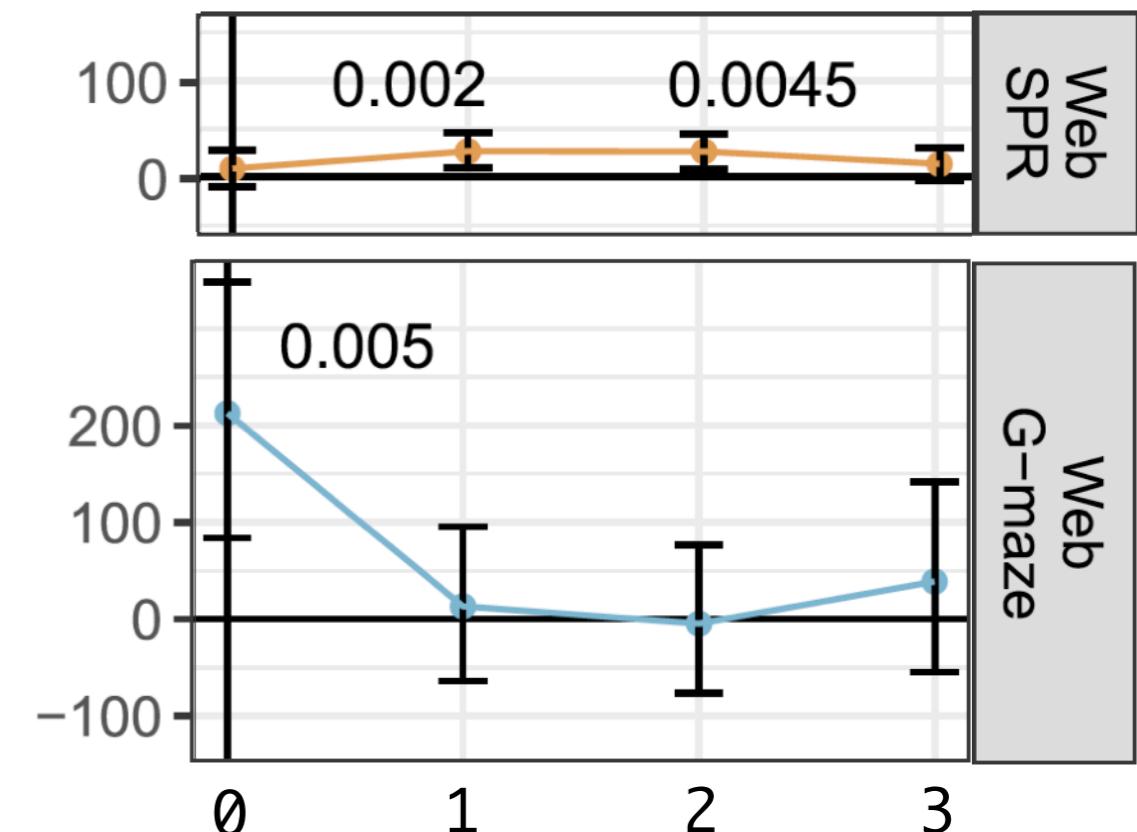
James will fix the car he drove **tomorrow**, but he will need some help.



Results in the lab



Results on the web (Mechanical Turk)



Incrementality, structure, and surprise

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**

Incrementality, structure, and surprise

Is the relative
clause reduced?

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**

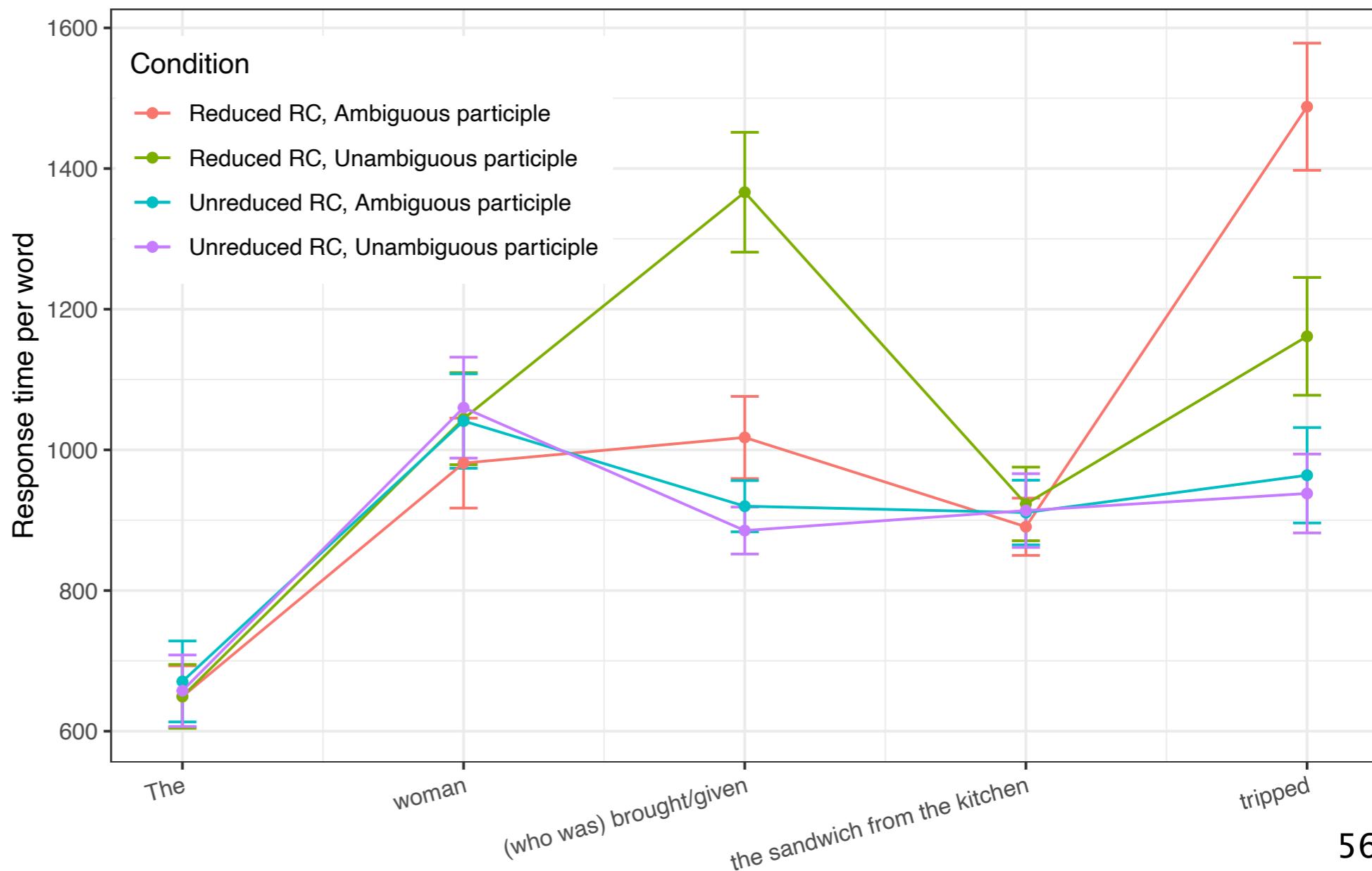
Incrementality, structure, and surprise

		Is the relative clause reduced?	Is the participle part-of-speech ambiguous?
<i>The woman brought the sandwich from the kitchen tripped.</i>		+	+
<i>The woman given the sandwich from the kitchen tripped.</i>		+	-
<i>The woman who was brought the sandwich from the kitchen tripped.</i>		-	+
<i>The woman who was given the sandwich from the kitchen tripped.</i>		-	-
Simple past	Past participle		
bring	brought	brought	
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Incrementality, structure, and surprise

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<i>The woman who was given the sandwich from the kitchen tripped.</i>		-	-

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



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

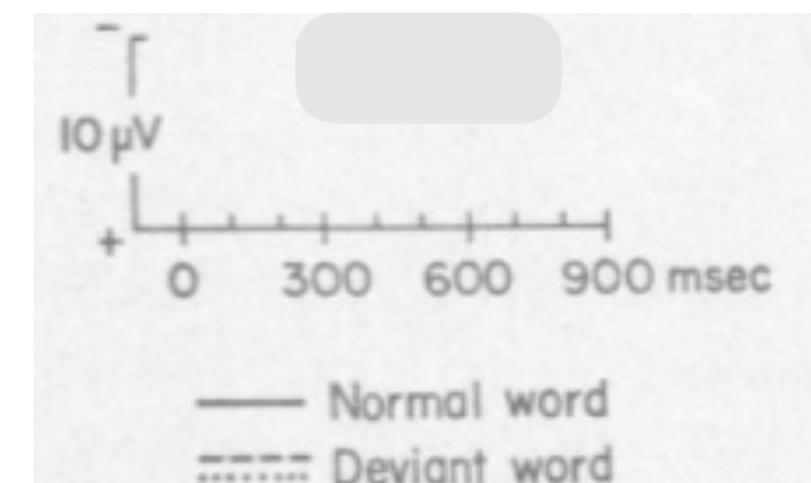
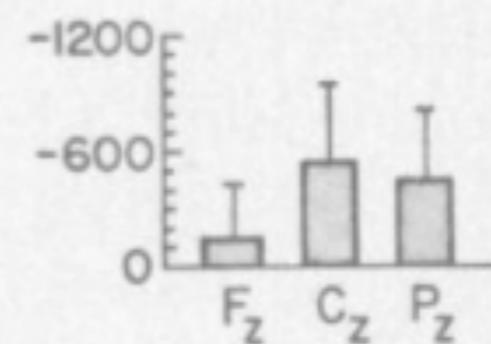
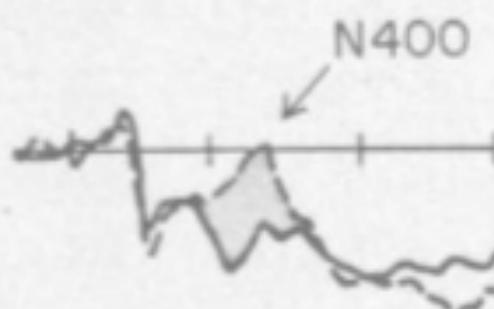
*

Rapid Serial Visual Presentation

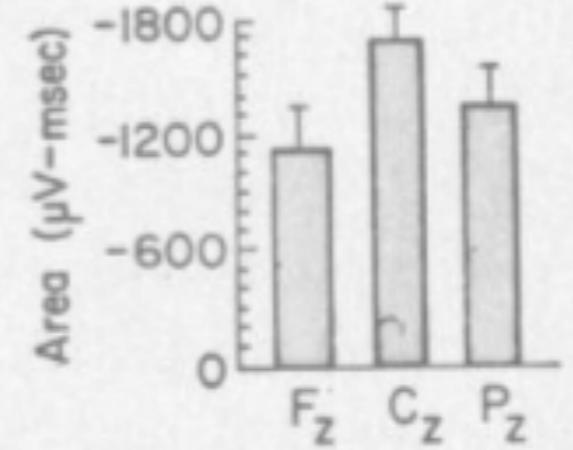
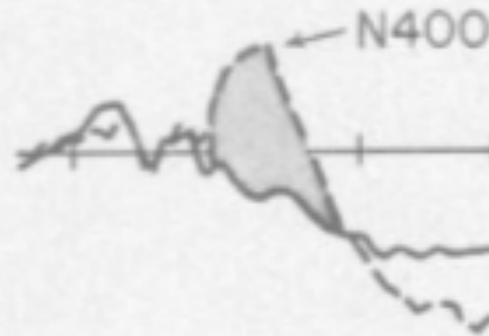
The N400 in language comprehension

- 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)

B Semantic - moderate



C Semantic-strong



(Kutas & Hillyard, 1980, 1984)

The P600 ERP component in language comprehension

The P600 ERP component in language comprehension

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

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.

The P600 ERP component in language comprehension

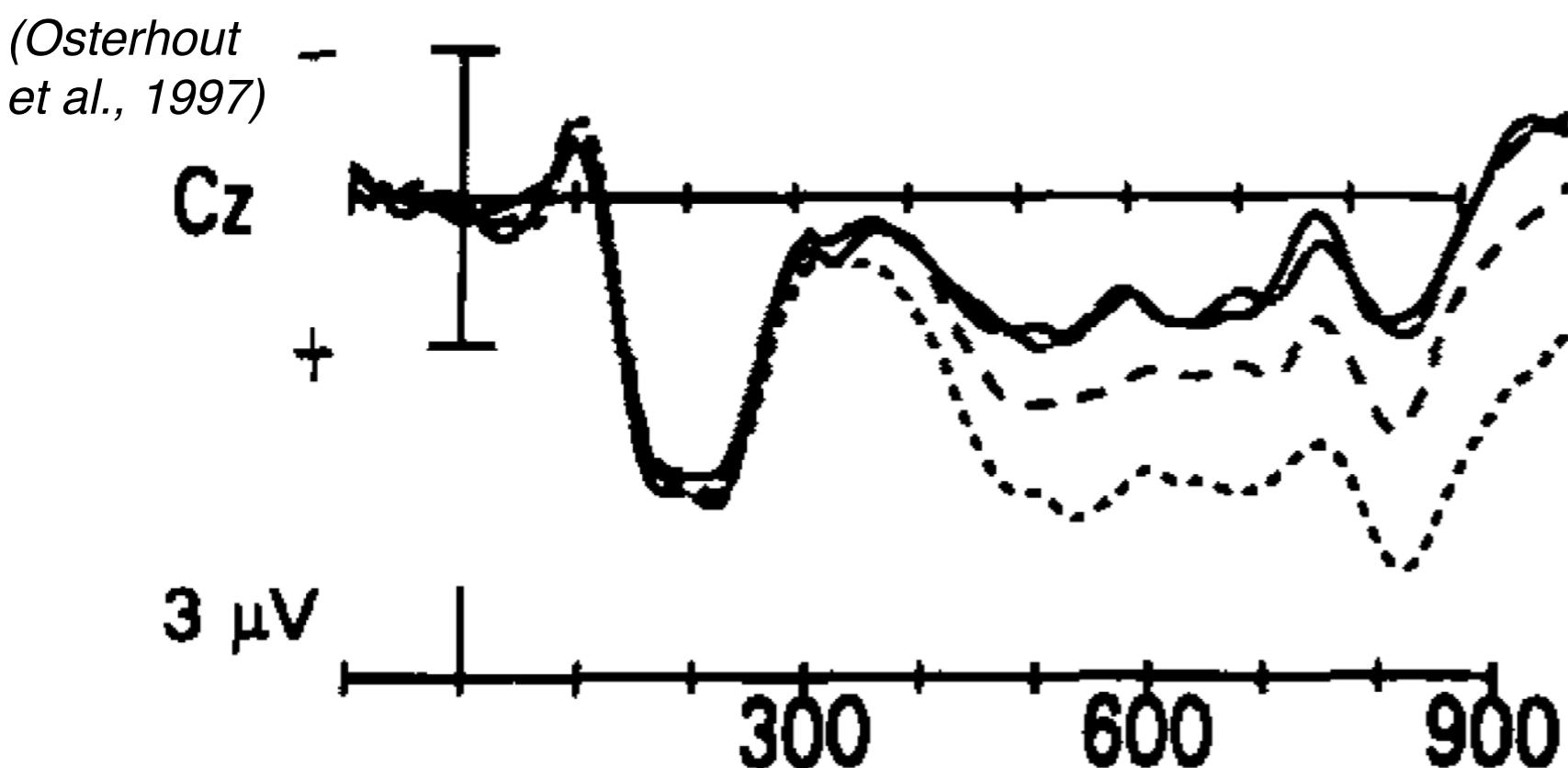
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*The man prepared **herself** for the interview.*

The P600 ERP component in language comprehension

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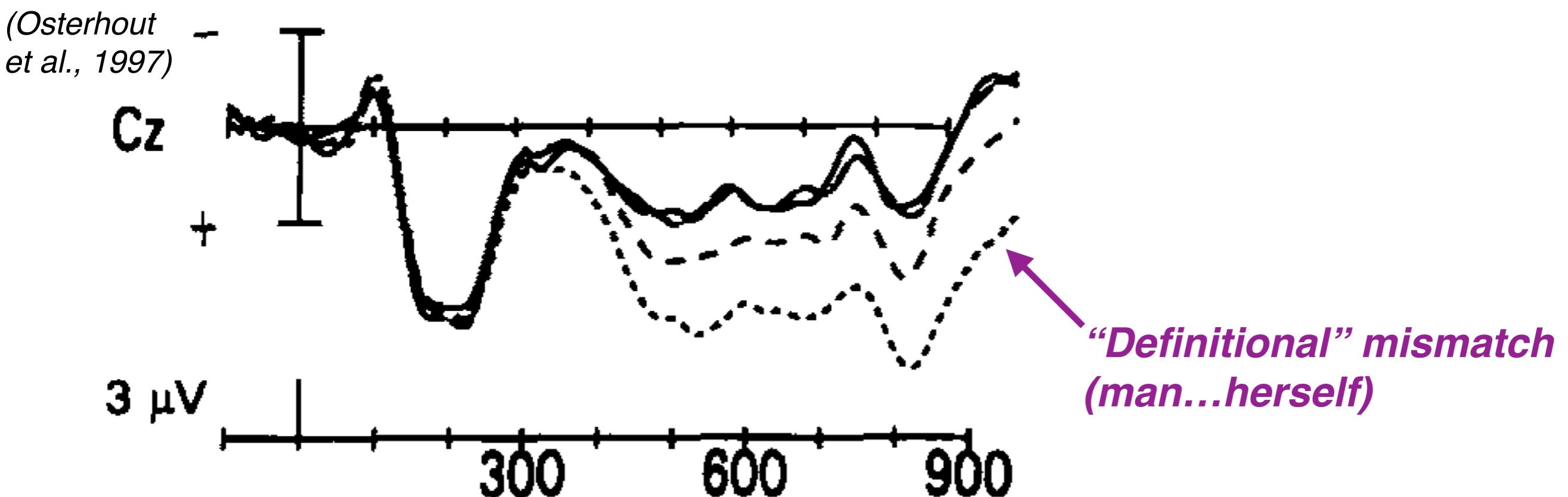
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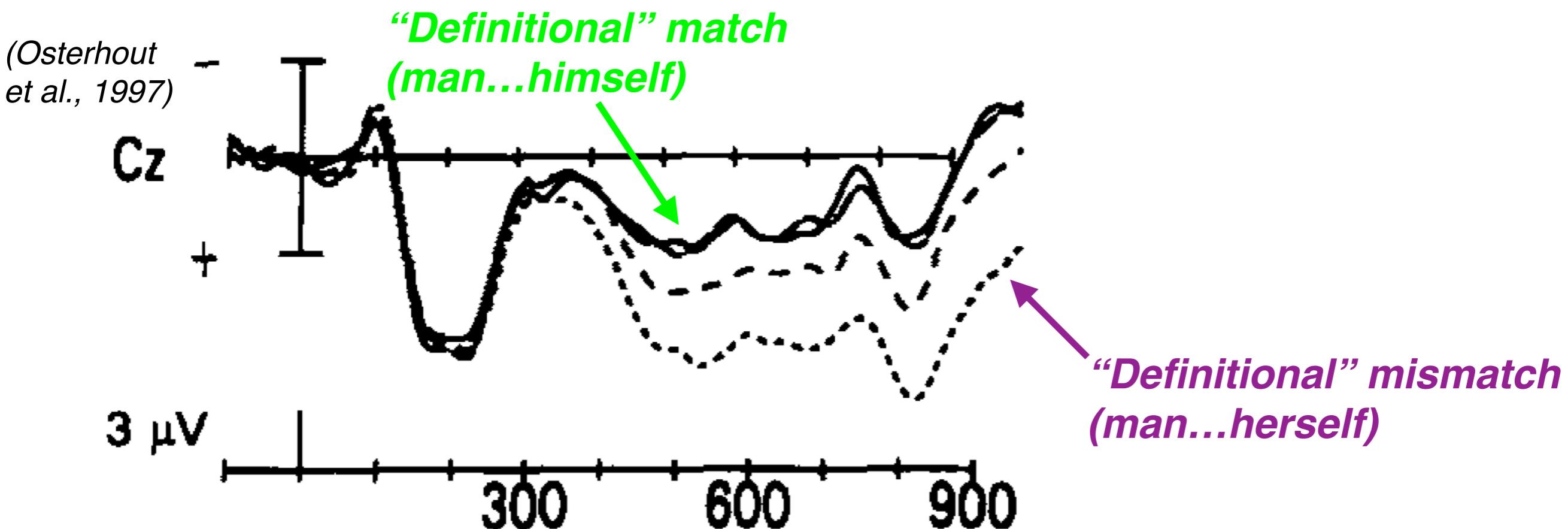
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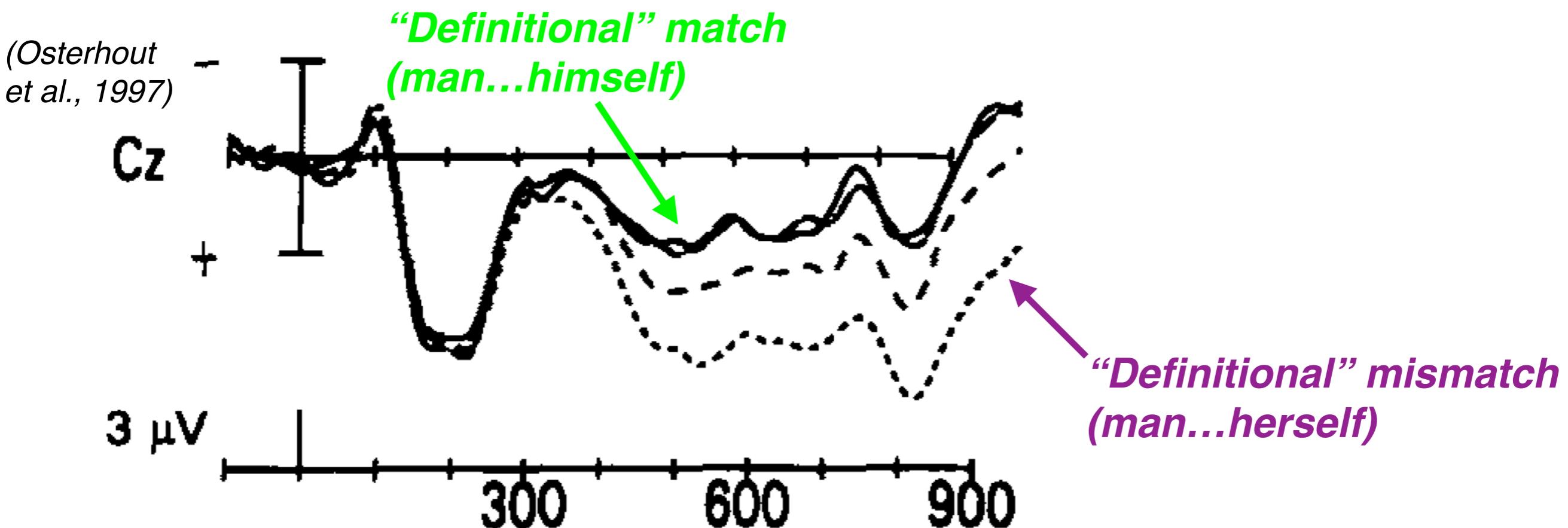
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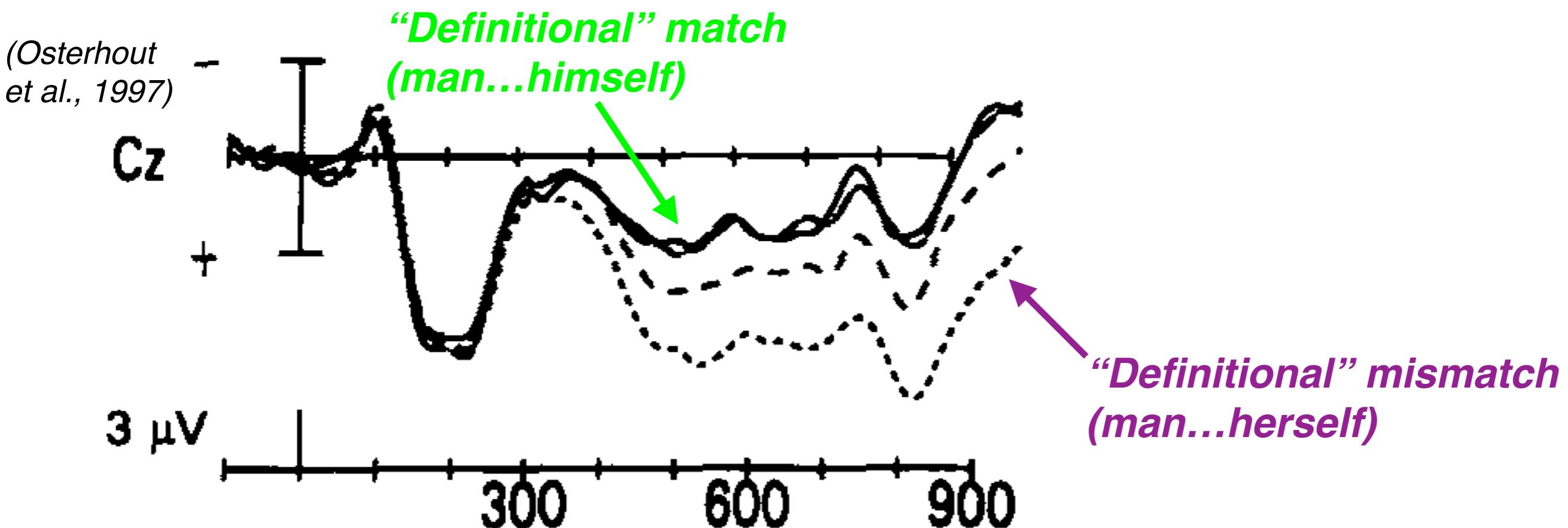
- Mismatches to stereotypical semantic properties induce similar violations

The nurse prepared himself for the operation.

The P600 ERP component in language comprehension

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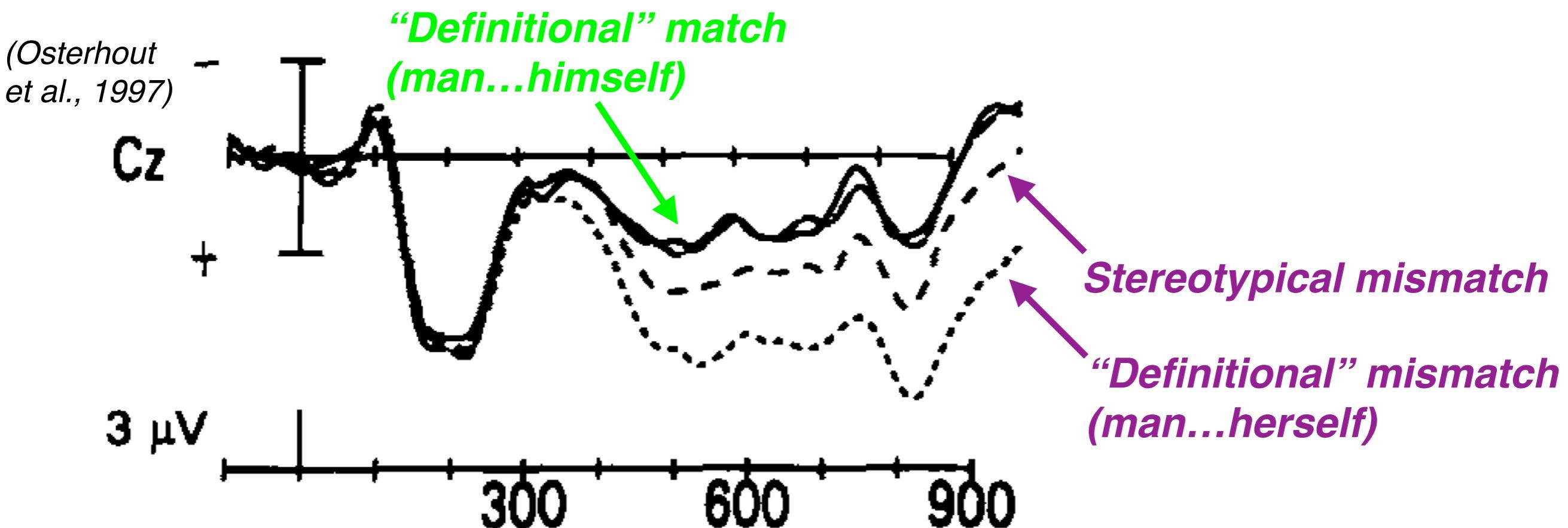
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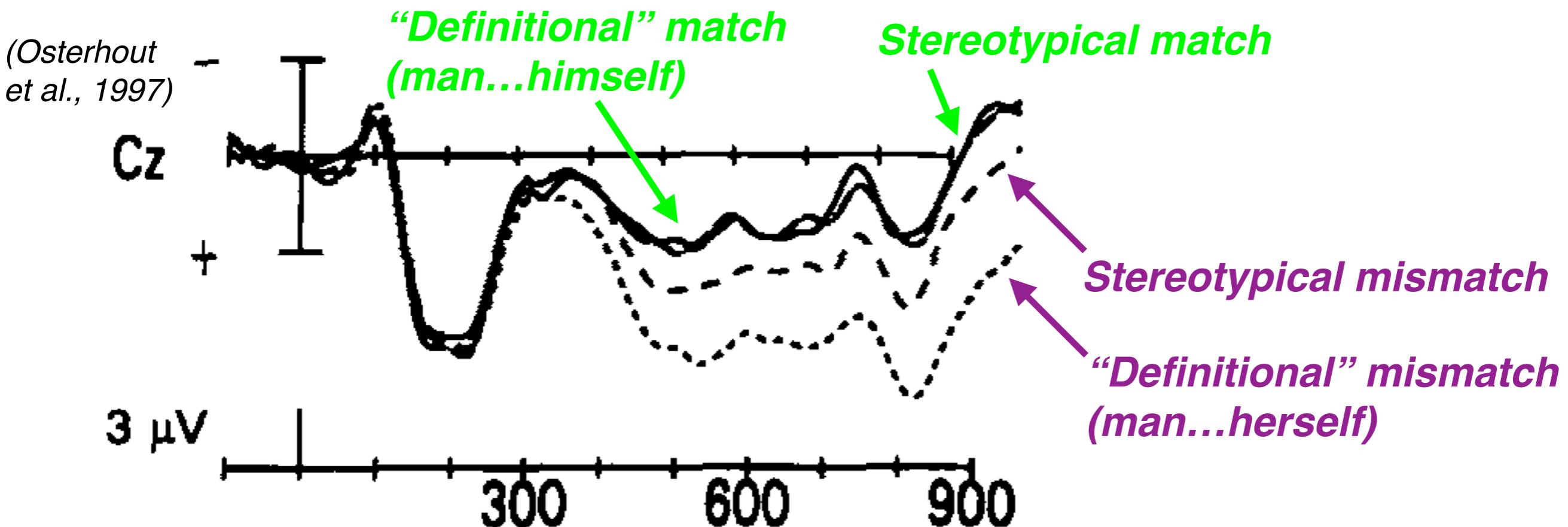
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- Mismatches to *stereotypical* semantic properties induce similar violations

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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



fMRI recordings during comprehension

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Sentences condition

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

Nonwords condition

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

fMRI recordings during comprehension

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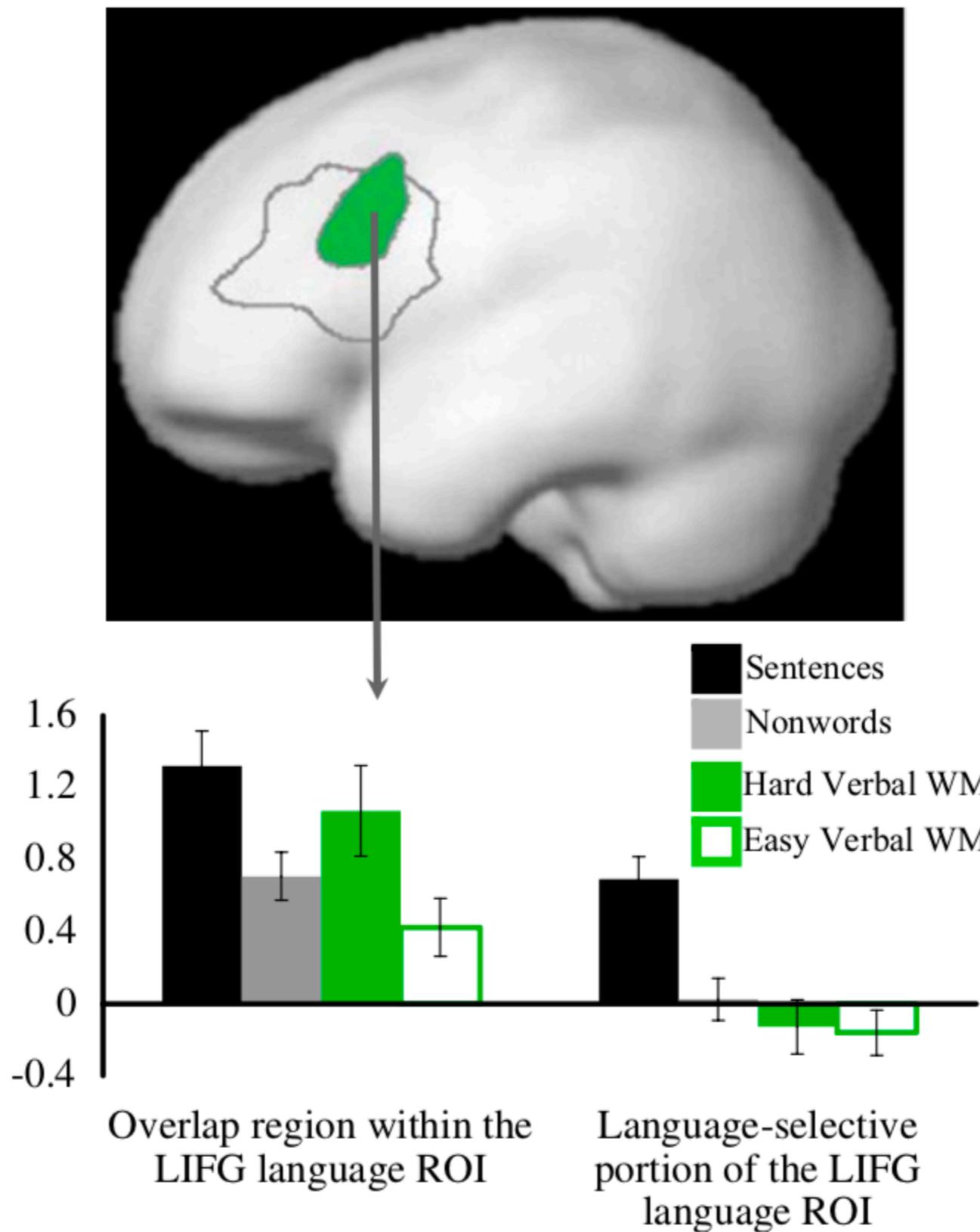
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-----	--------	------	----	------	-----	-----	---------	---	-----------------	---

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

Response	Feedback
+ 36241853 36248153	✓/✗ +

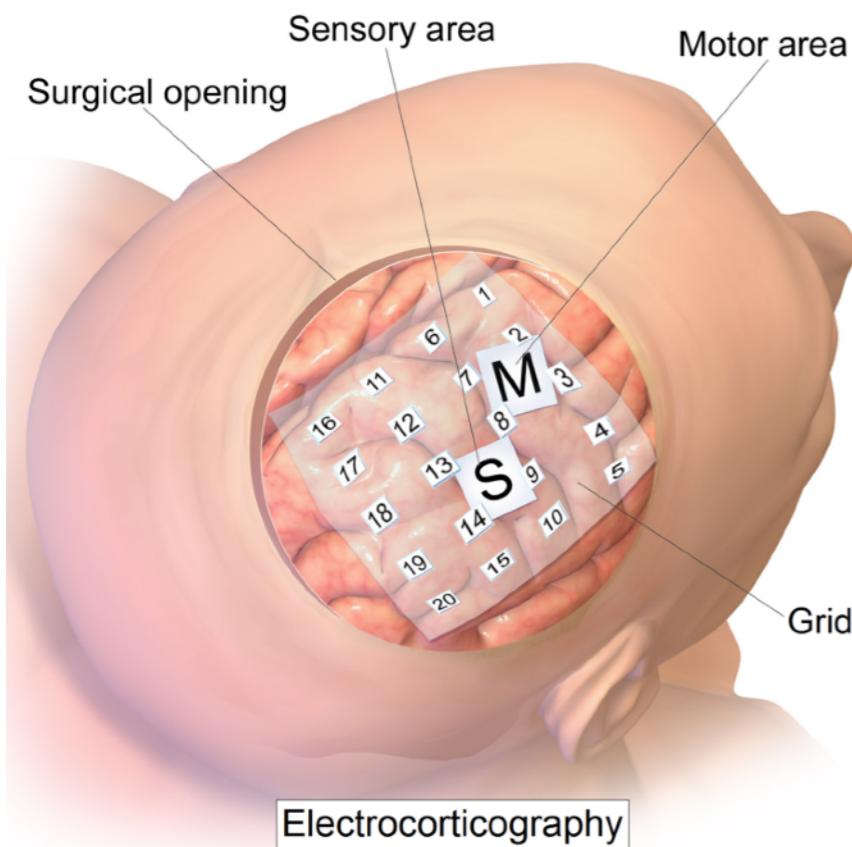
Functional brain specificity for language

Language and Verbal WM

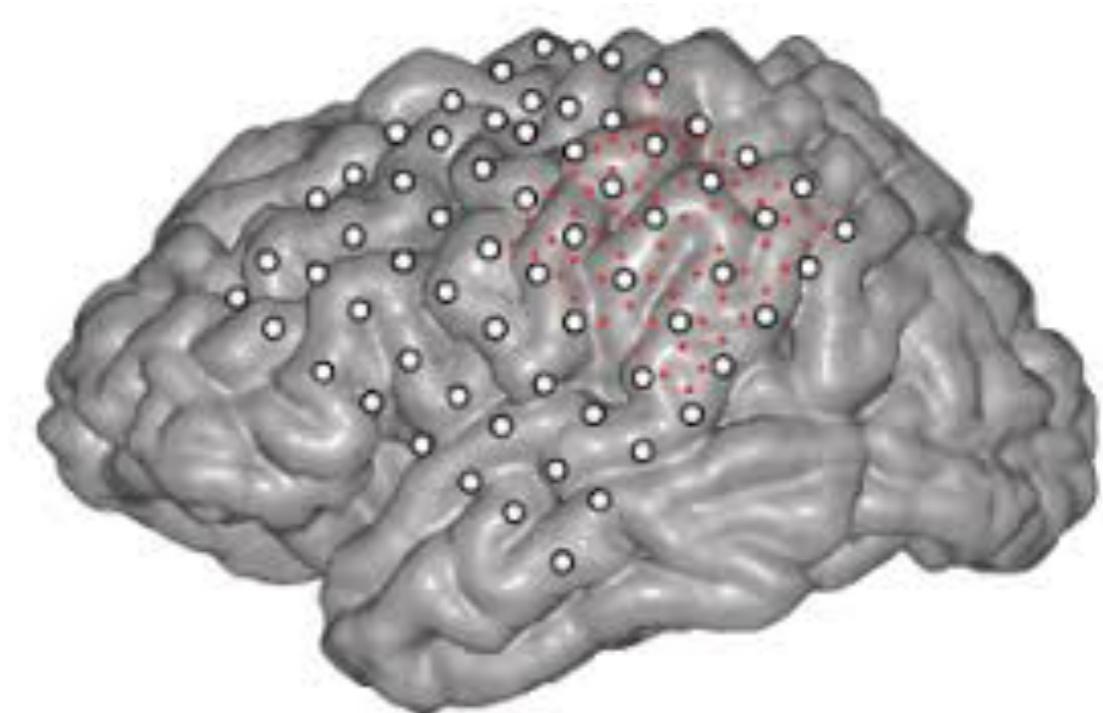


Electrocorticography

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



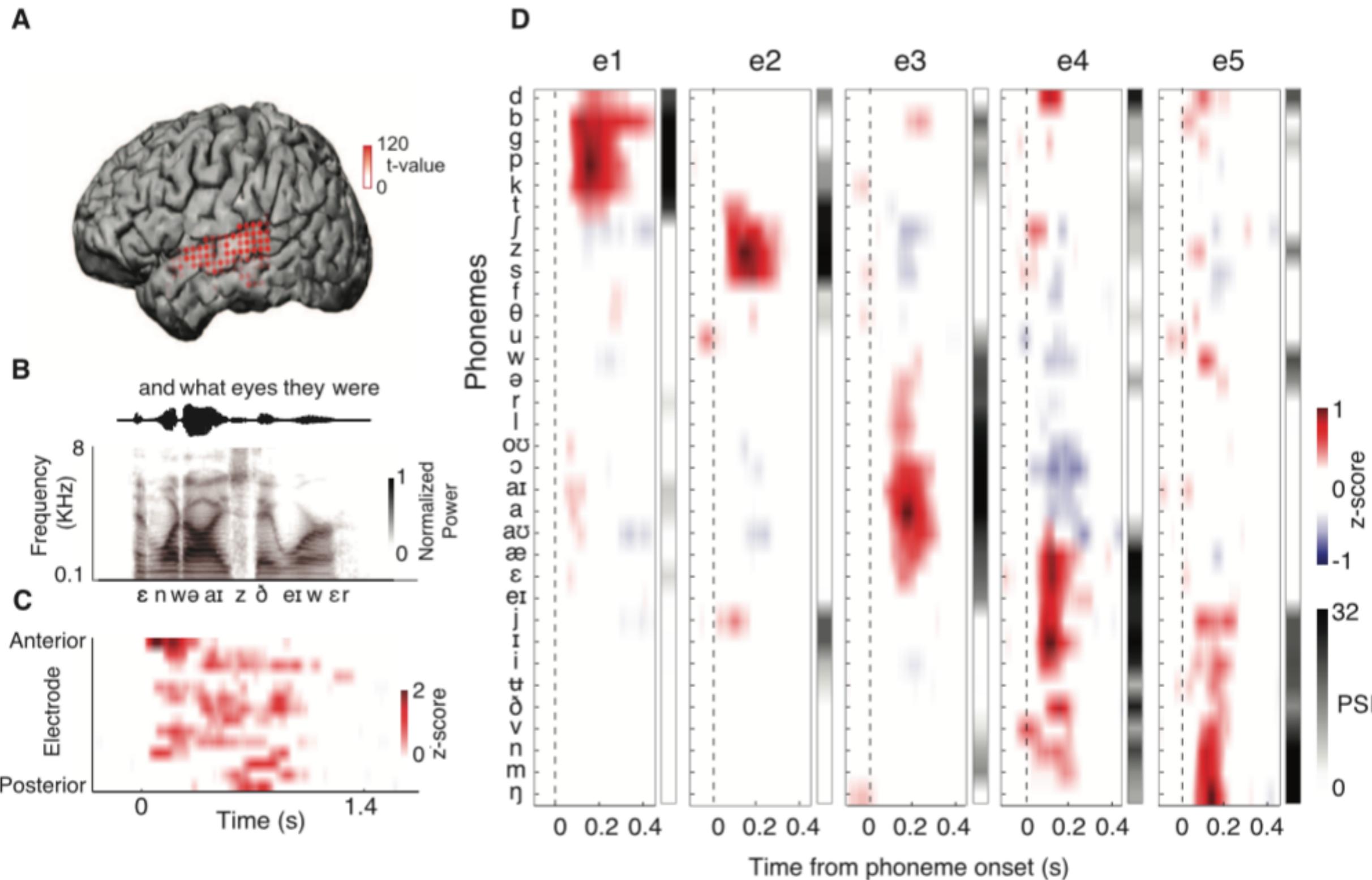
[https://commons.wikimedia.org/wiki/
File:Intracranial_electrode_grid_for_electrocorticography.png](https://commons.wikimedia.org/wiki/File:Intracranial_electrode_grid_for_electrocorticography.png)



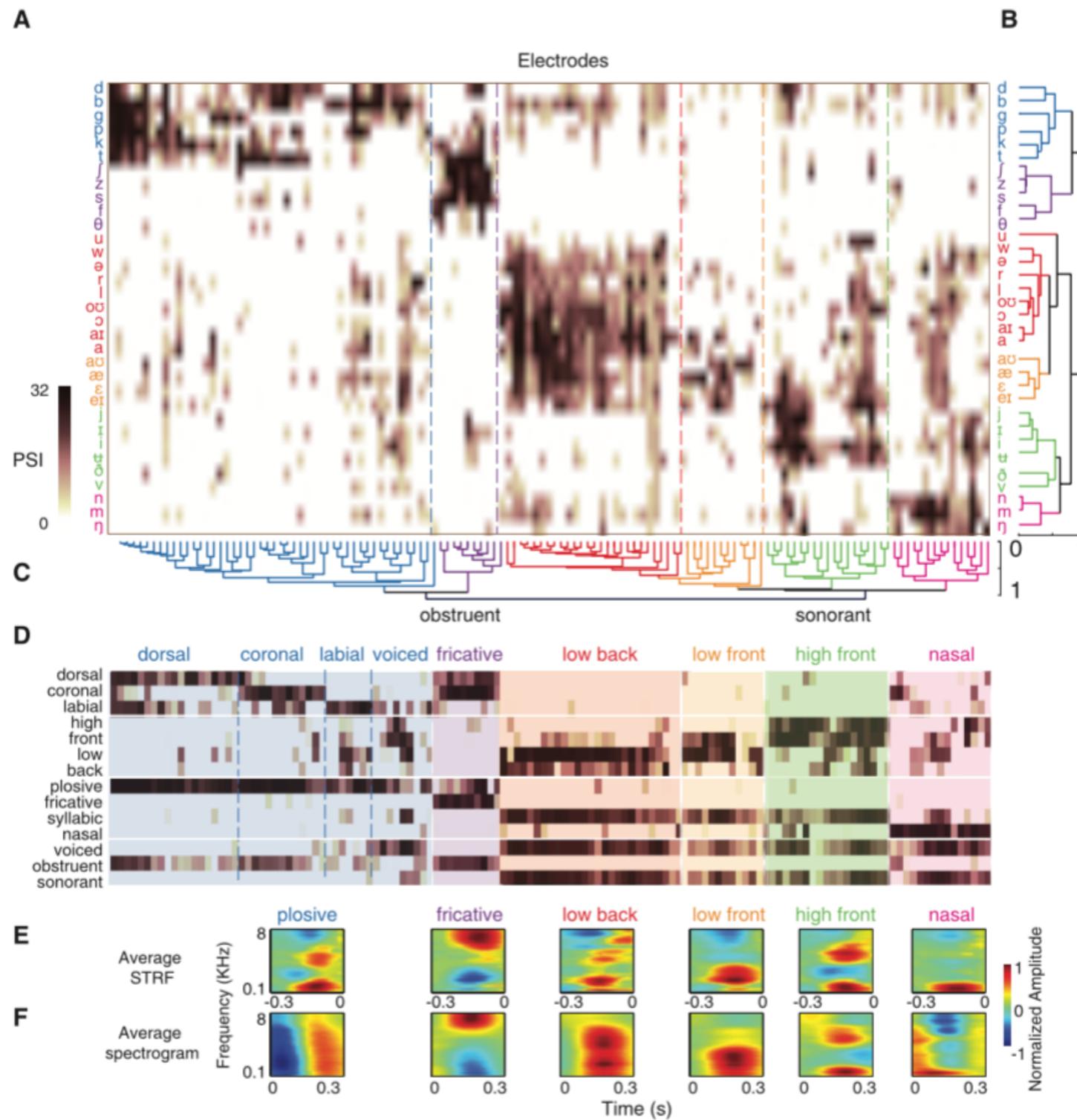
http://med.stanford.edu/neurosurgery/research/NPTL/research2/_jcr_content/main/panel_builder/panel_0/text_image.img.620.high.png

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

Neural phonemic representations



Neural consonant representations



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

Quantifying probabilistic online processing difficulty

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

$$\begin{aligned}\text{Surprisal}(w_i) &\equiv \log \frac{1}{P(w_i|\text{CONTEXT})} \\ &\left[\approx \log \frac{1}{P(w_i|w_1 \dots w_{i-1})} \right]\end{aligned}$$

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- 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)

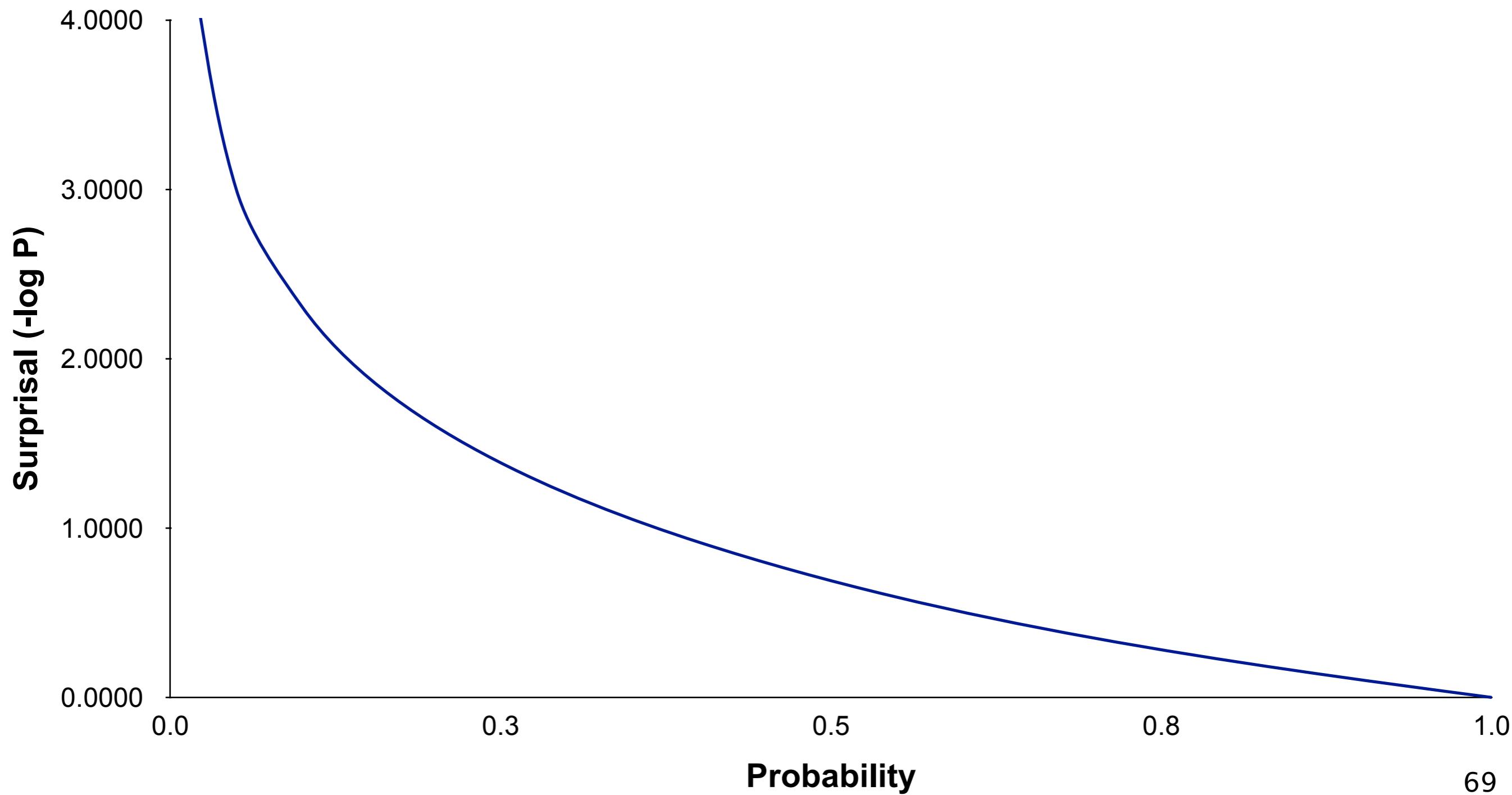
Quantifying probabilistic online processing difficulty

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

$$\begin{aligned}\text{Surprisal}(w_i) &\equiv \log \frac{1}{P(w_i|\text{CONTEXT})} \\ &\left[\approx \log \frac{1}{P(w_i|w_1 \dots w_{i-1})} \right]\end{aligned}$$

- 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*

The surprisal graph



Estimating probability/time curve shape

Estimating probability/time curve shape

- As a proxy for “processing difficulty,” reading time in two different methods: self-paced reading & eye-tracking

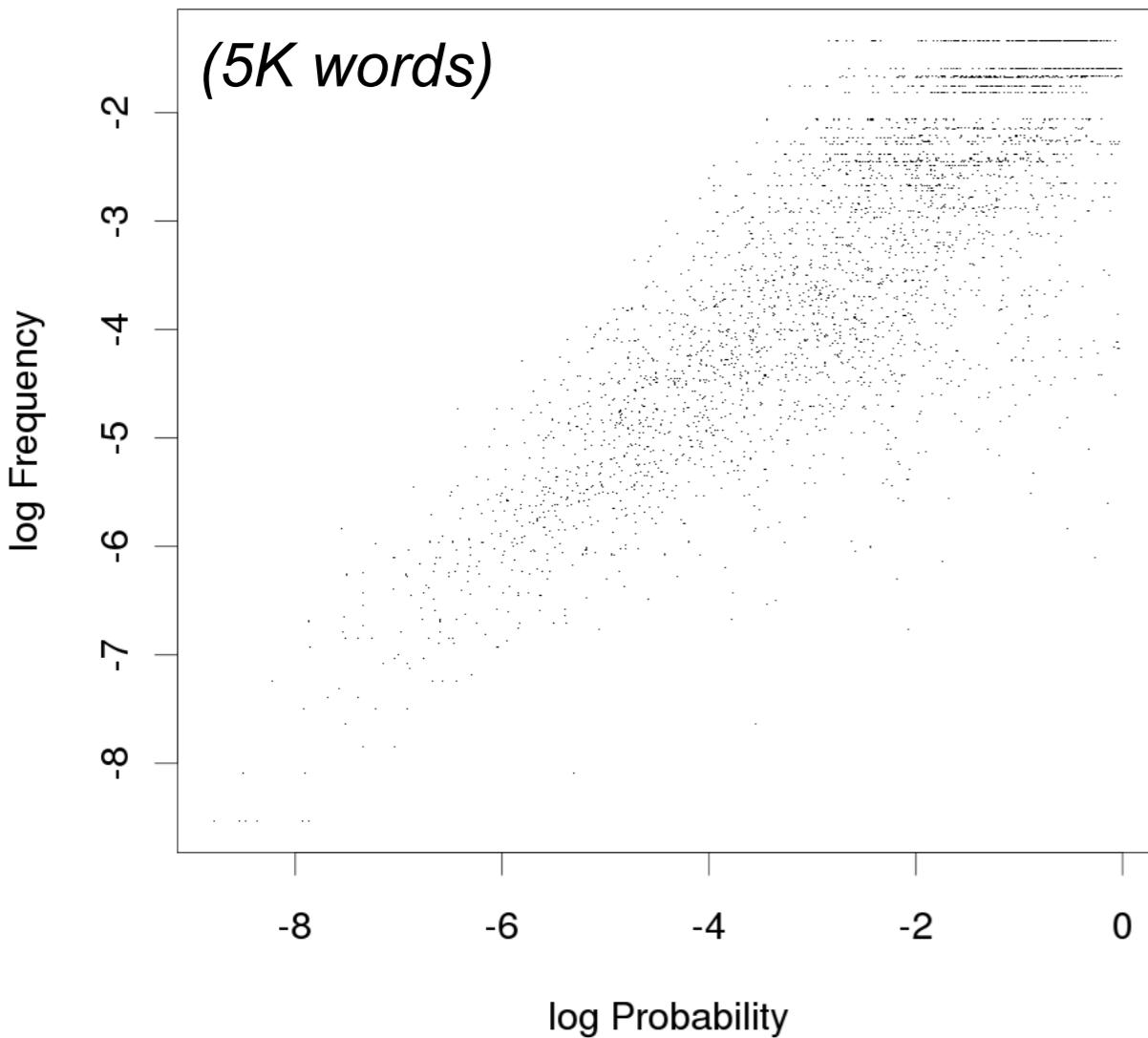
Estimating probability/time curve shape

- 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

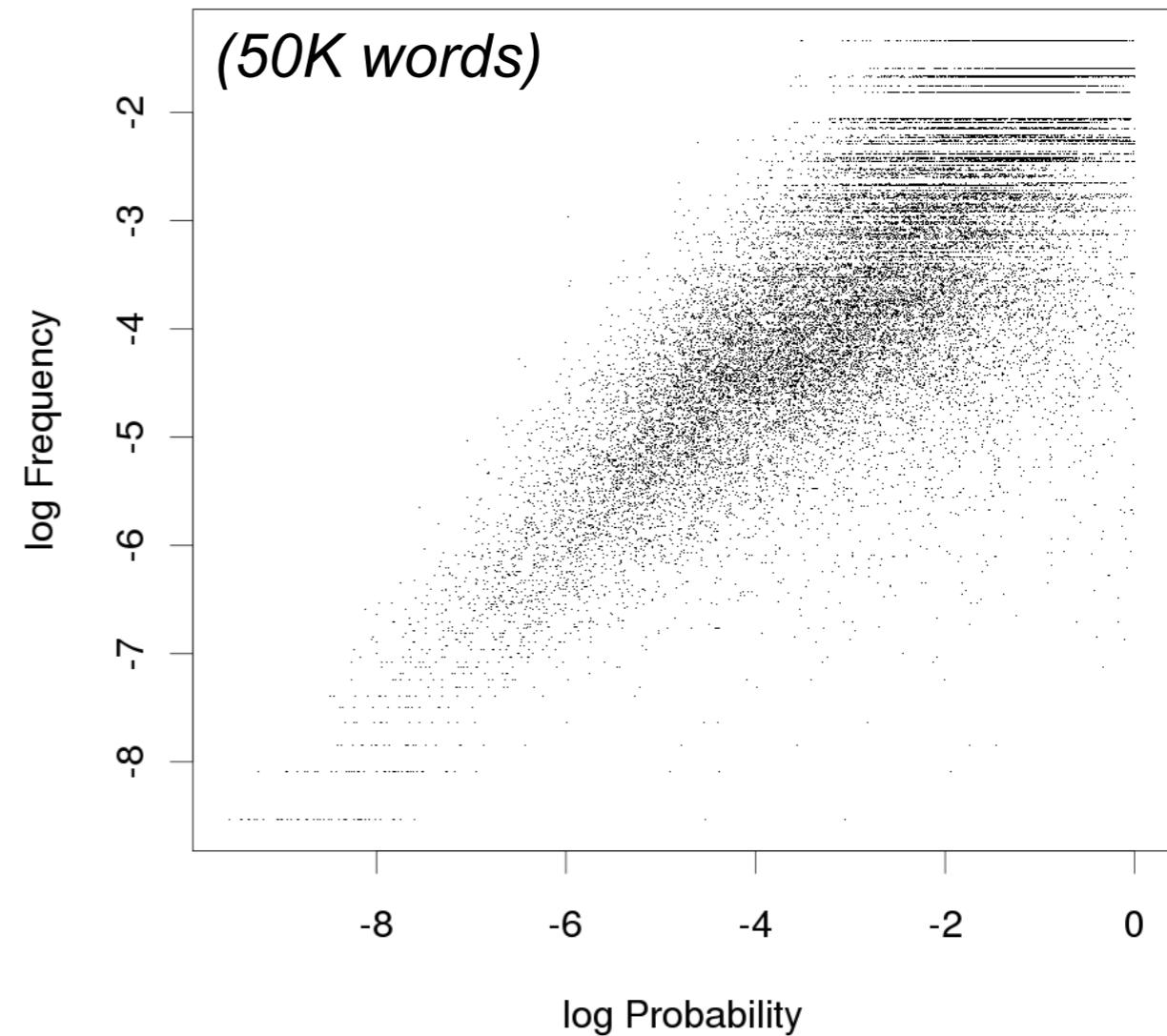
Estimating probability/time curve shape

- As a proxy for “processing difficulty,” reading time in two different methods: self-paced reading & eye-tracking
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Brown data availability



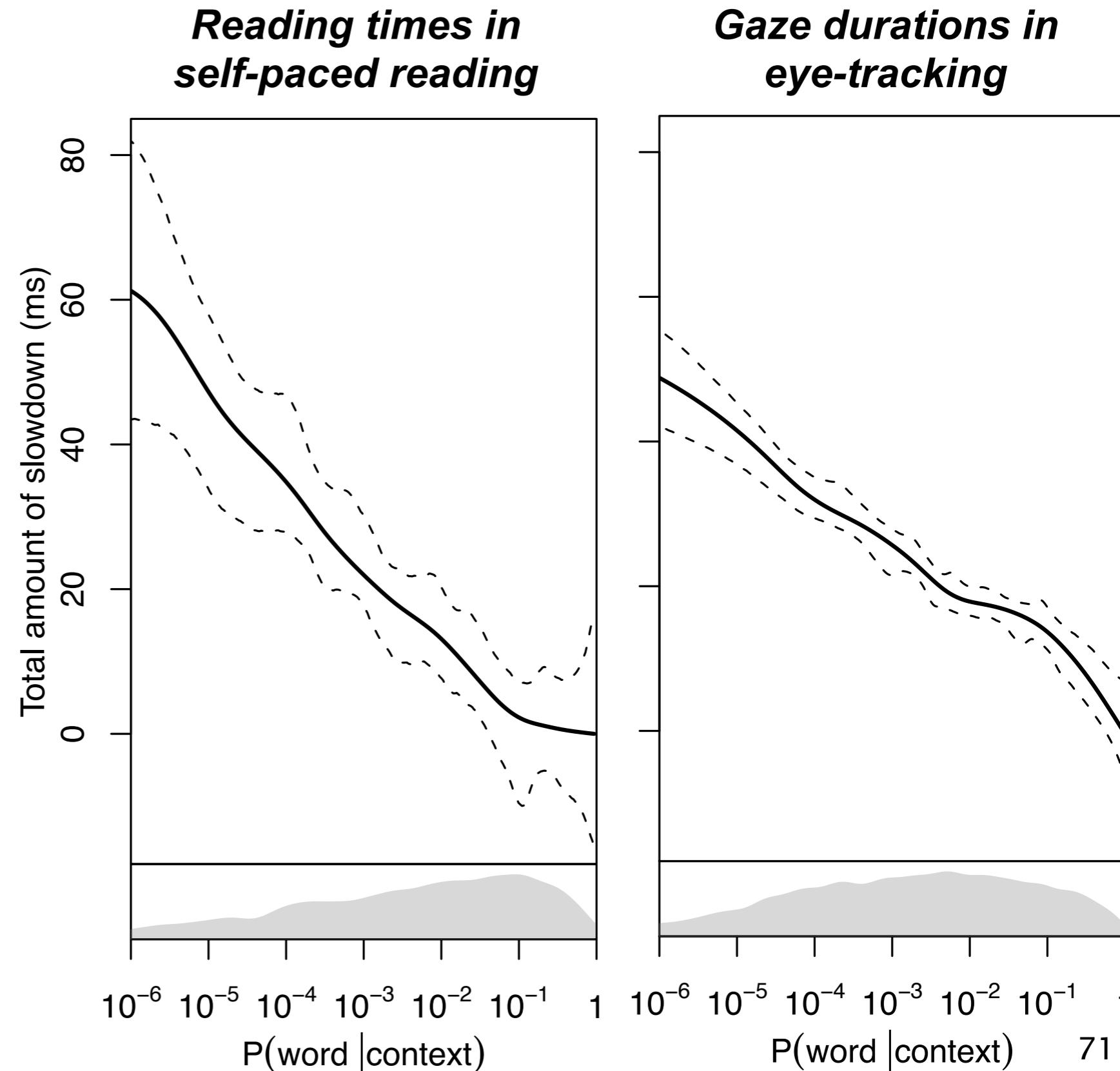
Dundee data availability



Estimating probability/time curve shape

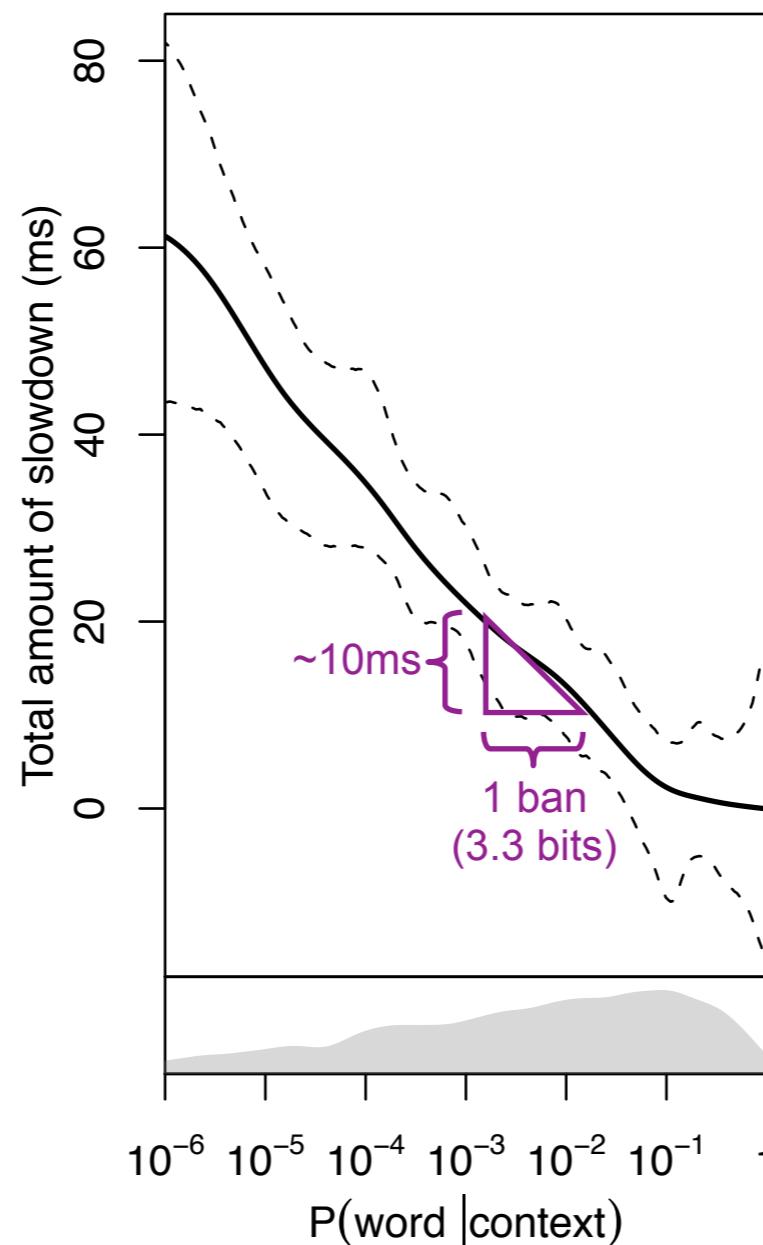
- Generalized additive model regression: total contribution of word (trigram) probability to RT near-linear over 6 orders of magnitude!

(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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