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

Roger Levy

9.19: Computational Psycholinguistics

27 September 2023

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

Acceptability judgments

(examples from Adger, 2003; ratings from Lau et al., 2017)

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- On a scale of 1 (worst) to 4 (best), how good does each of these sentences sound?
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  - She tried to leave.

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- A simple but high-sensitivity experimental method!
- Theoretically, most commonly used to get at the ***grammaticality status*** of a sentence
- But, they are also generally understood to reflect other factors

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Incrementality, structure, and surprise

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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

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

Incrementality, structure, and surprise

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who was

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

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	Simple past	Past participle
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Meaning can help us avoid surprise, too:

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

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Behavioral

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Neural

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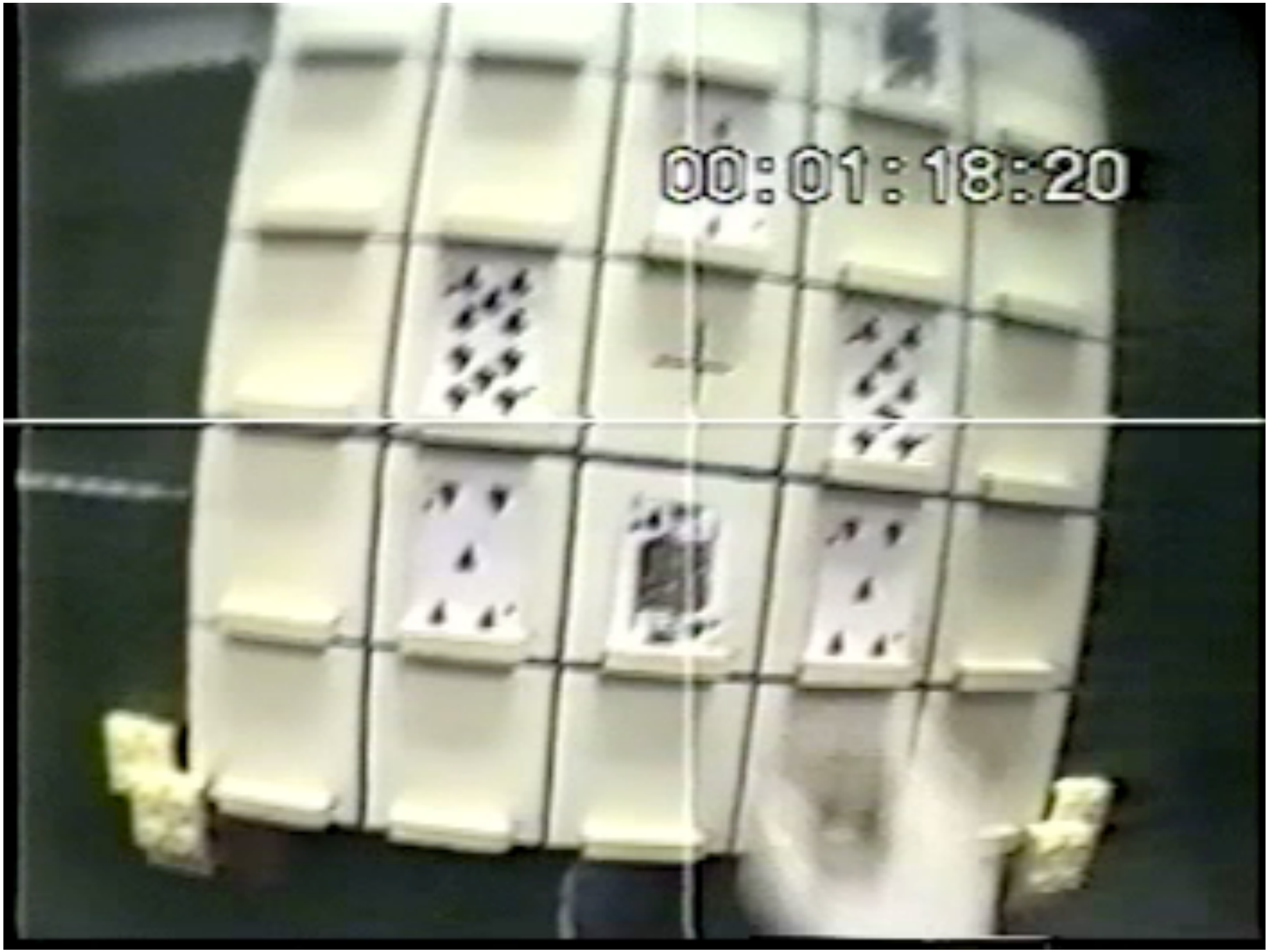

(Video courtesy of Mike Tanenhaus)

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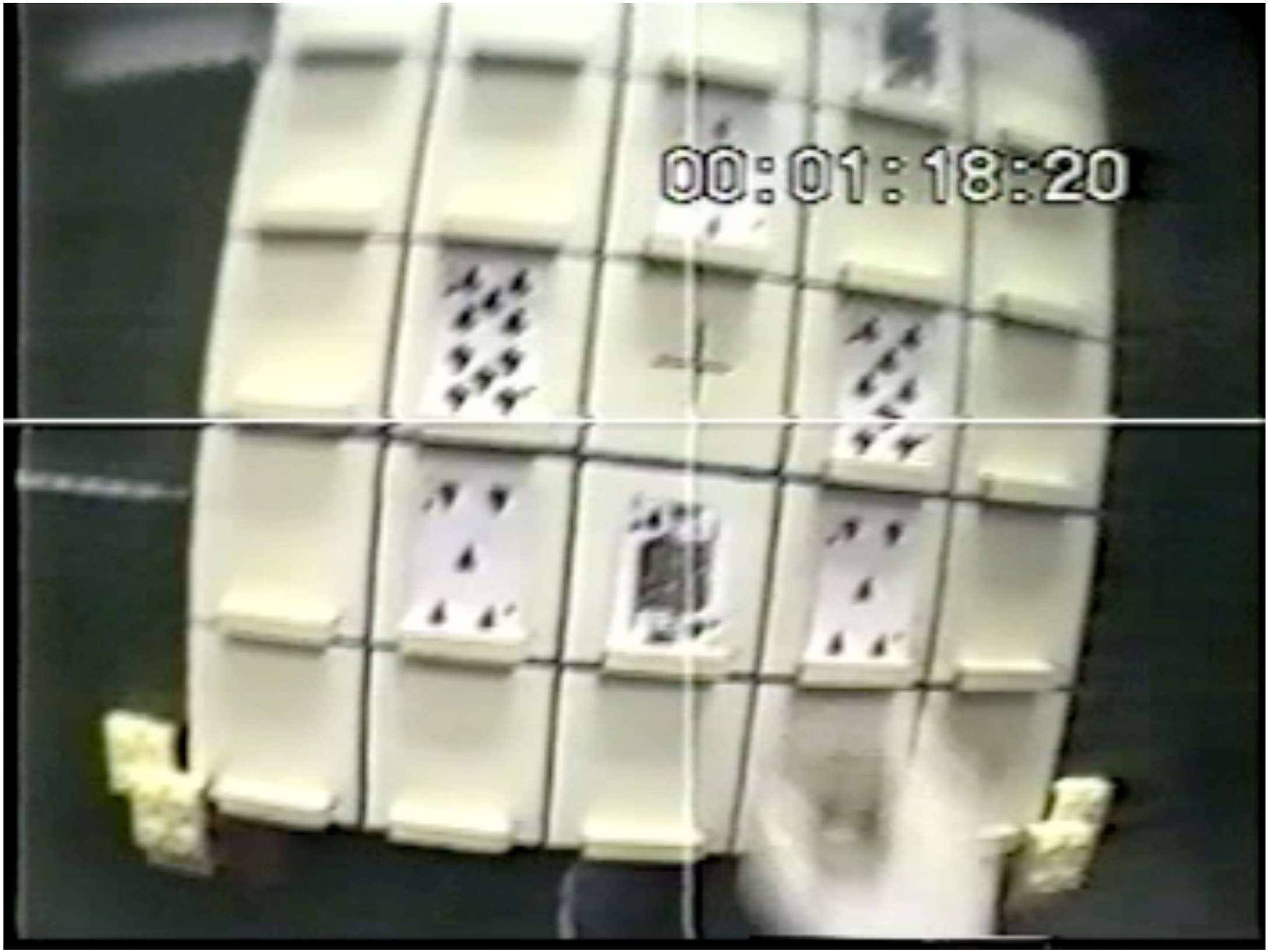

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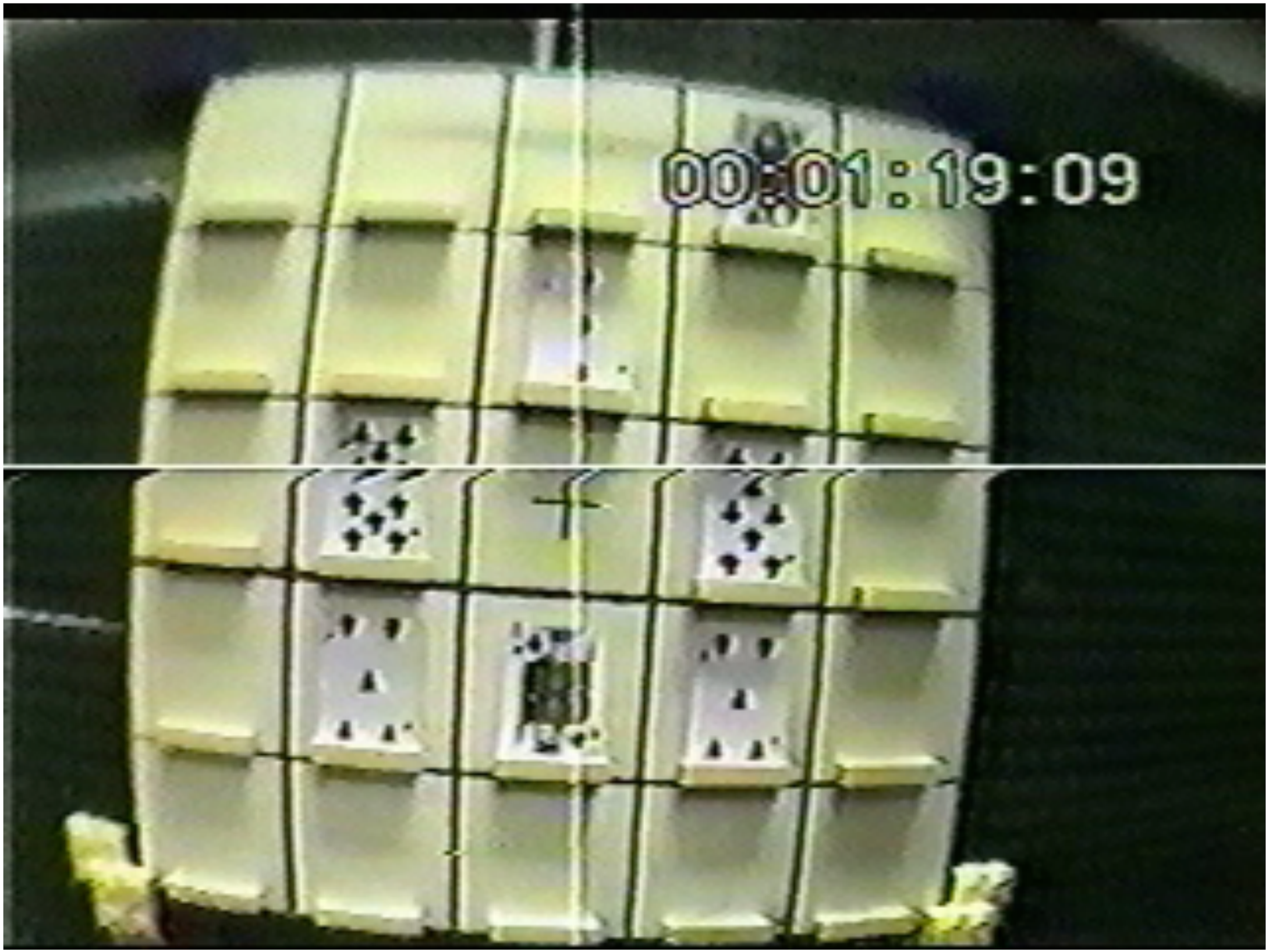

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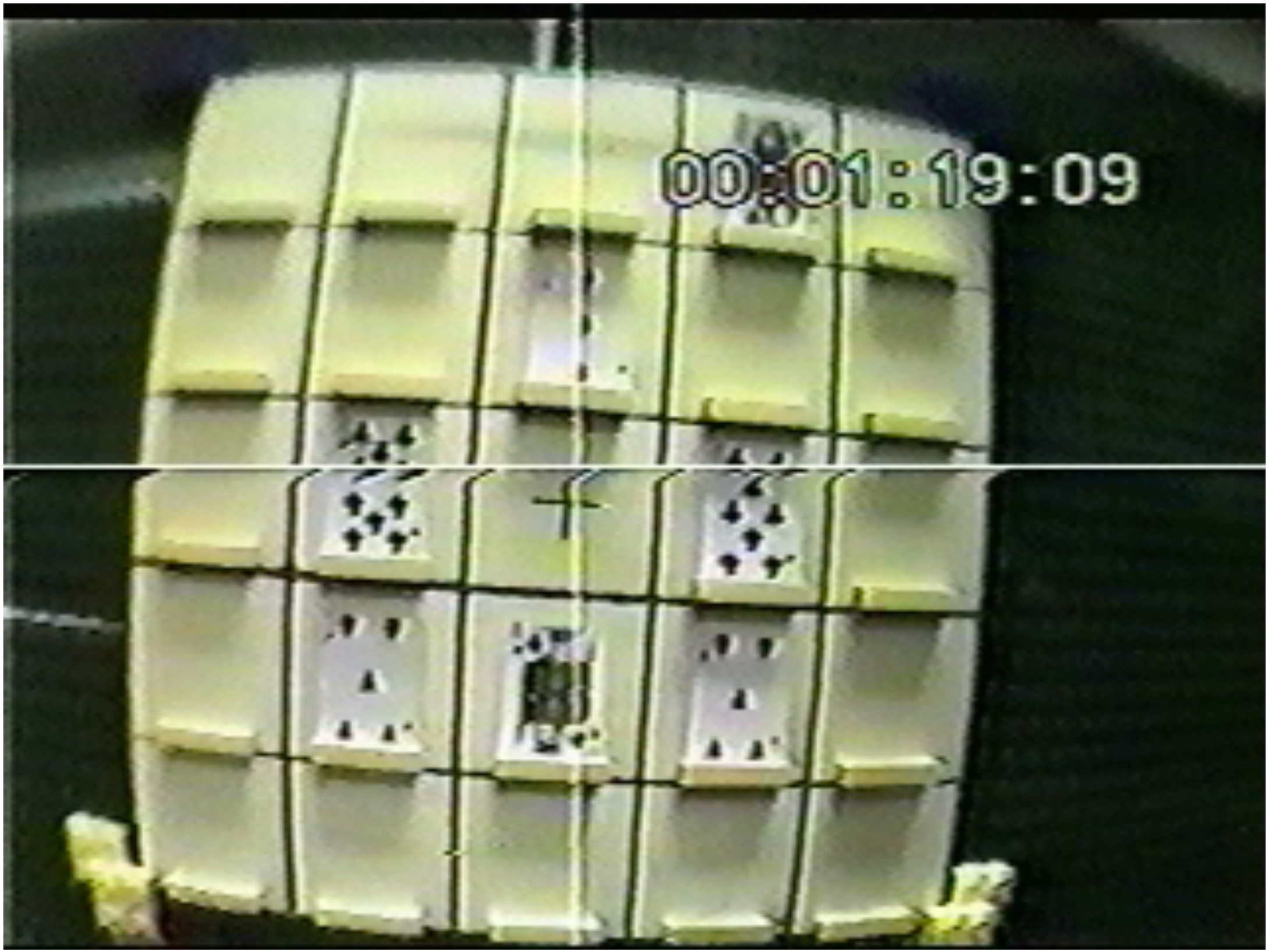

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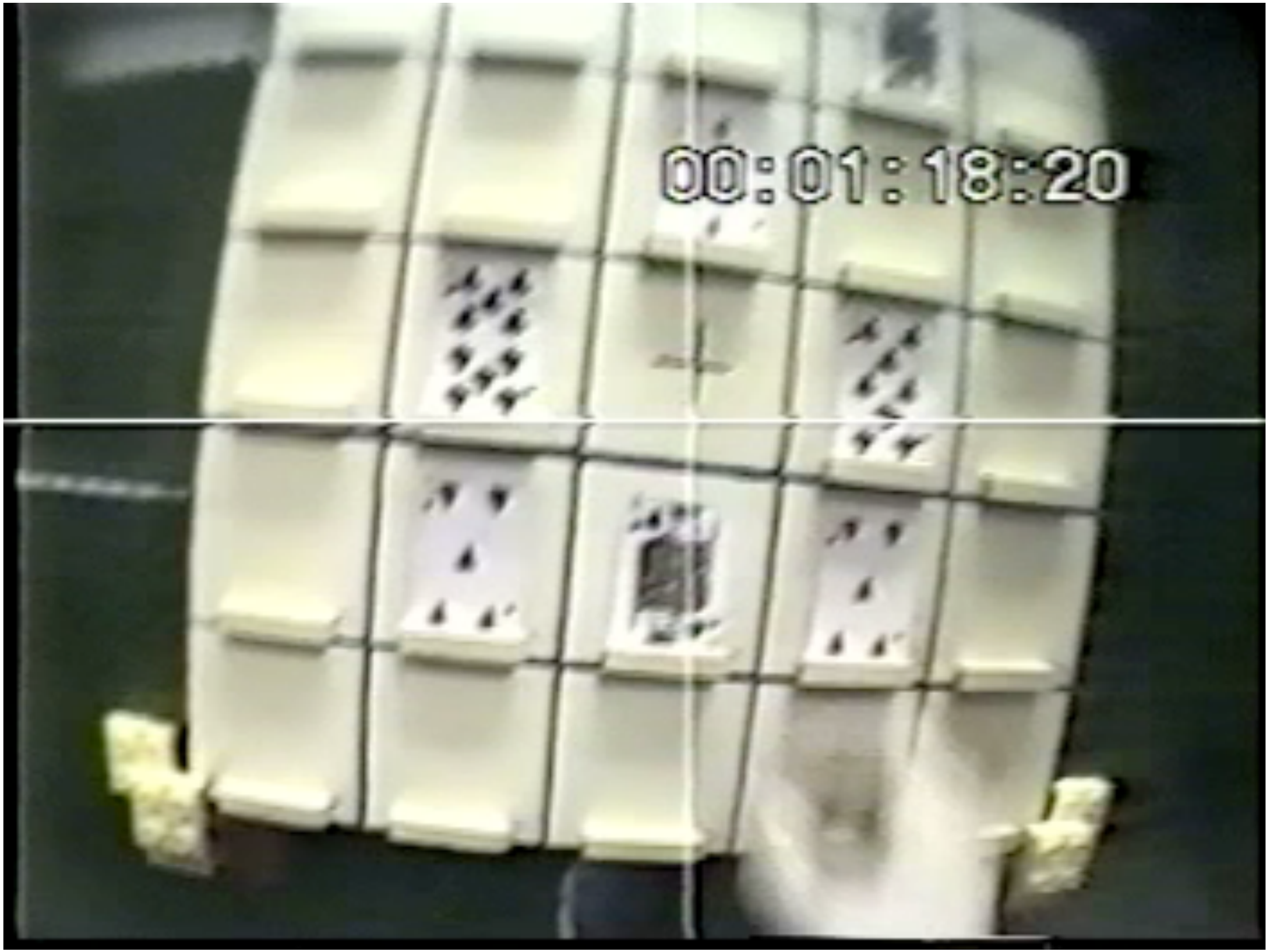

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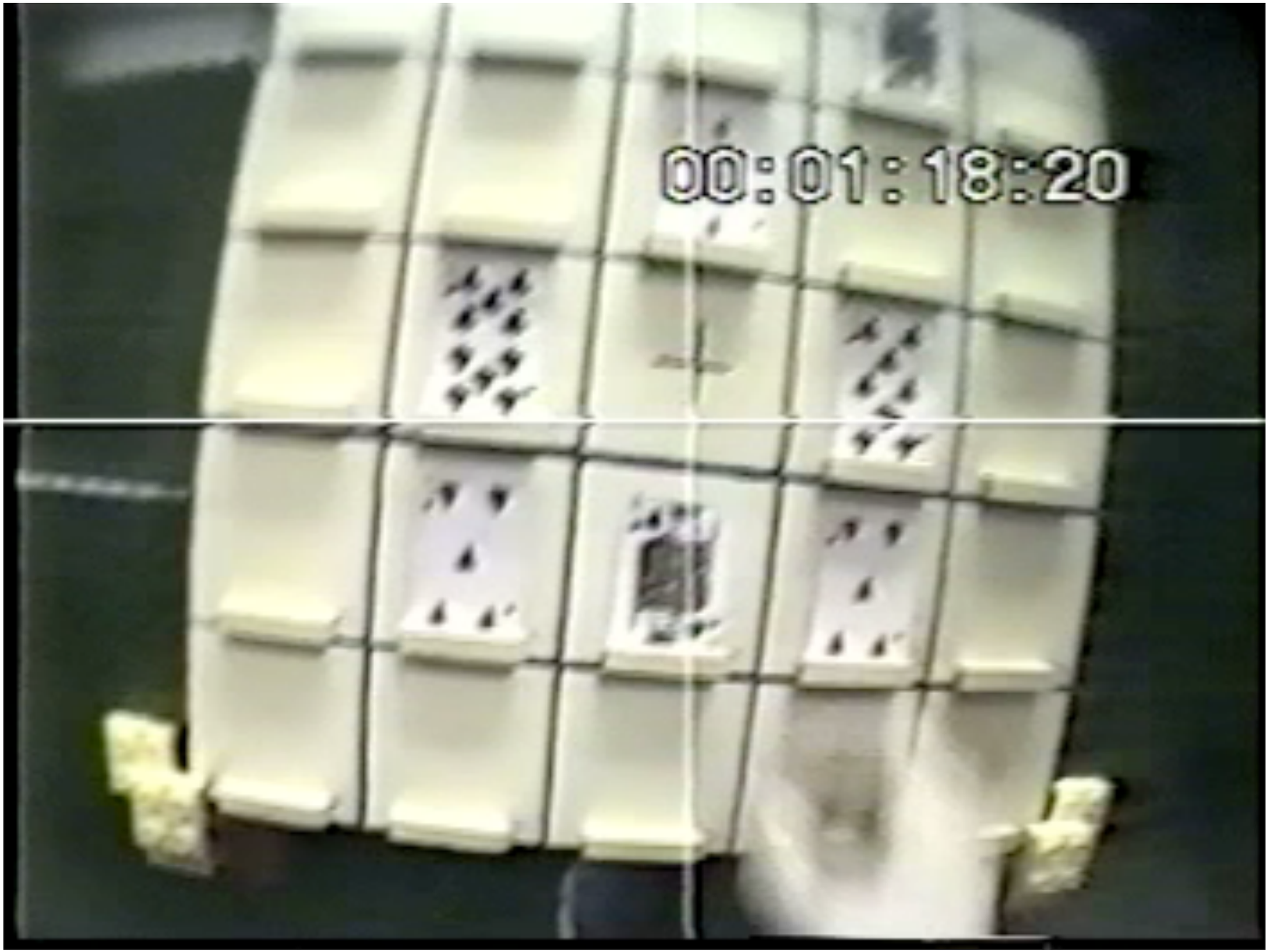

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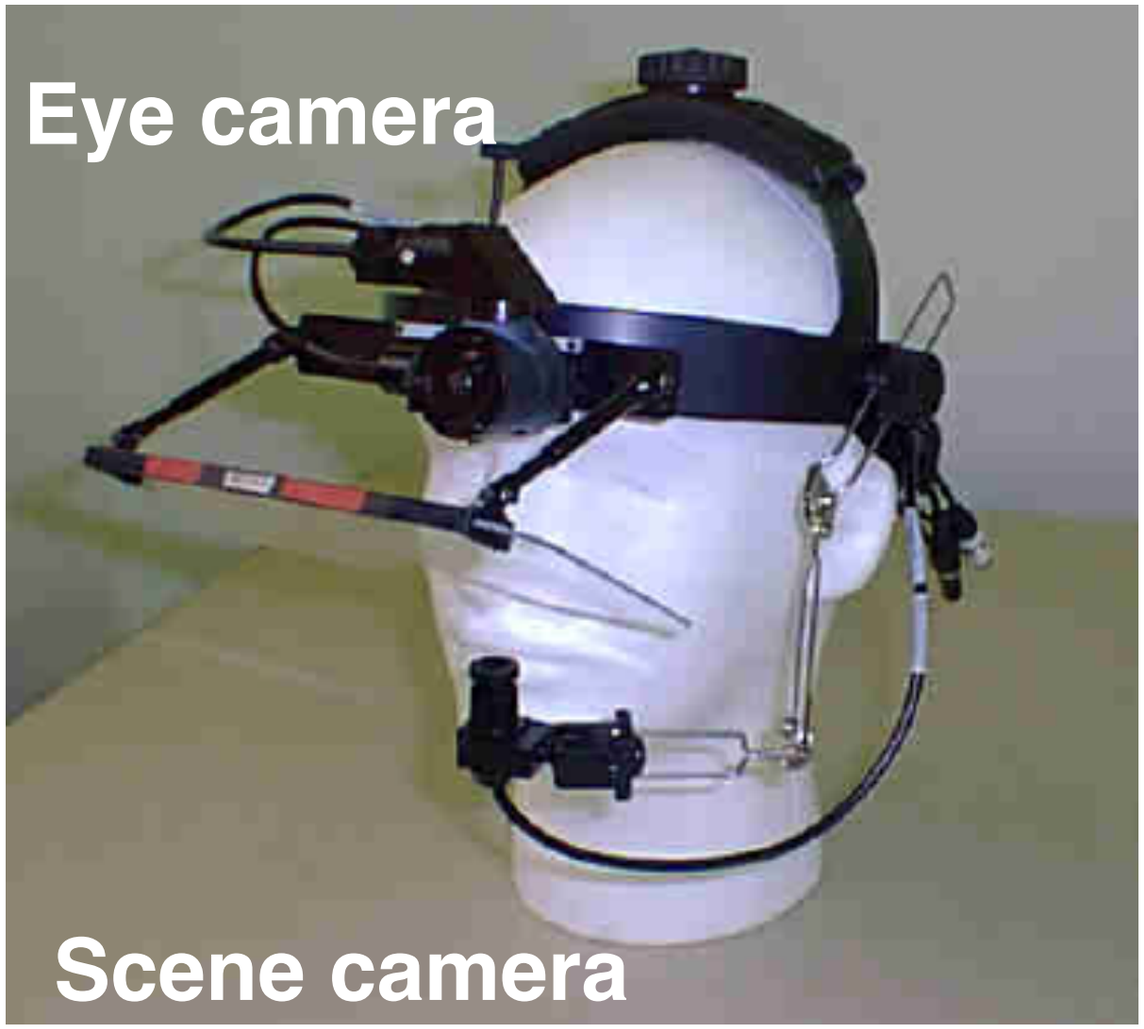
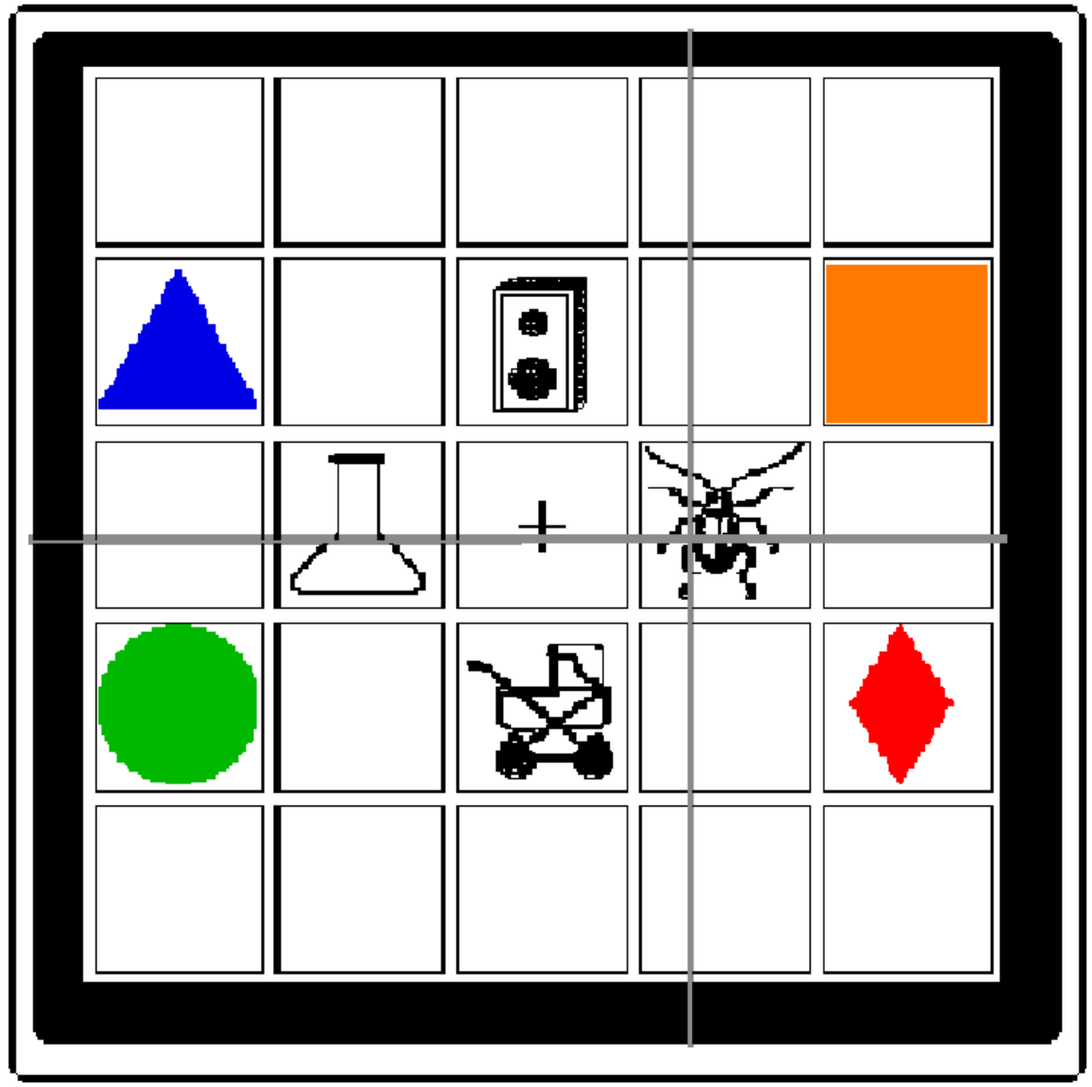
A visual world experiment





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Allopenna, Magnuson & Tanenhaus (1998)

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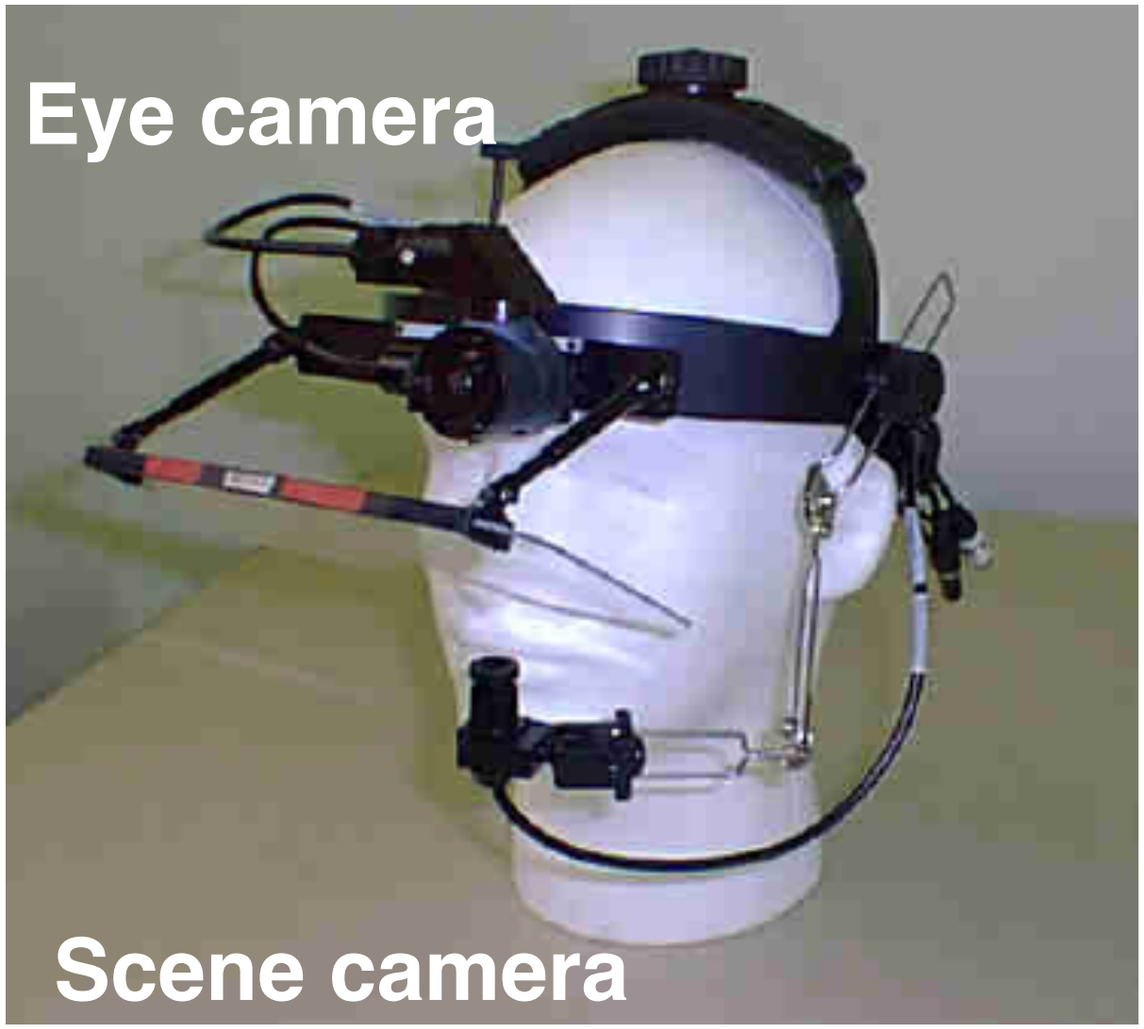

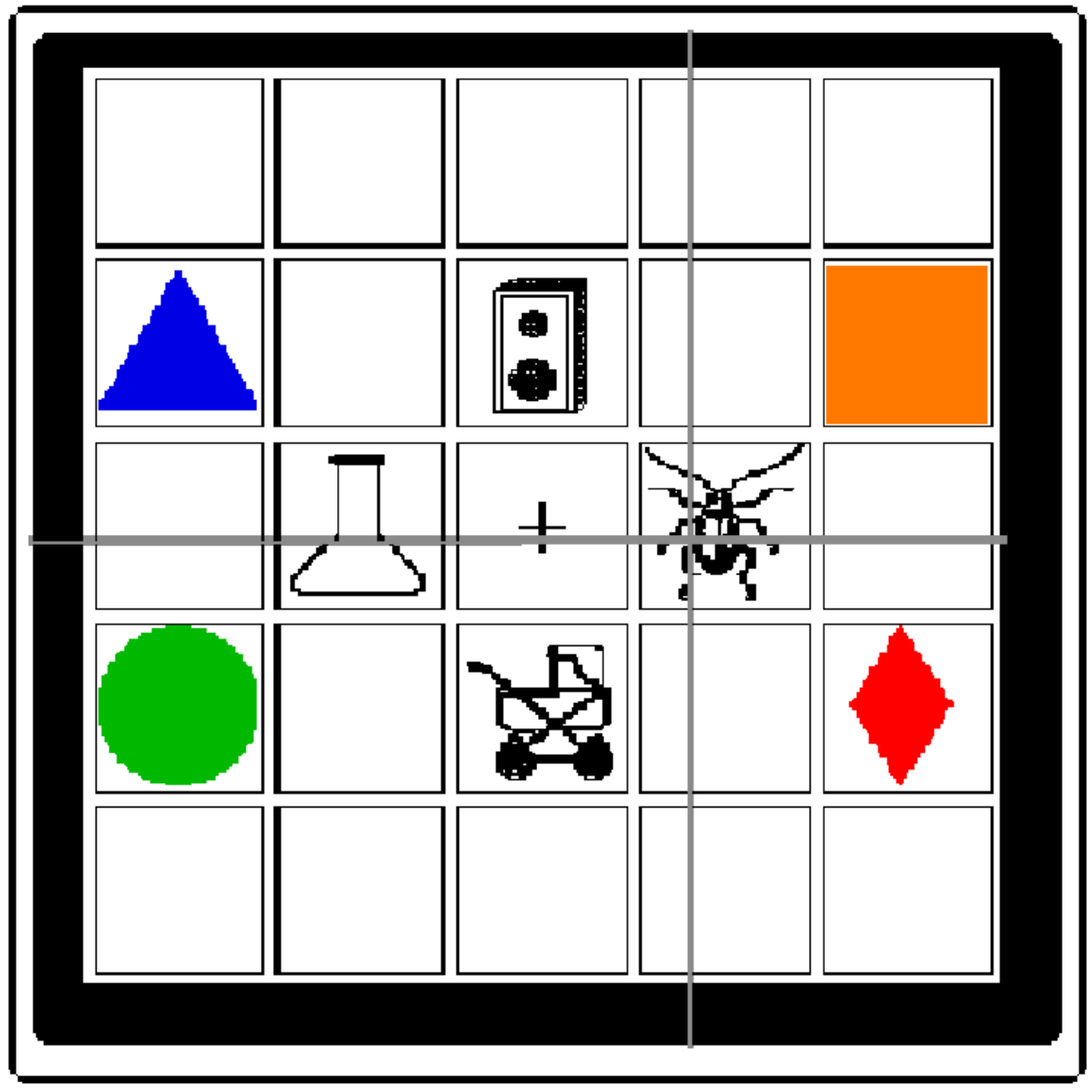

Instruction to experimental participant:

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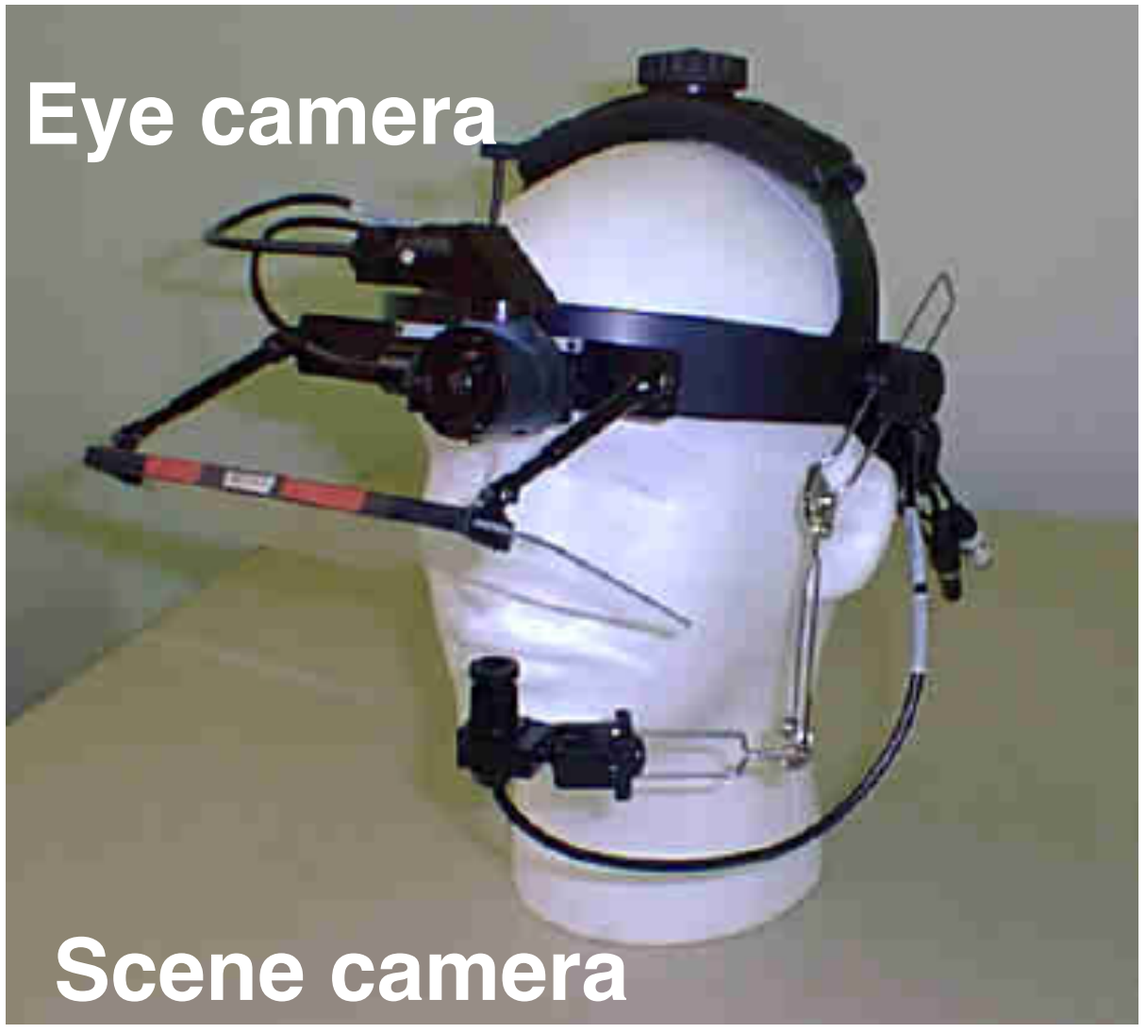

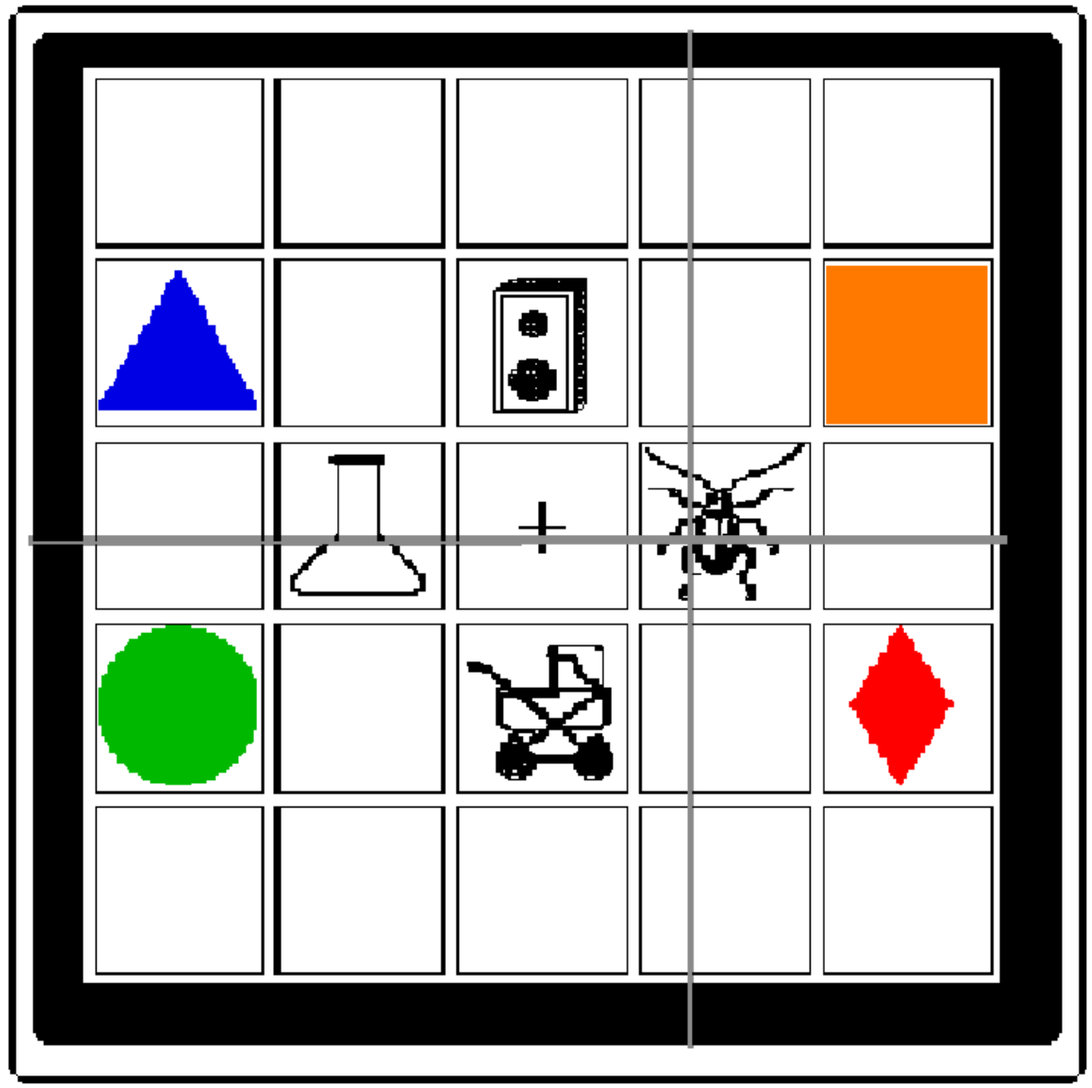

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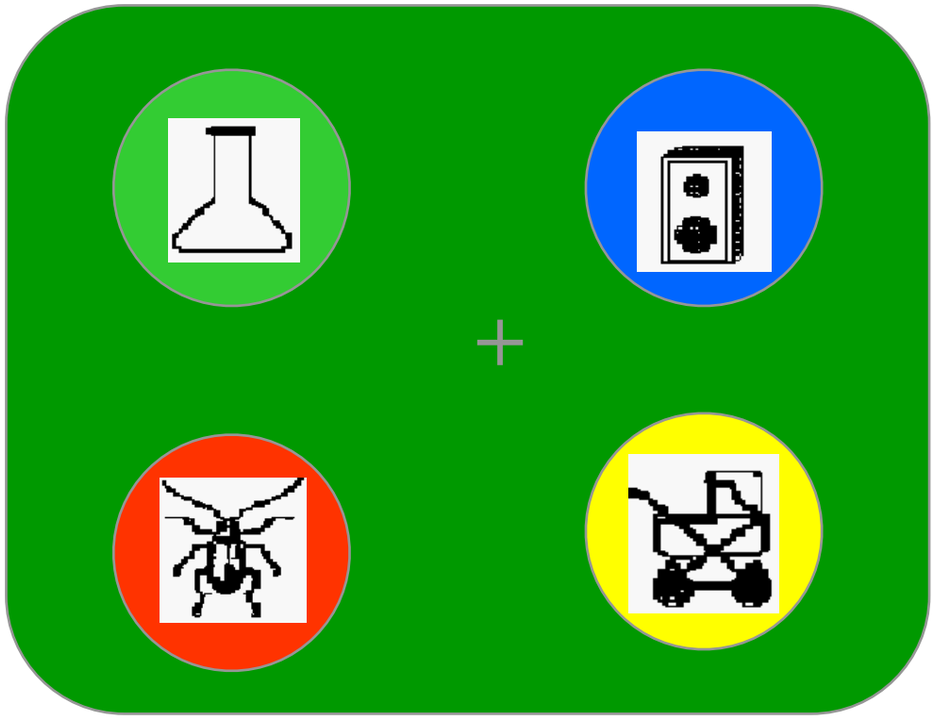

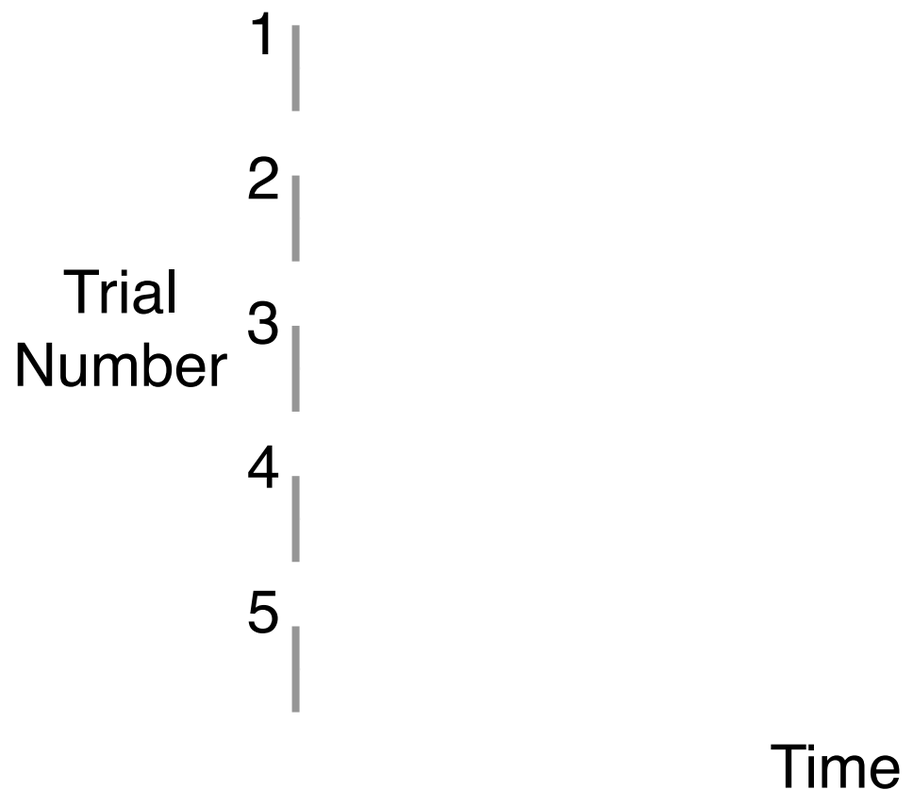

Target = beaker

Cohort = beetle

Unrelated = carriage

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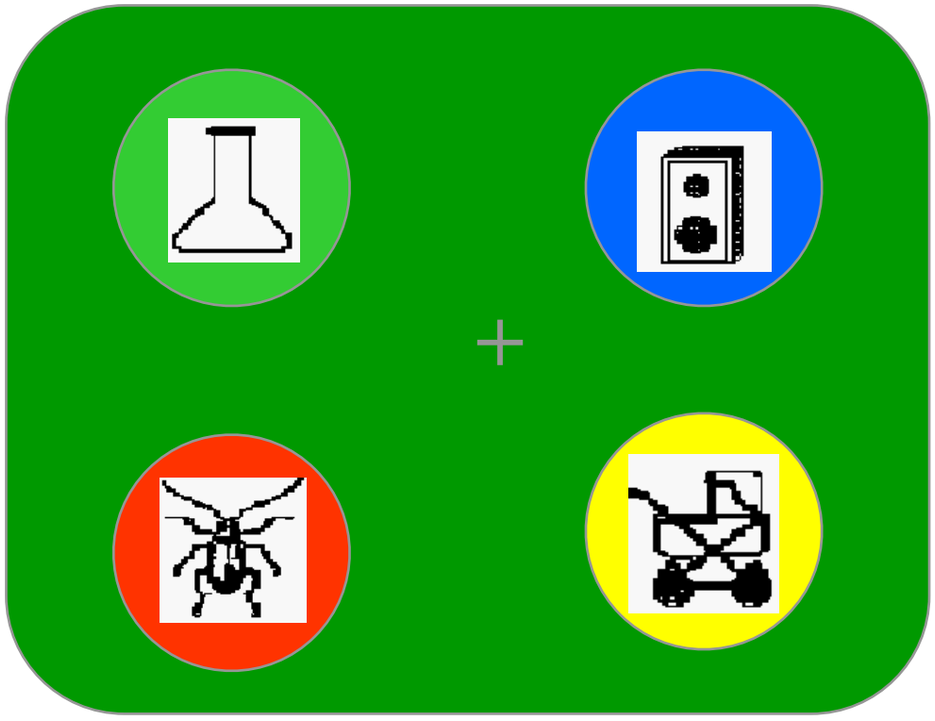

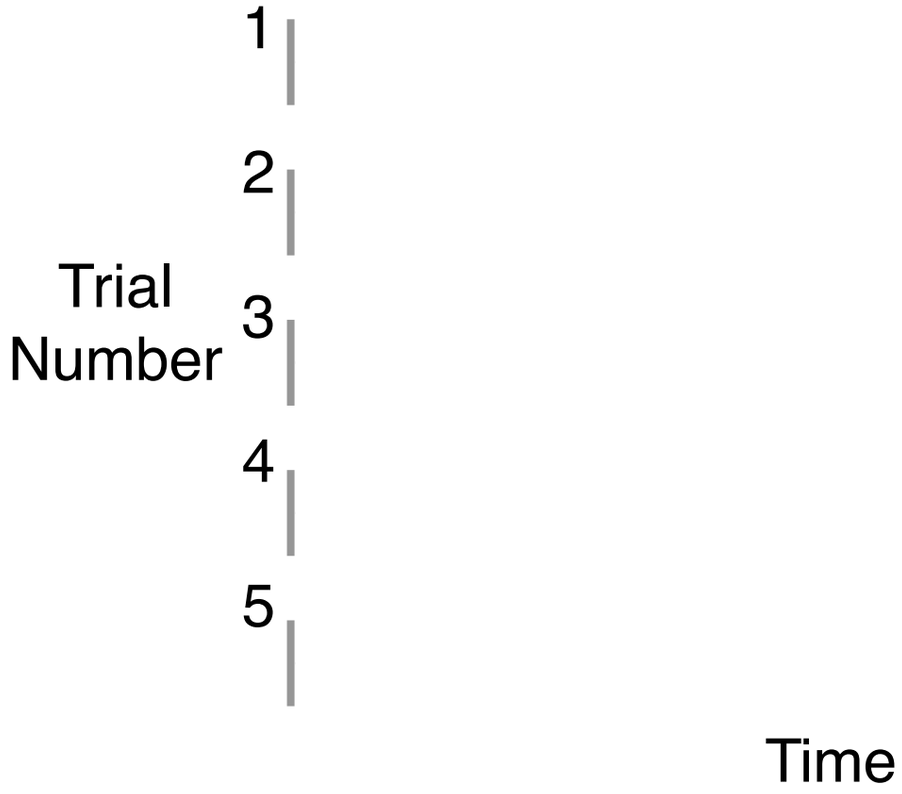

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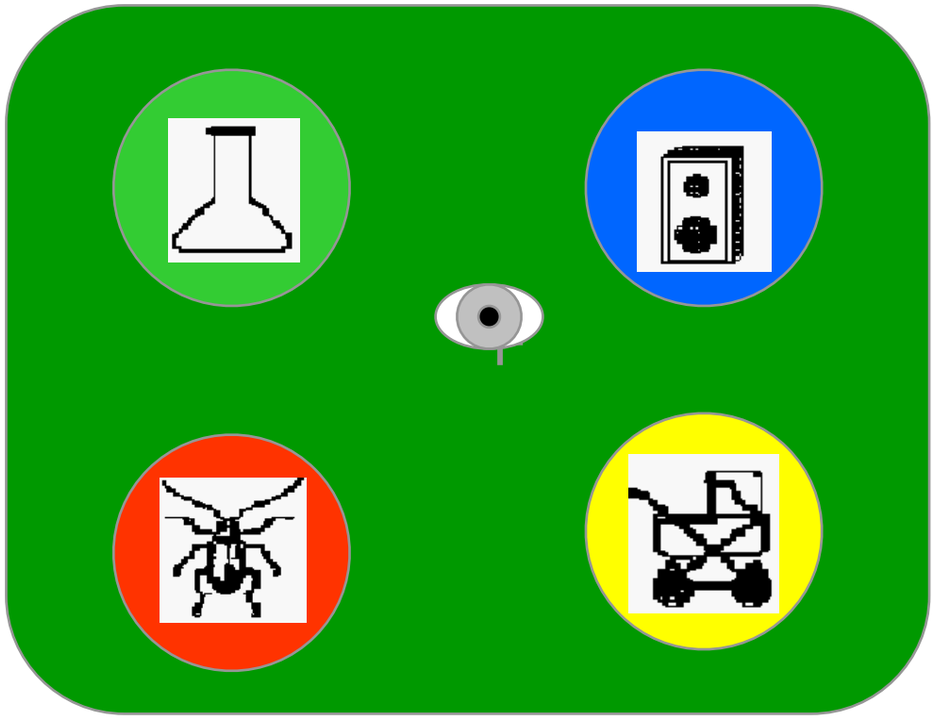

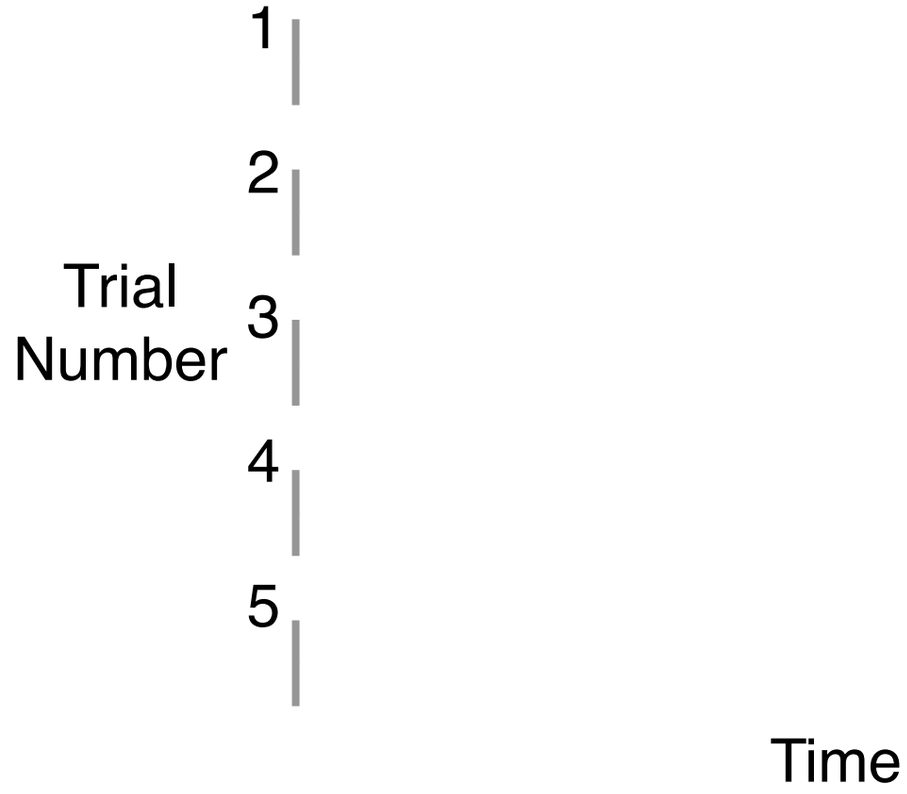

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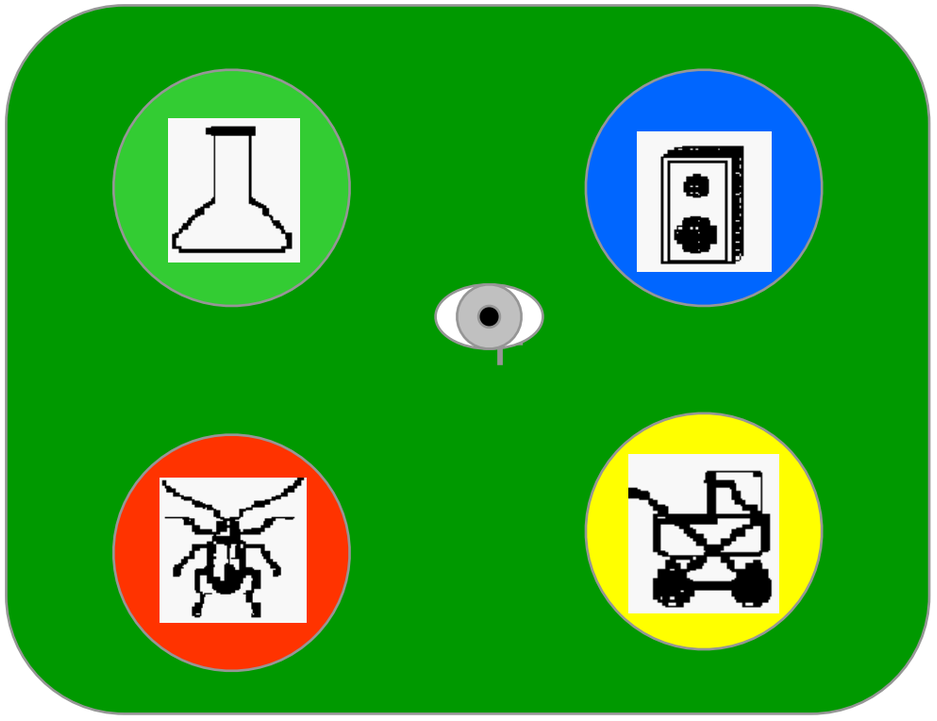

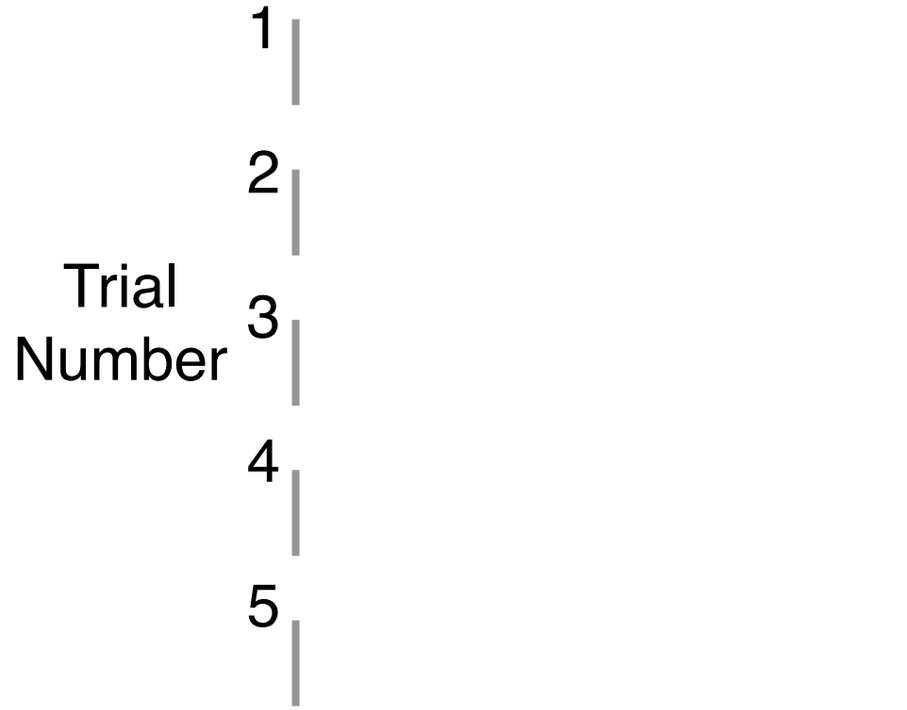

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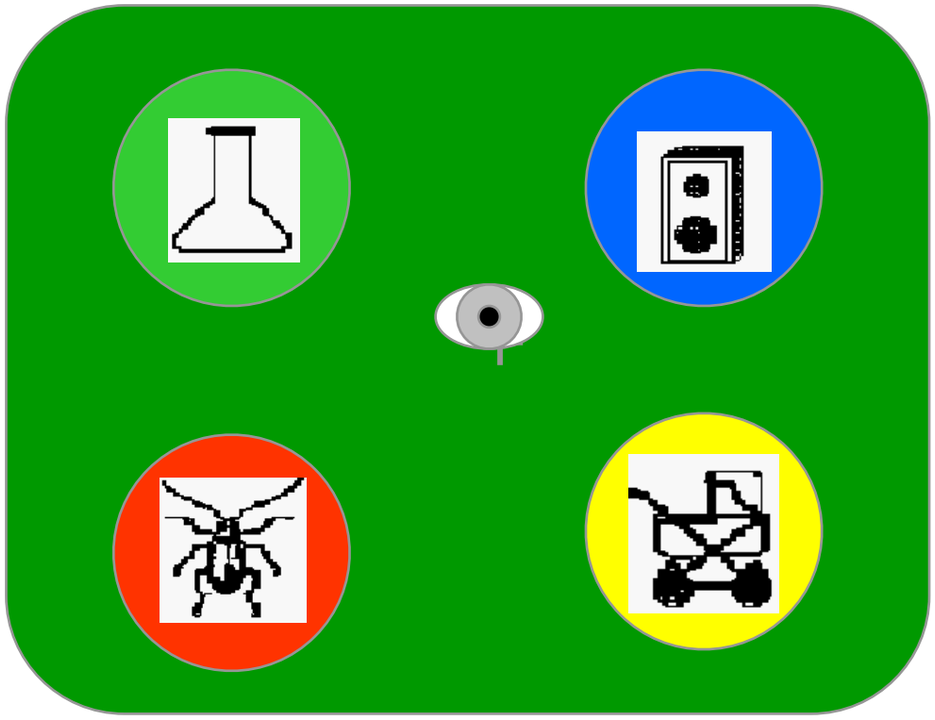

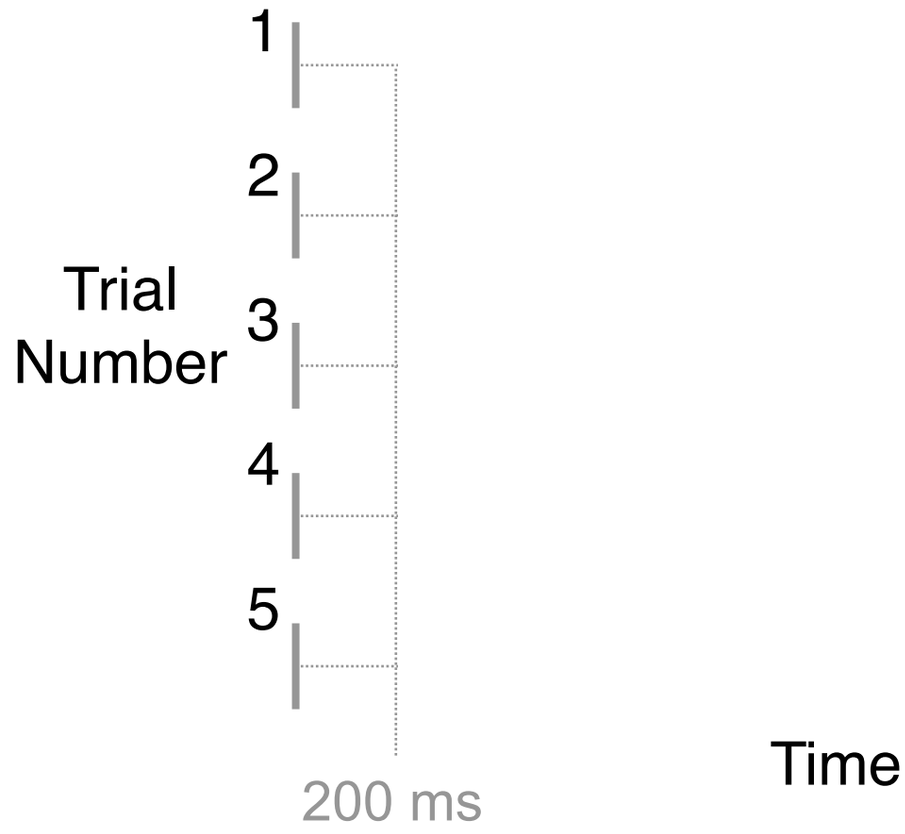

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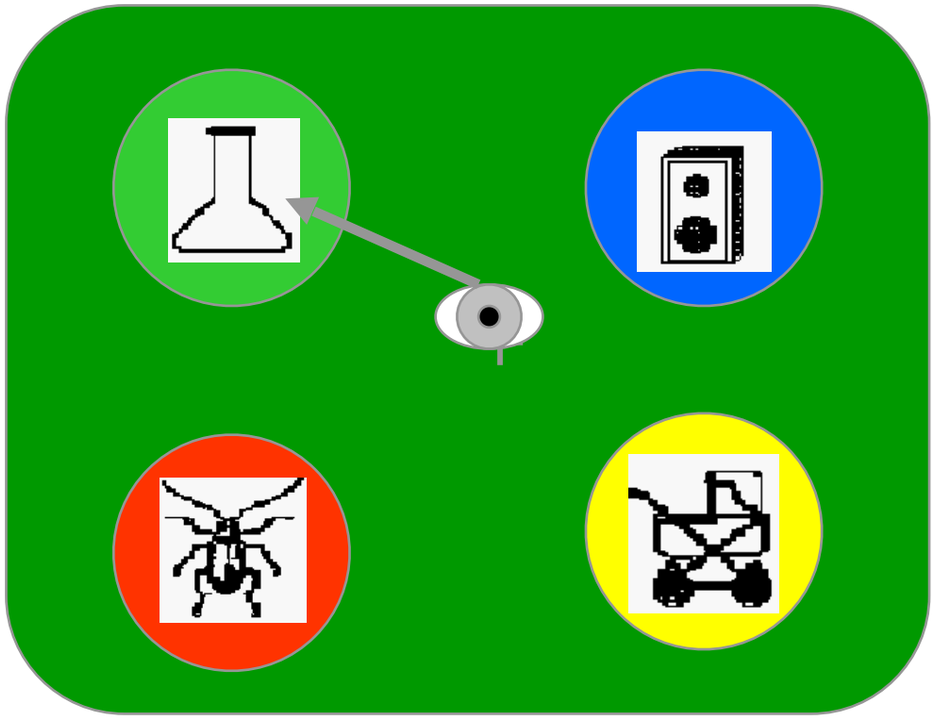

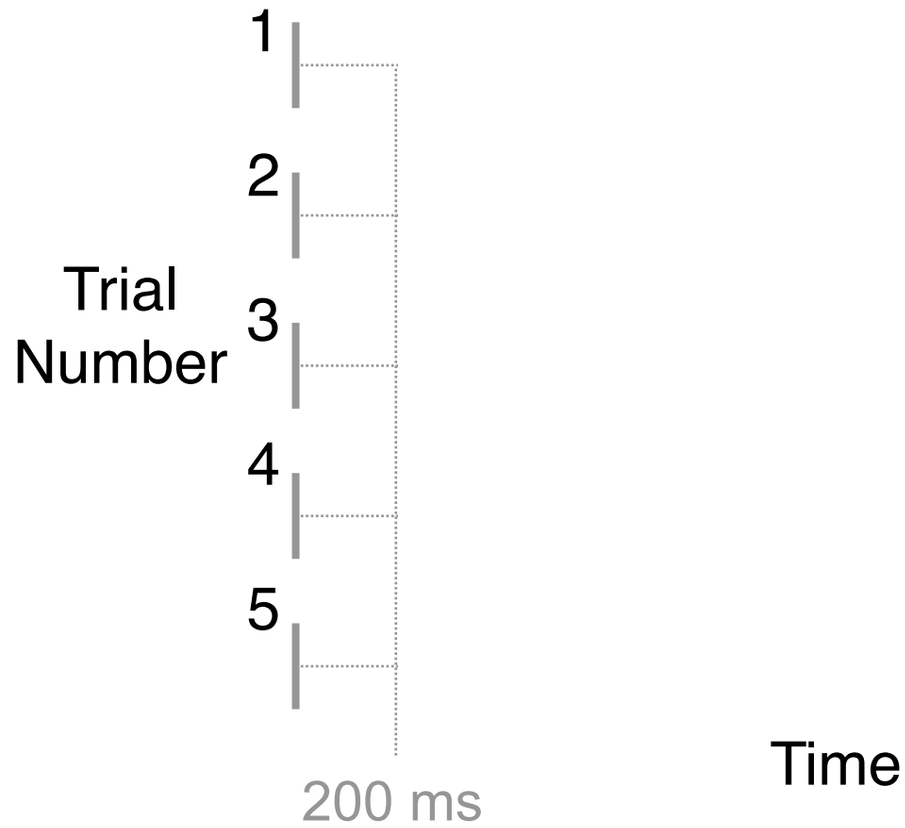

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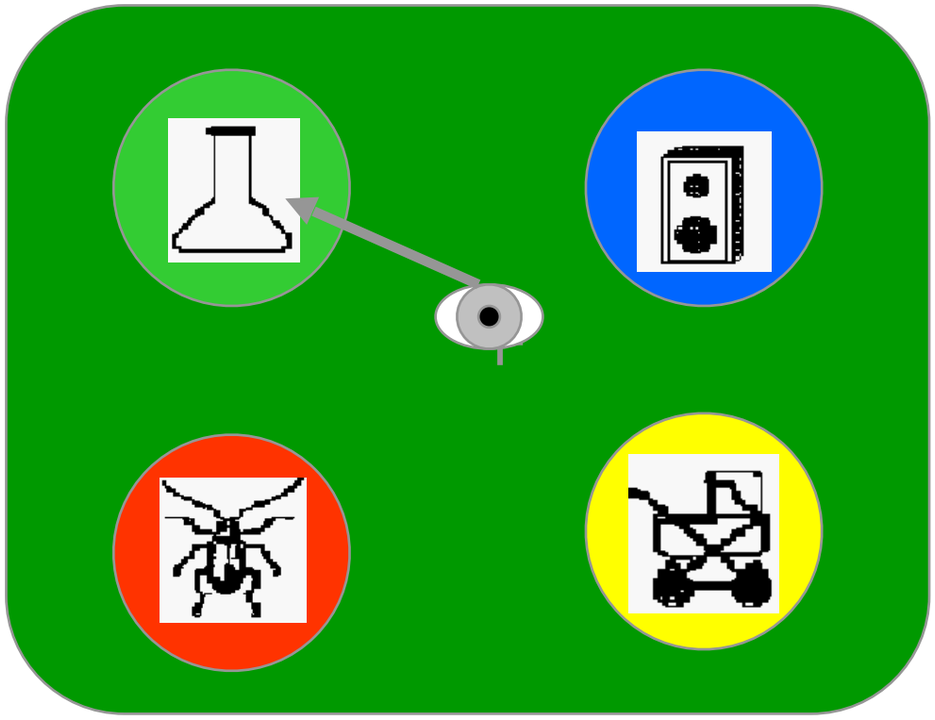

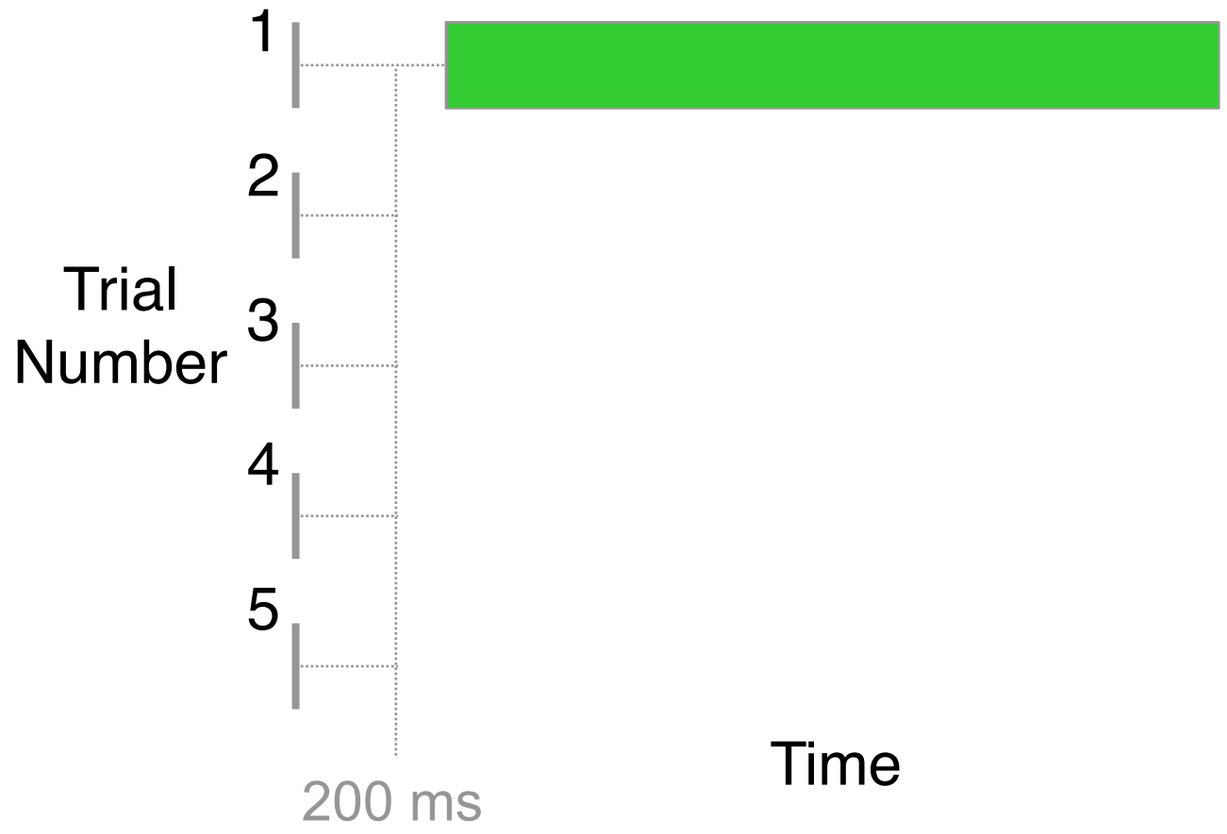

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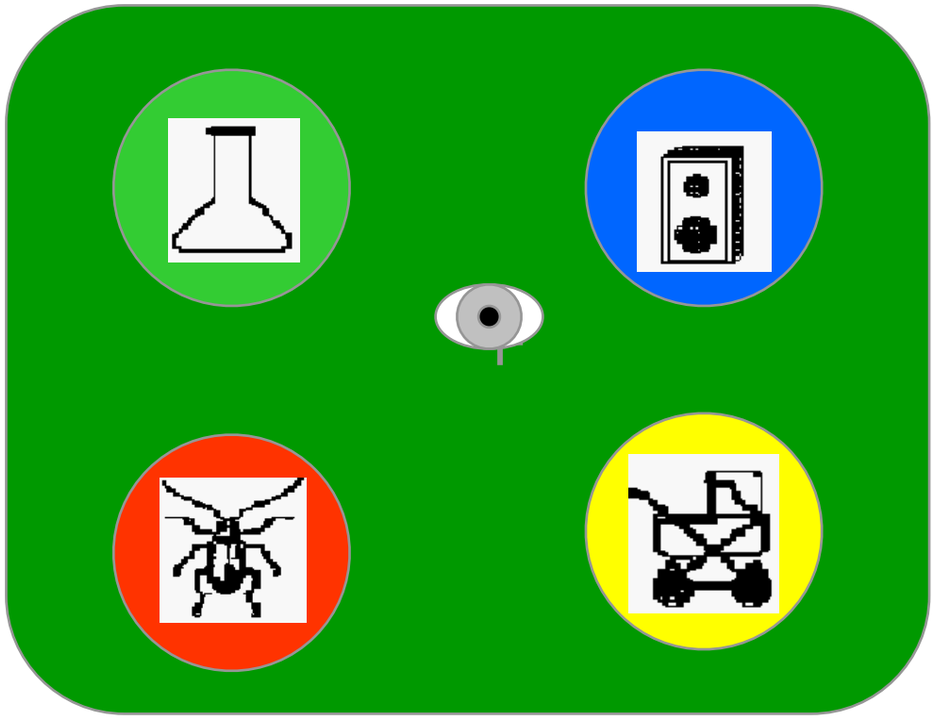

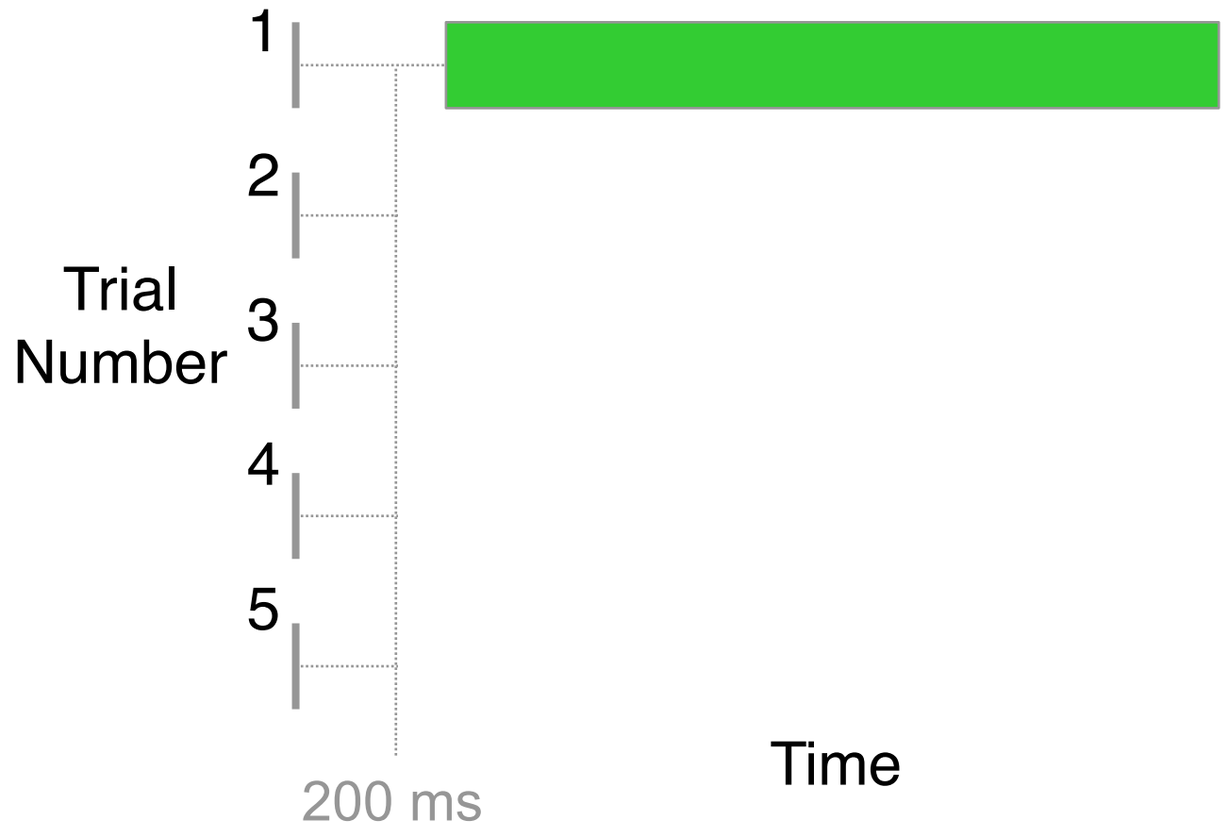

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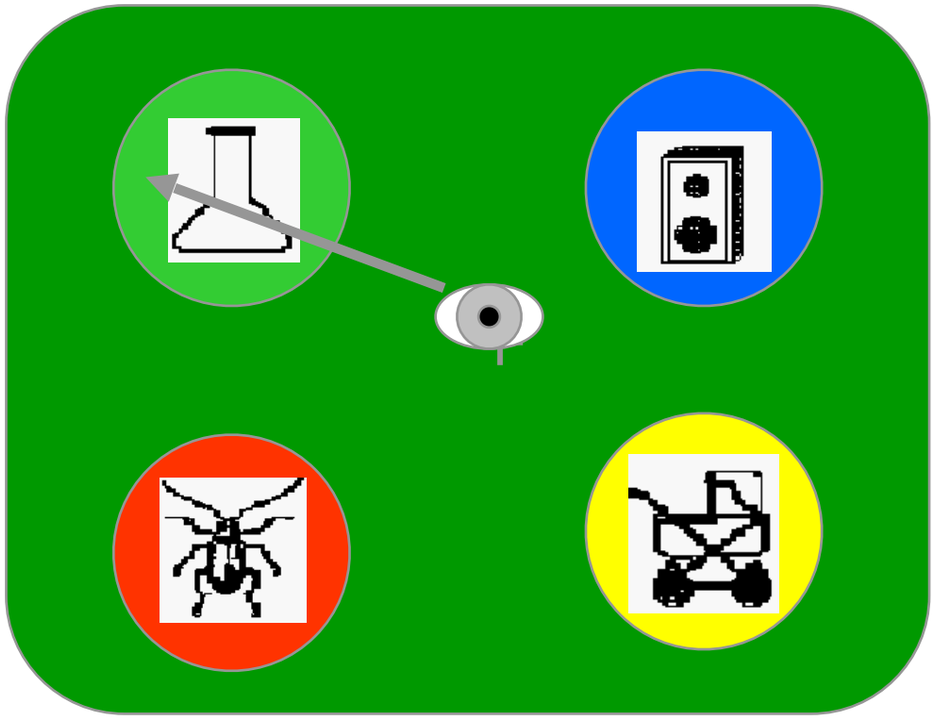

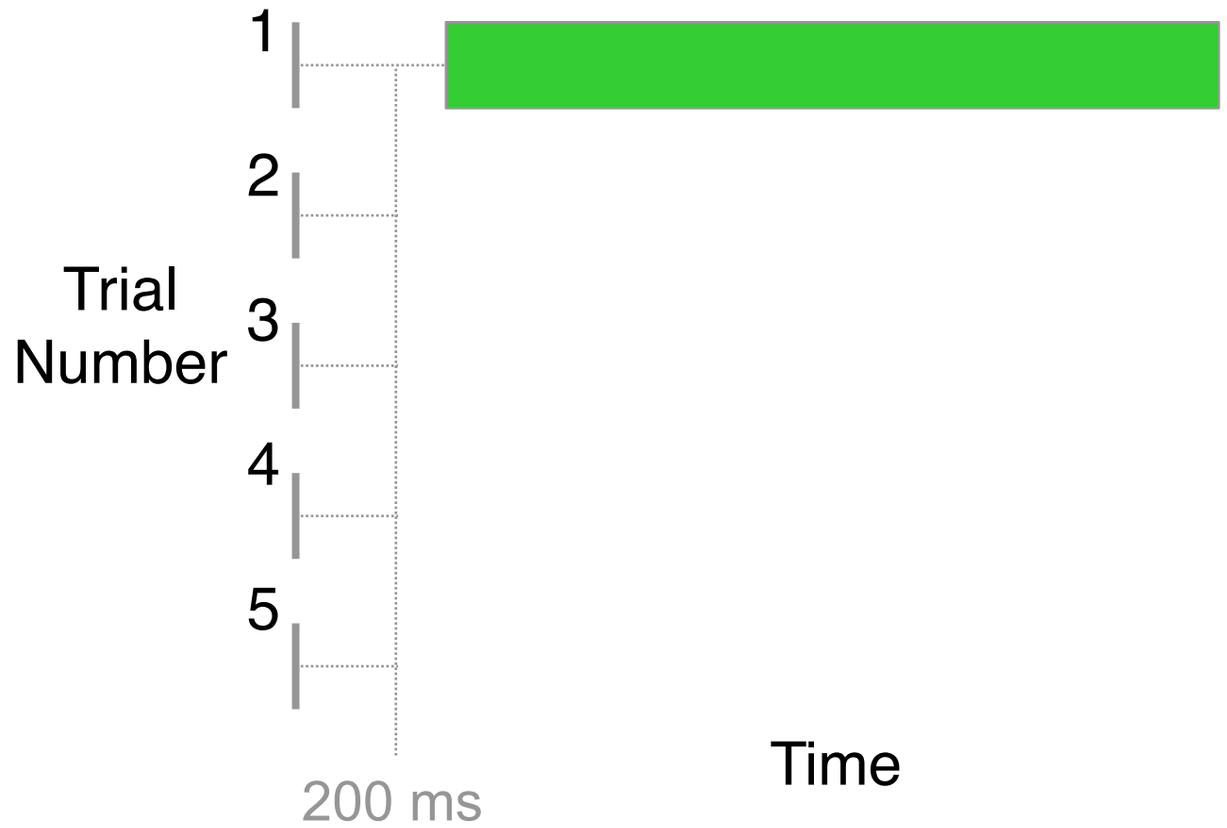

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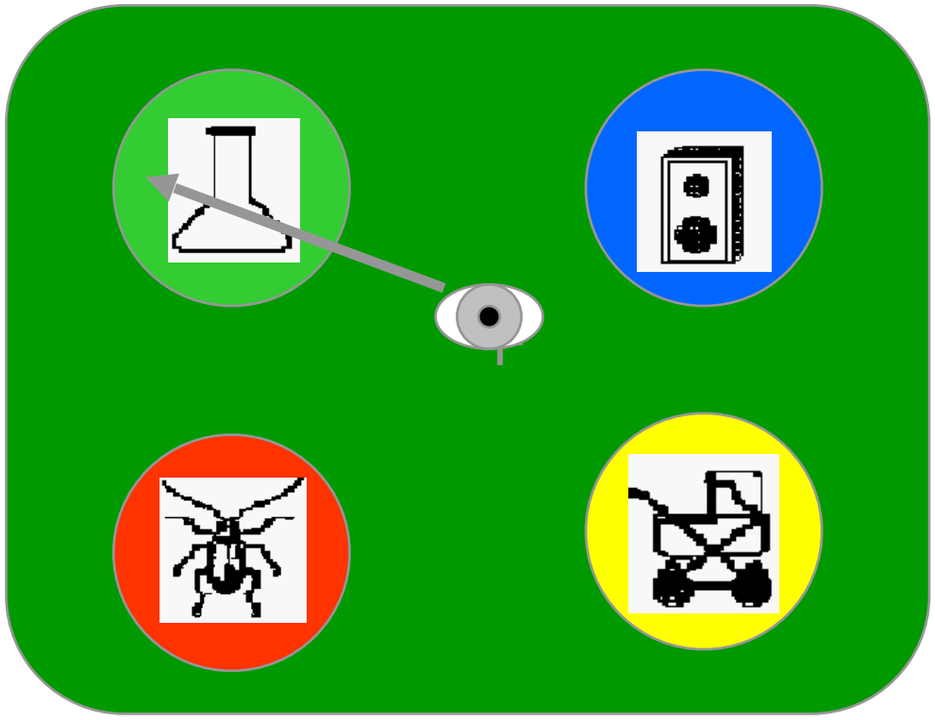

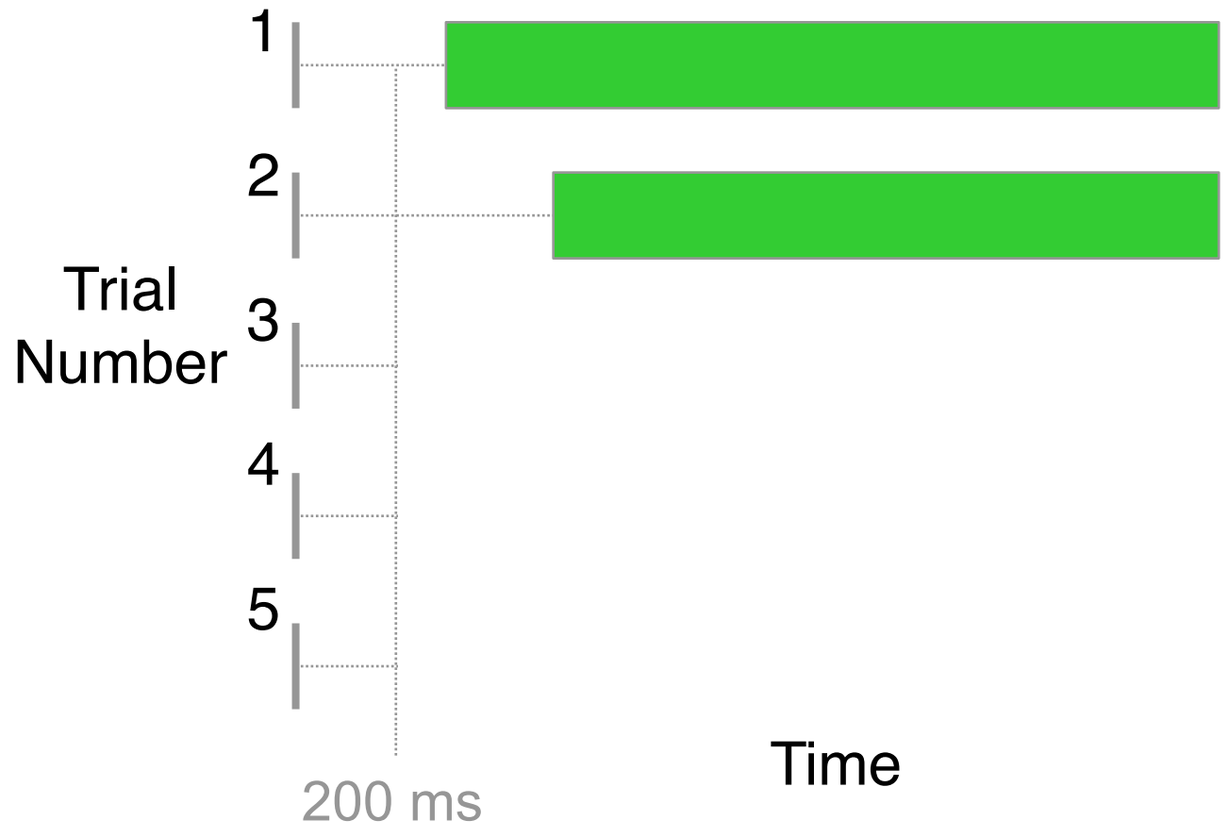

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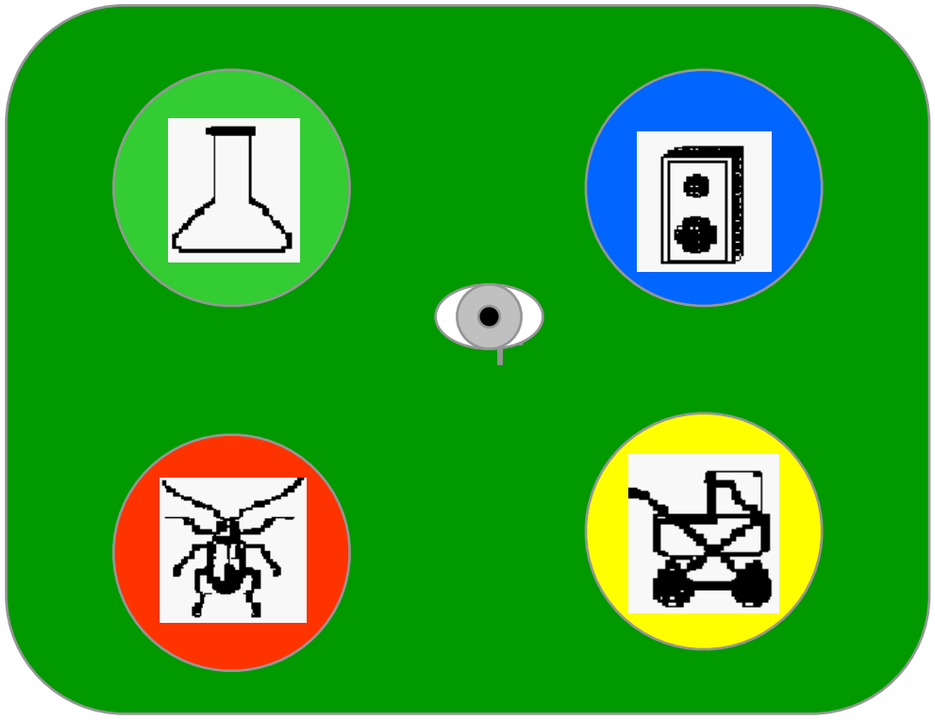

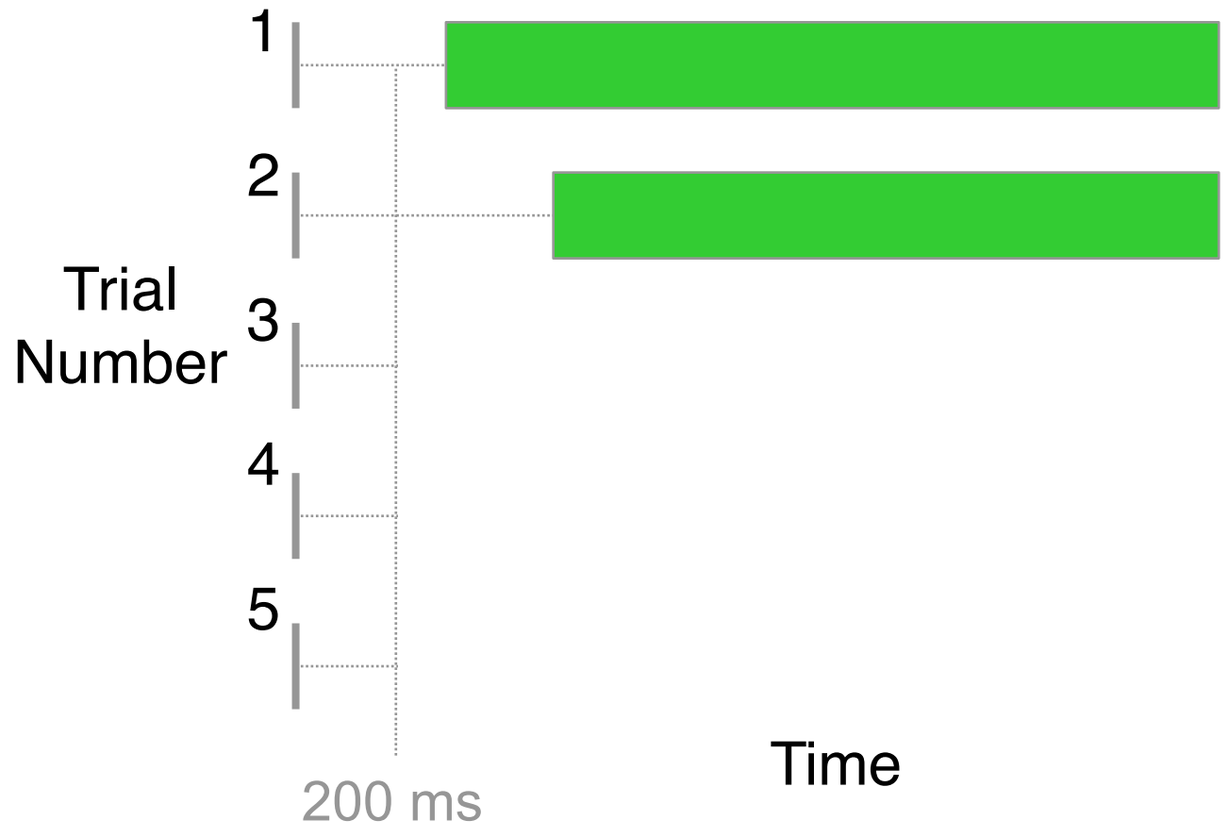

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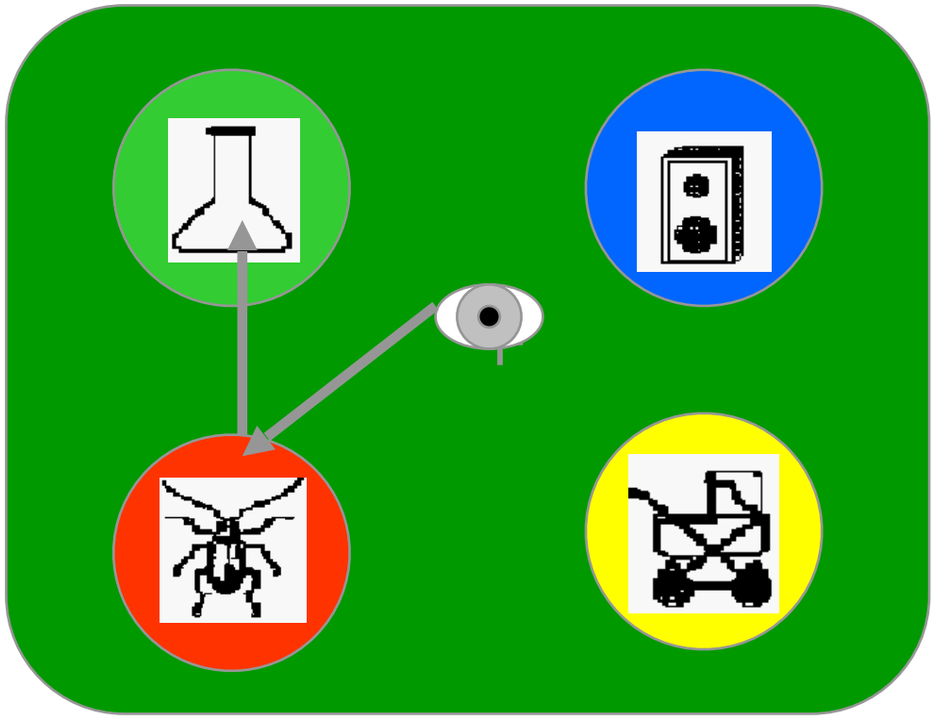

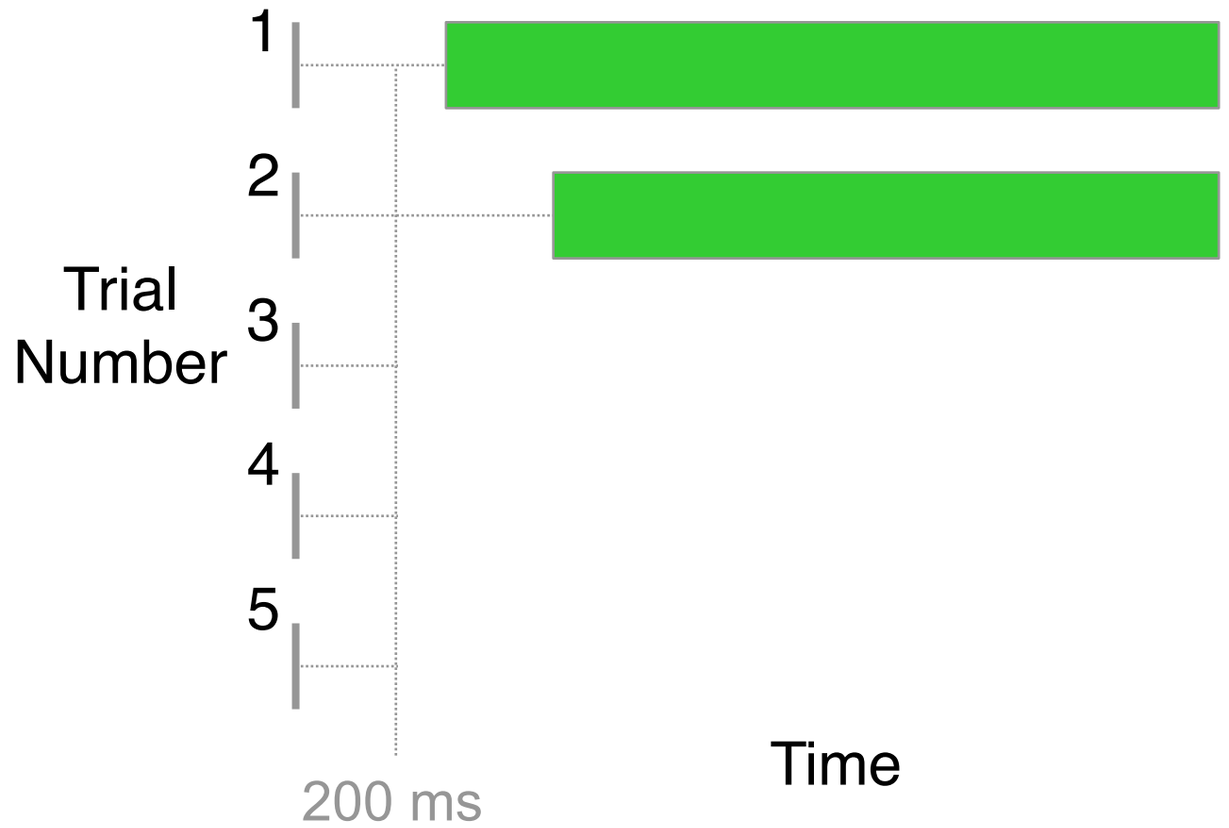

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Cohort = beetle

Unrelated = carriage

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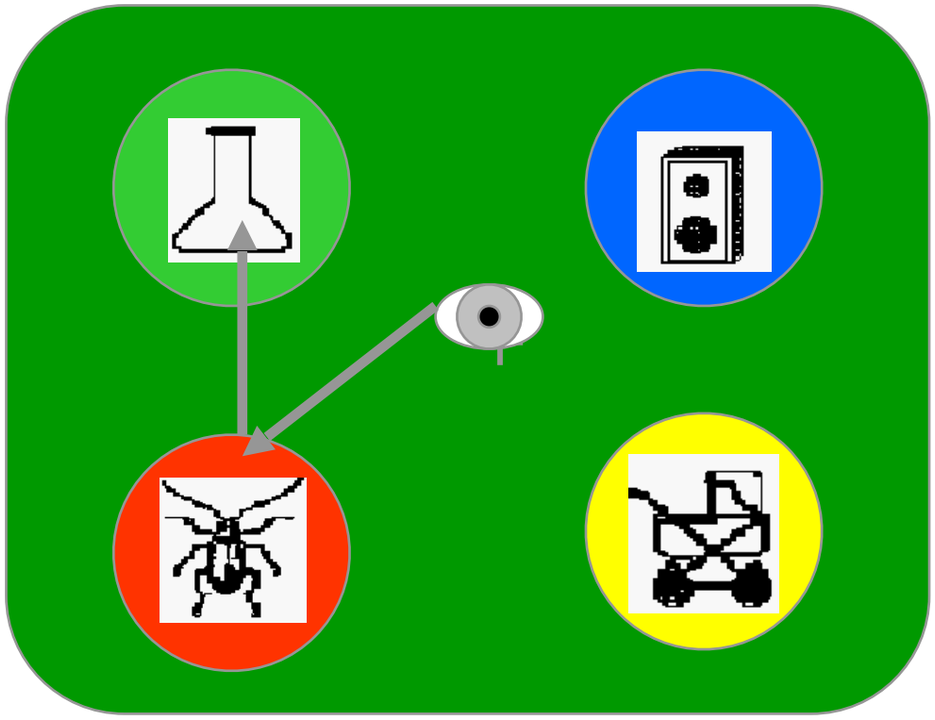

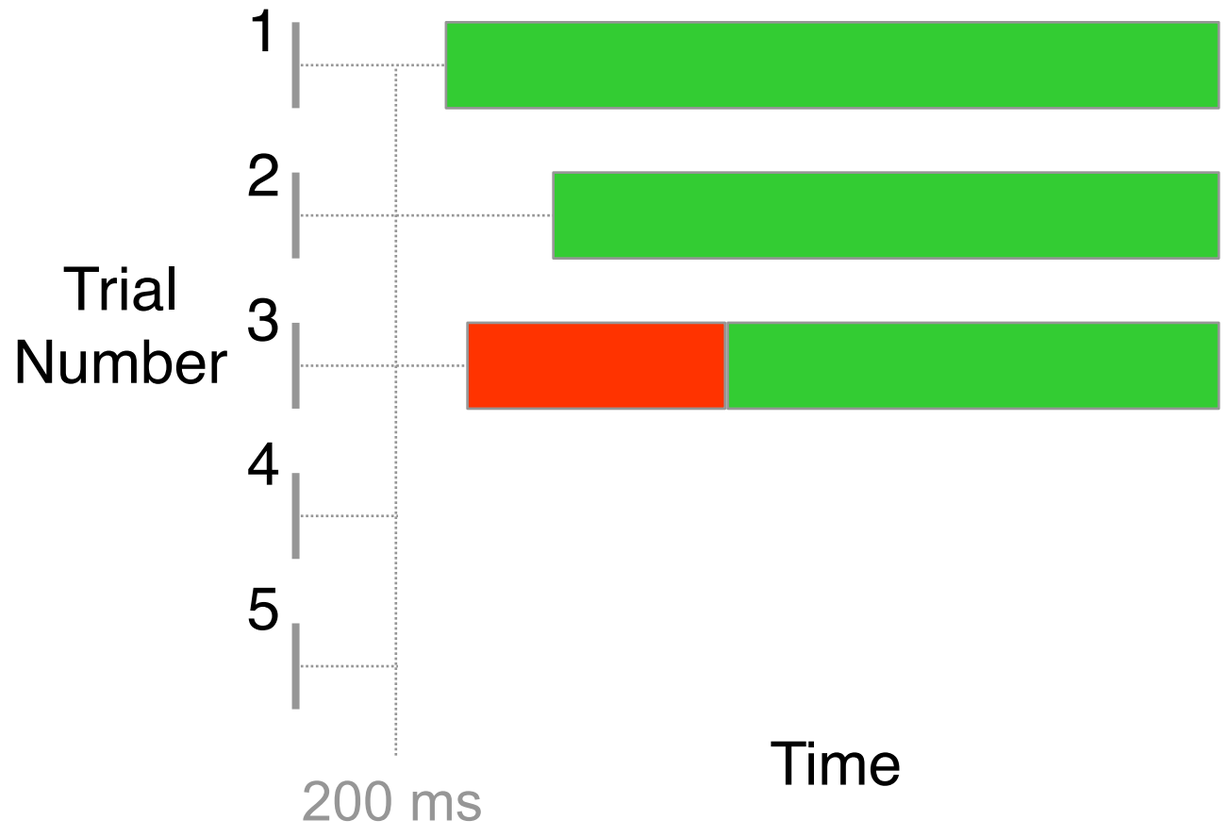

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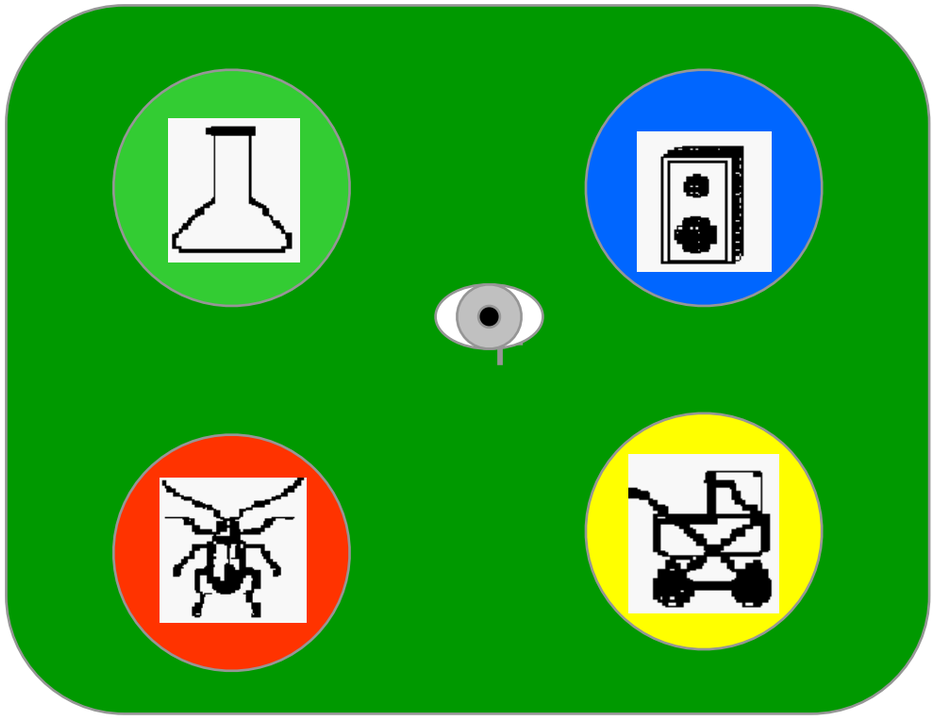

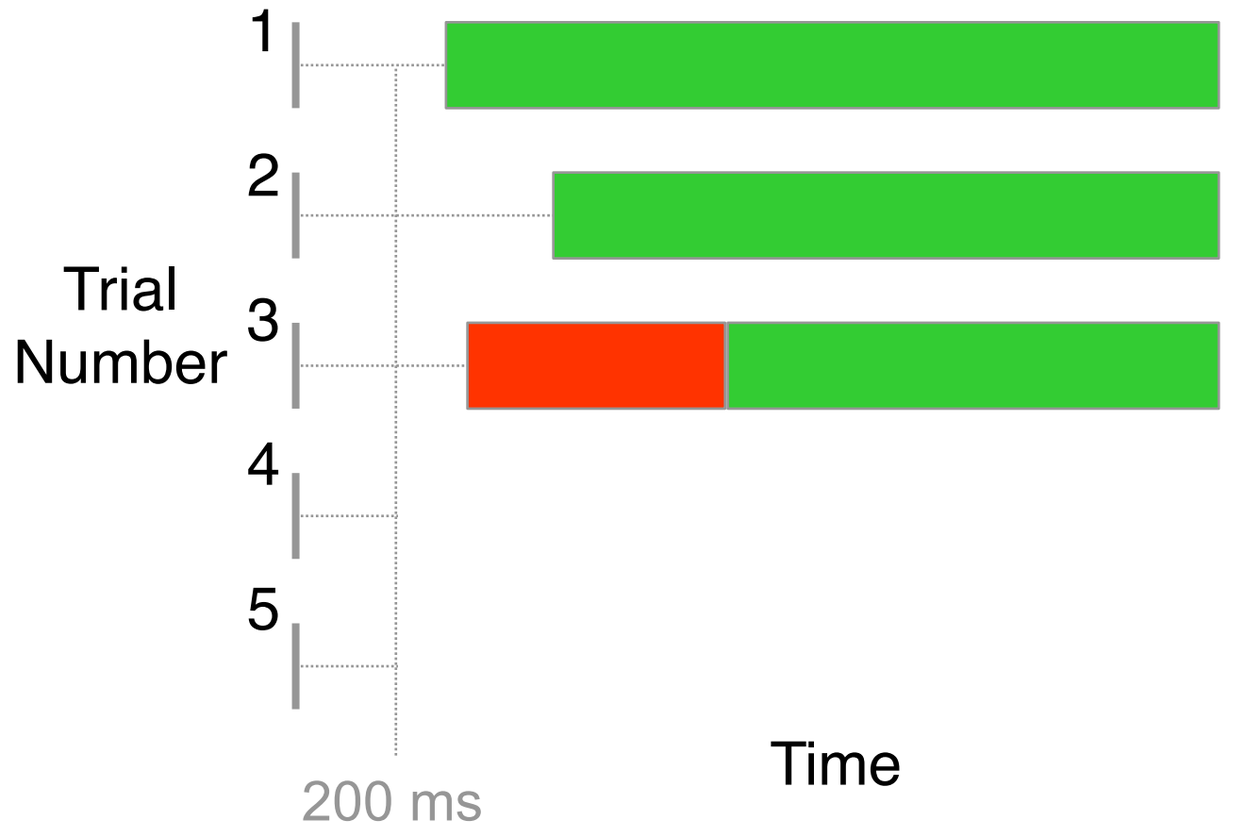

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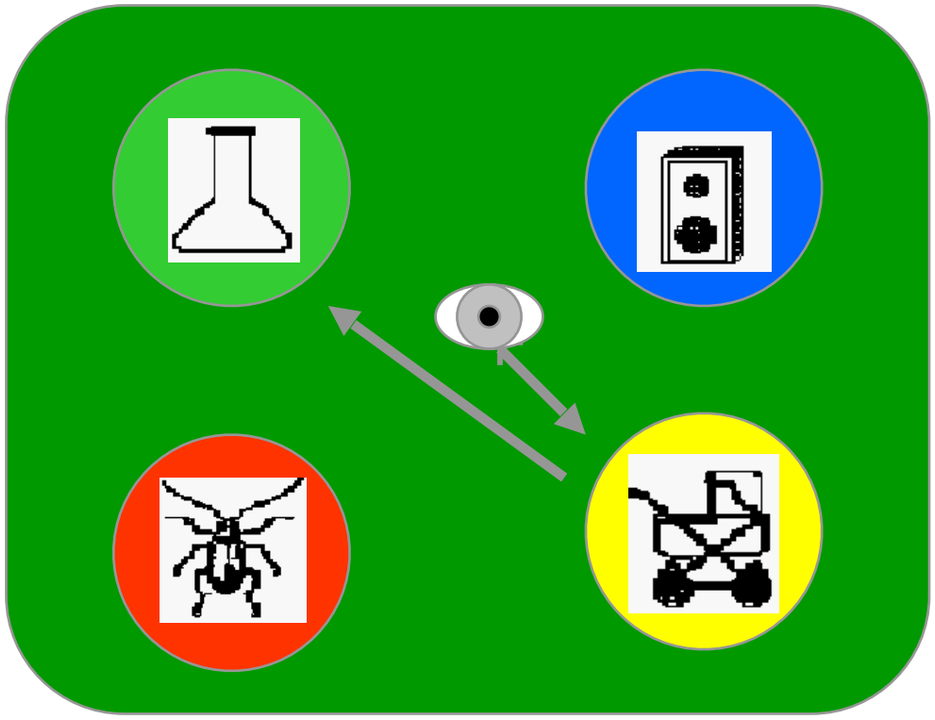

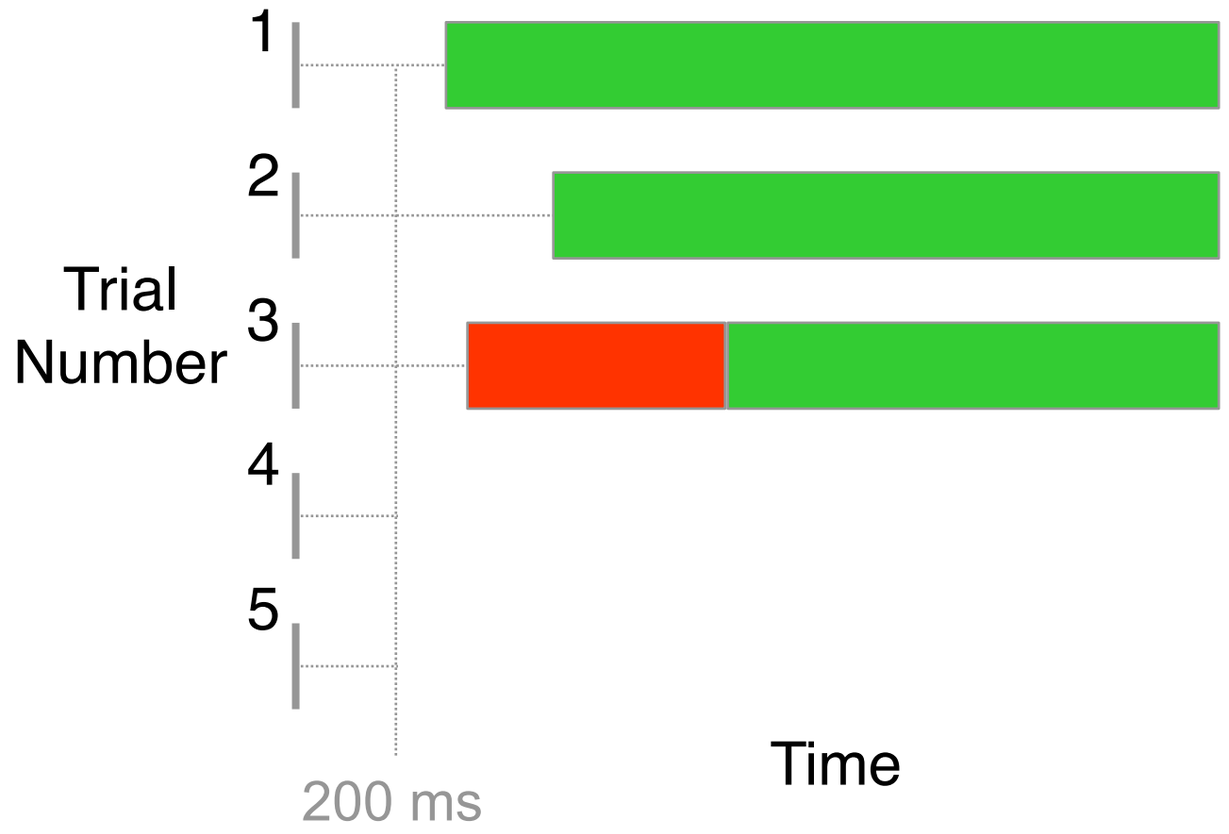

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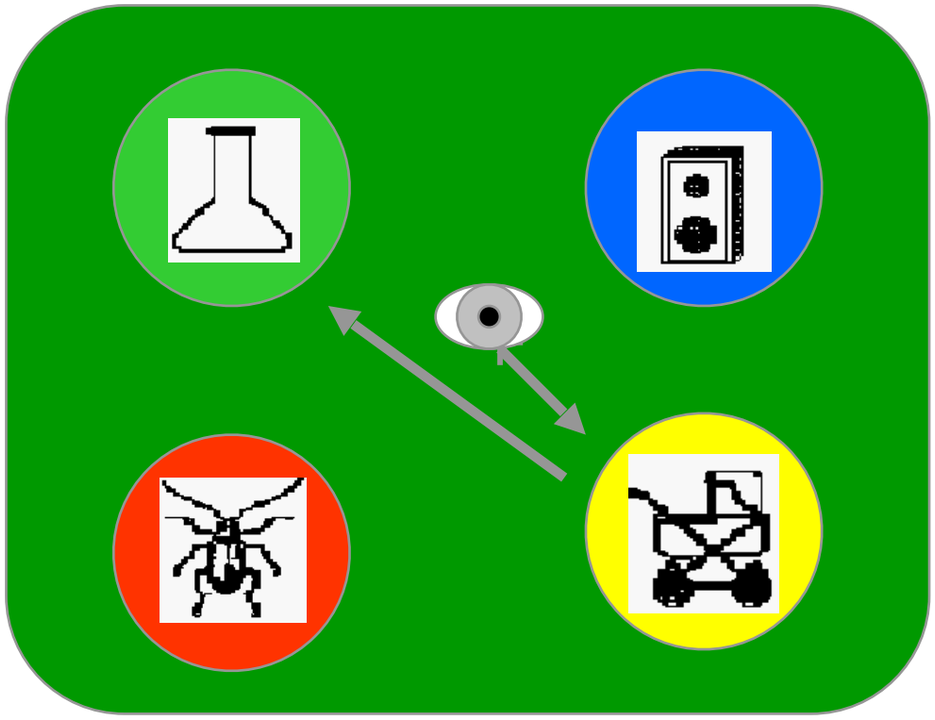

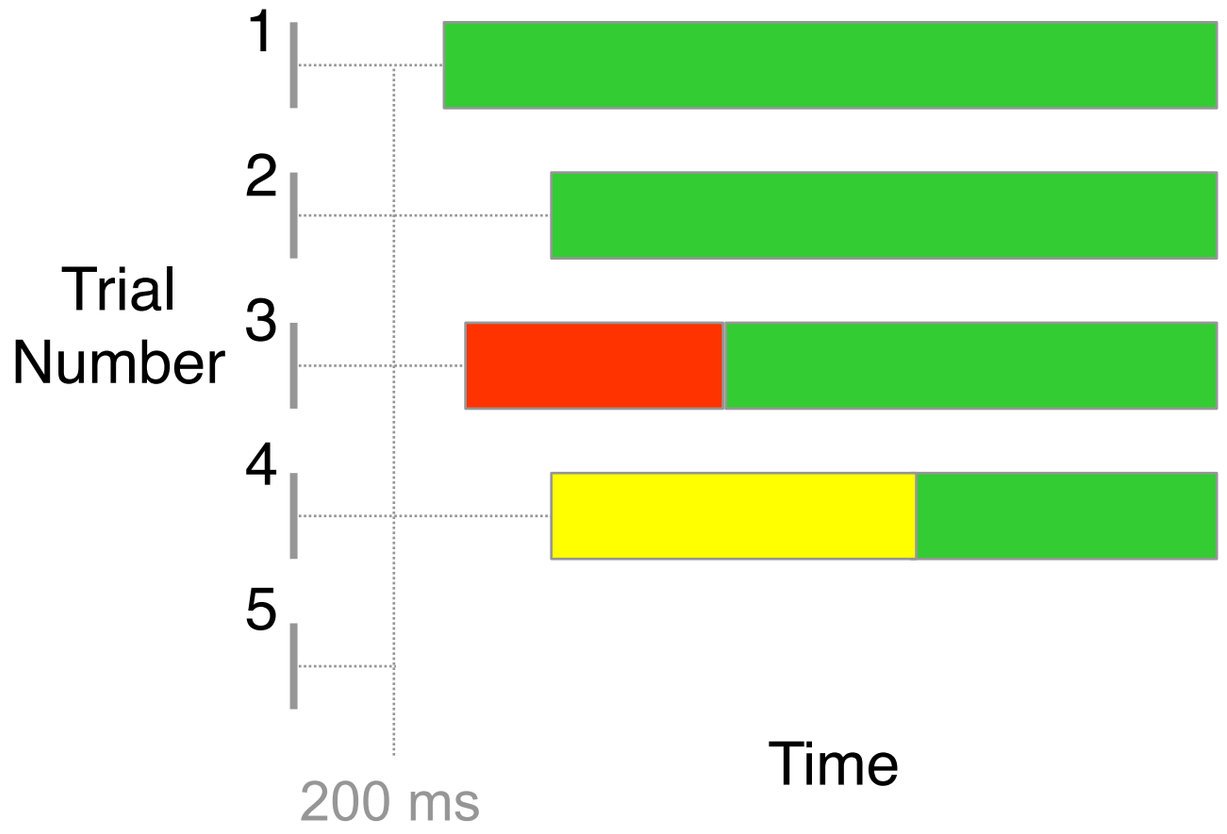

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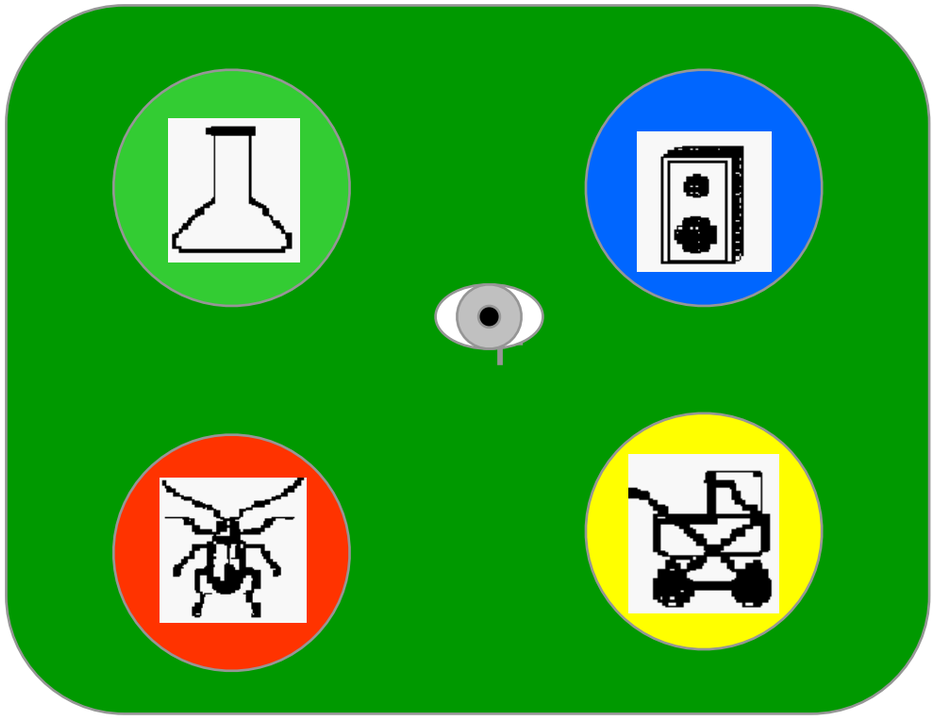

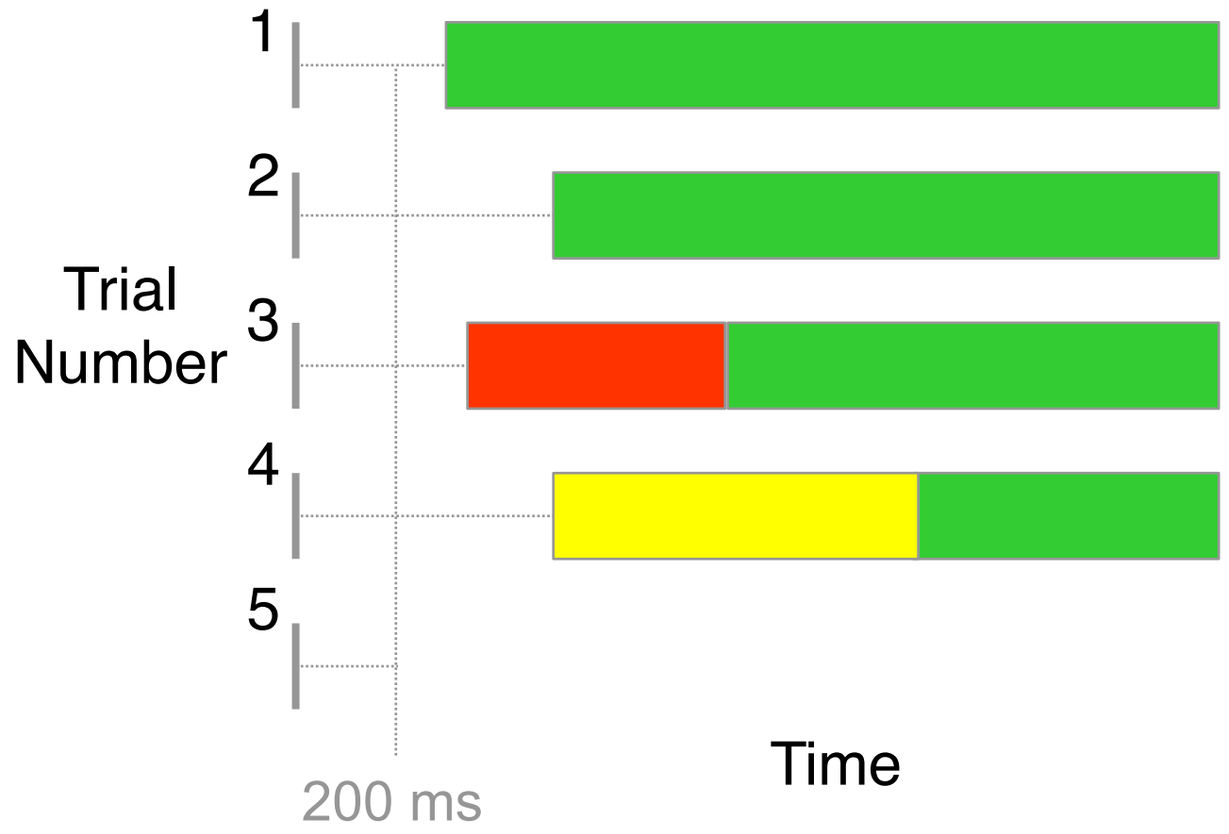

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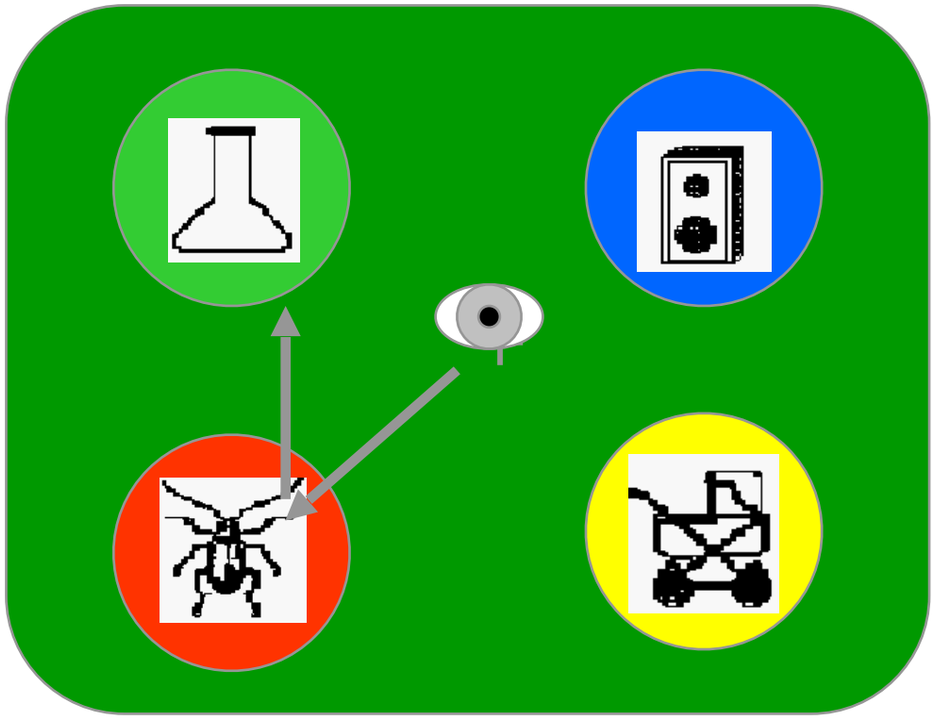

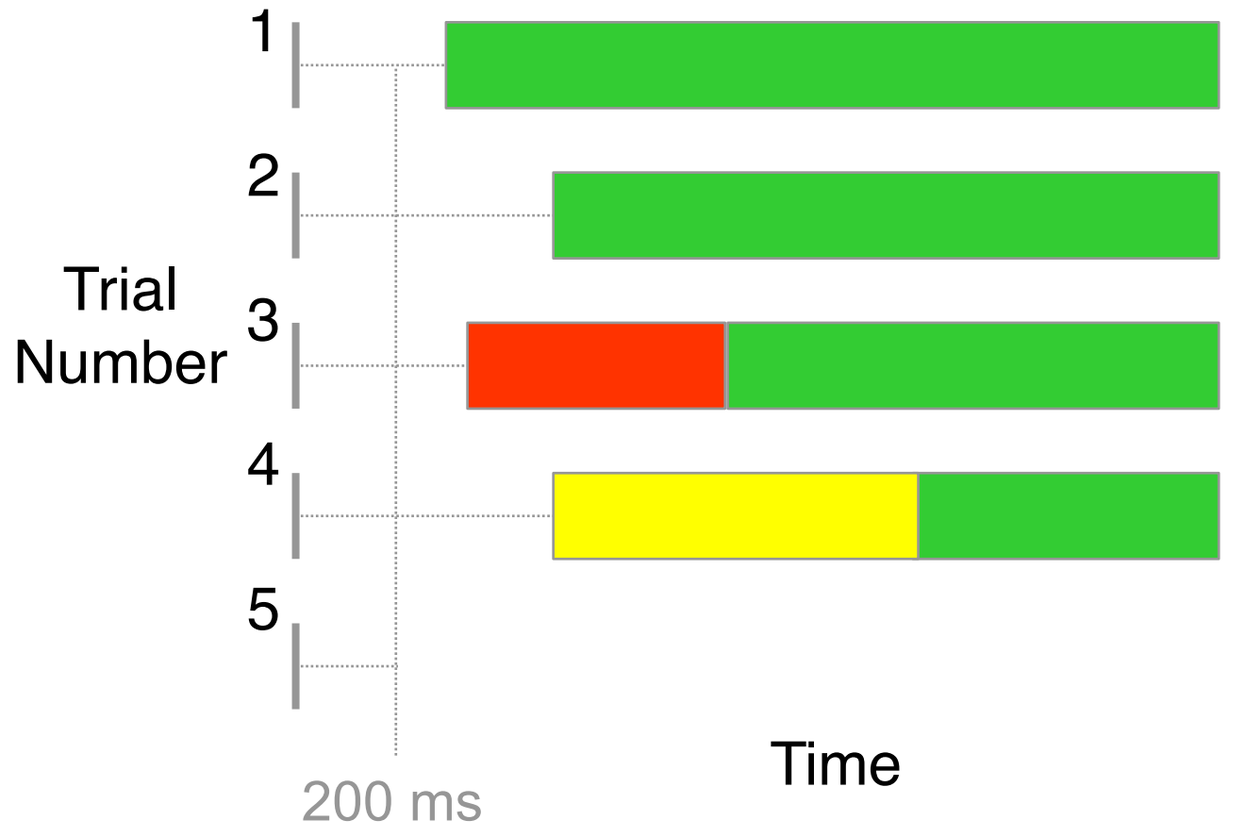

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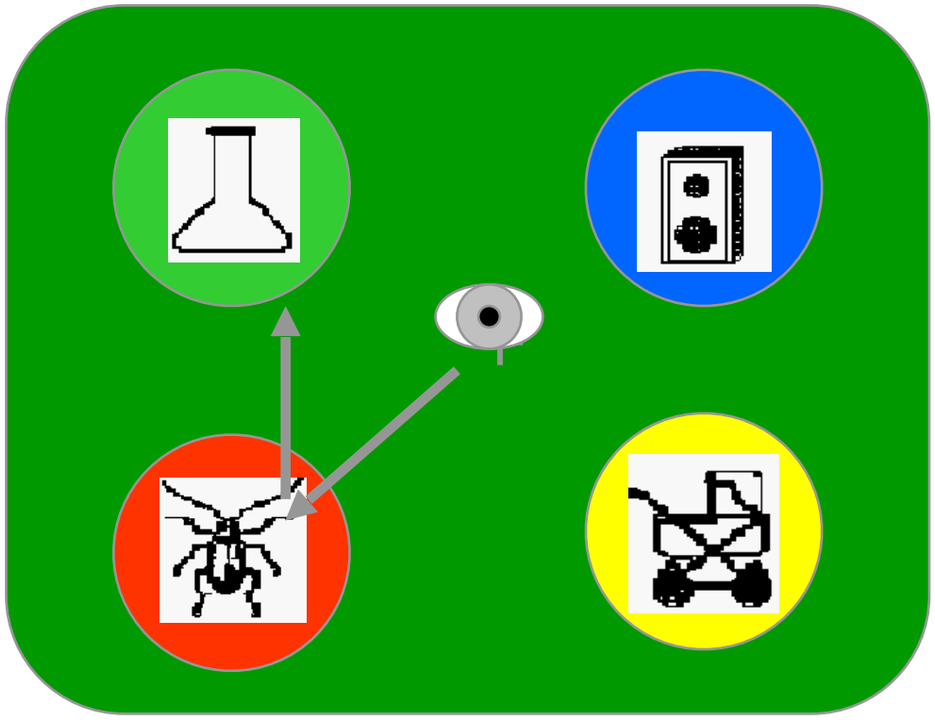

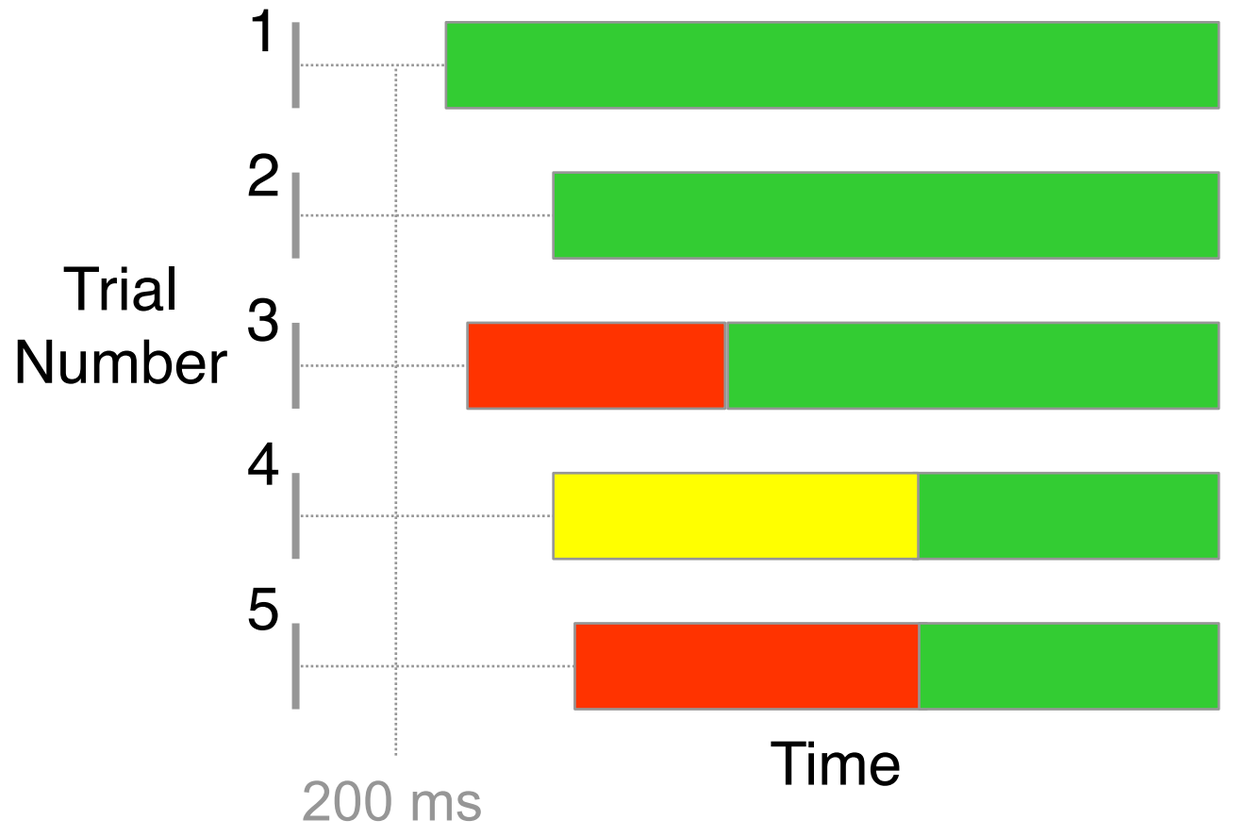

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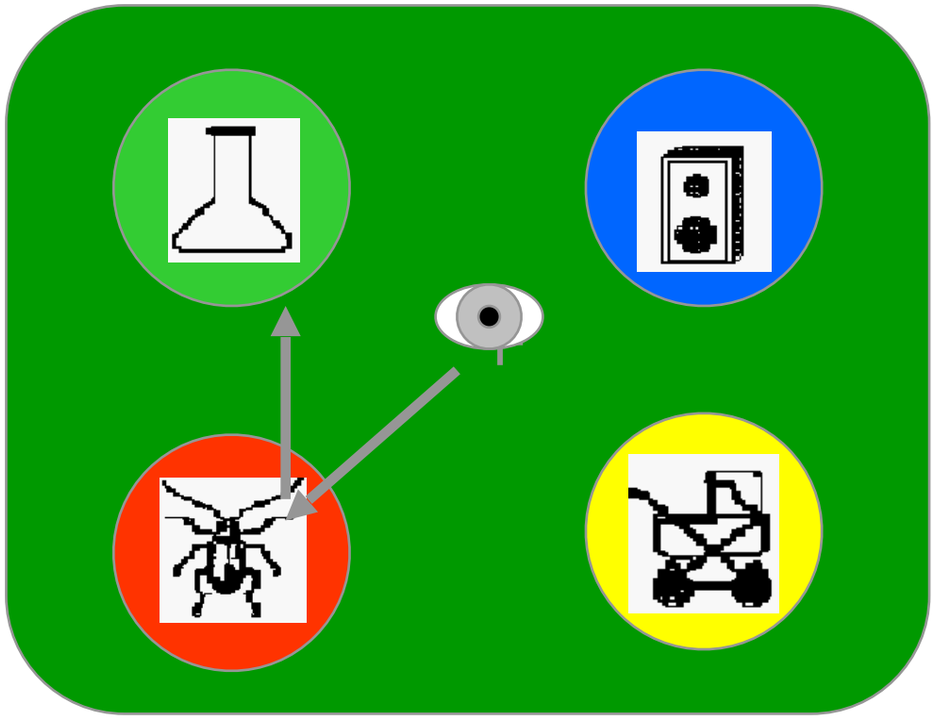

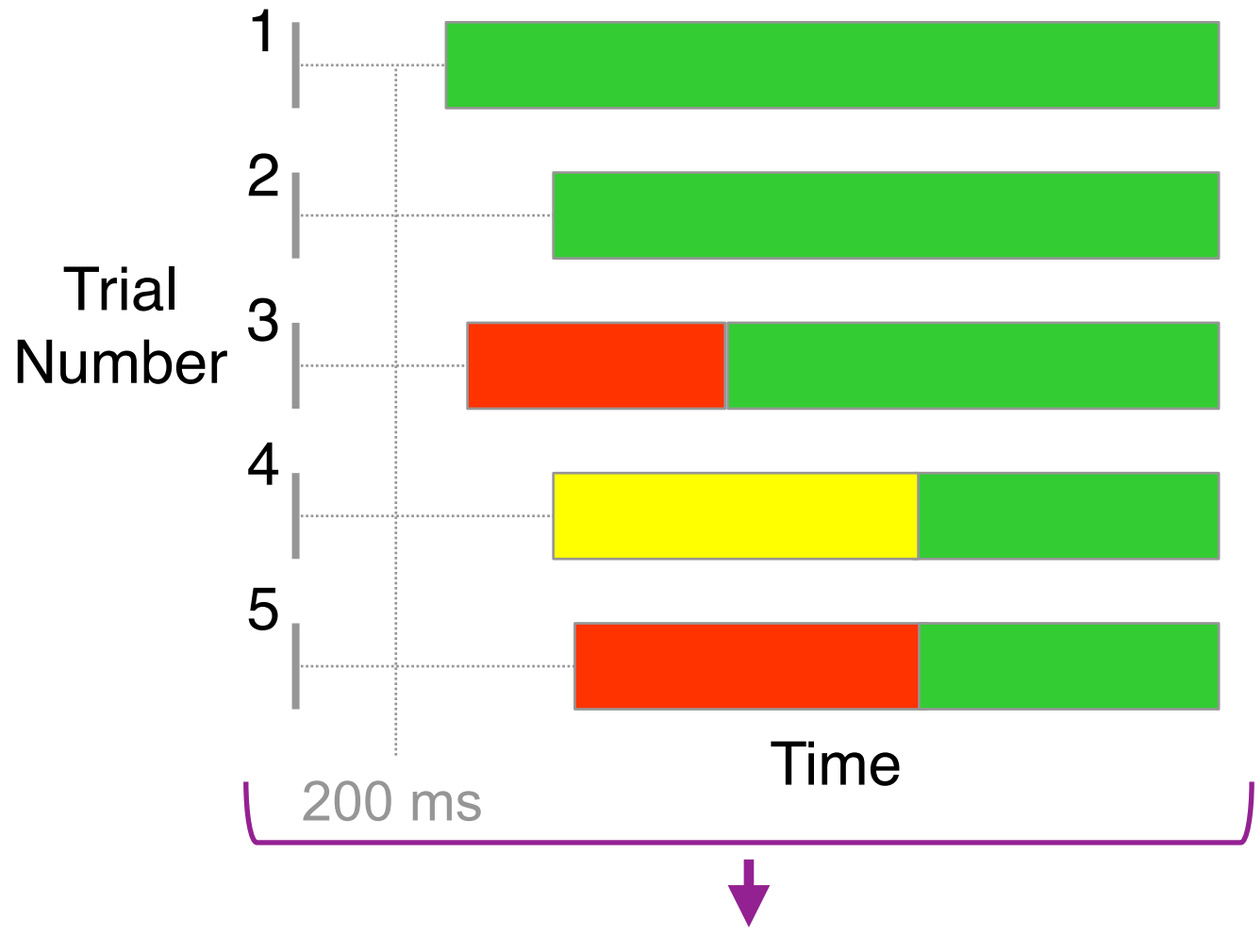

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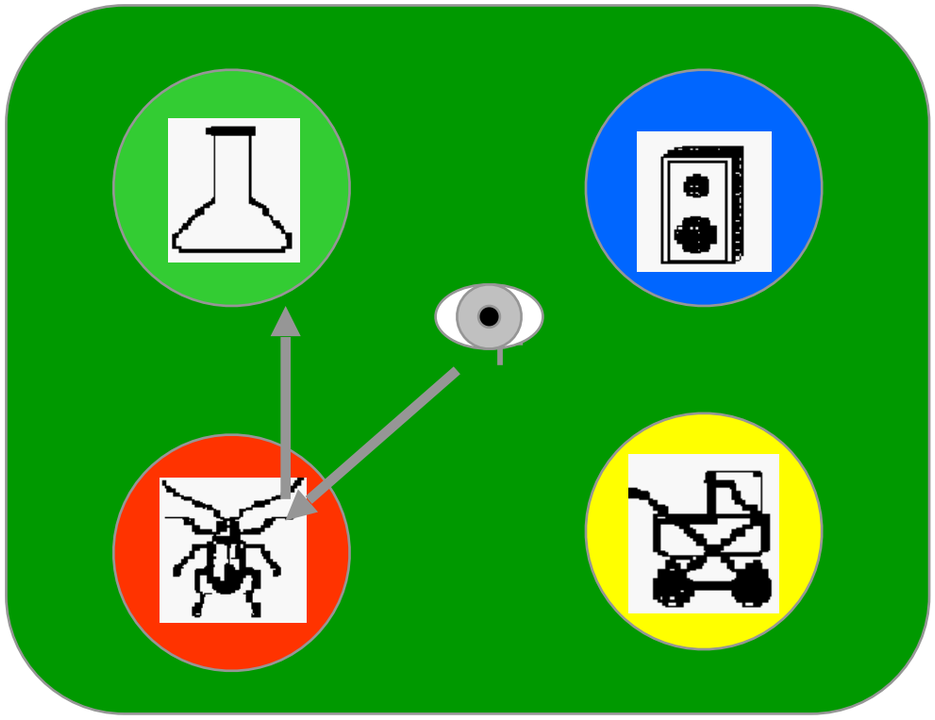

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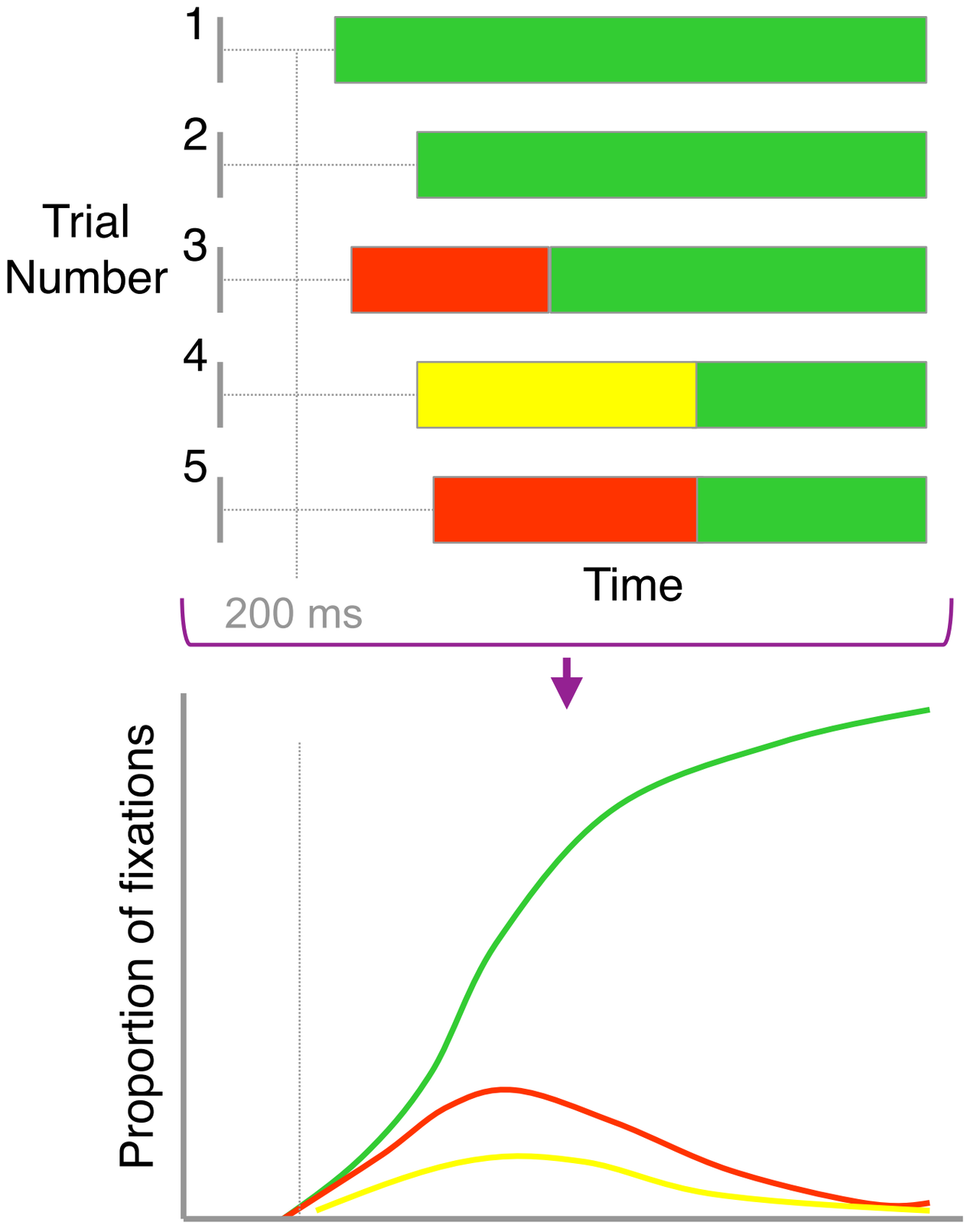

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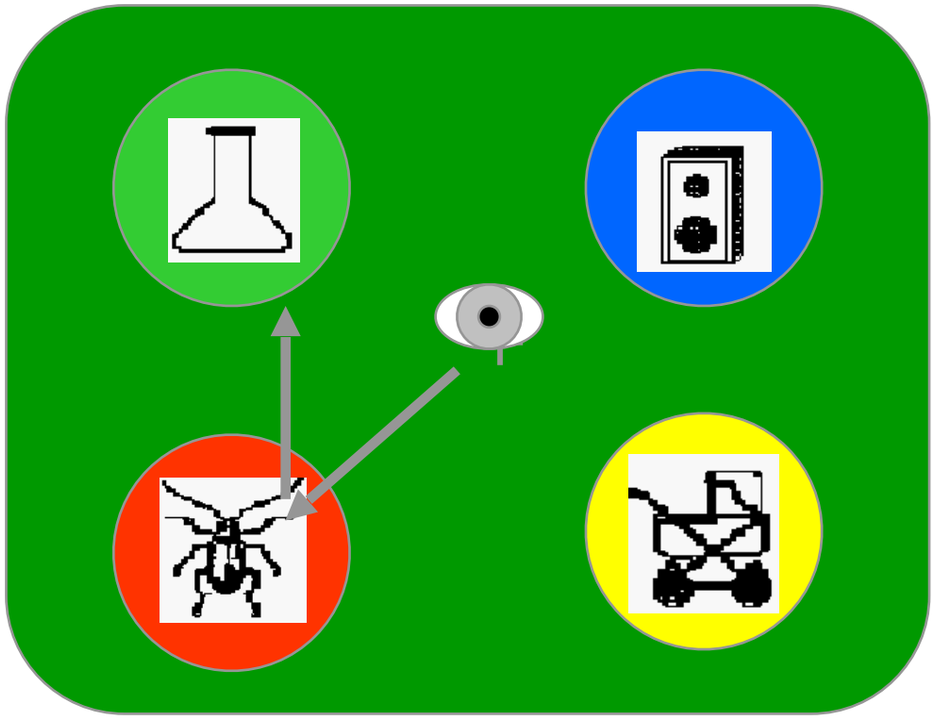

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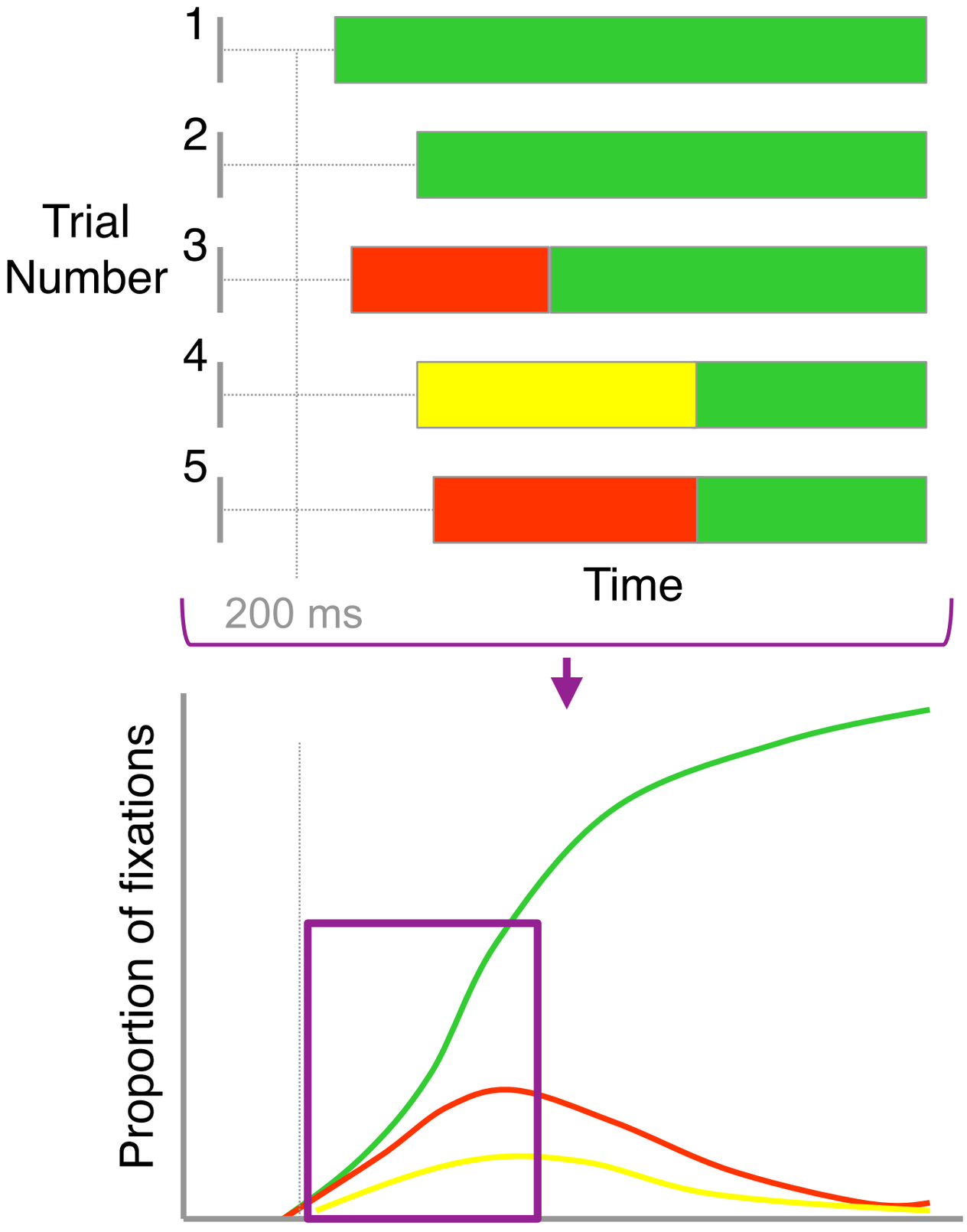

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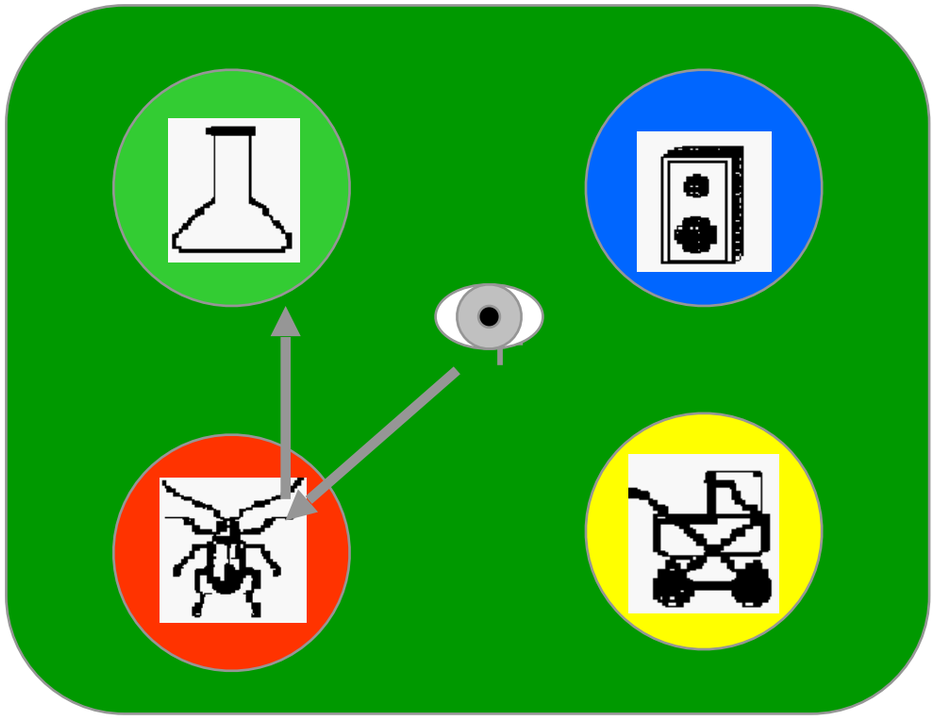

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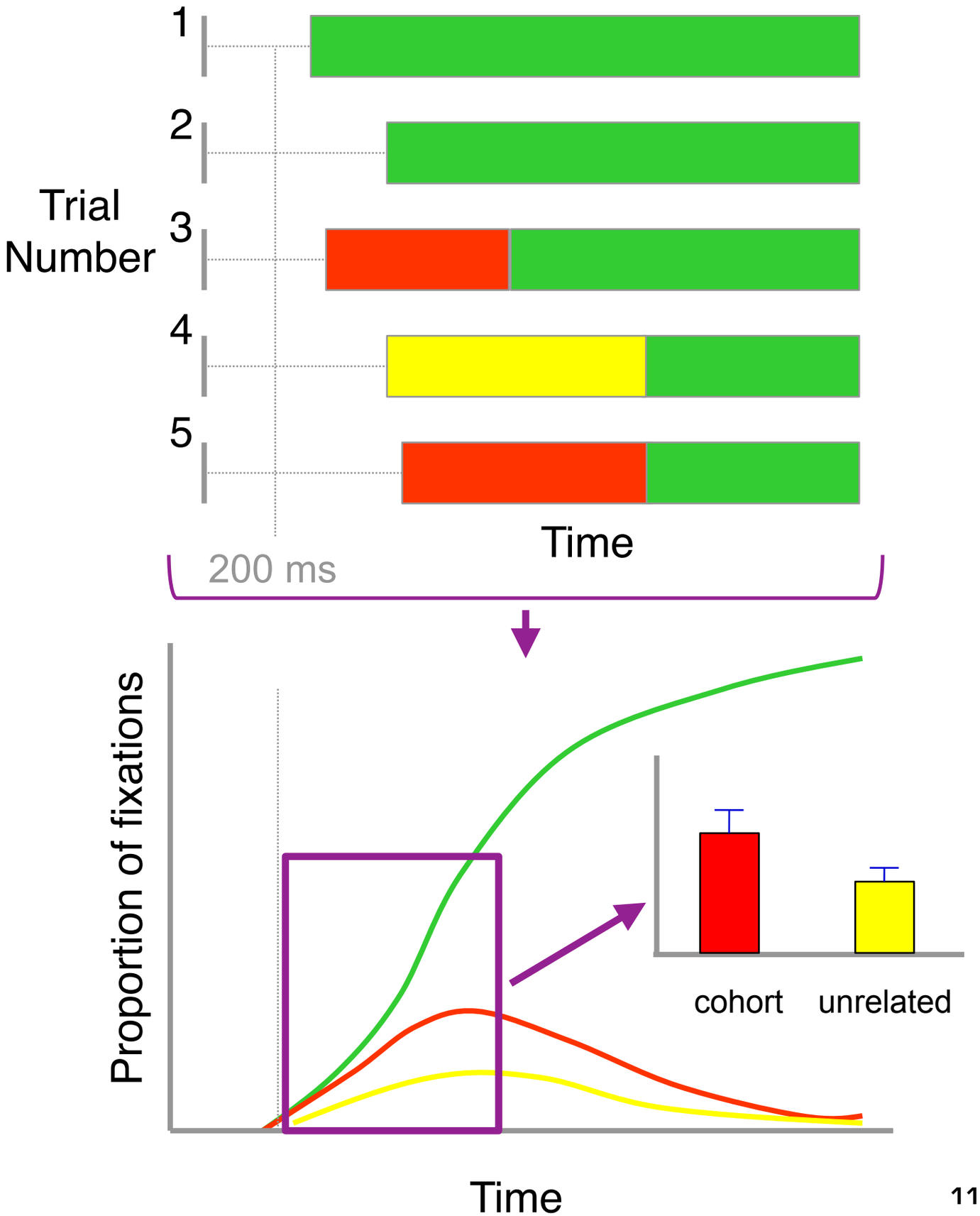

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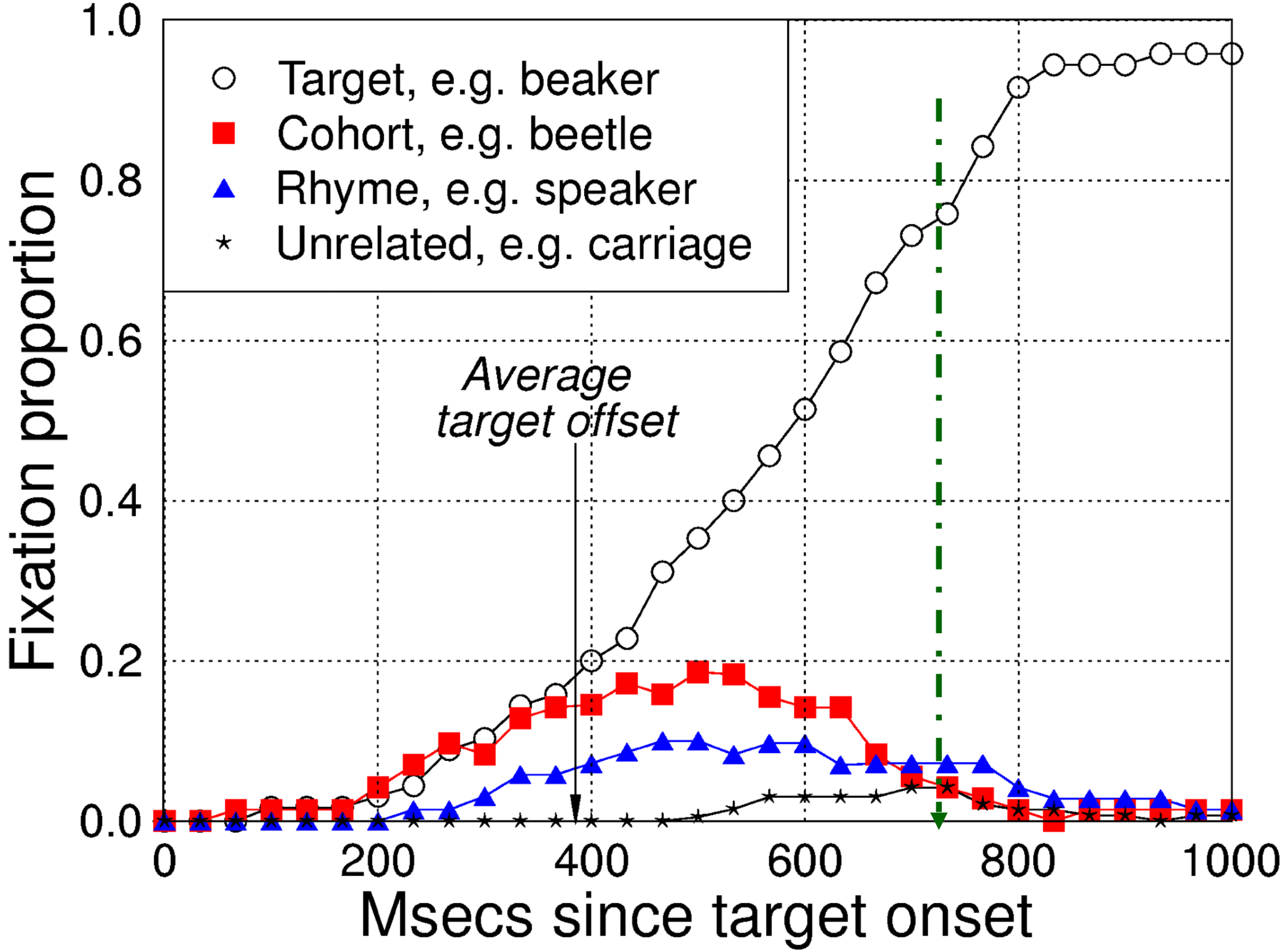
Allopenna, Magnuson & Tanenhaus (1998)



(Slide courtesy of Mike Tanenhaus)

How do people read?

(slide courtesy Yevgeni Berzak)

How do people read?

CNN wants to change its viewers' habits.

(slide courtesy Yevgeni Berzak)

Eye movements in reading

(movie by Piers Cornelissen)

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How do people read?

(slide courtesy Yevgeni Berzak)

How do people read?

Fixations

(slide courtesy Yevgeni Berzak)

How do people read?

Saccades

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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?

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(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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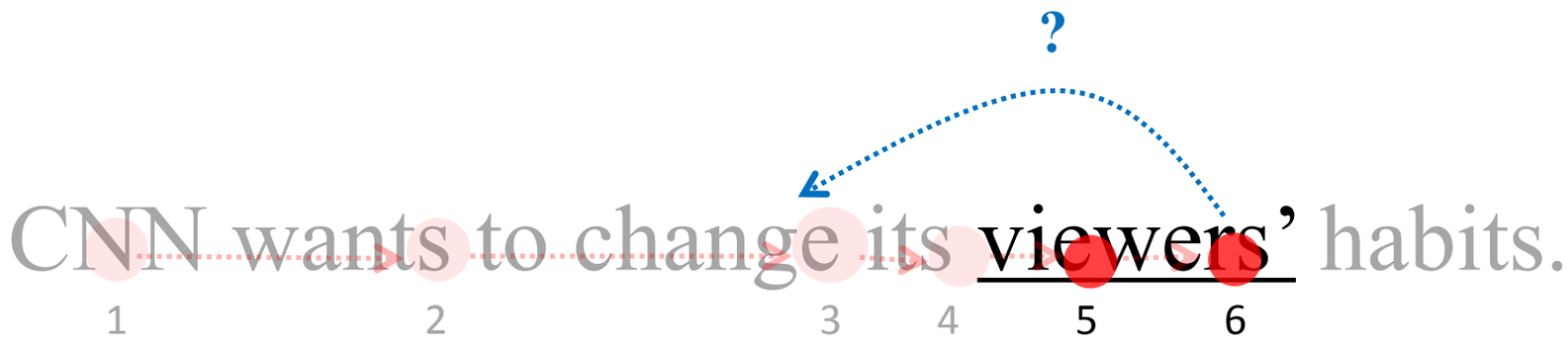

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(slide courtesy Yevgeni Berzak)

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

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

Generalizing incremental disambiguation

- Uncertainty in predictions about upcoming material

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

Generalizing incremental disambiguation

- Uncertainty in predictions about upcoming material

The old man stopped and stared at the

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

Generalizing incremental disambiguation

- Uncertainty in predictions about upcoming material

The old man stopped and stared at the statue?

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

Generalizing incremental disambiguation

- Uncertainty in predictions about upcoming material

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

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

Generalizing incremental disambiguation

- Uncertainty in predictions about upcoming material

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

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

Generalizing incremental disambiguation

- Uncertainty in predictions about upcoming material

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

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

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

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

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

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

Generalizing incremental disambiguation

- Uncertainty in predictions about upcoming material

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

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

Generalizing incremental disambiguation

- Uncertainty in predictions about upcoming material

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

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- 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

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

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 _____

(slide courtesy Yevgeni Berzak)

Rayner & Well 1996

The hikers slowly climbed up the _____

mountain (95%)

(slide courtesy Yevgeni Berzak)

Rayner & Well 1996

The hikers slowly climbed up the _____

mountain (95%)
hillside (3%)

(slide courtesy Yevgeni Berzak)

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
???

(slide courtesy Yevgeni Berzak)

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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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Subj V Subj

(slide courtesy Yevgeni Berzak)

Staub 2011

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Subj V Obj

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

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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.

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

(slide courtesy Yevgeni Berzak)

Staub 2011: word frequency & predictability effects

While the professor lectured the students walked across the quad.
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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

(slide courtesy Yevgeni Berzak)

Staub 2011: word frequency & predictability effects

High **F**requency

While the professor lectured the students walked across the quad.
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(slide courtesy Yevgeni Berzak)

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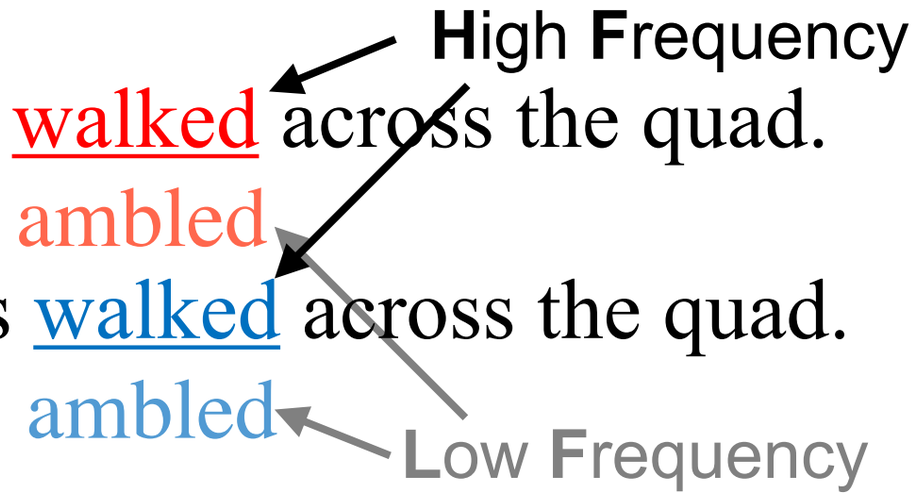

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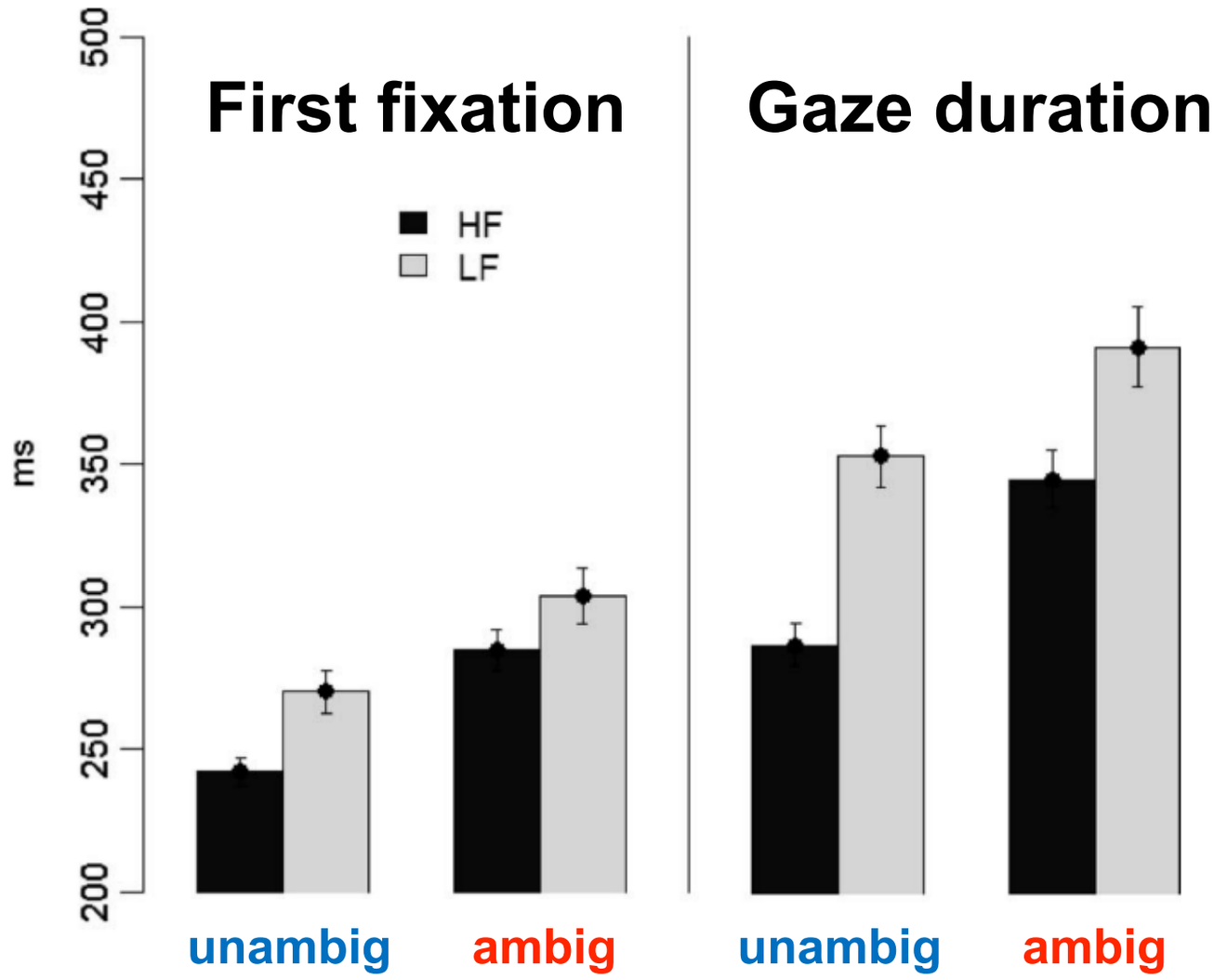
Low **F**requency



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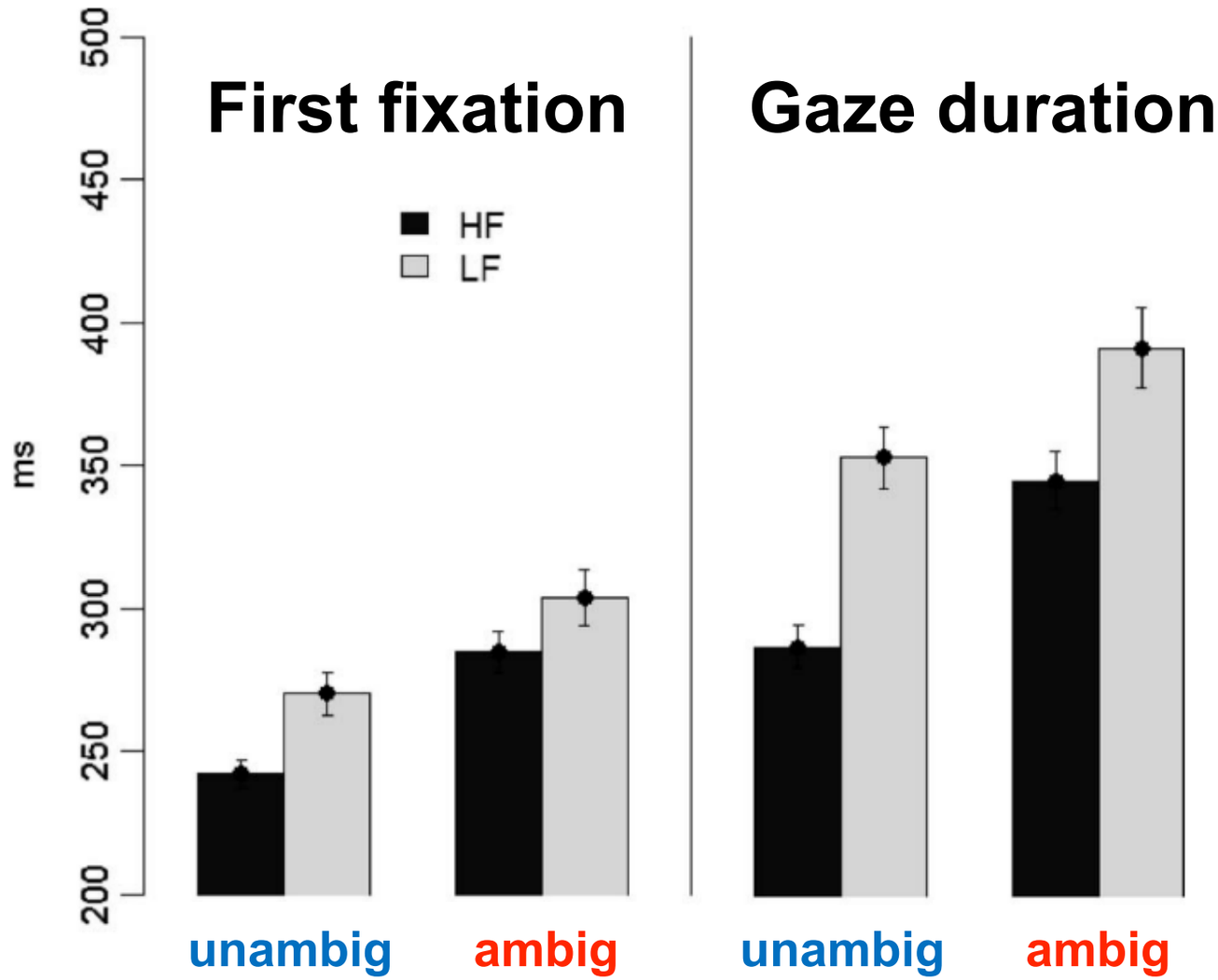

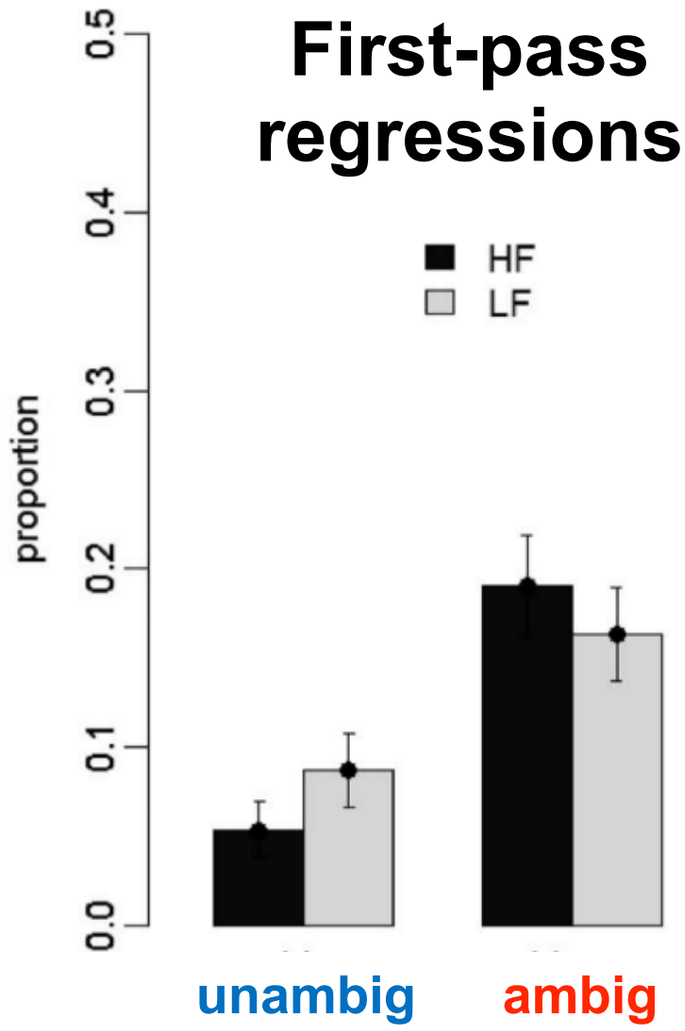

(slide courtesy Yevgeni Berzak)

Psycholinguistic methodology (2)

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

Psycholinguistic methodology (2)

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- Reveal each consecutive word with a button press

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While ----------------------------------------------------------
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Psycholinguistic methodology (2)

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Psycholinguistic methodology (2)

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--------- clouds ---------------------------------------------------
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Psycholinguistic methodology (2)

- A lower-tech method: **self-paced reading** (SPR)
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---------------- crackled, ----------------------------------------
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Psycholinguistic methodology (2)

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---------- 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)

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

Psycholinguistic methodology (3)

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

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

Psycholinguistic methodology (3)

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

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Psycholinguistic methodology (3)

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

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

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

F J

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

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The x-x-x

F J

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of	*dog*
F	J

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pretty chased

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`the` `eat`

F J

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the

eat

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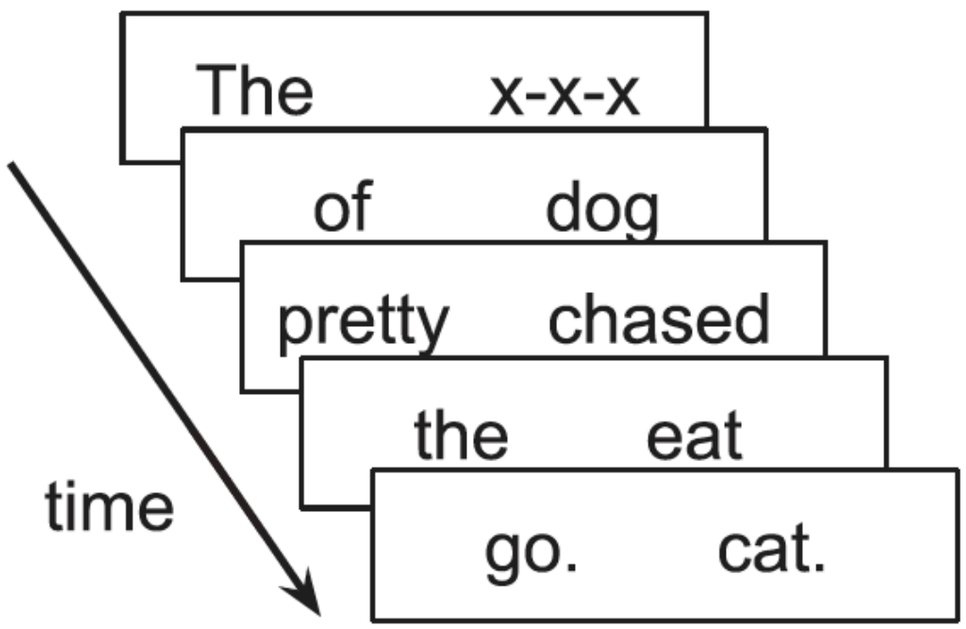


(Forster et al., 2009; Boyce et al., 2020)

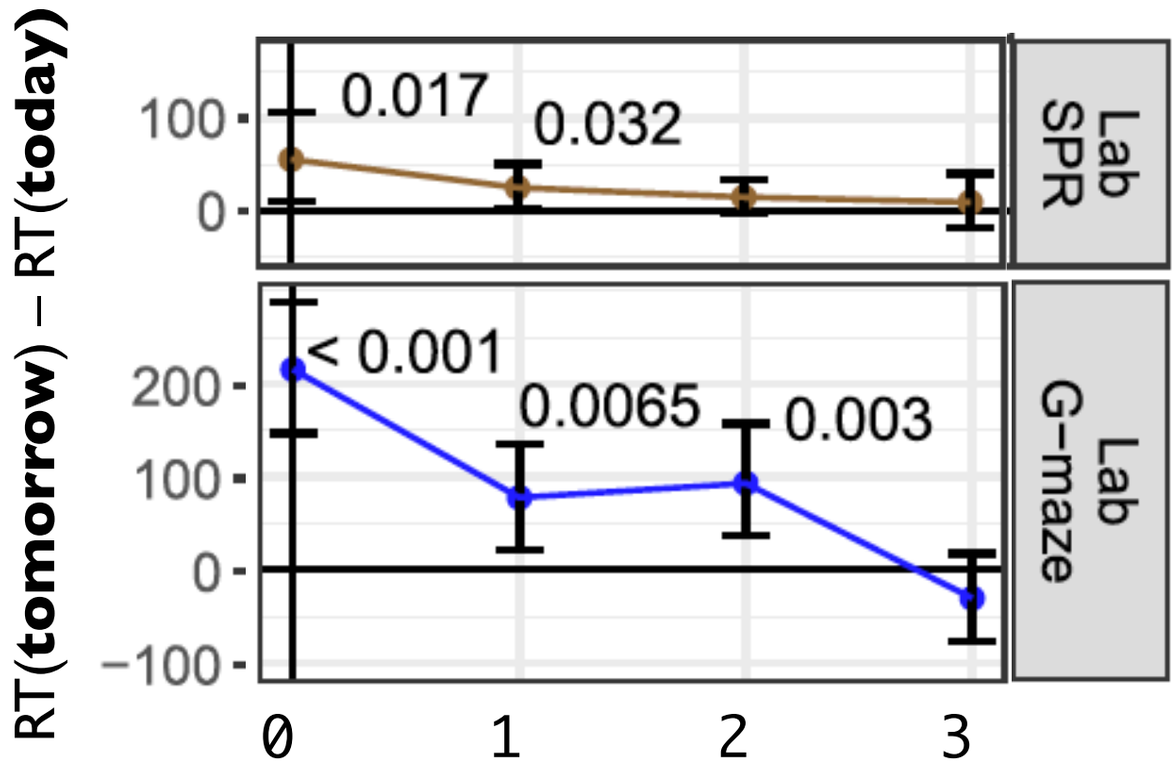
Example SPR and Maze results

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

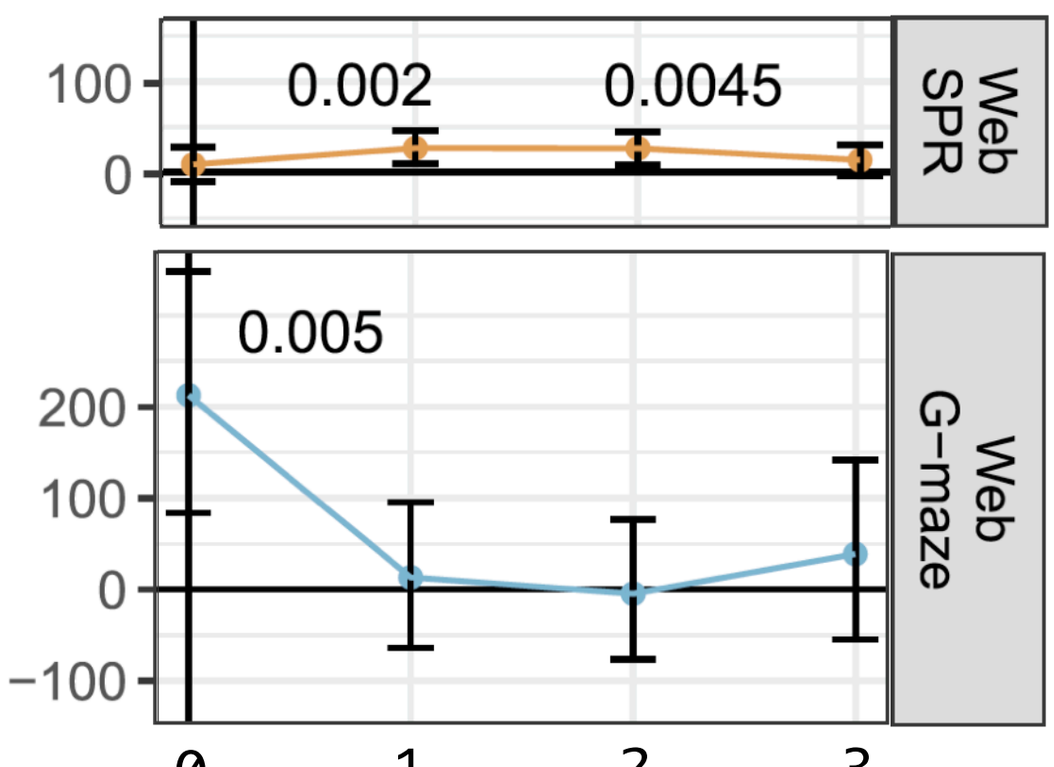
James will fix the car he drove **tomorrow,** but he will need some help.

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

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)

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***
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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.	–	–

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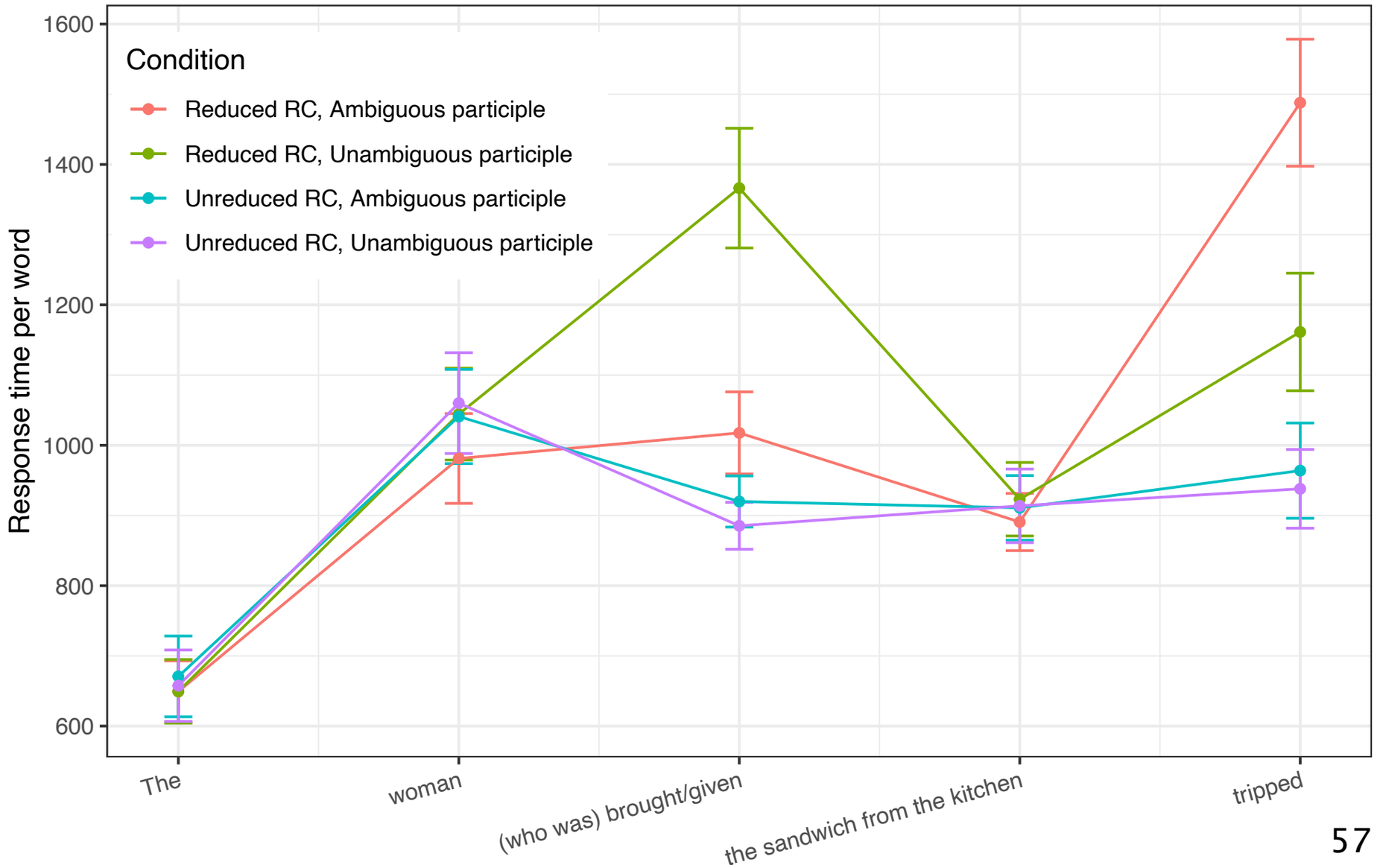

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Psycholinguistic methodology (3)

- *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

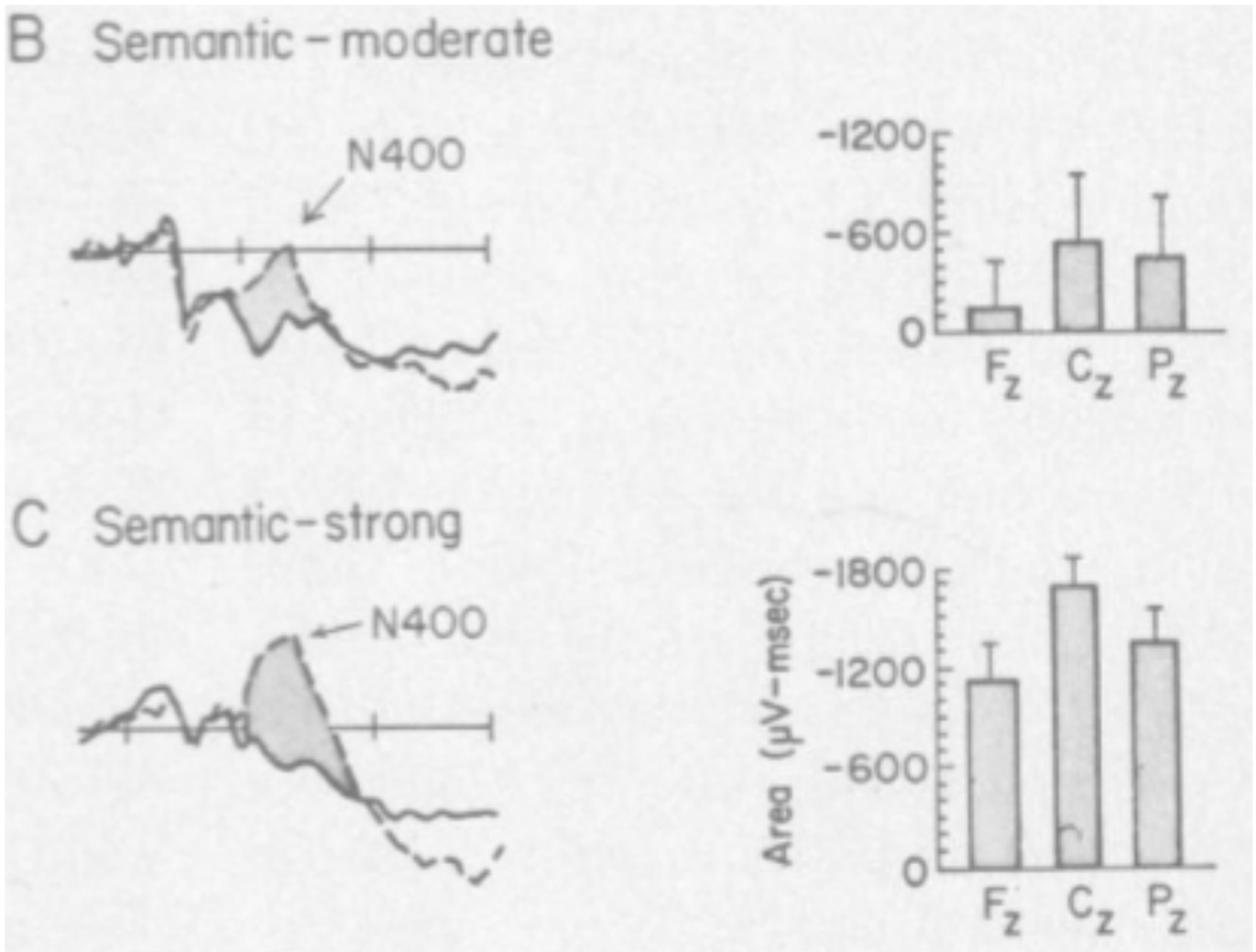
Rapid Serial Visual Presentation

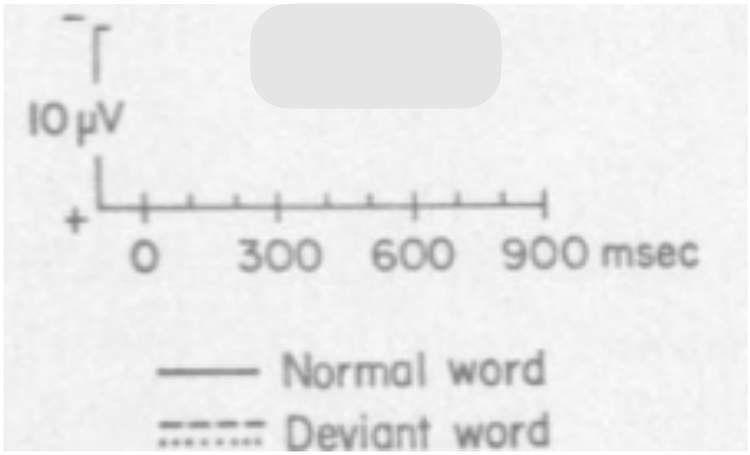
*

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)





(Kutas & Hillyard, 1980, 1984)

The P600 ERP component in language comprehension

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

The P600 ERP component in language comprehension

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

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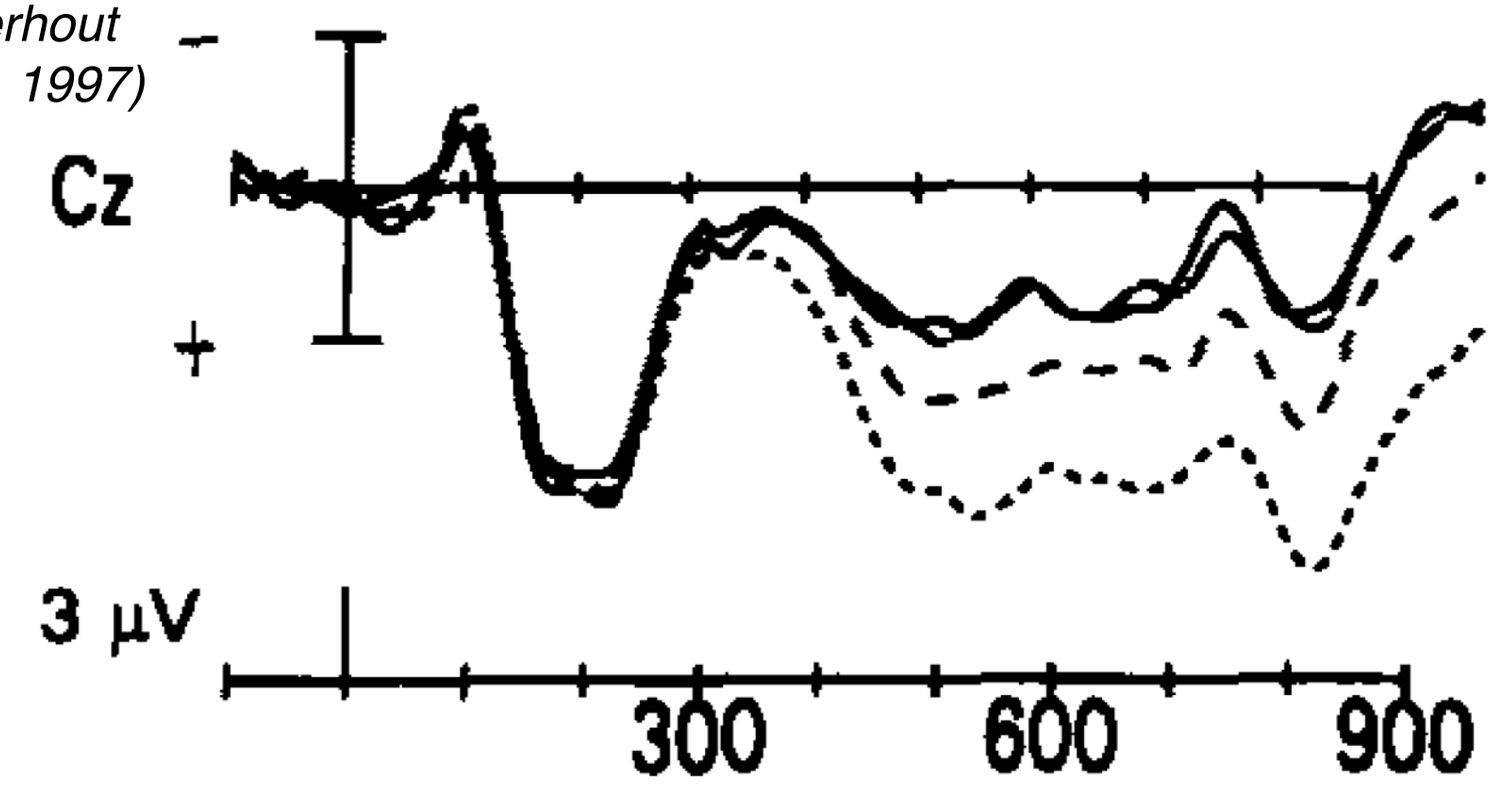

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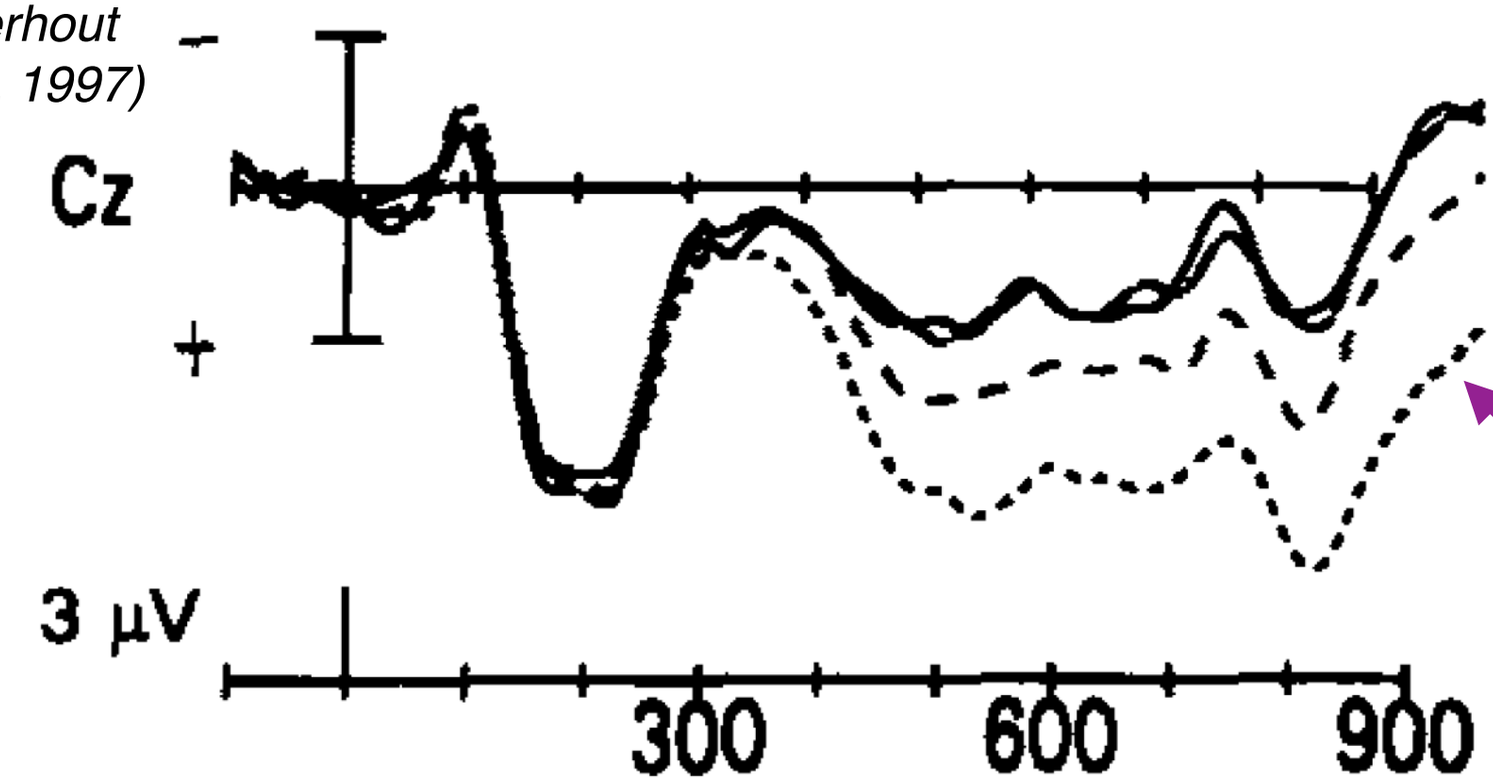

"Definitional" mismatch (man…herself)

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

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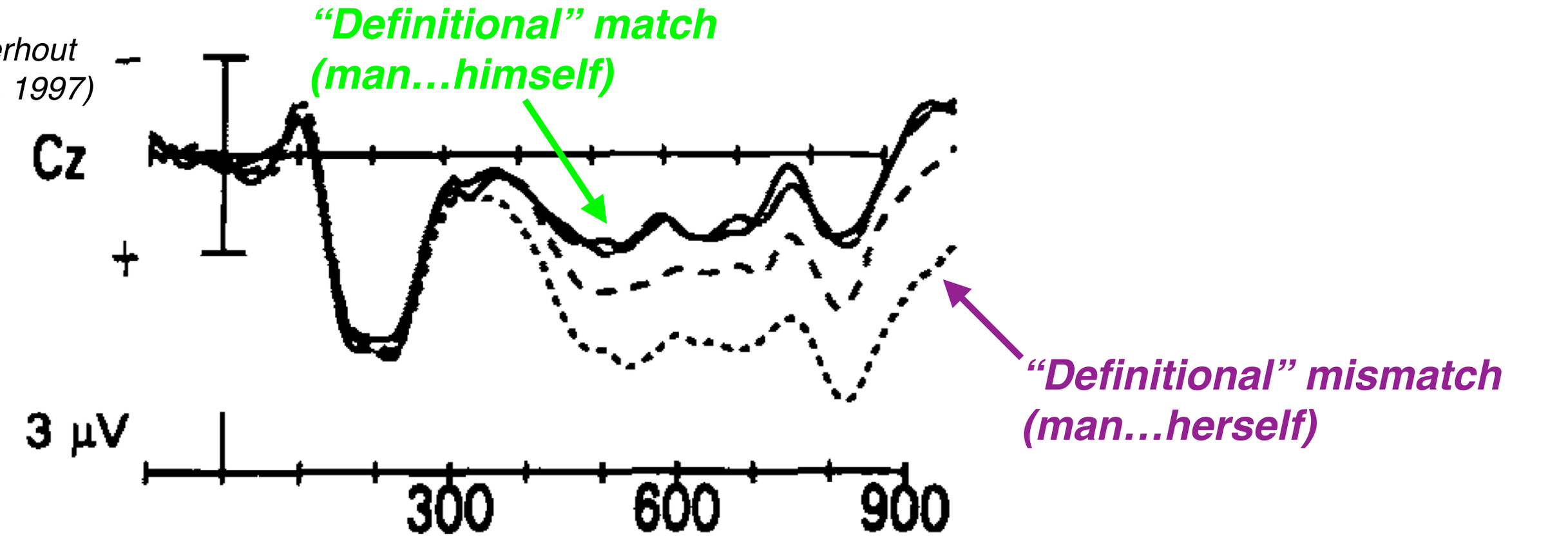

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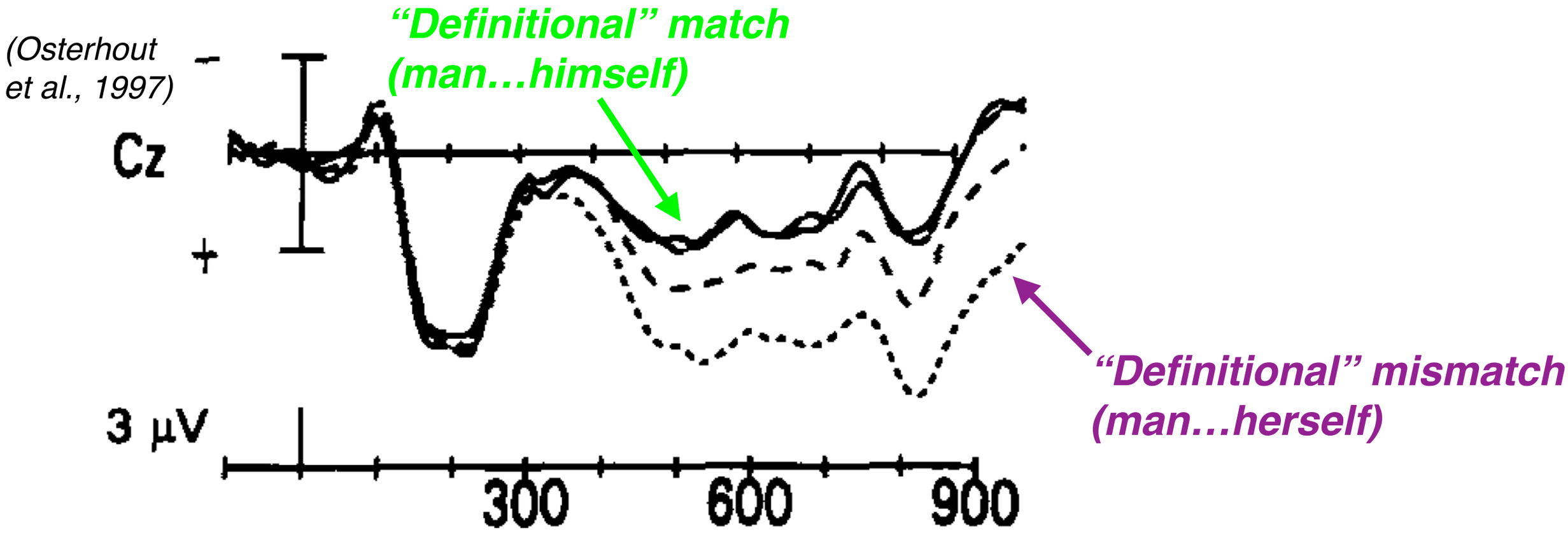

- Mismatches to *stereotypical* semantic properties induce similar violations

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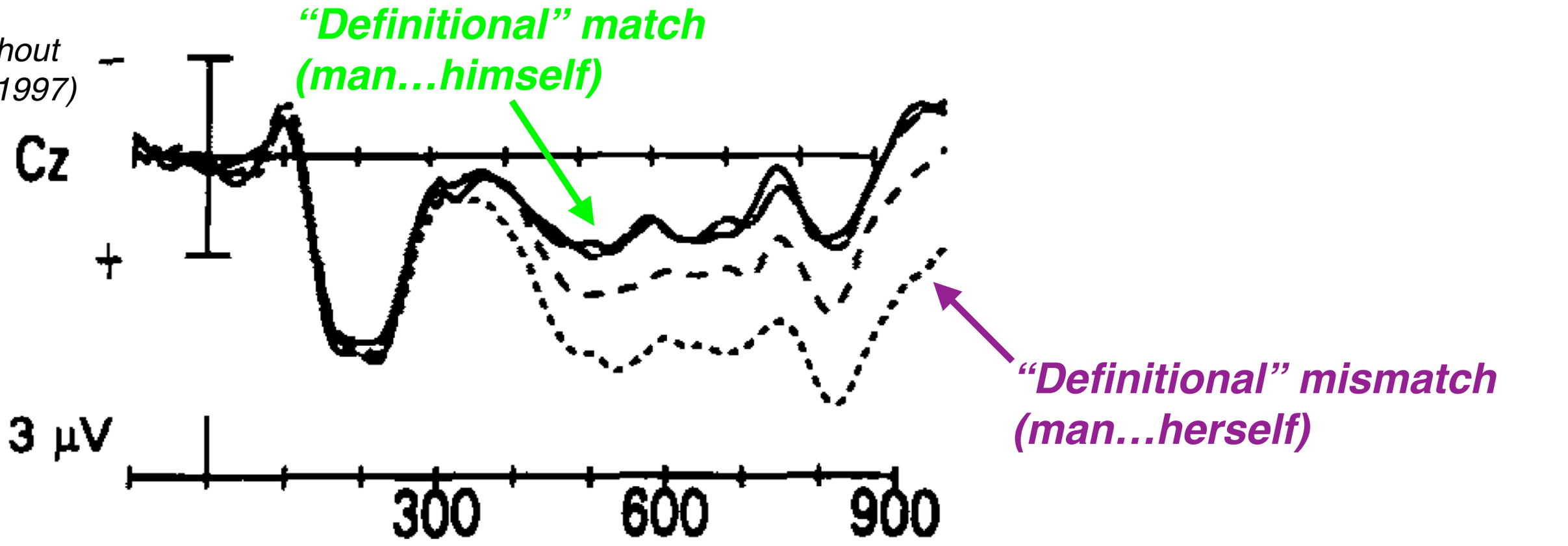

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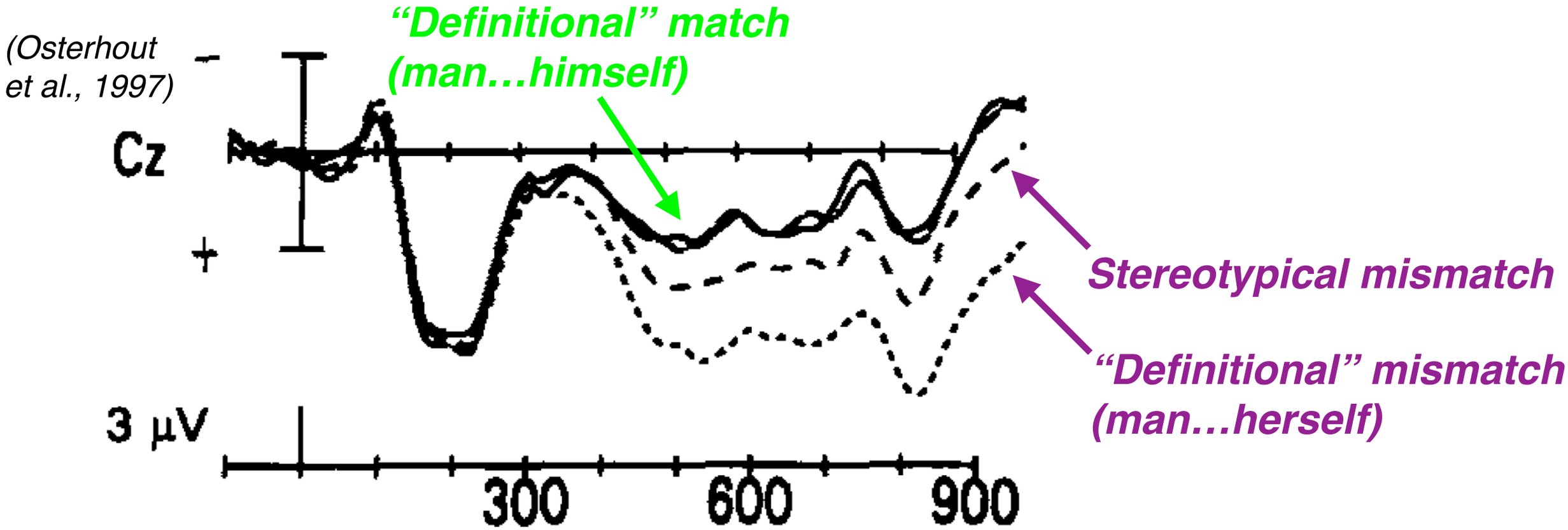

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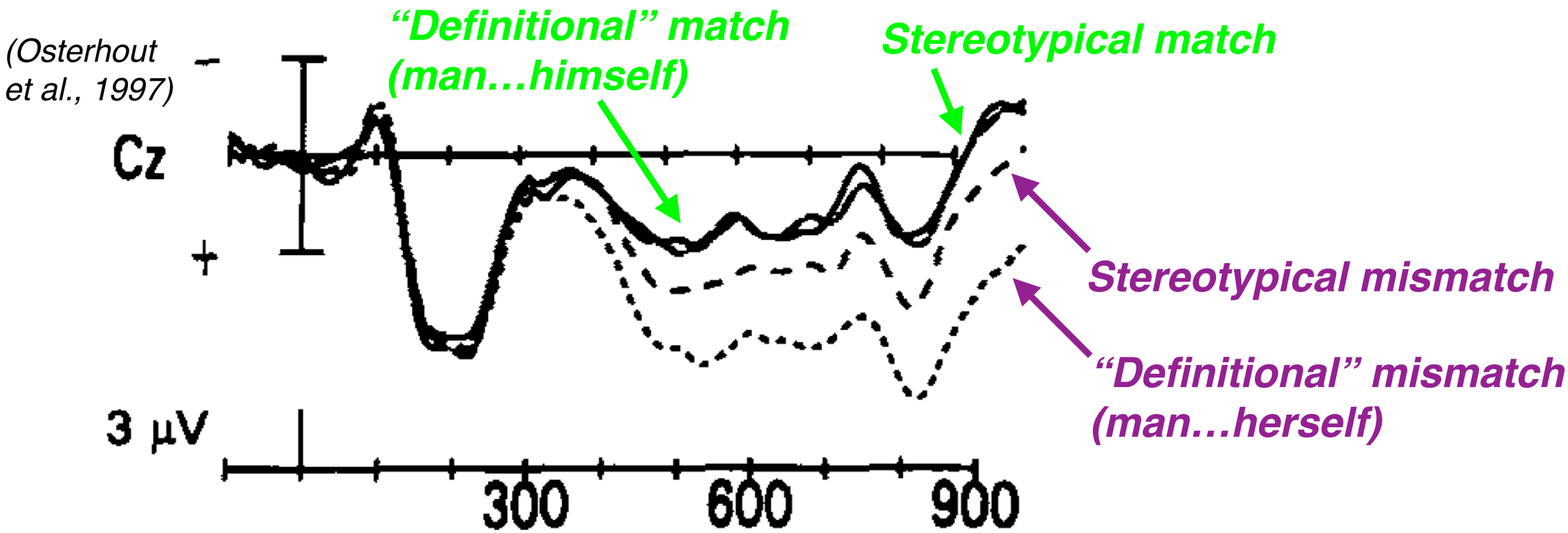

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fMRI recordings during comprehension

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

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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	+

(Fedorenko et al., 2011)

fMRI recordings during comprehension

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Nonwords condition

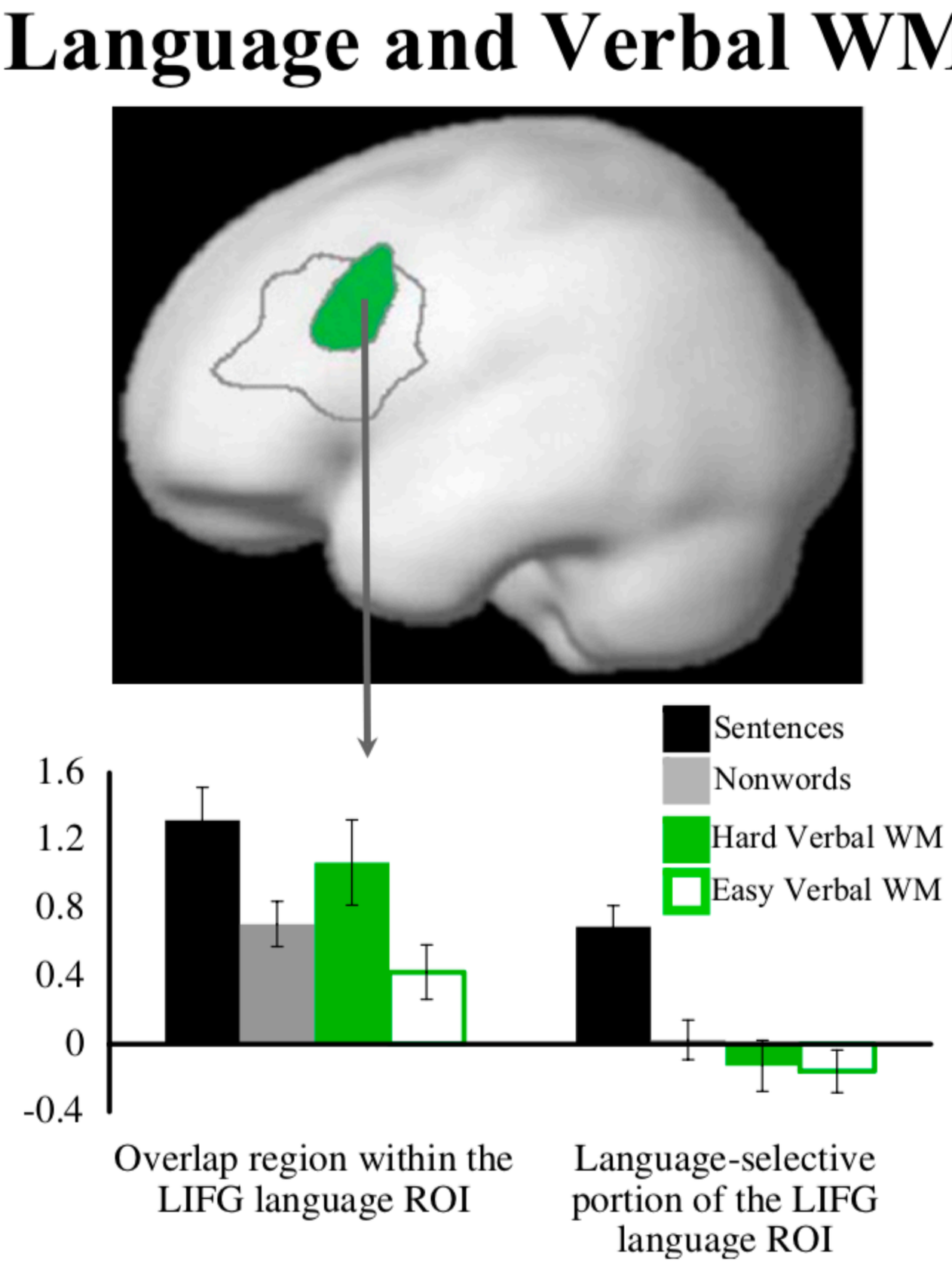
DAP	DRELLO	SMOP	UB	PLID	KAV	CRE	REPLODE	+	DRELLO/ NUZZ	+

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

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

(Fedorenko et al., 2011)

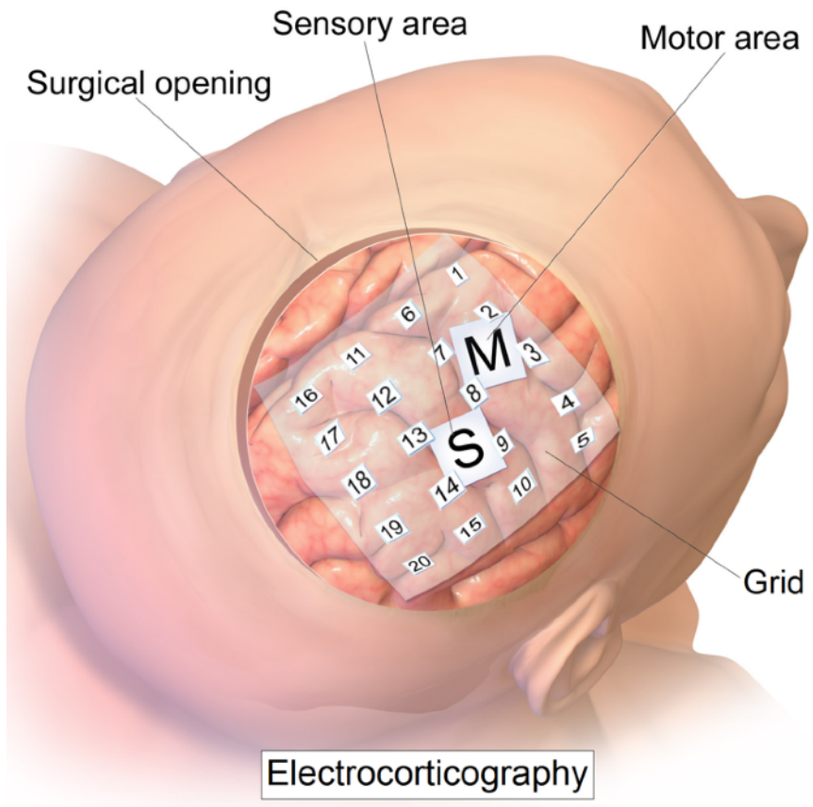
Functional brain specificity for language



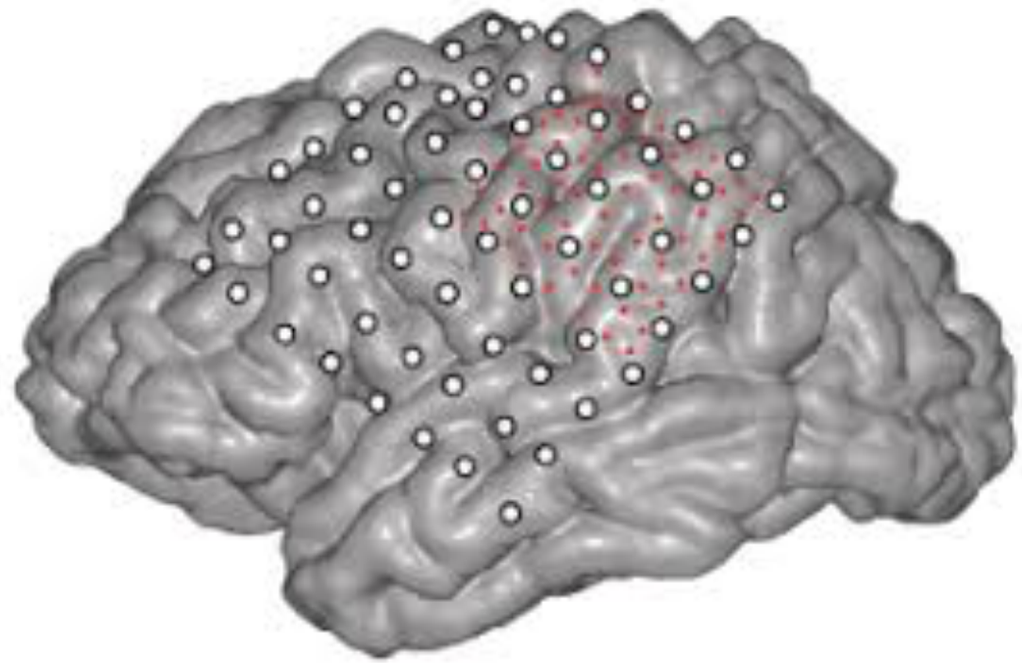
(Fedorenko et al., 2011)

Electrocorticography

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



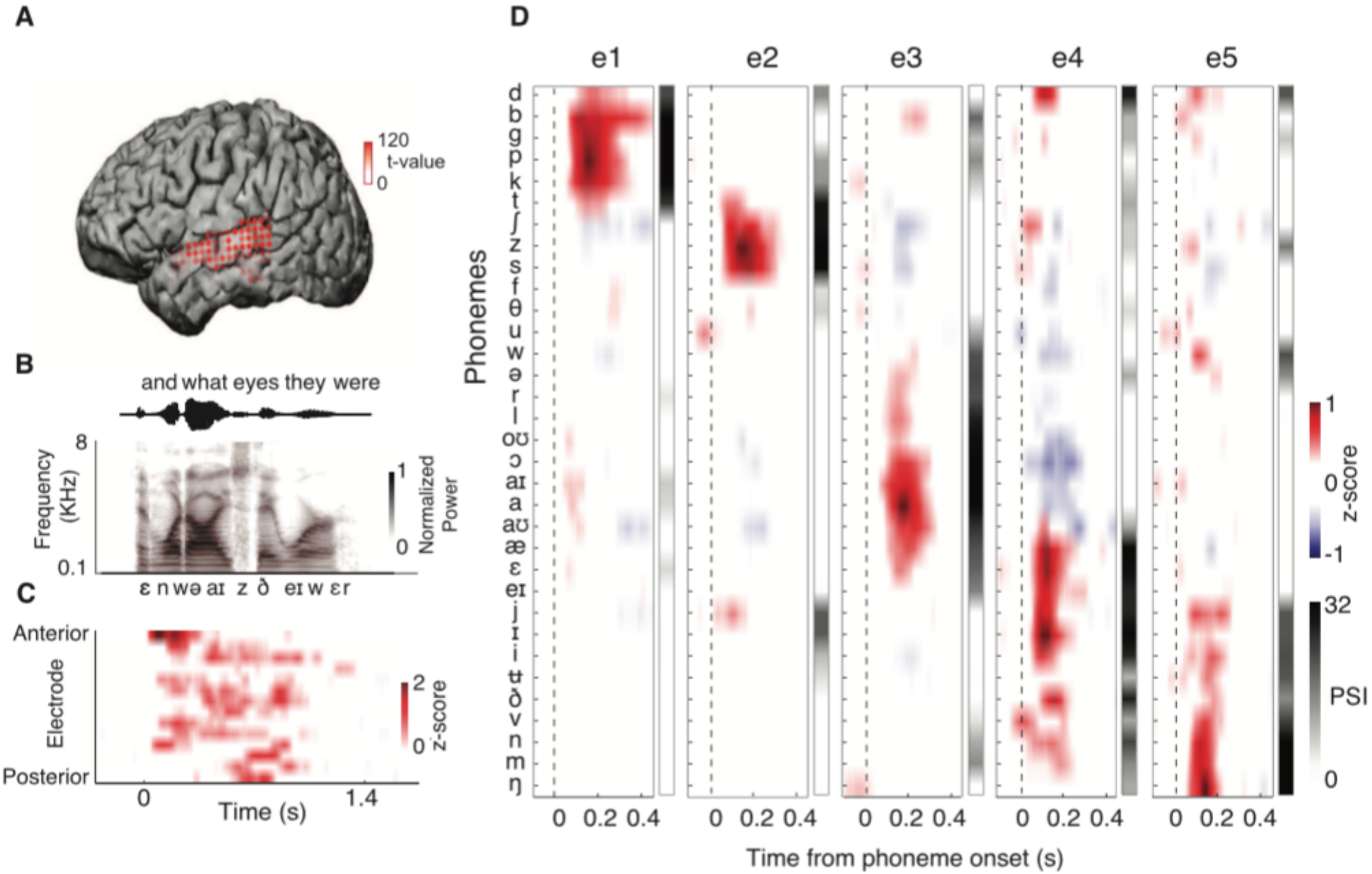
https://commons.wikimedia.org/wiki/File:Intracranial_electrode_grid_for_electrocorticography.png



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

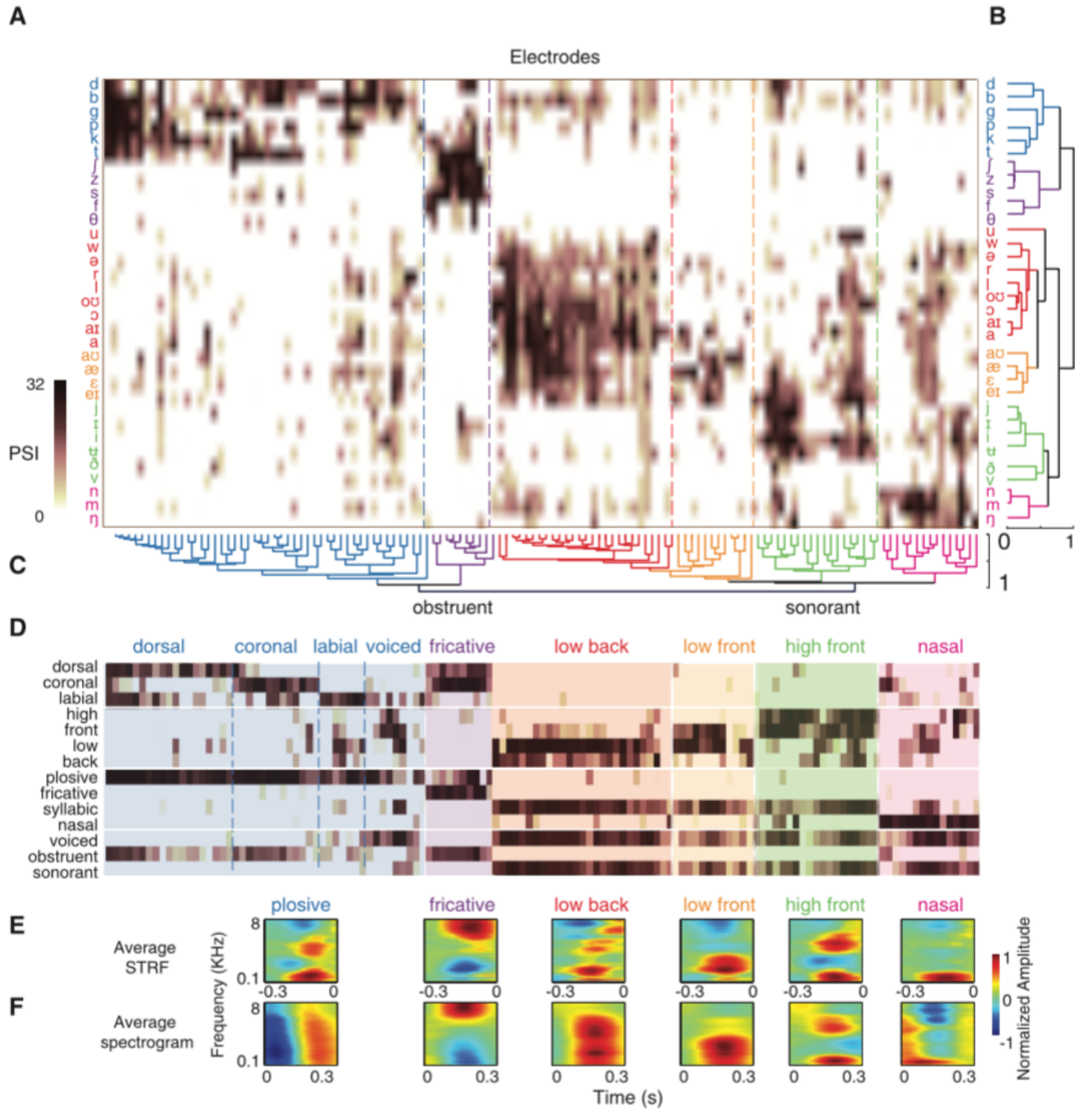
- During pre-surgical monitoring many patients generously donate their energy & attention for experiments

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

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