Syntactic adaptation to short-term cue-based distributional regularities

Weijie Xu[1], Jiaxuan Li[1], Ming Xiang[2], Richard Futrell[1]

[1]University of California, Irvine, [2]The University of Chicago

44th Annual Conference of the Cognitive Science Society

July 27 - 30, 2022

Introduction

- Humans make adaptation to short-term exposure [1-3]

- But…previous studies test repeated exposure to the same structure

  > Reduced-relative clause:

  e.g. The patient (that was) examined by the doctor was diagnosed with diabetes.

- We ask: ***Adaptation to context-dependent cue-based regularities?***

[1] Pickering & Ferreira (2008); [2] Tooley & Traxler (2010); [3] Fine, Jaeger, Farmer & Qian (2013)

Current Study

■ Context-dependent adaptation

> Animacy cue in reduced-relative clause garden-path sentences

Subj.NP Animacy (animate vs. inanimate) ⟷ **Parsing bias** (RR vs. MV)

> Predictions:

- If animate subj. → RR ; smaller GP effect for animate subj.
- If inanimate subj. → RR ; smaller GP effect for inanimate subj.

Self-paced reading experiment

- **Design**

Training Block → Testing Block

Self-paced reading experiment

Design

Training Block → Testing Block

> GP effect of RR sentences

Original bias: animate → larger GP ;
inanimate → smaller GP

Testing block sample stimuli

(1) Animate → RR

The patient (that was) examined by the doctor was diagnosed with diabetes.

(2) Inanimate → RR

The document (that was) examined by the lawyer turned out to be unreliable.

Self-paced reading experiment

Design

Training Block → Testing Block

- Manipulate cue-based regularities
- 3 treatment groups

- GP effect of RR sentences

Original bias: animate → larger GP ;
inanimate → smaller GP

Self-paced reading experiment

Design

Training Block → Testing Block

> Manipulate cue-based regularities

> 3 treatment groups

Group A (n=122):
animate → RR; inanimate → MV
animate → smaller GP; inanimate → larger GP

> GP effect of RR sentences

Original bias: animate → larger GP ;
inanimate → smaller GP

Group A sample stimuli

(1) Animate → RR

The defendant examined by the lawyer turned out to be unreliable.

(2) Inanimate → MV

The hypothesis examined the factors that affected the quality of language inputs.

Self-paced reading experiment

Design

Training Block → Testing Block

> Manipulate cue-based regularities

> 3 treatment groups

Group A (n=122):

animate → RR; inanimate → MV
animate → smaller GP; inanimate → larger GP

Group B (n=126):

animate → MV; inanimate → RR
animate → larger GP; inanimate → smaller GP

> GP effect of RR sentences

Original bias: animate → larger GP ;
inanimate → smaller GP

Group B sample stimuli

(1) Animate → MV

The defendant examined the testimony carefully before going to the court.

(2) Inanimate → RR

The hypothesis examined by the young scientist was not widely known until the recent years.

Self-paced reading experiment

Design

Training Block → Testing Block

> Manipulate cue-based regularities

> 3 treatment groups

Group A (n=122):
animate → RR; inanimate → MV
animate → smaller GP; inanimate → larger GP

Group B (n=126):
animate → MV; inanimate → RR
animate → larger GP; inanimate → smaller GP

Group C (n=125):
Filler items; show original bias

> GP effect of RR sentences

Original bias: animate → larger GP ;
inanimate → smaller GP

Self-paced reading experiment

- **Data Analysis**
  - > Reading times on test block

Animate subject

Ambiguous: *The patient examined by the doctor was diagnosed with diabetes.*
Unambiguous: *The patient that was examined by the doctor was diagnosed with diabetes.*

Inanimate subject

Ambiguous: *The document examined by the lawyer turned out to be unreliable.*
Unambiguous: *The document that was examined by the lawyer turned out to be unreliable.*

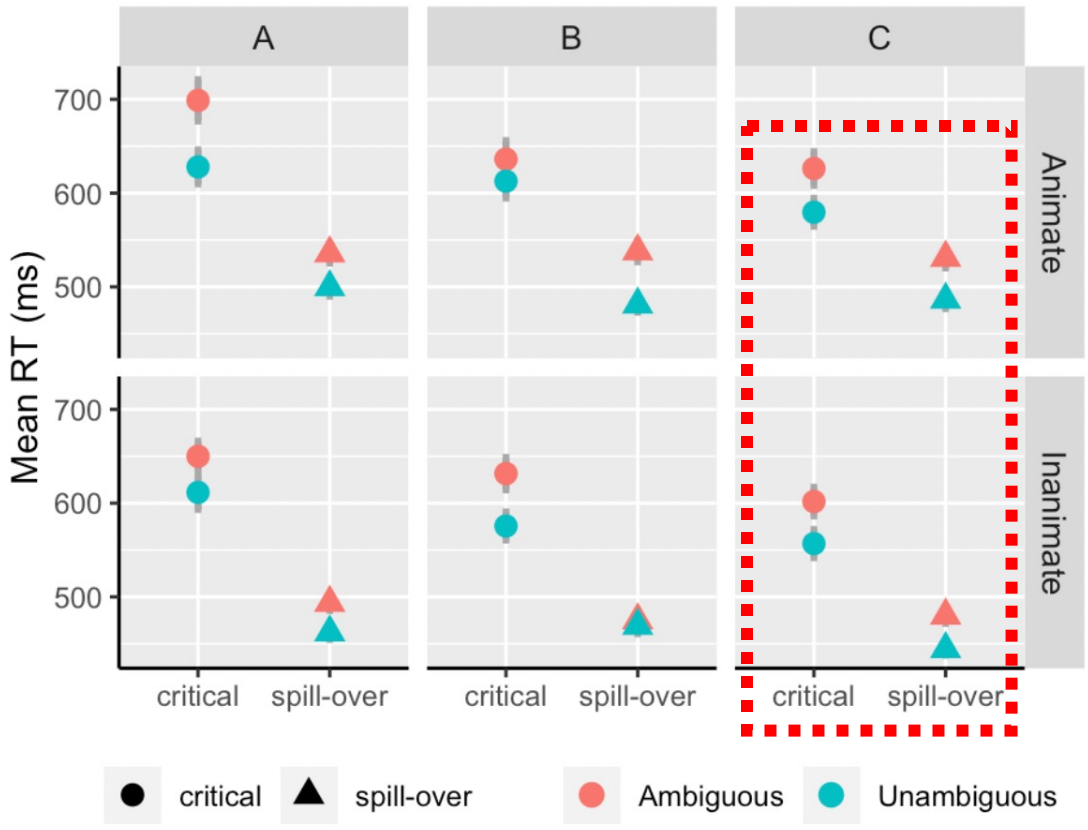
LMEM over log RTs: {disambiguating} {spill-over}

  - > GP effect: Ambiguity
  - > GP effect across subject animacy across treatment groups

Critical statistics: Ambiguity x Animacy x Group

Self-paced reading experiment

Results



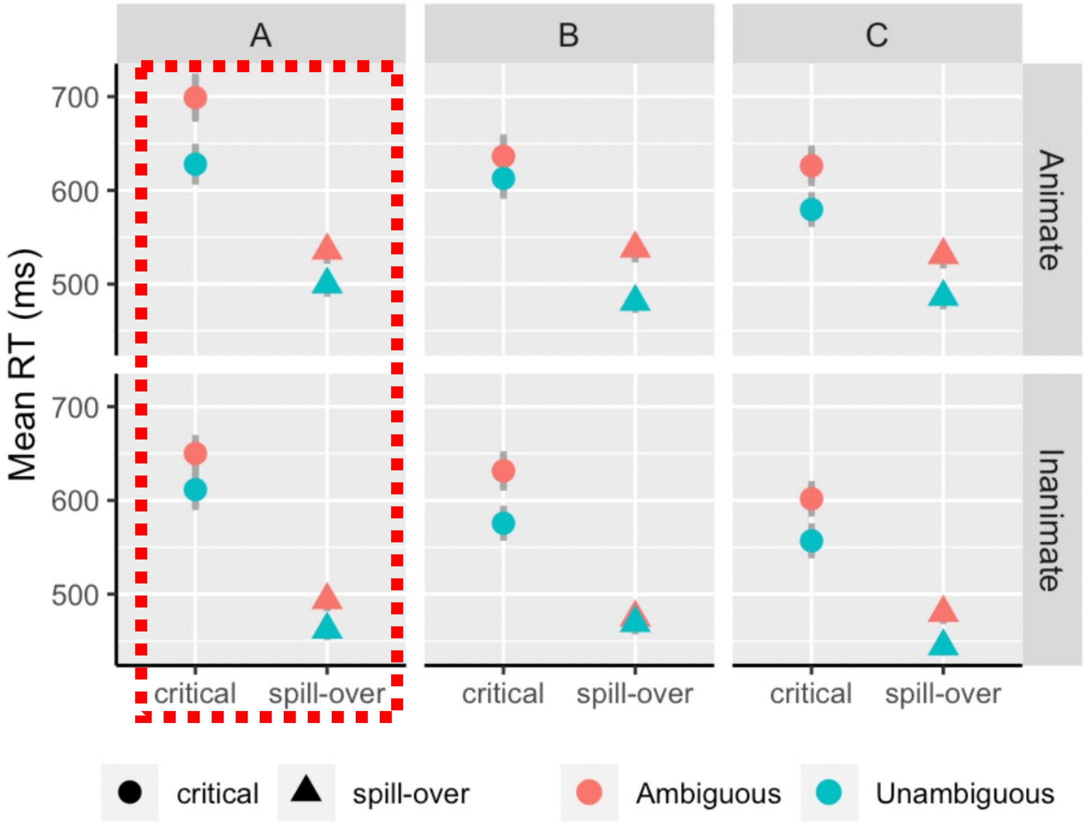
> For control Group C

- No effect in Group C
- GP of animate = GP of inanimate
- No bias towards either animate or inanimate

(see the formulation of statistical models in Appendix)

Self-paced reading experiment

Results



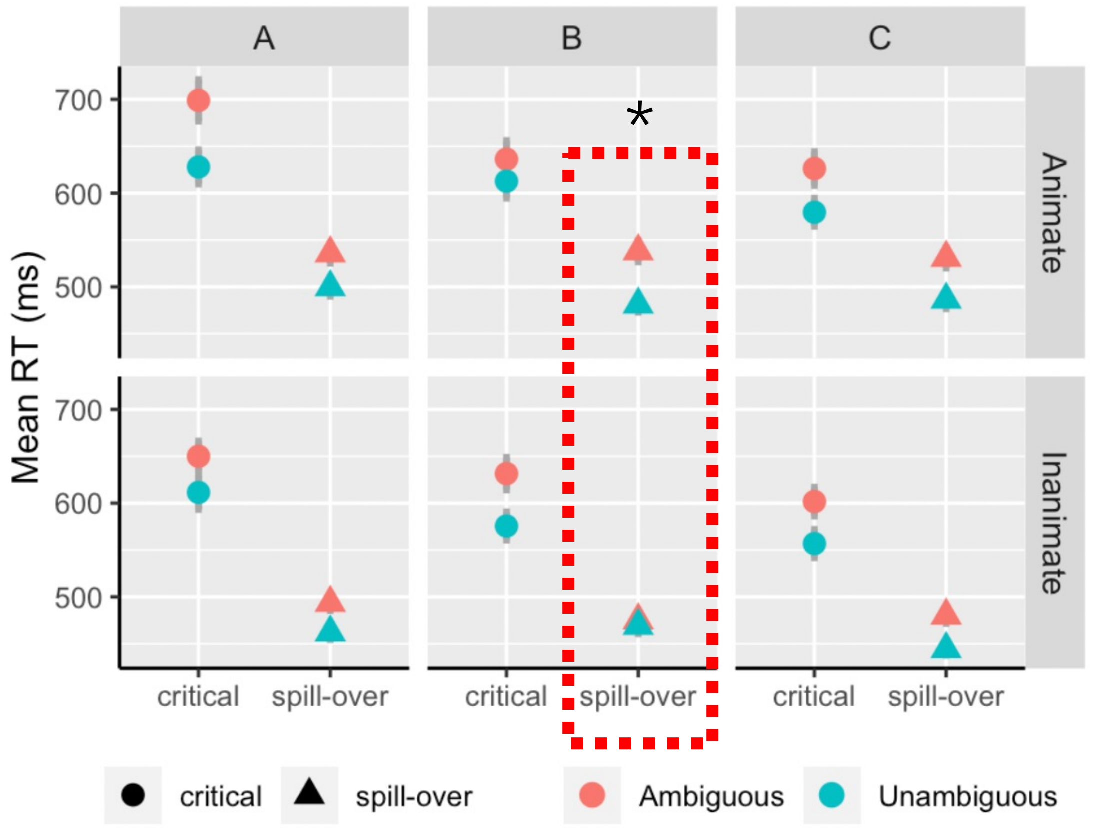
> For Group A

- No effect in Group A
- GP of animate = GP of inanimate
- No adaptation compared to Group C

(see the formulation of statistical models in Appendix)

Self-paced reading experiment

Results



> **For Group B**

- GP of animate > GP of inanimate (animate → MV ; inanimate → RR)
- **Adaptation compared to Group C !**
- Ambiguity x Animacy x Group not significant, due to statistical power [4]

(see the formulation of statistical models in Appendix)

[4] Prasad & Linzen (2019)

Conclusion

- Participants track and adapt to cue-based (animacy) short-term regularities
- But…only when consistent with long-term knowledge
  - i.e. inanimate → RR; animate → MV
- Inconsistent with inverse frequency effect [5]
- We propose a log-linear model for cue-based syntactic adaptation

(see modeling details in the remaining slides)

[5] Reitter, Keller & Moore (2011)

Thanks for your listening!

A Log-linear Model

- Objective: listener's syntactic expectation based on cues
- Why log-linear?
  - > A natural way to represent cues and to model the adaptation of cue weights
- Target quantity: $\boldsymbol{p(\mathrm{RR}|c)}$
  - > *The patient examined ……*

    c_{ani} $p(\mathrm{RR}|c_{\mathrm{ani}})$
- Log-linear model for $p(\mathrm{RR}|c)$:
  - > $w_{\mathrm{ani}}^{\mathrm{RR}}$ is association strength
  - > b^{RR} is long-term bias towards RR

$$p(\mathrm{RR} \mid c_{\mathrm{ani}}) = \frac{e^{w_{\mathrm{ani}}^{\mathrm{RR}}+b^{\mathrm{RR}}}}{e^{w_{\mathrm{ani}}^{\mathrm{RR}}+b^{\mathrm{RR}}} + e^{w_{\mathrm{ani}}^{\mathrm{MV}}+b^{\mathrm{MV}}}} = \frac{1}{1+e^{(w_{\mathrm{ani}}^{\mathrm{MV}}-w_{\mathrm{ani}}^{\mathrm{RR}})+(b^{\mathrm{MV}}-b^{\mathrm{RR}})}}.$$

A Log-linear Model

- Modeling adaptation

Adaptation coefficient → $w_{\text{ani}}^{\text{RR}} \pm k$

Subj.NP Animacy (animate vs. inanimate) ⟷ **Parsing bias** (RR vs. MV)

- In our SPR experiment

> **Group A**

animate → RR; inanimate → MV

$$w_{\text{ani}}^{\text{RR}}(\text{A}) = w_{\text{ani}}^{\text{RR}} + k_A$$
$$w_{\text{inani}}^{\text{RR}}(\text{A}) = w_{\text{inani}}^{\text{RR}} - k_A$$

> **Group B**

animate → MV; inanimate → RR

$$w_{\text{ani}}^{\text{RR}}(\text{B}) = w_{\text{ani}}^{\text{RR}} - k_B$$
$$w_{\text{inani}}^{\text{RR}}(\text{B}) = w_{\text{inani}}^{\text{RR}} + k_B$$

A Log-linear Model

- Linking $p(\mathrm{RR}|c)$ to empirical garden-path based on surprisal theory [6-7]

$$\begin{aligned}\mathrm{GP} &= \mathrm{RT}(\text{“by”} \mid c_{\text{ambig}}) - \mathrm{RT}(\text{“by”} \mid c_{\text{unambig}}) \\ &\propto -\ln p(\mathrm{RR} \mid c_{\text{ambig}})\end{aligned}$$

- Proof

➡ $\mathrm{RT}(\text{“by”} \mid c) \propto -\ln p(\text{“by”} \mid c)$

➡ $$\begin{aligned}p(\text{“by”} \mid c) &= p(\mathrm{RR} \mid c)p(\text{“by”} \mid \mathrm{RR}, c) + p(\mathrm{MV} \mid c)p(\text{“by”} \mid \mathrm{MV}, c) \\ &= p(\mathrm{RR} \mid c)p(\text{“by”} \mid \mathrm{RR}, c)\end{aligned}$$

➡ $$\begin{aligned}\mathrm{GP} &\propto -\ln p(\mathrm{RR} \mid c_{\text{ambig}})p(\text{“by”} \mid \mathrm{RR}, c_{\text{ambig}}) + \ln p(\mathrm{RR} \mid c_{\text{unambig}})p(\text{“by”} \mid \mathrm{RR}, c_{\text{unambig}}) \\ &= -\ln p(\mathrm{RR} \mid c_{\text{ambig}})p(\text{“by”} \mid \mathrm{RR}, c_{\text{ambig}}) + \ln p(\text{“by”} \mid \mathrm{RR}, c_{\text{unambig}}) \\ &= -\ln \left(\frac{p(\mathrm{RR} \mid c_{\text{ambig}})p(\text{“by”} \mid \mathrm{RR}, c_{\text{ambig}})}{p(\text{“by”} \mid \mathrm{RR}, c_{\text{unambig}})}\right) \\ &= -\ln p(\mathrm{RR} \mid c_{\text{ambig}})\end{aligned}$$

[6] Levy (2008); [7] Hale (2001)

A Log-linear Model

$$p(\text{RR} \mid c_{\text{ani}}) = \frac{e^{w_{\text{ani}}^{\text{RR}} + b^{\text{RR}}}}{e^{w_{\text{ani}}^{\text{RR}} + b^{\text{RR}}} + e^{w_{\text{ani}}^{\text{MV}} + b^{\text{MV}}}} = \frac{1}{1 + e^{(w_{\text{ani}}^{\text{MV}} - w_{\text{ani}}^{\text{RR}}) + (b^{\text{MV}} - b^{\text{RR}})}}.$$

$$b' \equiv b^{\text{MV}} - b^{\text{RR}}$$

$$w'_{\text{ani}} \equiv w_{\text{ani}}^{\text{MV}} - w_{\text{ani}}^{\text{RR}}$$

- Model-predicted GP ***before*** adaptation

$$\text{RT effect} \propto -\ln p(\text{RR} \mid c_{\text{ani}}) = \ln\left(1 + e^{w'_{\text{ani}} + b'}\right),$$

- Model-predicted GP ***after*** adaptation

> **Group A**

animate → RR; inanimate → MV

$$\text{RT}(\text{A} \mid c_{\text{ani}}) \text{ effect} \propto -\ln p(\text{RR} \mid c_{\text{ani}}) = \ln(1 + e^{((w'_{\text{ani}} - k_A) + b'})$$

$$\text{RT}(\text{A} \mid c_{\text{inani}}) \text{ effect} \propto -\ln p(\text{RR} \mid c_{\text{inani}}) = \ln(1 + e^{((w'_{\text{inani}} + k_A) + b'})$$

> **Group B**

animate → MV; inanimate → RR

$$\text{RT}(\text{B} \mid c_{\text{ani}}) \text{ effect} \propto -\ln p(\text{RR} \mid c_{\text{ani}}) = \ln(1 + e^{((w'_{\text{ani}} + k_B) + b'})$$

$$\text{RT}(\text{B} \mid c_{\text{inani}}) \text{ effect} \propto -\ln p(\text{RR} \mid c_{\text{inani}}) = \ln(1 + e^{((w'_{\text{inani}} - k_B) + b'})$$

Estimating Parameters

- Estimating bias ***b'*** by solving:

$$p(\mathrm{RR}) = \frac{1}{1+e^{b'}}$$

- $\boldsymbol{p}(\mathbf{RR})$: Penn Treebank Frequencies

  MV construction: (NP-SBJ !<< @VP) $+ @VP

  RR construction: NP-SBJ < (NP $ @VP)

  p(RR) = 0.008

Estimating Parameters

- Estimating association strength ***w'*** by solving the log-linear model:

$$p(\mathrm{RR} \mid c_{\mathrm{ani}}) \propto e^{w'_{\mathrm{ani}}+b'}$$

- $\boldsymbol{p(\mathrm{RR}|c)}$: GPT-3 surprisals

h(suffix | c_ambig): the patient examined by the doctor …

h (suffix | c_umambig): the patient that was examined by …

$$\begin{aligned}-\ln p(\mathrm{RR} \mid c) &= h(\mathrm{RR} \mid c) \\ &= h(\mathrm{suffix} \mid c_{\mathrm{ambig}}) - h(\mathrm{suffix} \mid c_{\mathrm{unambig}})\end{aligned}$$

Estimating Parameters

- Estimating adaptation coefficient ***k***
  - Step 1: link LM predicted effect $\boldsymbol{p(\mathbf{RR}|c)}$ to the empirical reading time of *Group C* with linear regression

$$\text{RT effect} = -\lambda \ln p(\text{RR} \mid c)$$

  - Step 2: with the estimated $\boldsymbol{\lambda}$, fit linear models

$$\text{RT}(\text{A} \mid c_{\text{ani}}) \text{ effect} \propto -\ln p(\text{RR} \mid c_{\text{ani}}) = \ln(1 + e^{((w'_{\text{ani}} - k_A) + b'})$$

$$\text{RT}(\text{B} \mid c_{\text{ani}}) \text{ effect} \propto -\ln p(\text{RR} \mid c_{\text{ani}}) = \ln(1 + e^{((w'_{\text{ani}} + k_B) + b'})$$

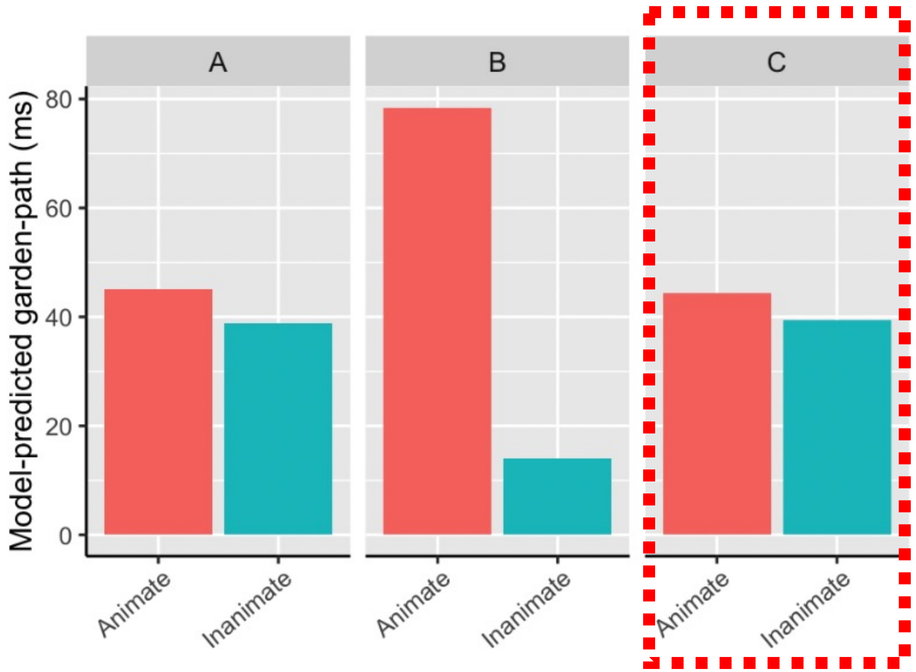
$$\text{RT}(\text{A} \mid c_{\text{inani}}) \text{ effect} \propto -\ln p(\text{RR} \mid c_{\text{inani}}) = \ln(1 + e^{((w'_{\text{inani}} + k_A) + b'})$$

$$\text{RT}(\text{B} \mid c_{\text{inani}}) \text{ effect} \propto -\ln p(\text{RR} \mid c_{\text{inani}}) = \ln(1 + e^{((w'_{\text{inani}} - k_B) + b'})$$

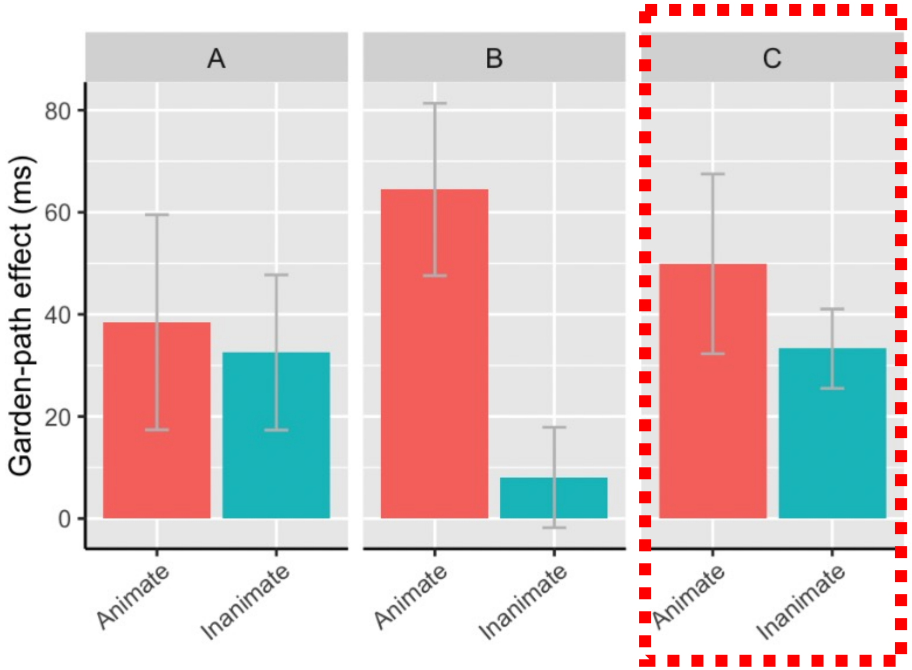
Simulation Results

- Group C: control group with no exposure **(k_c = 0)**

Model Prediction



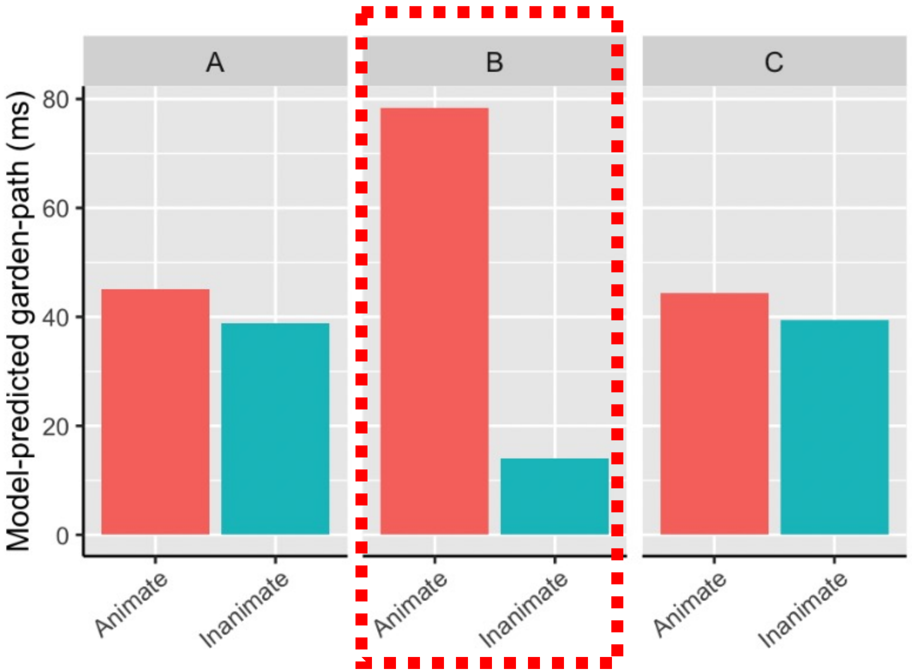
Human Experiment



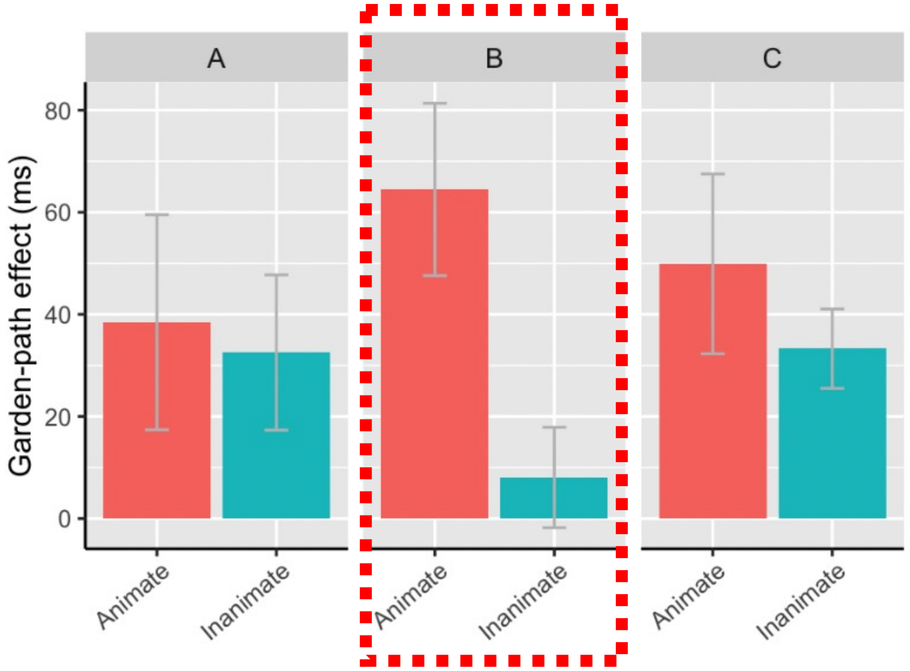
Simulation Results

- Group B: animate → MV; inanimate → RR (k_B = **1.81**)

Model Prediction



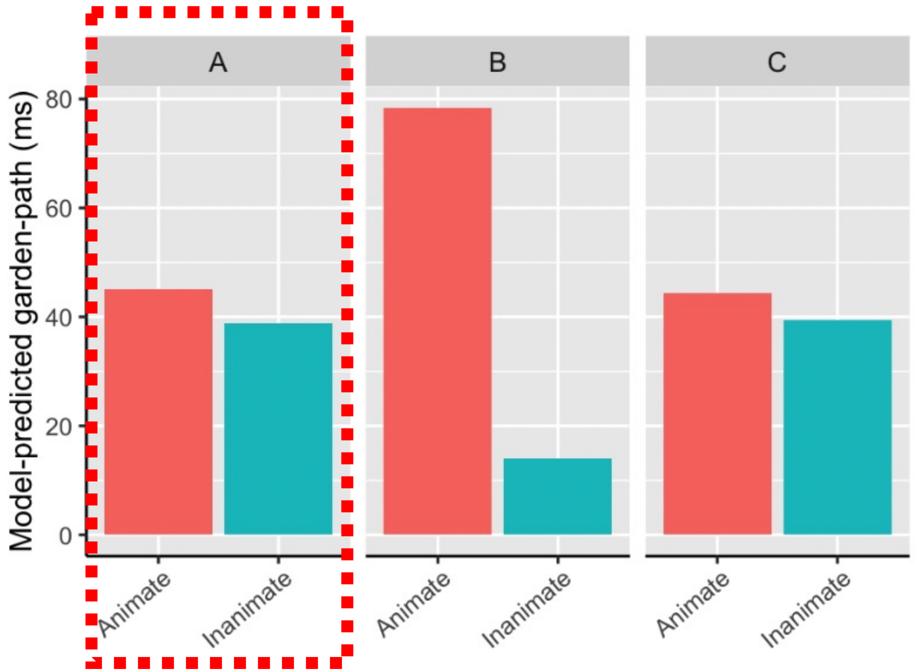
Human Experiment



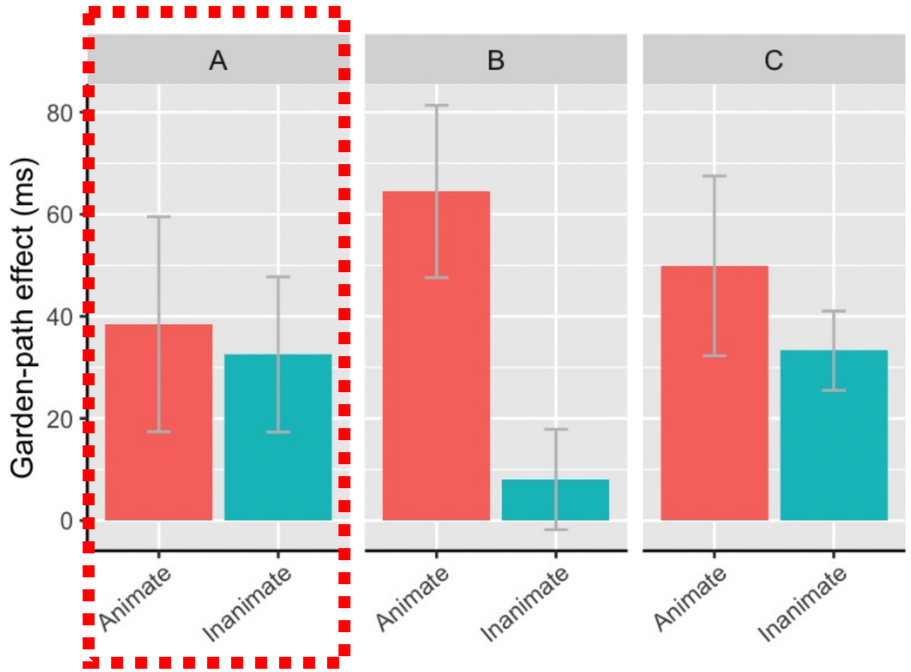
Simulation Results

- Group A: inanimate → MV; animate → RR **(k_A = -0.04)**

Model Prediction



Human Experiment



Cognitive Implications

- Asymmetry in cue-based adaptation: Stronger adaptation when the training is consistent with the long-term statistics ($|k_B| > |k_A|$)
- A quantitative view of cue-based adaptation in the realm of surprisal theory, complementing the qualitative conclusions in the behavioral experiment

Appendix

- Formulation of statistical models in SPR experiment

Linear mixed-effect model for each individual group

$$\text{logRT} \sim \text{logRT.previous.region} + \text{Word.length} + \text{Ambiguity} * \text{Animacy} + (1 + \text{Ambiguity} * \text{Animacy} \mid \text{Subj}) + (1 + \text{Ambiguity} \mid \text{Item})$$

Linear mixed-effect model with group contrasts for A vs. C and B vs. C

$$\text{logRT} \sim \text{logRT.previous.region} + \text{Word.length} + \text{Ambiguity} * \text{Animacy} * \text{Group} + (1 + \text{Ambiguity} * \text{Animacy} \mid \text{Subj}) + (1 + \text{Ambiguity} * \text{Group} \mid \text{Item})$$