How children are and aren't like adults when it comes to interpreting pronouns: A developmental modeling investigation

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Pronoun interpretation

The girls wave at the teacher…

???

…and then **she** leaves.

Pronoun interpretation

The girls wave at the teacher…

pl

???

…and then **she** leaves.

sg

Agreement mismatch: “she” is singular but “girls” is plural

Pronoun interpretation

The girls wave at the teacher…

pl sg

???

…and then **she** leaves.

sg

Agreement match: both “she” and “teacher” are singular

Pronoun interpretation

The girls wave at the teacher…
sg

…and then **she** leaves.
sg

How to choose?
Use linguistic knowledge of agreement.

Pronoun interpretation

The girl waves at the teacher…

???

…and then **she** leaves.

sg

Pronoun interpretation

The girl waves at the teacher…

sg

???

…and then **she** leaves.

sg

This could work: both “she” and “girl” are singular.

Pronoun interpretation

The girl waves at the teacher…

sg sg

???

…and then **she** leaves.

sg

But so could this: both “she” and “teacher” are singular.

Pronoun interpretation

The girl waves at the teacher…
sg sg
???
…and then **she** leaves.
sg

How to choose?

Pronoun interpretation

The girl waves at the teacher…
sg sg
???
…and then **she** leaves.
sg

How to choose?
Use contextual knowledge (who's likely to be leaving)

Maybe the girl is getting ready to leave the classroom.

Pronoun interpretation

The girl waves at the teacher…

≈subject — sg — sg

???

…and then **she** leaves.

sg

How to choose?

Use linguistic knowledge about connectives.

Maybe pronouns after “and then” tend to refer to the previous subject.

Pronoun interpretation

The girls wave at the teacher…

≈subject pl sg

???

…and then **she** leaves.

sg

What about when interpretation cues conflict?

Pronoun interpretation

The girls wave at the teacher…

≈subject pl sg

???

…and then **she** leaves.

sg

What about when interpretation cues conflict?

Here, the connective “and then” signals the subject “the girls",
while the agreement signals the object “the teacher”.

Pronoun interpretation

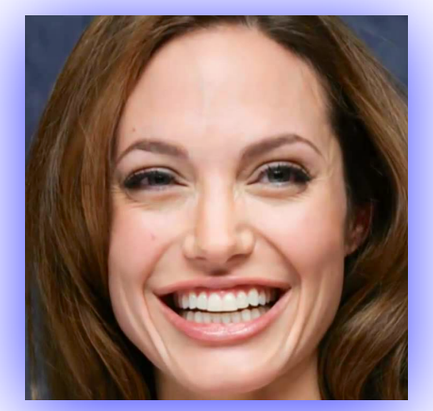
The girls wave at the teacher…

≈subject pl sg

???

…and then **she** leaves.

sg



What about when interpretation cues conflict?
Here, English-speaking adults let agreement matter more than the connective.
So, they interpret “she” as “the teacher”.

Pronoun interpretation

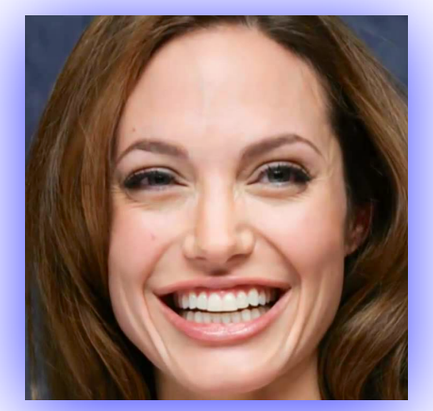
The girls wave at the teacher…

≈subject pl sg

???

…and then **she** leaves.

sg



Something English-speaking adults have learned:
How to resolve interpretation cue conflicts in context.

Pronoun interpretation

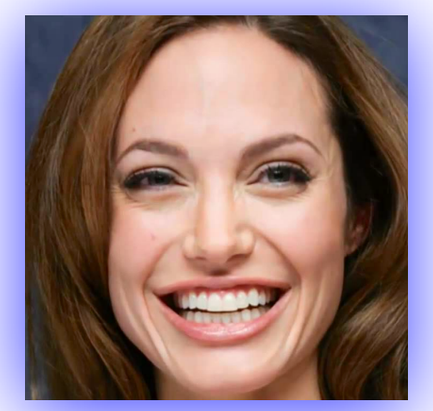
The girls wave at the teacher…

≈subject pl sg

???

…and then **she** leaves.

sg



The need to integrate multiple cues to interpretation doesn't just happen in English, of course.

Pronoun interpretation

Las niñas saludan a la maestra…

The girls wave at the teacher…

pl sg

???

…y después **ella** sale.

*… and then **she** leaves.*

sg

Here's the same sentence in Spanish.

Pronoun interpretation

Las niñas saludan a la maestra…

The girls wave at the teacher…

pl sg

???

…y después Ø sale.

… and then ***PRONOUN*** *leaves.*

sg

Spanish also allows the form of the pronoun to be null (this means the agreement information is on the verb).

Pronoun interpretation

Las niñas saludan a la maestra…

The girls wave at the teacher…

pl sg

???

…y después Ø sale.

*… and then **PRONOUN** leaves.*

sg

Just like English, there are multiple cues available to interpret the pronoun.

Pronoun interpretation

Las niñas saludan a la maestra…
The girls wave at the teacher…
pl sg
???

…y después Ø sale.
… and then ***PRONOUN*** *leaves.*
sg

Spanish-speaking adults also have interpretation preferences.

Pronoun interpretation

Las niñas saludan a la maestra…

The girls wave at the teacher…

≈subject pl sg ???

…y después Ø sale.

… and then ***PRONOUN*** *leaves.*

sg

For Spanish-speaking adults…

…the connective favors the subject.

Pronoun interpretation

Las niñas saludan a la maestra…

The girls wave at the teacher…

≈subject pl = sg ???

…y después Ø sale.

… and then ***PRONOUN*** *leaves.*

sg

For Spanish-speaking adults…

…the (singular) agreement (on the verb) indicates the singular object.

Pronoun interpretation

Las niñas saludan a la maestra…

The girls wave at the teacher…

subject — pl — = sg ???

…y después Ø sale.

… and then ***PRONOUN*** *leaves.*

sg

For Spanish-speaking adults…

…the (null) form favors the subject.

Pronoun interpretation

Las niñas saludan a la maestra…

The girls wave at the teacher…

subject — pl — = sg ???

…y después Ø sale.

… and then ***PRONOUN*** *leaves.*

sg

For Spanish-speaking adults…

…this collection of cues generally causes the pronoun to be interpreted as the singular object (agreement matters the most).

Pronoun interpretation development

Las niñas saludan a la maestra…

The girls wave at the teacher…

subject — pl — = sg ???

…y después Ø sale.

… and then ***PRONOUN*** *leaves.*

sg

How do Spanish-learning children develop this ability to interpret pronouns in context?

Pronoun interpretation development

PRONOUN =

Children's ability to interpret a pronoun in an adult-like way depends on (at least) two things.

Pronoun interpretation development

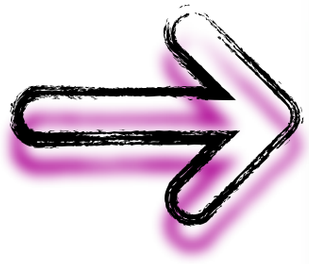
PRONOUN

First, children need adult-like knowledge of what each cue signals.

Pronoun interpretation development

PRONOUN

Second, children need adult-like ability to deploy that knowledge in real time.



Pronoun interpretation development

PRONOUN

When both of these are adult-like, we should get adult-like pronoun interpretation.

Pronoun interpretation development

≈ *PRONOUN* =

But if we get non-adult-like pronoun interpretation, then it could be due to immature knowledge, immature deployment of that knowledge, or both!

Pronoun interpretation development

How do we tell what the differences are between child and adult pronoun interpretation? When we understand this better, we'll understand what children need to do to become adults.

Understanding pronoun interpretation development

The plan, part 1: Get some empirical data on how children and adults interpret the same pronoun in a context where multiple cues are available.

Case study: Mexican Spanish

Forsythe & Pearl 2019, in prep

Understanding pronoun interpretation development

PRONOUN

The plan, part 1: Get some empirical data on how children and adults interpret the same pronoun in a context where multiple cues are available.

≠

This will highlight what the observable differences are in interpretation behavior.

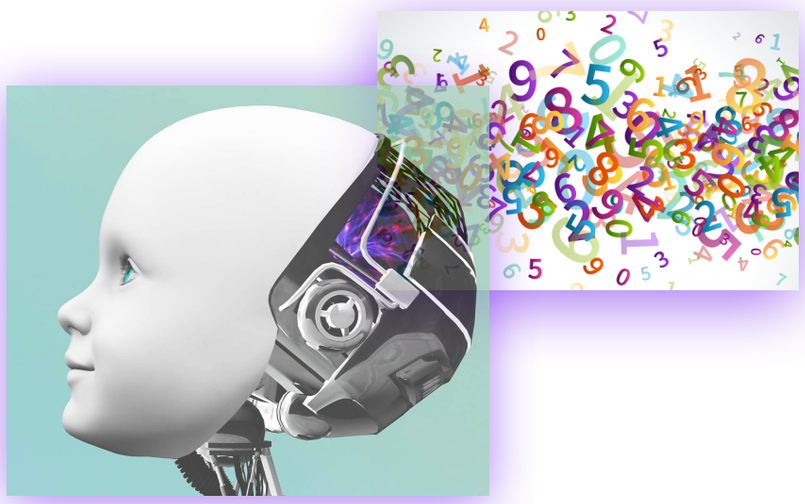
Forsythe & Pearl 2019, in prep

Understanding pronoun interpretation development

≈ PRONOUN =

≠

The plan, part 2: Use computational cognitive modeling to formally articulate the potential process of pronoun interpretation in the context of these multiple cues.



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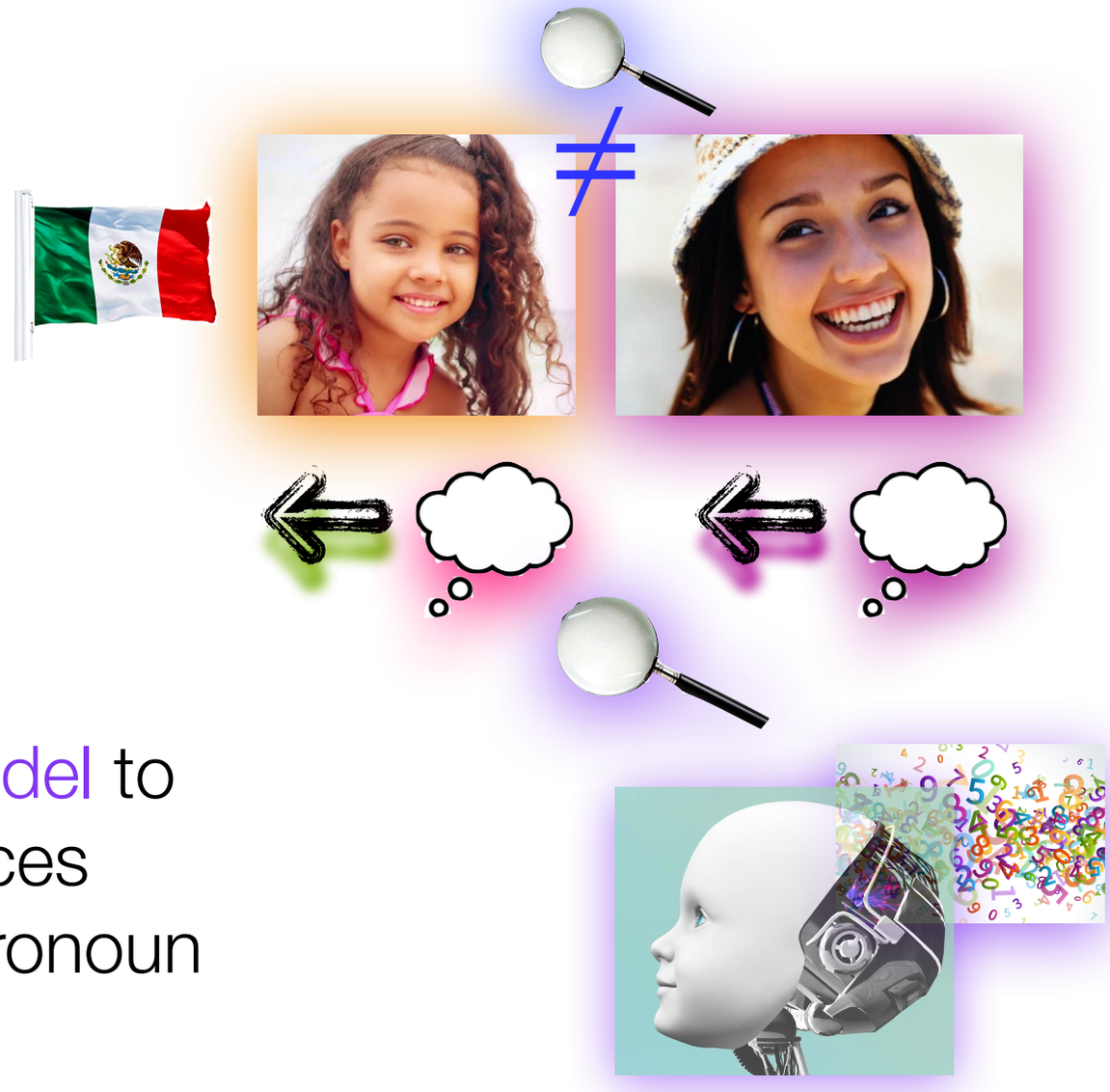
Understanding pronoun interpretation development

The plan, part 2: Use the computational cognitive model to identify the specific differences leading to child and adult pronoun interpretation in context.



Forsythe & Pearl 2019, in prep

Empirical data on pronoun interpretation

Forsythe & Pearl 2019, in prep

Empirical data on pronoun interpretation

Las niñas saludan a la maestra…

The girls wave at the teacher…

subject pl ≠ sg ???

…y después Ø sale.

… and then ***PRONOUN*** *leaves.* sg

Children (~3, 4, and ~5) and adults are asked to interpret pronouns in the kind of contexts we saw before.

<=3:	*1;11-3;10*	*(N=33)*
4:	*4;0-4;11*	*(N=35)*
>=5:	*5;0-6;9*	*(N=29)*
Adults		*(N=47)*

Forsythe & Pearl 2019, in prep

Empirical data on pronoun interpretation

~3yrs 4yrs ~5yrs adults

Las niñas saludan a la maestra…

The girls wave at the teacher…

subject pl =sg ???

…y después Ø sale.

… and then ***PRONOUN*** *leaves.*

sg

Forsythe & Pearl 2019, in prep

Empirical data on pronoun interpretation

Las niñas saludan a la maestra…

The girls wave at the teacher…

subject pl ≠ sg ???

…y después Ø sale.

… and then ***PRONOUN*** *leaves.*

sg

≠

~3yrs 4yrs ~5yrs adults

Rate of subject responses

Choice: Is the pronoun interpreted as the subject or the object?

We can plot the rate of subject responses.

Forsythe & Pearl 2019, in prep

Empirical data on pronoun interpretation

Las niñas saludan a la maestra…

The girls wave at the teacher…

pl sg

???

…y después Ø sale.

… and then ***PRONOUN*** *leaves.*

sg

≠

~3yrs 4yrs ~5yrs adults

Rate of subject responses

Context:

Does agreement favor the subject or the object?

subject object

Favored by agreement

Forsythe & Pearl 2019, in prep

Empirical data on pronoun interpretation

Las niñas saludan a la maestra…
The girls wave at the teacher…
=pl sg
???
…y después Ø salen.
… and then ***PRONOUN*** *leave.*
pl

≠

~3yrs 4yrs ~5yrs adults

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Las niñas saludan a la maestra…

The girls wave at the teacher…

pl ≠ sg

???

…y después Ø sale.

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sg

≠

~3yrs 4yrs ~5yrs adults

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Empirical data on pronoun interpretation

Las niñas saludan a la maestra…
The girls wave at the teacher…
pl sg
???
…y después Ø sale.
… and then ***PRONOUN*** *leaves.*
sg

≠

~3yrs 4yrs ~5yrs adults

Rate of subject responses

Context:
Does the pronoun form favor the subject or the object?

subject object

Favored by agreement

Forsythe & Pearl 2019, in prep

Empirical data on pronoun interpretation

Las niñas saludan a la maestra…

The girls wave at the teacher…

≈ subject pl

sg

???

…y después Ø sale.

… and then ***PRONOUN*** *leaves.*

sg

≠

~3yrs 4yrs ~5yrs adults

Rate of subject responses

Context:

Does the pronoun form favor the subject or the object?

Ø (favors subject)

subject object

Favored by agreement

Forsythe & Pearl 2019, in prep

Empirical data on pronoun interpretation

Las niñas saludan a la maestra…
The girls wave at the teacher…
pl sg ≈ object
???
…y después ella sale.
… and then ***PRONOUN*** *leaves.*
sg

≠

~3yrs 4yrs ~5yrs adults

Rate of subject responses

Context:
Does the pronoun form favor the subject or the object?

overt (favors object)

subject object

Favored by agreement

Forsythe & Pearl 2019, in prep

Empirical data on pronoun interpretation

Las niñas saludan a la maestra…
The girls wave at the teacher…
pl sg

…y después ∅ sale.
… and then ***PRONOUN*** *leaves.*
??? sg

≠

~3yrs 4yrs ~5yrs adults

Rate of subject responses

Context:
Does the connective favor the subject or the object?

Favored by form
(favors subject) overt (favors object)

subject object

Favored by agreement

Forsythe & Pearl 2019, in prep

Empirical data on pronoun interpretation

Las niñas saludan a la maestra…

The girls wave at the teacher…

≈subject pl

sg

???

…y después Ø sale.

… and then ***PRONOUN*** *leaves.*

sg

≠

~3yrs 4yrs ~5yrs adults

Rate of subject respon

Context:

Does the connective favor the subject or the object?

y después (favors subject)

subject object

Favored by form

(favors subject) overt (favors object)

Favored by agreement

Forsythe & Pearl 2019, in prep

Empirical data on pronoun interpretation

Las niñas saludan a la maestra…

The girls wave at the teacher…

pl sg ≈ object

???

…porque Ø sale.

… because ***PRONOUN*** *leaves.*

sg

≠

~3yrs 4yrs ~5yrs adults

Rate of subject respon

Context:

Does the connective favor the subject or the object?

porque (favors object)

subject object

Favored by form

(favors subject) overt (favors object)

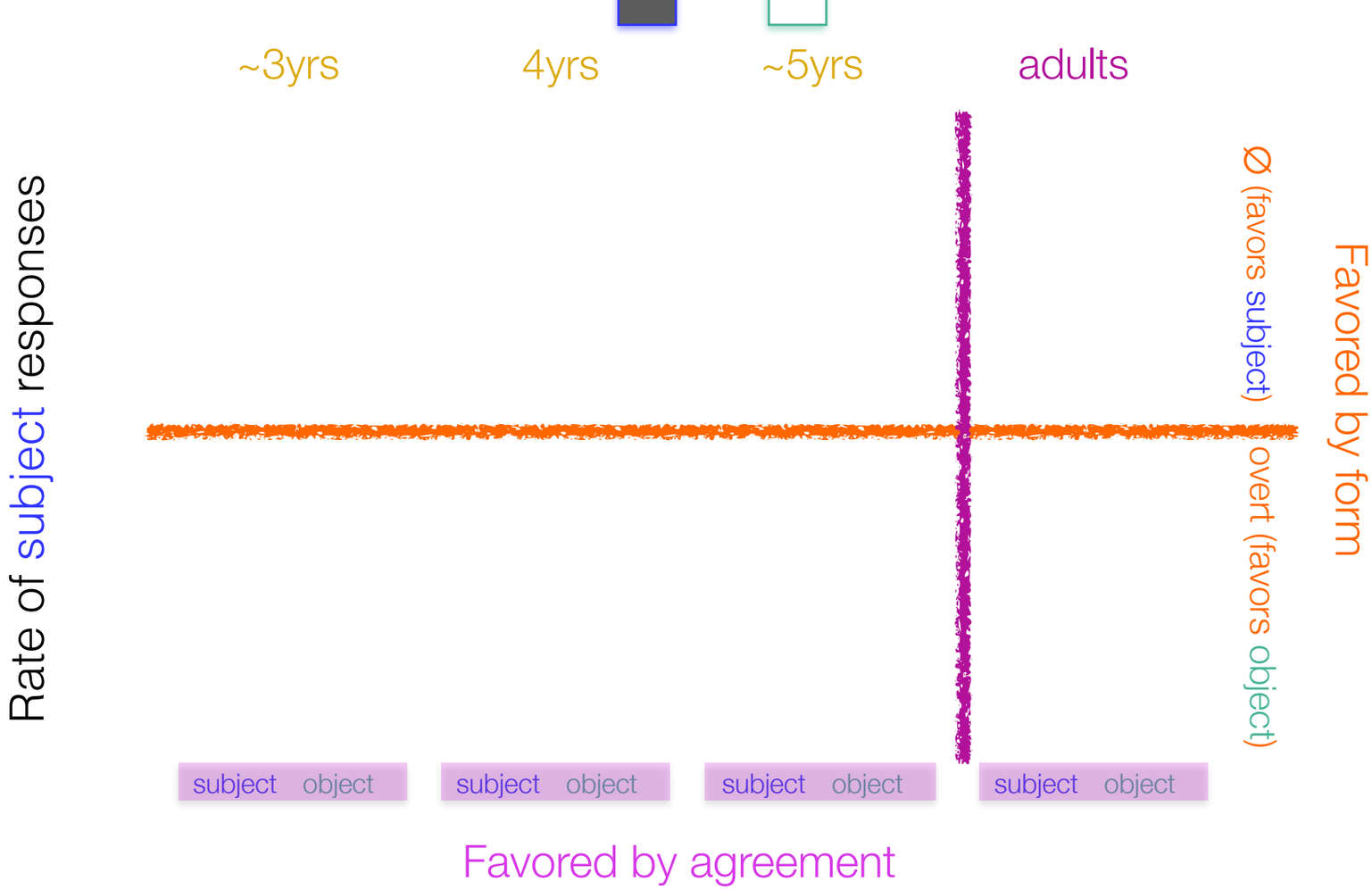
Favored by agreement

Forsythe & Pearl 2019, in prep

Empirical data on pronoun interpretation

Favored by connective

y después (favors subject) porque (favors object)

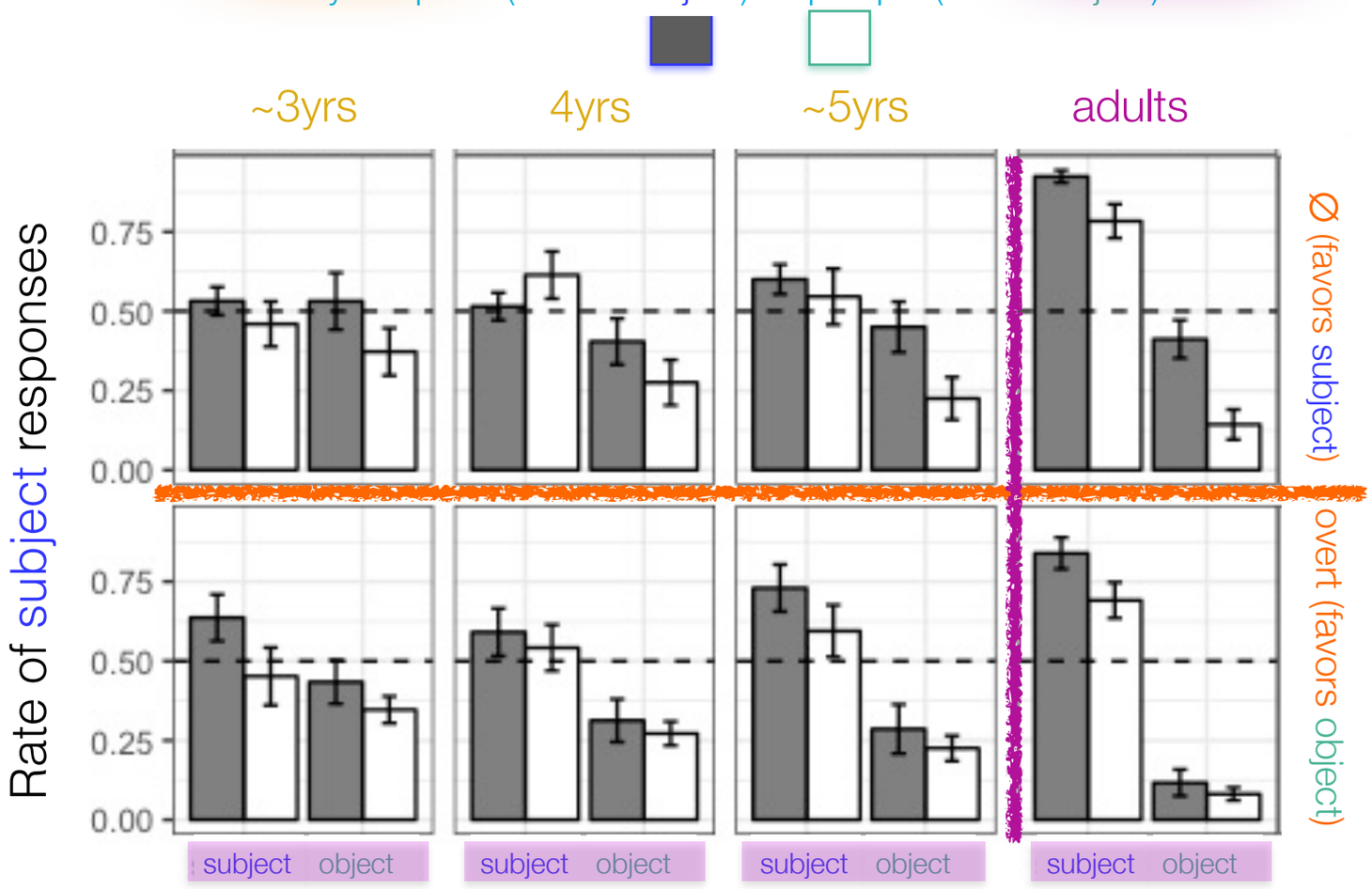


Forsythe & Pearl 2019, in prep

Empirical data on pronoun interpretation

Favored by connective

y después (favors subject) porque (favors object)

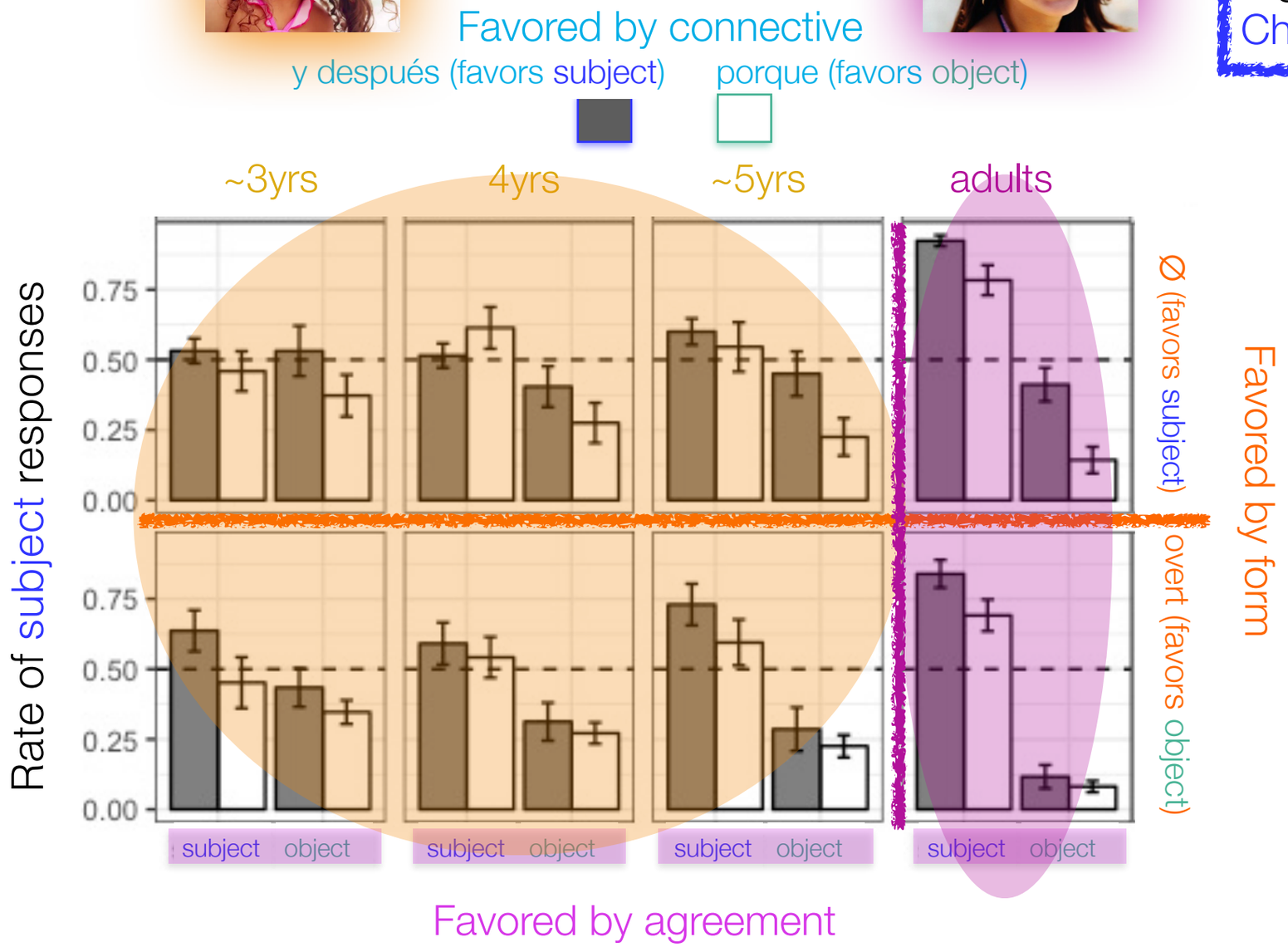


Forsythe & Pearl 2019, in prep

Empirical data on pronoun interpretation

≠

Big qualitative picture:
Children don't behave like adults.

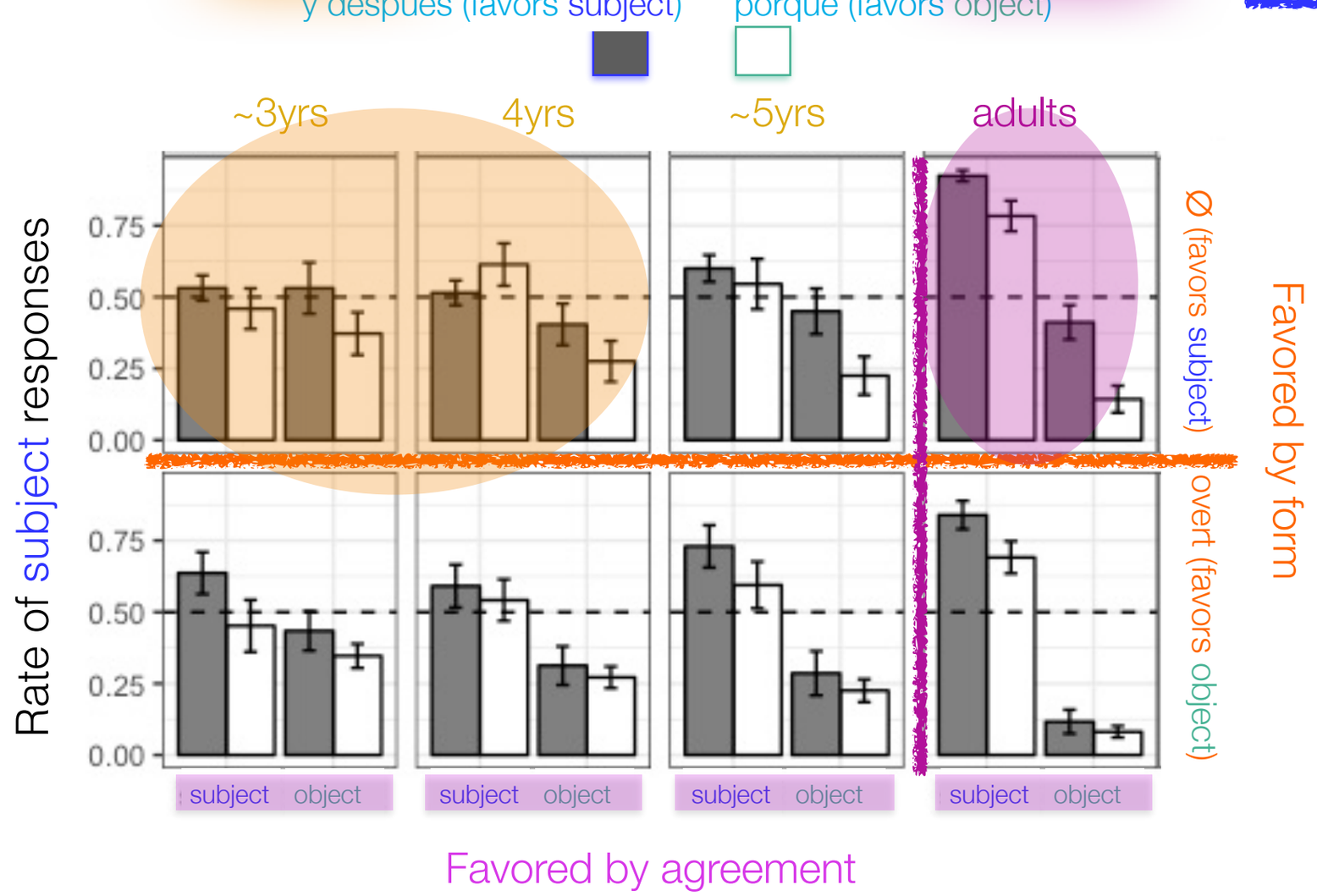


Forsythe & Pearl 2019, in prep

Empirical data on pronoun interpretation

Favored by connective

y después (favors subject) porque (favors object)



Big qualitative picture:
Children don't behave like adults.

Some nuances:
Younger children seem to differ more, especially in certain contexts.

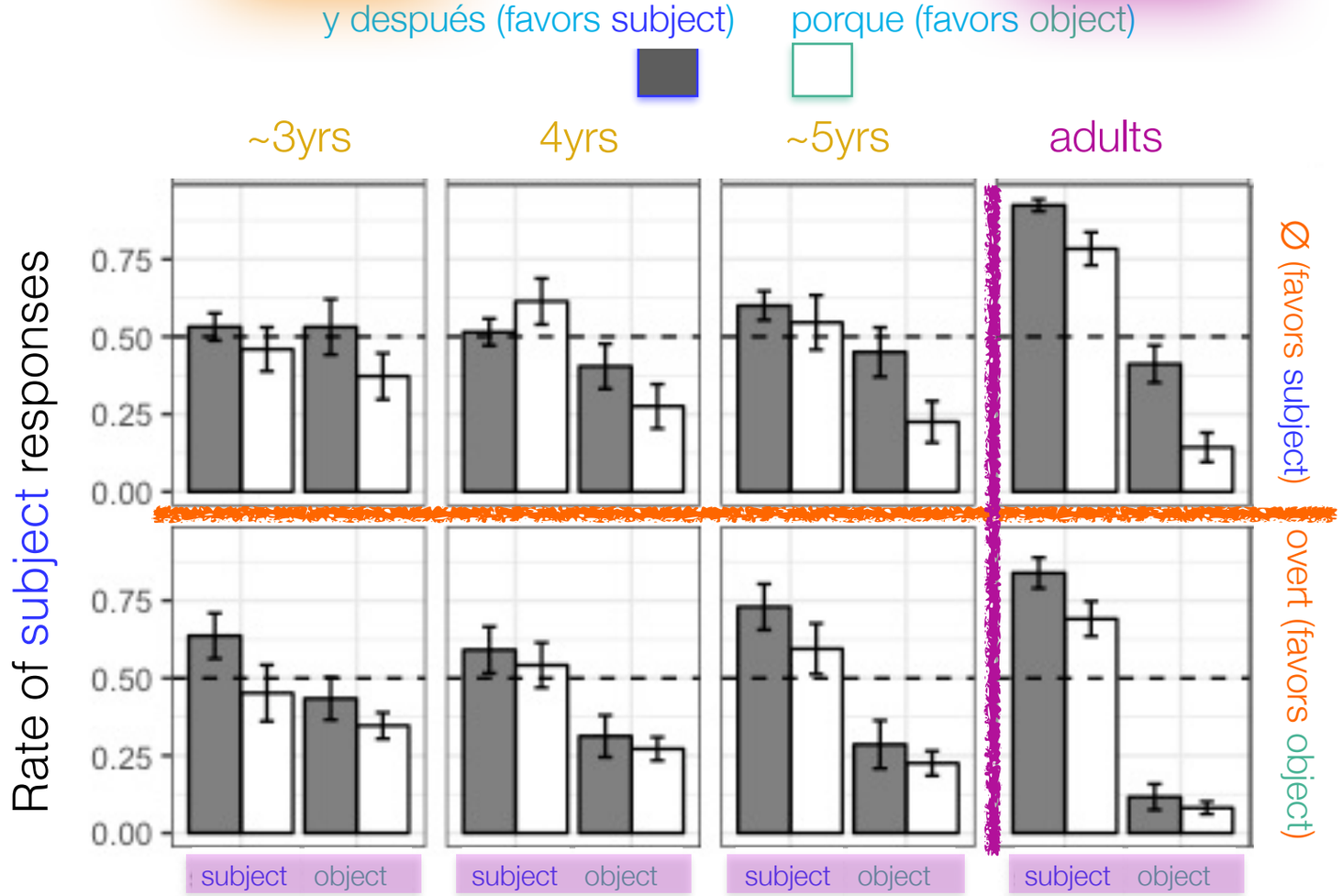
Forsythe & Pearl 2019, in prep

Empirical data on pronoun interpretation

≠

Favored by connective

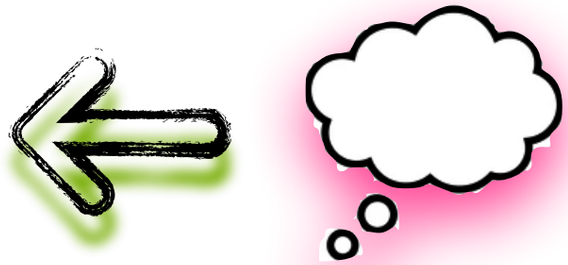
y después (favors subject) porque (favors object)



Something needs to change for children to become adult-like — but what?

Forsythe & Pearl 2019, in prep

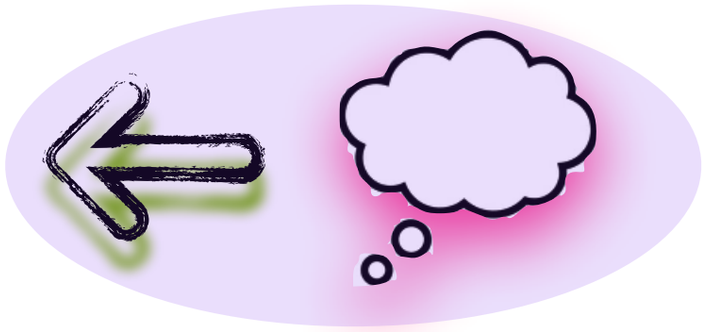
Understanding pronoun interpretation development



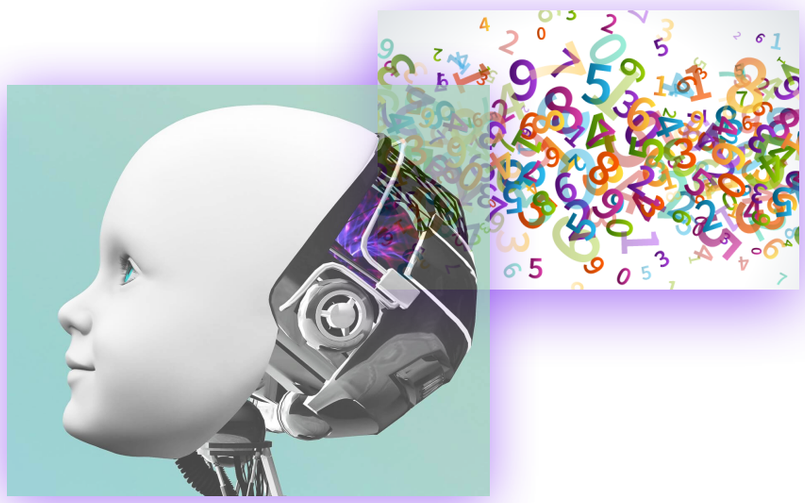
The plan, part 2:
Use computational cognitive modeling to formally articulate the potential process of pronoun interpretation in the context of these multiple cues.

Forsythe & Pearl 2019, in prep

Understanding pronoun interpretation development

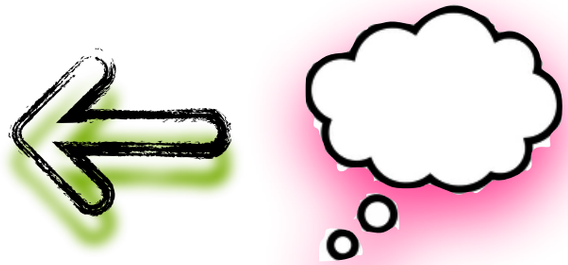


The computational cognitive model formally articulates and implements (what we think are) relevant aspects of pronoun interpretation in context.



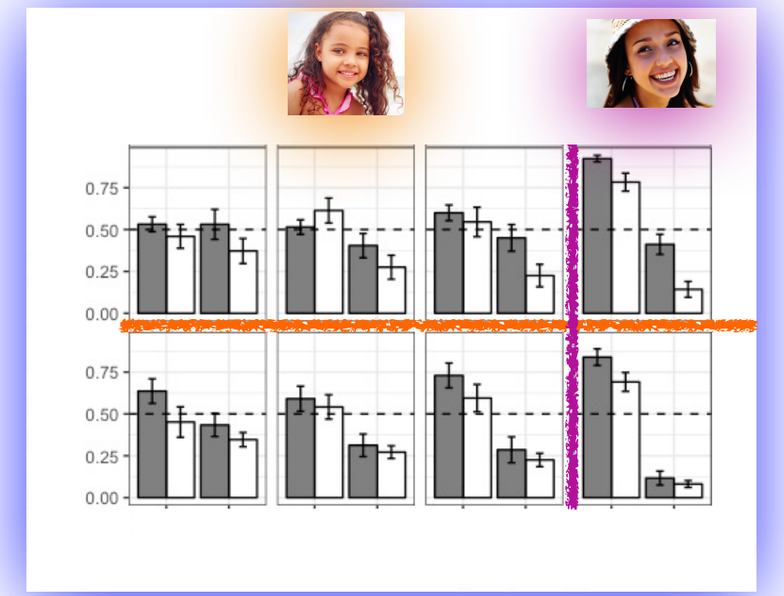
Forsythe & Pearl 2019, in prep

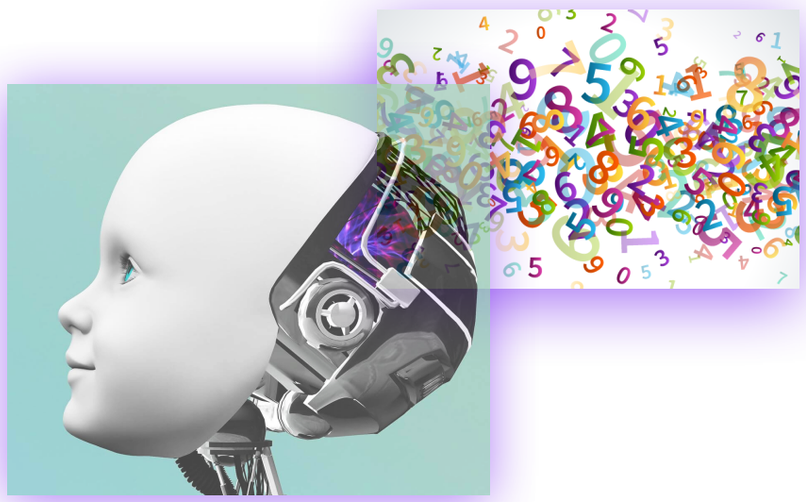
Understanding pronoun interpretation development



PRONOUN =

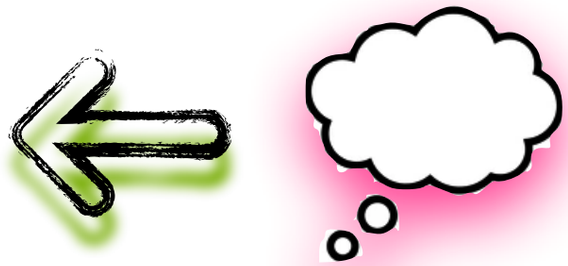
Here: Implement how a modeled listener represents pronoun information and deploys that information in order to predict the probability of a particular interpretation in context.





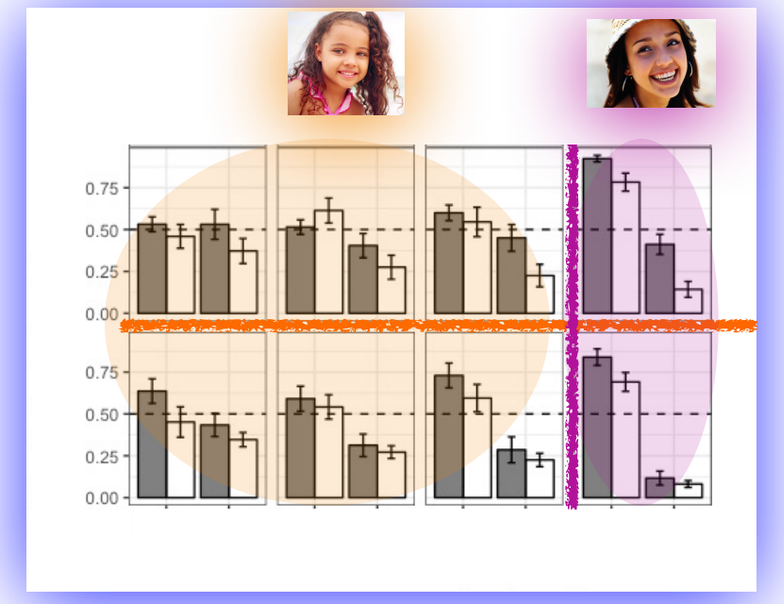
Forsythe & Pearl 2019, in prep

Understanding pronoun interpretation development



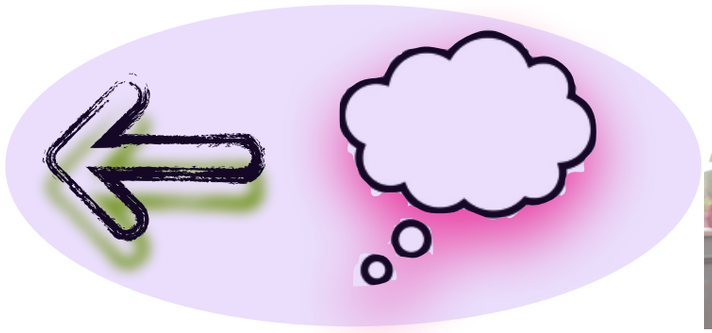
≈ PRONOUN =

Then, see which options for representation and deployment best match child vs. adult pronoun interpretation behavior.



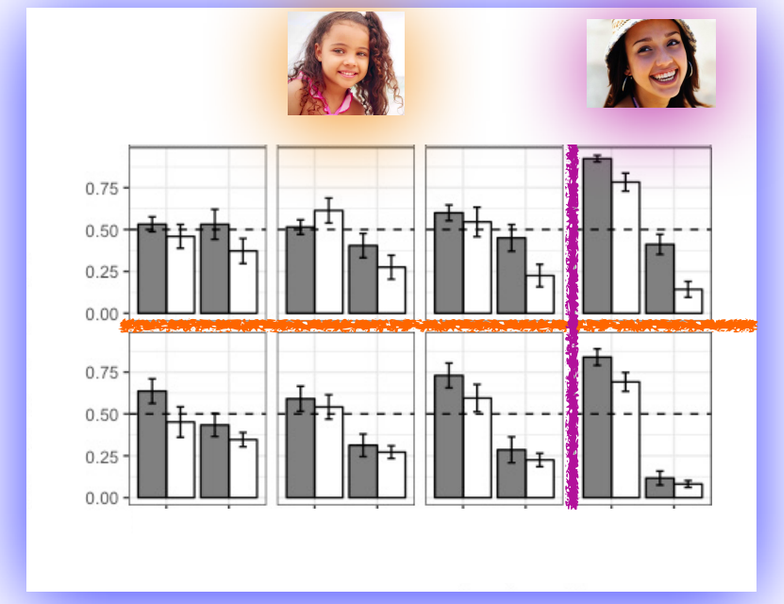
Forsythe & Pearl 2019, in prep

Understanding pronoun interpretation development



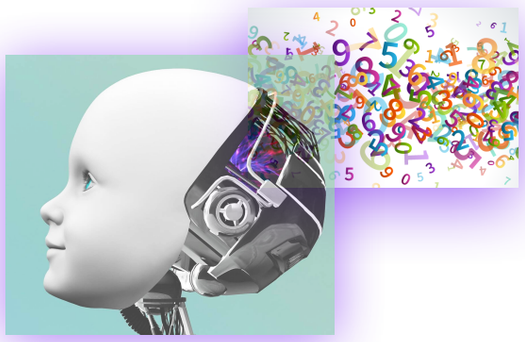
PRONOUN =

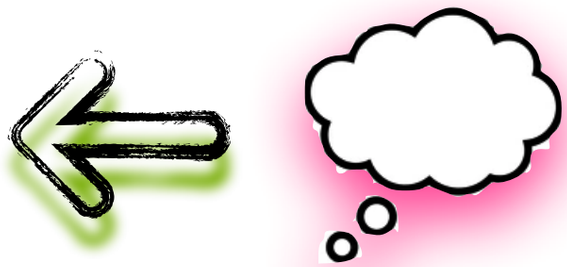
This will articulate how children differ from adults, and what needs to develop in children for them to become adult-like.



Forsythe & Pearl 2019, in prep

Modeling pronoun interpretation in context





PRONOUN =

The model uses Bayesian inference to implement the cognitive mechanism that combines information to generate a particular interpretation in context.

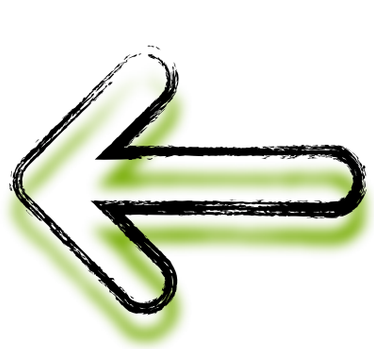
Forsythe & Pearl 2019, in prep

Modeling pronoun interpretation in context

Bayesian inference is commonly used to model human cognition in general and language development in particular, since it matches human behavior quite well (see Pearl in press and b for recent reviews).

Forsythe & Pearl 2019, in prep

Modeling pronoun interpretation in context



Bayesian inference

PRONOUN

The particular Bayesian model we use is adapted from Gagliardi, Feldman & Lidz (2017), and offers one way to separate out the contributions of information representation vs. information deployment in the moment.

Forsythe & Pearl 2019, in prep

Modeling pronoun interpretation in context

Bayesian inference

PRONOUN

interpretation

$$p(\alpha_{subj.\text{SG}}|\textbf{FORM}, \textbf{CON}, \textbf{MOR}) \propto p(\alpha_{subj.\text{SG}}) * p(\textbf{FORM}, \textbf{CON}, \textbf{MOR}|\alpha_{subj.\text{SG}})$$

Interpreting the pronoun as the subject, which is singular….

Forsythe & Pearl 2019, in prep

Modeling pronoun interpretation in context

Bayesian inference

PRONOUN

interpretation context

$$p(\alpha_{subj.\text{SG}}|\textbf{FORM}, \textbf{CON}, \textbf{MOR}) \propto p(\alpha_{subj.\text{SG}}) * p(\textbf{FORM}, \textbf{CON}, \textbf{MOR}|\alpha_{subj.\text{SG}})$$

Ø *ella*

…given the particular context involving the pronoun's form,

Forsythe & Pearl 2019, in prep

Modeling pronoun interpretation in context

Bayesian inference

PRONOUN

interpretation context

$$p(\alpha_{subj.\text{SG}}|\text{FORM}, \text{CON}, \text{MOR}) \propto p(\alpha_{subj.\text{SG}}) * p(\text{FORM}, \text{CON}, \text{MOR}|\alpha_{subj.\text{SG}})$$

y después *porque*

…given the particular context involving
the pronoun's form,
the connective,

Forsythe & Pearl 2019, in prep

Modeling pronoun interpretation in context

Bayesian inference

PRONOUN

interpretation context

$$p(\alpha_{subj.\text{SG}}|\text{FORM}, \text{CON}, \text{MOR}) \propto p(\alpha_{subj.\text{SG}}) * p(\text{FORM}, \text{CON}, \text{MOR}|\alpha_{subj.\text{SG}})$$

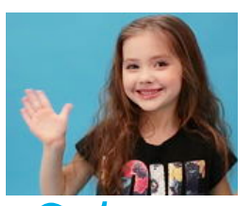
sg *pl*

…given the particular context involving
the pronoun's form,
the connective,
and the agreement morphology.

Forsythe & Pearl 2019, in prep

Modeling pronoun interpretation in context

Bayesian inference



PRONOUN

interpretation context

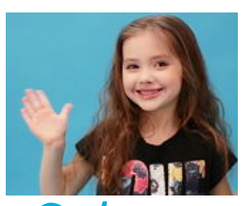
$$p(\alpha_{subj.\text{SG}}|\text{FORM}, \text{CON}, \text{MOR}) \propto p(\alpha_{subj.\text{SG}}) * p(\text{FORM}, \text{CON}, \text{MOR}|\alpha_{subj.\text{SG}})$$

This is proportional to the prior probability of that interpretation irrespective of this particular context…

Forsythe & Pearl 2019, in prep

Modeling pronoun interpretation in context

Bayesian inference



PRONOUN

interpretation context

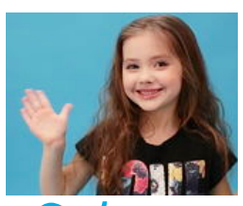
$$p(\alpha_{subj.\text{SG}}|\text{FORM}, \text{CON}, \text{MOR}) \propto p(\alpha_{subj.\text{SG}}) * p(\text{FORM}, \text{CON}, \text{MOR}|\alpha_{subj.\text{SG}})$$

…multiplied by the likelihood of these context values, given this kind of interpretation (a singular subject).

Forsythe & Pearl 2019, in prep

Modeling pronoun interpretation in context

Bayesian inference



PRONOUN

interpretation context

$$p(\alpha_{subj.\mathrm{SG}}|\mathrm{FORM},\mathrm{CON},\mathrm{MOR}) \propto p(\alpha_{subj.\mathrm{SG}}) * p(\mathrm{FORM}|\alpha_{subj.\mathrm{SG}}) * p(\mathrm{CON}|\alpha_{subj.\mathrm{SG}}) * p(\mathrm{MOR}|\alpha_{subj.\mathrm{SG}})$$

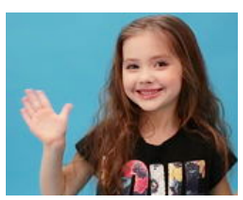
Here, we assume these context values are independent, so we can calculate the likelihood this way.

(For example, the probability of a particular pronoun form, given a certain interpretation, is assumed to be independent from the probability of a particular connective, given a certain interpretation.)

Forsythe & Pearl 2019, in prep

Modeling pronoun interpretation in context

Bayesian inference



PRONOUN

interpretation context

$$p(\alpha_{subj.\text{SG}}|\text{FORM}, \text{CON}, \text{MOR}) \propto p(\alpha_{subj.\text{SG}}) * p(\text{FORM}|\alpha_{subj.\text{SG}}) * p(\text{CON}|\alpha_{subj.\text{SG}}) * p(\text{MOR}|\alpha_{subj.\text{SG}})$$

This is the baseline model, which has accurate representations of information and accurately deploys those representations in the moment.

Forsythe & Pearl 2019, in prep

Modeling pronoun interpretation in context

Bayesian inference

PRONOUN

interpretation context

$$p(\alpha_{subj.\text{SG}}|\text{FORM}, \text{CON}, \text{MOR}) \propto p(\alpha_{subj.\text{SG}}) * p(\text{FORM}|\alpha_{subj.\text{SG}}) * p(\text{CON}|\alpha_{subj.\text{SG}}) * p(\text{MOR}|\alpha_{subj.\text{SG}})$$

What about a modeled listener who has inaccurate representations? This could involve inaccurately representing the prior or the likelihood information, or both.

Forsythe & Pearl 2019, in prep

Modeling pronoun interpretation in context

Bayesian inference

PRONOUN

interpretation context

$$p(\alpha_{subj.\text{SG}}|\text{FORM}, \text{CON}, \text{MOR}) \propto p(\alpha_{subj.\text{SG}}) * p(\text{FORM}|\alpha_{subj.\text{SG}}) * p(\text{CON}|\alpha_{subj.\text{SG}}) * p(\text{MOR}|\alpha_{subj.\text{SG}})$$

inaccurate representations

We implement this as a softmax on the true probability (prior or likelihood), with contrast parameter σ.

$$e^{\sigma * ln(probability)} = probability^{\sigma}$$

Forsythe & Pearl 2019, in prep

Modeling pronoun interpretation in context

Bayesian inference

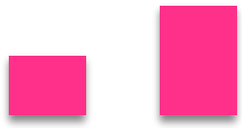
PRONOUN

interpretation context

$$p(\alpha_{subj.\text{SG}} | \text{FORM}, \text{CON}, \text{MOR}) \propto p(\alpha_{subj.\text{SG}}) * p(\text{FORM} | \alpha_{subj.\text{SG}}) * p(\text{CON} | \alpha_{subj.\text{SG}}) * p(\text{MOR} | \alpha_{subj.\text{SG}})$$

inaccurate representations

$probability^{\sigma}$



About σ:

σ <1: probability differences are smoothed away.

σ =1: probabilities remain accurate.

σ >1: probability differences are sharpened.

0.324 vs. 0.676

Forsythe & Pearl 2019, in prep

Modeling pronoun interpretation in context

Bayesian inference

PRONOUN

interpretation context

$$p(\alpha_{subj.\text{SG}}|\text{FORM}, \text{CON}, \text{MOR}) \propto p(\alpha_{subj.\text{SG}}) * p(\text{FORM}|\alpha_{subj.\text{SG}}) * p(\text{CON}|\alpha_{subj.\text{SG}}) * p(\text{MOR}|\alpha_{subj.\text{SG}})$$

inaccurate representations

$probability^{\sigma}$

About σ:

σ =0.5: probability differences are smoothed away. 0.409 vs. 0.591

σ =1: probabilities remain accurate. *0.324 vs. 0.676*

σ >1: probability differences are sharpened.

Forsythe & Pearl 2019, in prep

Modeling pronoun interpretation in context

Bayesian inference

PRONOUN

interpretation context

$$p(\alpha_{subj.\mathrm{SG}}|\mathrm{FORM}, \mathrm{CON}, \mathrm{MOR}) \propto p(\alpha_{subj.\mathrm{SG}}) * p(\mathrm{FORM}|\alpha_{subj.\mathrm{SG}}) * p(\mathrm{CON}|\alpha_{subj.\mathrm{SG}}) * p(\mathrm{MOR}|\alpha_{subj.\mathrm{SG}})$$

inaccurate representations

$probability^{\sigma}$

About σ:

σ <1: probability differences are smoothed away.

σ =1: probabilities remain accurate.

σ = 2: probability differences are sharpened.

0.324 vs. 0.676

0.187 vs. 0.813

Forsythe & Pearl 2019, in prep

Modeling pronoun interpretation in context

Bayesian inference

PRONOUN

probability$^{\sigma}$

interpretation context

$$p_\sigma(\alpha_{num}, \alpha_{subj?} | \mathrm{FORM}, \mathrm{CON}, \mathrm{MOR}) \propto p(\alpha_{num}, \alpha_{subj?})^{\sigma_\alpha} * p(\mathrm{FORM} | \alpha_{num}, \alpha_{subj?})^{\sigma_{form}} * p(\mathrm{CON} | \alpha_{num}, \alpha_{subj?})^{\sigma_{con}} * p(\mathrm{MOR} | \alpha_{num}, \alpha_{subj?})^{\sigma_{mor}}$$

inaccurate representations

One σ for each information type:

(in the prior) σ_α

(in the likelihood) σ_{form}, σ_{con}, σ_{mor}

Forsythe & Pearl 2019, in prep

Modeling pronoun interpretation in context

Bayesian inference

PRONOUN

probability$^{\sigma}$

interpretation context

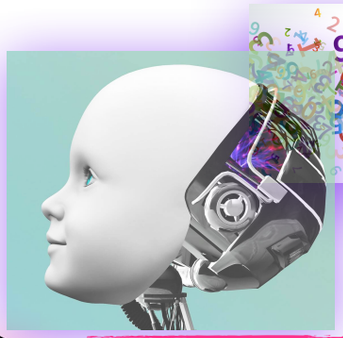
$$p_\sigma(\alpha_{num}, \alpha_{subj?} | \text{FORM}, \text{CON}, \text{MOR}) \propto p(\alpha_{num}, \alpha_{subj?})^{\sigma_\alpha} * p(\text{FORM} | \alpha_{num}, \alpha_{subj?})^{\sigma_{form}} * p(\text{CON} | \alpha_{num}, \alpha_{subj?})^{\sigma_{con}} * p(\text{MOR} | \alpha_{num}, \alpha_{subj?})^{\sigma_{mor}}$$

inaccurate representations

We allow $0.01 \leq \sigma \leq 4$, and see which σ value combinations best predict child and adult pronoun interpretation behavior.

Forsythe & Pearl 2019, in prep

Modeling pronoun interpretation in context

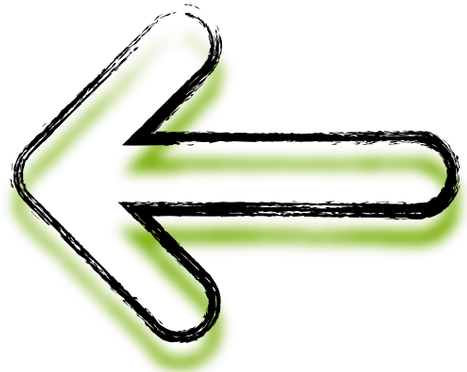


Bayesian inference

inaccurate representations

p_σ

PRONOUN



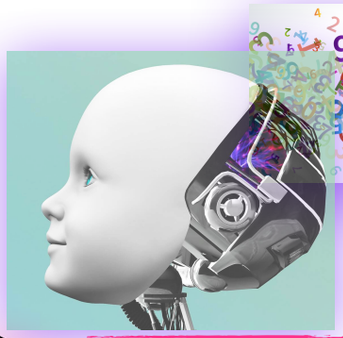
interpretation context

$$p(\alpha_{subj.\text{SG}}|\text{FORM}, \text{CON}, \text{MOR}) \propto p(\alpha_{subj.\text{SG}}) * p(\text{FORM}|\alpha_{subj.\text{SG}}) * p(\text{CON}|\alpha_{subj.\text{SG}}) * p(\text{MOR}|\alpha_{subj.\text{SG}})$$

What about a modeled listener who has inaccurate deployment of information in the representations? This could involve inaccurately deploying the prior or the likelihood information, or both.

Forsythe & Pearl 2019, in prep

Modeling pronoun interpretation in context

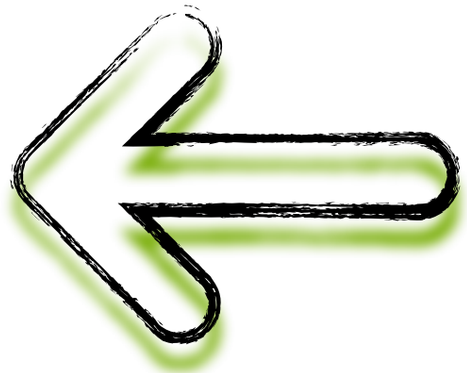


Bayesian inference

inaccurate representations

p_σ

PRONOUN



$$p(\alpha_{subj.\mathrm{SG}} | \mathrm{FORM}, \mathrm{CON}, \mathrm{MOR}) \propto p(\alpha_{subj.\mathrm{SG}}) * p(\mathrm{FORM} | \alpha_{subj.\mathrm{SG}}) * p(\mathrm{CON} | \alpha_{subj.\mathrm{SG}}) * p(\mathrm{MOR} | \alpha_{subj.\mathrm{SG}})$$

interpretation

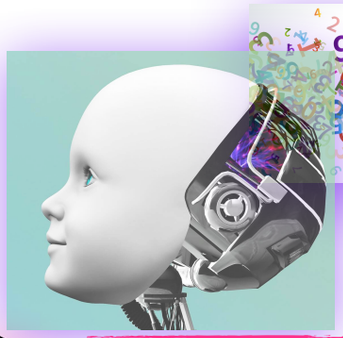
context

inaccurate deployment

We implement this as ignoring that information. So, for any piece of information, the modeled listener either pays attention to it (and so uses it) or ignores it in the moment.

Forsythe & Pearl 2019, in prep

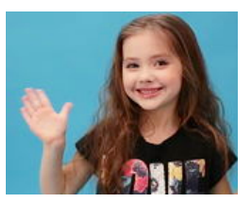
Modeling pronoun interpretation in context



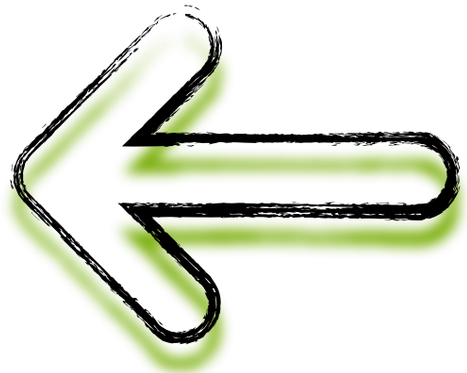
Bayesian inference

inaccurate representations

p_σ



PRONOUN



interpretation context

$$p(\alpha_{subj.\text{SG}} | \text{FORM}, \text{CON}, \text{MOR}) \propto p(\alpha_{subj.\text{SG}}) * p(\text{FORM} | \alpha_{subj.\text{SG}}) * p(\text{CON} | \alpha_{subj.\text{SG}}) * p(\text{MOR} | \alpha_{subj.\text{SG}})$$

inaccurate deployment

Not using information means not incorporating it into the inference.

Forsythe & Pearl 2019, in prep

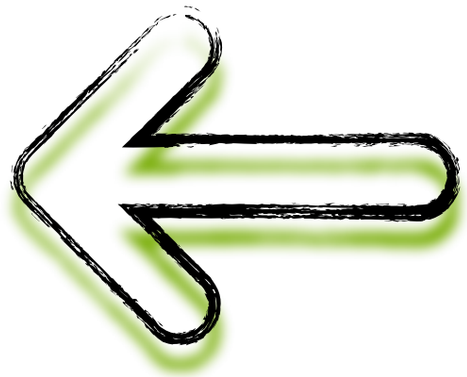
Modeling pronoun interpretation in context

Bayesian inference

inaccurate representations

p_σ

PRONOUN



interpretation context

$$p_{\text{UNIF}}(\alpha_{num}, \alpha_{subj?} | \text{FORM}, \text{CON}, \text{MOR}) \propto p(\text{UNIF})$$
$$* \, p(\text{FORM} | \alpha_{num}, \alpha_{subj?})$$
$$* \, p(\text{CON} | \alpha_{num}, \alpha_{subj?})$$
$$* \, p(\text{MOR} | \alpha_{num}, \alpha_{subj?})$$

inaccurate deployment

Not using the prior means relying on a uniform prior.

Forsythe & Pearl 2019, in prep

Modeling pronoun interpretation in context

Bayesian inference

inaccurate representations

p_σ

PRONOUN

interpretation context

$$p(\alpha_{subj.\text{SG}}|\text{FORM}, \text{CON}, \text{MOR}) \propto p(\alpha_{subj.\text{SG}}) * p(\text{FORM}|\alpha_{subj.\text{SG}}) * p(\text{CON}|\alpha_{subj.\text{SG}}) * p(\text{MOR}|\alpha_{subj.\text{SG}})$$

inaccurate deployment

Not using likelihood information for a cue means not using that cue's information. For example, ignoring morphology information means not using the morphology likelihood.

Forsythe & Pearl 2019, in prep

Modeling pronoun interpretation in context

Bayesian inference

inaccurate representations

p_σ

PRONOUN

interpretation context

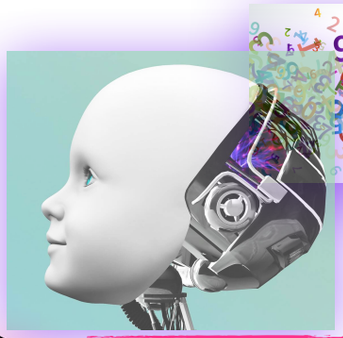
$$p(\alpha_{num}, \alpha_{subj?}|\textbf{FORM}, \textbf{CON}) \propto p(\alpha_{num}, \alpha_{subj?}) * p(\textbf{FORM}|\alpha_{num}, \alpha_{subj?}) * p(\textbf{CON}|\alpha_{num}, \alpha_{subj?})$$

inaccurate deployment

Not using likelihood information for a cue means not using that cue's information. For example, ignoring morphology information means not using the morphology likelihood.

Forsythe & Pearl 2019, in prep

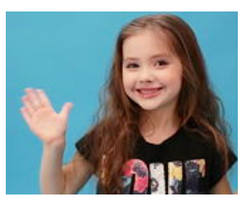
Modeling pronoun interpretation in context



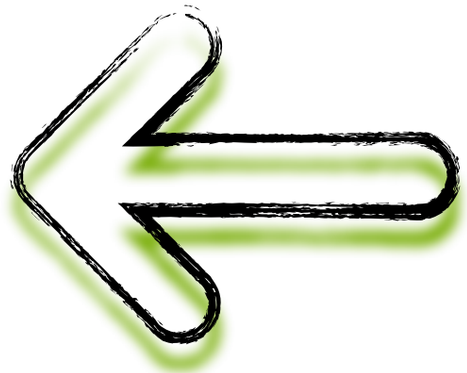
Bayesian inference

inaccurate representations

p_σ



PRONOUN



interpretation context

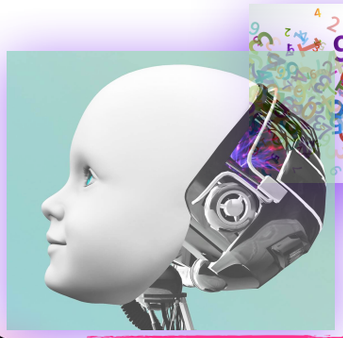
$$p(\alpha_{subj.\text{SG}} | \text{FORM}, \text{CON}, \text{MOR}) \propto p(\alpha_{subj.\text{SG}}) * p(\text{FORM} | \alpha_{subj.\text{SG}}) * p(\text{CON} | \alpha_{subj.\text{SG}}) * p(\text{MOR} | \alpha_{subj.\text{SG}})$$

inaccurate deployment

For any information, the modeled listener could use or not use it in the moment. Use parameter β determines whether a particular information type is used.

Forsythe & Pearl 2019, in prep

Modeling pronoun interpretation in context

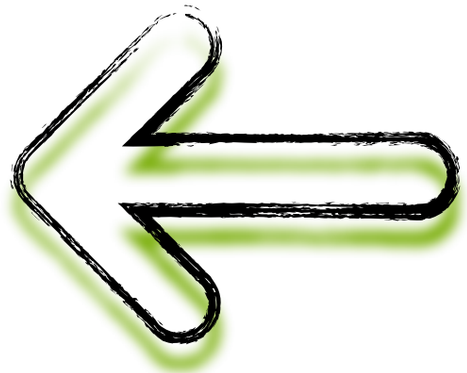


Bayesian inference

inaccurate representations

p_σ

PRONOUN



interpretation context

$$p(\alpha_{subj.\text{SG}} | \text{FORM}, \text{CON}, \text{MOR}) \propto p(\alpha_{subj.\text{SG}}) * p(\text{FORM} | \alpha_{subj.\text{SG}}) * p(\text{CON} | \alpha_{subj.\text{SG}}) * p(\text{MOR} | \alpha_{subj.\text{SG}})$$

inaccurate deployment

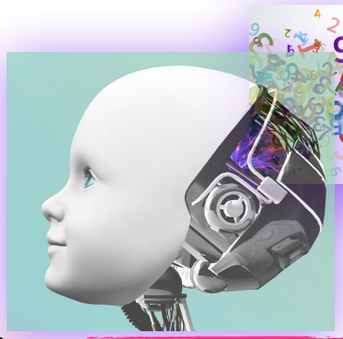
Each of the four information types has its own β:

(prior) β_α

(likelihood) β_{form}, β_{con}, β_{mor}

Forsythe & Pearl 2019, in prep

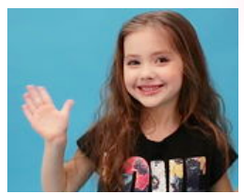
Modeling pronoun interpretation in context

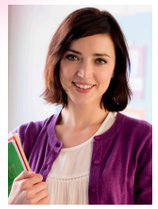


Bayesian inference

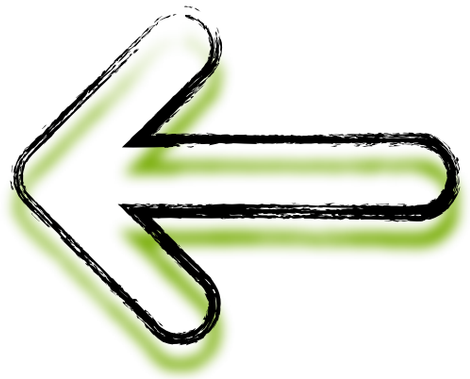
inaccurate representations p_σ

inaccurate deployment





$\approx$ PRONOUN $=$



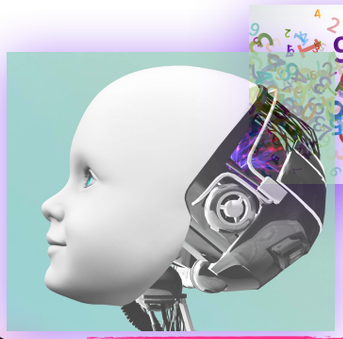
$$p_\beta(\alpha|\underbrace{\text{FORM}}_{\text{interpretation}}, \underbrace{\text{CON}, \text{MOR}}_{\text{context}}, \alpha_{num}, \alpha_{subj?}) =$$

β_{form}	β_{con}	β_{mor}	β_α	
✓	✓	✓	✓	$(\beta_{form})(\beta_{con})(\beta_{mor})(\beta_\alpha) * p(\alpha\|\text{FORM}, \text{CON}, \text{MOR}, \alpha_{num}, \alpha_{subj?})+$
✓	✓	✓		$(\beta_{form})(\beta_{con})(\beta_{mor})(1-\beta_\alpha) * p_{\text{UNIF}}(\alpha\|\text{FORM}, \text{CON}, \text{MOR}, \alpha_{num}, \alpha_{subj?})+$
	✓	✓	✓	$(1-\beta_{form})(\beta_{con})(\beta_{mor})(\beta_\alpha) * p(\alpha\|\text{CON}, \text{MOR}, \alpha_{num}, \alpha_{subj?})+$
	✓	✓		$(1-\beta_{form})(\beta_{con})(\beta_{mor})(1-\beta_\alpha) * p_{\text{UNIF}}(\alpha\|\text{CON}, \text{MOR}, \alpha_{num}, \alpha_{subj?})+$
✓		✓	✓	$(\beta_{form})(1-\beta_{con})(\beta_{mor})(\beta_\alpha) * p(\alpha\|\text{FORM}, \text{MOR}, \alpha_{num}, \alpha_{subj?})+$
✓		✓		$(\beta_{form})(1-\beta_{con})(\beta_{mor})(1-\beta_\alpha) * p_{\text{UNIF}}(\alpha\|\text{FORM}, \text{MOR}, \alpha_{num}, \alpha_{subj?})+$
✓	✓		✓	$(\beta_{form})(\beta_{con})(1-\beta_{mor})(\beta_\alpha) * p(\alpha\|\text{FORM}, \text{CON}, \alpha_{num}, \alpha_{subj?})+$
✓	✓			$(\beta_{form})(\beta_{con})(1-\beta_{mor})(1-\beta_\alpha) * p_{\text{UNIF}}(\alpha\|\text{FORM}, \text{CON}, \alpha_{num}, \alpha_{subj?})+$
		✓	✓	$(1-\beta_{form})(1-\beta_{con})(\beta_{mor})(\beta_\alpha) * p(\alpha\|\text{MOR}, \alpha_{num}, \alpha_{subj?})+$
		✓		$(1-\beta_{form})(1-\beta_{con})(\beta_{mor})(1-\beta_\alpha) * p_{\text{UNIF}}(\alpha\|\text{MOR}, \alpha_{num}, \alpha_{subj?})+$
✓			✓	$(\beta_{form})(1-\beta_{con})(1-\beta_{mor})(\beta_\alpha) * p(\alpha\|\text{FORM}, \alpha_{num}, \alpha_{subj?})+$
✓				$(\beta_{form})(1-\beta_{con})(1-\beta_{mor})(1-\beta_\alpha) * p_{\text{UNIF}}(\alpha\|\text{FORM}, \alpha_{num}, \alpha_{subj?})+$
	✓		✓	$(1-\beta_{form})(\beta_{con})(1-\beta_{mor})(\beta_\alpha) * p(\alpha\|\text{CON}, \alpha_{num}, \alpha_{subj?})+$
	✓			$(1-\beta_{form})(\beta_{con})(1-\beta_{mor})(1-\beta_\alpha) * p_{\text{UNIF}}(\alpha\|\text{CON}, \alpha_{num}, \alpha_{subj?})+$
			✓	$(1-\beta_{form})(1-\beta_{con})(1-\beta_{mor})(\beta_\alpha) * p(\alpha_{num}, \alpha_{subj?})+$
				$(1-\beta_{form})(1-\beta_{con})(1-\beta_{mor})(1-\beta_\alpha) * p(\text{UNIF})$

This yields 16 possible use combinations for any particular moment, implemented with a mixture model p_β.

Forsythe & Pearl 2019, in prep

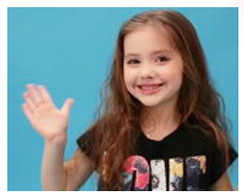
Modeling pronoun interpretation in context

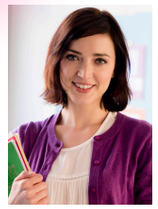


Bayesian inference

inaccurate representations

p_σ



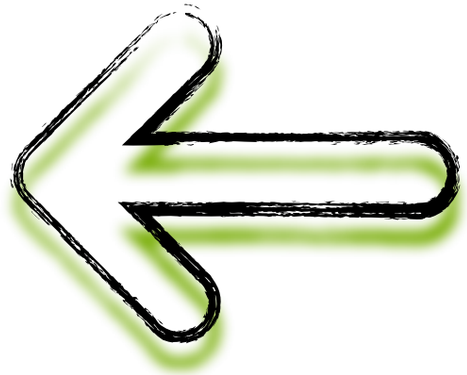


PRONOUN

inaccurate deployment

interpretation context

$$p_\beta(\alpha|\text{FORM}, \text{CON}, \text{MOR}, \alpha_{num}, \alpha_{subj?}) =$$
$$(\beta_{form})(\beta_{con})(\beta_{mor})(\beta_\alpha) * p(\alpha|\text{FORM}, \text{CON}, \text{MOR}, \alpha_{num}, \alpha_{subj?}) +$$
$$(\beta_{form})(\beta_{con})(\beta_{mor})(1-\beta_\alpha) * p_{\text{UNIF}}(\alpha|\text{FORM}, \text{CON}, \text{MOR}, \alpha_{num}, \alpha_{subj?}) +$$
$$(1-\beta_{form})(\beta_{con})(\beta_{mor})(\beta_\alpha) * p(\alpha|\text{CON}, \text{MOR}, \alpha_{num}, \alpha_{subj?}) +$$
$$(1-\beta_{form})(\beta_{con})(\beta_{mor})(1-\beta_\alpha) * p_{\text{UNIF}}(\alpha|\text{CON}, \text{MOR}, \alpha_{num}, \alpha_{subj?}) +$$
$$(\beta_{form})(1-\beta_{con})(\beta_{mor})(\beta_\alpha) * p(\alpha|\text{FORM}, \text{MOR}, \alpha_{num}, \alpha_{subj?}) +$$
$$(\beta_{form})(1-\beta_{con})(\beta_{mor})(1-\beta_\alpha) * p_{\text{UNIF}}(\alpha|\text{FORM}, \text{MOR}, \alpha_{num}, \alpha_{subj?}) +$$
$$(\beta_{form})(\beta_{con})(1-\beta_{mor})(\beta_\alpha) * p(\alpha|\text{FORM}, \text{CON}, \alpha_{num}, \alpha_{subj?}) +$$
$$(\beta_{form})(\beta_{con})(1-\beta_{mor})(1-\beta_\alpha) * p_{\text{UNIF}}(\alpha|\text{FORM}, \text{CON}, \alpha_{num}, \alpha_{subj?}) +$$
$$(1-\beta_{form})(1-\beta_{con})(\beta_{mor})(\beta_\alpha) * p(\alpha|\text{MOR}, \alpha_{num}, \alpha_{subj?}) +$$
$$(1-\beta_{form})(1-\beta_{con})(\beta_{mor})(1-\beta_\alpha) * p_{\text{UNIF}}(\alpha|\text{MOR}, \alpha_{num}, \alpha_{subj?}) +$$
$$(\beta_{form})(1-\beta_{con})(1-\beta_{mor})(\beta_\alpha) * p(\alpha|\text{FORM}, \alpha_{num}, \alpha_{subj?}) +$$
$$(\beta_{form})(1-\beta_{con})(1-\beta_{mor})(1-\beta_\alpha) * p_{\text{UNIF}}(\alpha|\text{FORM}, \alpha_{num}, \alpha_{subj?}) +$$
$$(1-\beta_{form})(\beta_{con})(1-\beta_{mor})(\beta_\alpha) * p(\alpha|\text{CON}, \alpha_{num}, \alpha_{subj?}) +$$
$$(1-\beta_{form})(\beta_{con})(1-\beta_{mor})(1-\beta_\alpha) * p_{\text{UNIF}}(\alpha|\text{CON}, \alpha_{num}, \alpha_{subj?}) +$$
$$(1-\beta_{form})(1-\beta_{con})(1-\beta_{mor})(\beta_\alpha) * p(\alpha_{num}, \alpha_{subj?}) +$$
$$(1-\beta_{form})(1-\beta_{con})(1-\beta_{mor})(1-\beta_\alpha) * p(\text{UNIF})$$



We allow $0 \leq \beta \leq 1$, and see which β value combinations best predict child and adult pronoun interpretation behavior.

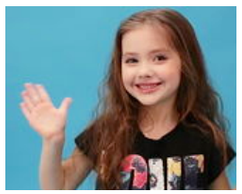
Forsythe & Pearl 2019, in prep

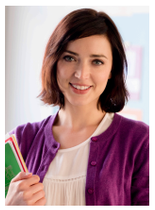
Modeling pronoun interpretation in context

Bayesian inference

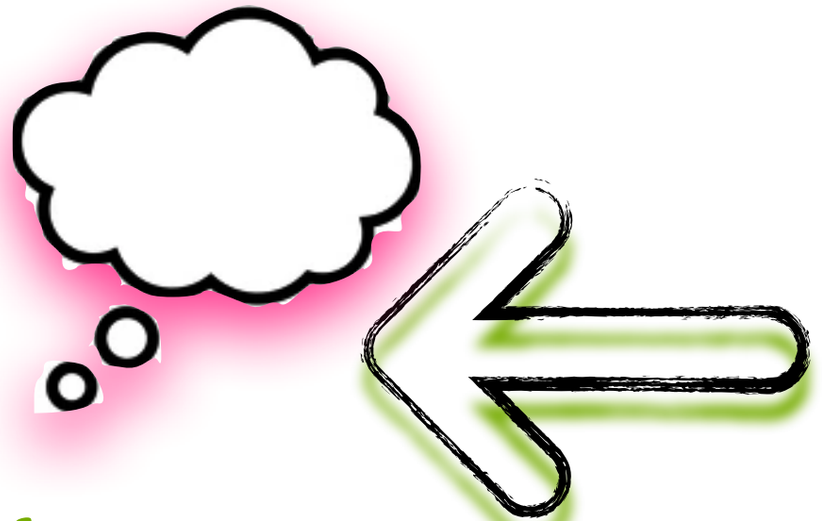
inaccurate representations p_σ

inaccurate deployment p_β





PRONOUN



interpretation context

$$p(\alpha_{subj.\text{SG}}|\text{FORM}, \text{CON}, \text{MOR}) \propto p(\alpha_{subj.\text{SG}}) * p(\text{FORM}|\alpha_{subj.\text{SG}}) * p(\text{CON}|\alpha_{subj.\text{SG}}) * p(\text{MOR}|\alpha_{subj.\text{SG}})$$

What about a modeled listener who has both inaccurate representations of information and inaccurate deployment of those representations?

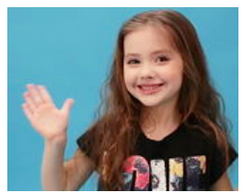
Forsythe & Pearl 2019, in prep

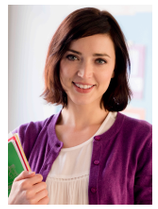
Modeling pronoun interpretation in context

Bayesian inference

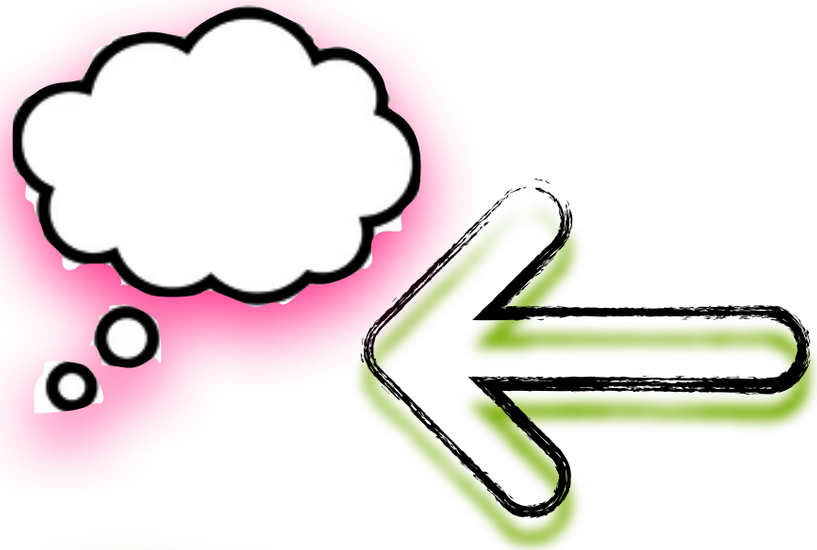
inaccurate representations p_σ

inaccurate deployment p_β





PRONOUN



inaccurate both

p_σ

$$p_\sigma(\alpha_{num}, \alpha_{subj?}|\text{FORM, CON, MOR}) \propto p(\alpha_{num}, \alpha_{subj?})^{\sigma_\alpha} * p(\text{FORM}|\alpha_{num}, \alpha_{subj?})^{\sigma_{form}} * p(\text{CON}|\alpha_{num}, \alpha_{subj?})^{\sigma_{con}} * p(\text{MOR}|\alpha_{num}, \alpha_{subj?})^{\sigma_{mor}}$$

$p_{\sigma,\beta}$

p_β

$$\begin{aligned}
p_\beta(\alpha|\text{FORM, CON, MOR}, \alpha_{num}, \alpha_{subj?}) = \\
(\beta_{form})(\beta_{con})(\beta_{mor})(\beta_\alpha) * p(\alpha|\text{FORM, CON, MOR}, \alpha_{num}, \alpha_{subj?}) + \\
(\beta_{form})(\beta_{con})(\beta_{mor})(1-\beta_\alpha) * p_{\text{UNIF}}(\alpha|\text{FORM, CON, MOR}, \alpha_{num}, \alpha_{subj?}) + \\
(1-\beta_{form})(\beta_{con})(\beta_{mor})(\beta_\alpha) * p(\alpha|\text{CON, MOR}, \alpha_{num}, \alpha_{subj?}) + \\
(1-\beta_{form})(\beta_{con})(\beta_{mor})(1-\beta_\alpha) * p_{\text{UNIF}}(\alpha|\text{CON, MOR}, \alpha_{num}, \alpha_{subj?}) + \\
(\beta_{form})(1-\beta_{con})(\beta_{mor})(\beta_\alpha) * p(\alpha|\text{FORM, MOR}, \alpha_{num}, \alpha_{subj?}) + \\
(\beta_{form})(1-\beta_{con})(\beta_{mor})(1-\beta_\alpha) * p_{\text{UNIF}}(\alpha|\text{FORM, MOR}, \alpha_{num}, \alpha_{subj?}) + \\
(\beta_{form})(\beta_{con})(1-\beta_{mor})(\beta_\alpha) * p(\alpha|\text{FORM, CON}, \alpha_{num}, \alpha_{subj?}) + \\
(\beta_{form})(\beta_{con})(1-\beta_{mor})(1-\beta_\alpha) * p_{\text{UNIF}}(\alpha|\text{FORM, CON}, \alpha_{num}, \alpha_{subj?}) + \\
(1-\beta_{form})(1-\beta_{con})(\beta_{mor})(\beta_\alpha) * p(\alpha|\text{MOR}, \alpha_{num}, \alpha_{subj?}) + \\
(1-\beta_{form})(1-\beta_{con})(\beta_{mor})(1-\beta_\alpha) * p_{\text{UNIF}}(\alpha|\text{MOR}, \alpha_{num}, \alpha_{subj?}) + \\
(\beta_{form})(1-\beta_{con})(1-\beta_{mor})(\beta_\alpha) * p(\alpha|\text{FORM}, \alpha_{num}, \alpha_{subj?}) + \\
(\beta_{form})(1-\beta_{con})(1-\beta_{mor})(1-\beta_\alpha) * p_{\text{UNIF}}(\alpha|\text{FORM}, \alpha_{num}, \alpha_{subj?}) + \\
(1-\beta_{form})(\beta_{con})(1-\beta_{mor})(\beta_\alpha) * p(\alpha|\text{CON}, \alpha_{num}, \alpha_{subj?}) + \\
(1-\beta_{form})(\beta_{con})(1-\beta_{mor})(1-\beta_\alpha) * p_{\text{UNIF}}(\alpha|\text{CON}, \alpha_{num}, \alpha_{subj?}) + \\
(1-\beta_{form})(1-\beta_{con})(1-\beta_{mor})(\beta_\alpha) * p(\alpha_{num}, \alpha_{subj?}) + \\
(1-\beta_{form})(1-\beta_{con})(1-\beta_{mor})(1-\beta_\alpha) * p(\text{UNIF})
\end{aligned}$$

We implement this as a combination of the previous two modeled listeners, including σ values for inaccurate representations and β values for inaccurate deployment.

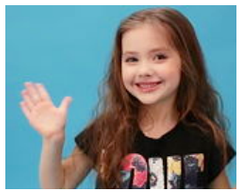
Forsythe & Pearl 2019, in prep

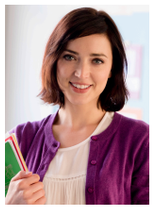
Modeling pronoun interpretation in context

Bayesian inference

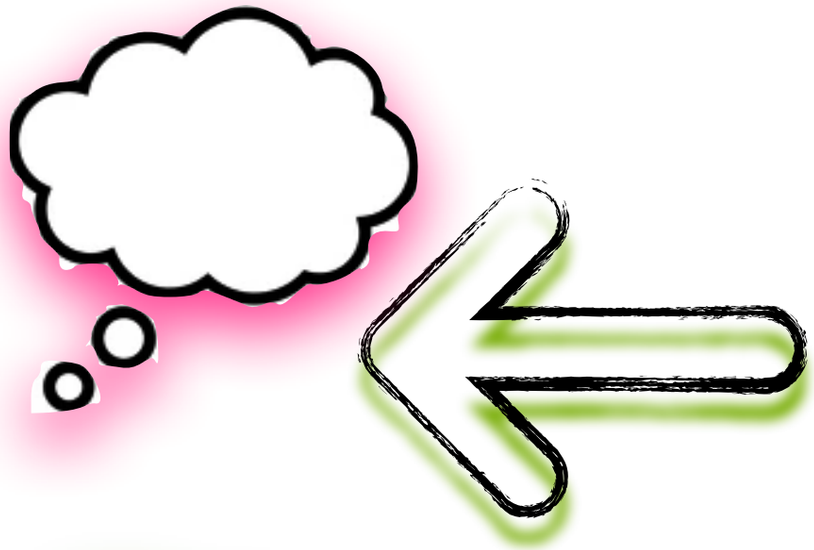
inaccurate representations p_σ

inaccurate deployment p_β





PRONOUN



inaccurate both

p_σ $p_{\sigma,\beta}$ p_β

$$p_\sigma(\alpha_{num}, \alpha_{subj?} | \text{FORM, CON, MOR}) \propto p(\alpha_{num}, \alpha_{subj?})^{\sigma_\alpha} * p(\text{FORM}|\alpha_{num}, \alpha_{subj?})^{\sigma_{form}} * p(\text{CON}|\alpha_{num}, \alpha_{subj?})^{\sigma_{con}} * p(\text{MOR}|\alpha_{num}, \alpha_{subj?})^{\sigma_{mor}}$$

$$\begin{aligned}
p_\beta(\alpha|\text{FORM, CON, MOR}, \alpha_{num}, \alpha_{subj?}) = \\
(\beta_{form})(\beta_{con})(\beta_{mor})(\beta_\alpha) * p(\alpha|\text{FORM, CON, MOR}, \alpha_{num}, \alpha_{subj?}) + \\
(\beta_{form})(\beta_{con})(\beta_{mor})(1-\beta_\alpha) * p_{\text{UNIF}}(\alpha|\text{FORM, CON, MOR}, \alpha_{num}, \alpha_{subj?}) + \\
(1-\beta_{form})(\beta_{con})(\beta_{mor})(\beta_\alpha) * p(\alpha|\text{CON, MOR}, \alpha_{num}, \alpha_{subj?}) + \\
(1-\beta_{form})(\beta_{con})(\beta_{mor})(1-\beta_\alpha) * p_{\text{UNIF}}(\alpha|\text{CON, MOR}, \alpha_{num}, \alpha_{subj?}) + \\
(\beta_{form})(1-\beta_{con})(\beta_{mor})(\beta_\alpha) * p(\alpha|\text{FORM, MOR}, \alpha_{num}, \alpha_{subj?}) + \\
(\beta_{form})(1-\beta_{con})(\beta_{mor})(1-\beta_\alpha) * p_{\text{UNIF}}(\alpha|\text{FORM, MOR}, \alpha_{num}, \alpha_{subj?}) + \\
(\beta_{form})(\beta_{con})(1-\beta_{mor})(\beta_\alpha) * p(\alpha|\text{FORM, CON}, \alpha_{num}, \alpha_{subj?}) + \\
(\beta_{form})(\beta_{con})(1-\beta_{mor})(1-\beta_\alpha) * p_{\text{UNIF}}(\alpha|\text{FORM, CON}, \alpha_{num}, \alpha_{subj?}) + \\
(1-\beta_{form})(1-\beta_{con})(\beta_{mor})(\beta_\alpha) * p(\alpha|\text{MOR}, \alpha_{num}, \alpha_{subj?}) + \\
(1-\beta_{form})(1-\beta_{con})(\beta_{mor})(1-\beta_\alpha) * p_{\text{UNIF}}(\alpha|\text{MOR}, \alpha_{num}, \alpha_{subj?}) + \\
(\beta_{form})(1-\beta_{con})(1-\beta_{mor})(\beta_\alpha) * p(\alpha|\text{FORM}, \alpha_{num}, \alpha_{subj?}) + \\
(\beta_{form})(1-\beta_{con})(1-\beta_{mor})(1-\beta_\alpha) * p_{\text{UNIF}}(\alpha|\text{FORM}, \alpha_{num}, \alpha_{subj?}) + \\
(1-\beta_{form})(\beta_{con})(1-\beta_{mor})(\beta_\alpha) * p(\alpha|\text{CON}, \alpha_{num}, \alpha_{subj?}) + \\
(1-\beta_{form})(\beta_{con})(1-\beta_{mor})(1-\beta_\alpha) * p_{\text{UNIF}}(\alpha|\text{CON}, \alpha_{num}, \alpha_{subj?}) + \\
(1-\beta_{form})(1-\beta_{con})(1-\beta_{mor})(\beta_\alpha) * p(\alpha_{num}, \alpha_{subj?}) + \\
(1-\beta_{form})(1-\beta_{con})(1-\beta_{mor})(1-\beta_\alpha) * p(\text{UNIF})
\end{aligned}$$

Each term of p_β has σ values for all information types that are used.

Forsythe & Pearl 2019, in prep

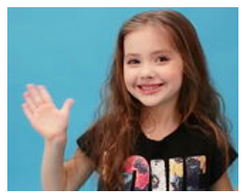
Modeling pronoun interpretation in context

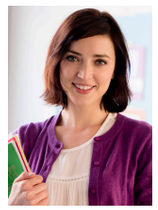
Bayesian inference

inaccurate representations p_σ

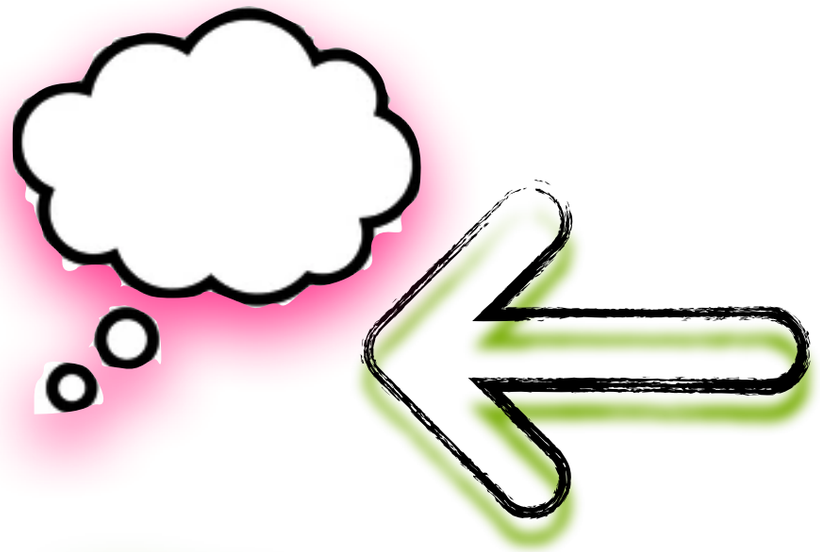
inaccurate deployment p_β

inaccurate both





PRONOUN



p_σ

$$p_\sigma(\alpha_{num}, \alpha_{subj?} | \text{FORM, CON, MOR}) \propto p(\alpha_{num}, \alpha_{subj?})^{\sigma_\alpha} * p(\text{FORM}|\alpha_{num}, \alpha_{subj?})^{\sigma_{form}} * p(\text{CON}|\alpha_{num}, \alpha_{subj?})^{\sigma_{con}} * p(\text{MOR}|\alpha_{num}, \alpha_{subj?})^{\sigma_{mor}}$$

$p_{\sigma,\beta}$

p_β

$$\begin{aligned}
p_\beta(\alpha|\text{FORM, CON, MOR}, \alpha_{num}, \alpha_{subj?}) = \\
(\beta_{form})(\beta_{con})(\beta_{mor})(\beta_\alpha) * p(\alpha|\text{FORM, CON, MOR}, \alpha_{num}, \alpha_{subj?}) + \\
(\beta_{form})(\beta_{con})(\beta_{mor})(1-\beta_\alpha) * p_{\text{UNIF}}(\alpha|\text{FORM, CON, MOR}, \alpha_{num}, \alpha_{subj?}) + \\
(1-\beta_{form})(\beta_{con})(\beta_{mor})(\beta_\alpha) * p(\alpha|\text{CON, MOR}, \alpha_{num}, \alpha_{subj?}) + \\
(1-\beta_{form})(\beta_{con})(\beta_{mor})(1-\beta_\alpha) * p_{\text{UNIF}}(\alpha|\text{CON, MOR}, \alpha_{num}, \alpha_{subj?}) + \\
(\beta_{form})(1-\beta_{con})(\beta_{mor})(\beta_\alpha) * p(\alpha|\text{FORM, MOR}, \alpha_{num}, \alpha_{subj?}) + \\
(\beta_{form})(1-\beta_{con})(\beta_{mor})(1-\beta_\alpha) * p_{\text{UNIF}}(\alpha|\text{FORM, MOR}, \alpha_{num}, \alpha_{subj?}) + \\
(\beta_{form})(\beta_{con})(1-\beta_{mor})(\beta_\alpha) * p(\alpha|\text{FORM, CON}, \alpha_{num}, \alpha_{subj?}) + \\
(\beta_{form})(\beta_{con})(1-\beta_{mor})(1-\beta_\alpha) * p_{\text{UNIF}}(\alpha|\text{FORM, CON}, \alpha_{num}, \alpha_{subj?}) + \\
(1-\beta_{form})(1-\beta_{con})(\beta_{mor})(\beta_\alpha) * p(\alpha|\text{MOR}, \alpha_{num}, \alpha_{subj?}) + \\
(1-\beta_{form})(1-\beta_{con})(\beta_{mor})(1-\beta_\alpha) * p_{\text{UNIF}}(\alpha|\text{MOR}, \alpha_{num}, \alpha_{subj?}) + \\
(\beta_{form})(1-\beta_{con})(1-\beta_{mor})(\beta_\alpha) * p(\alpha|\text{FORM}, \alpha_{num}, \alpha_{subj?}) + \\
(\beta_{form})(1-\beta_{con})(1-\beta_{mor})(1-\beta_\alpha) * p_{\text{UNIF}}(\alpha|\text{FORM}, \alpha_{num}, \alpha_{subj?}) + \\
(1-\beta_{form})(\beta_{con})(1-\beta_{mor})(\beta_\alpha) * p(\alpha|\text{CON}, \alpha_{num}, \alpha_{subj?}) + \\
(1-\beta_{form})(\beta_{con})(1-\beta_{mor})(1-\beta_\alpha) * p_{\text{UNIF}}(\alpha|\text{CON}, \alpha_{num}, \alpha_{subj?}) + \\
(1-\beta_{form})(1-\beta_{con})(1-\beta_{mor})(\beta_\alpha) * p(\alpha_{num}, \alpha_{subj?}) + \\
(1-\beta_{form})(1-\beta_{con})(1-\beta_{mor})(1-\beta_\alpha) * p(\text{UNIF})
\end{aligned}$$

So, $p_{\sigma,\beta}$ has 8 parameter values:

(in the prior) σ_α, β_α

(in the likelihood) σ_{form}, σ_{con}, σ_{mor}, β_{form}, β_{con}, β_{mor}

Forsythe & Pearl 2019, in prep

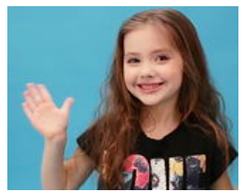
Modeling pronoun interpretation in context

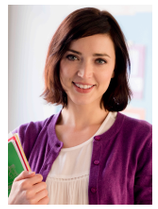
Bayesian inference

inaccurate representations p_σ

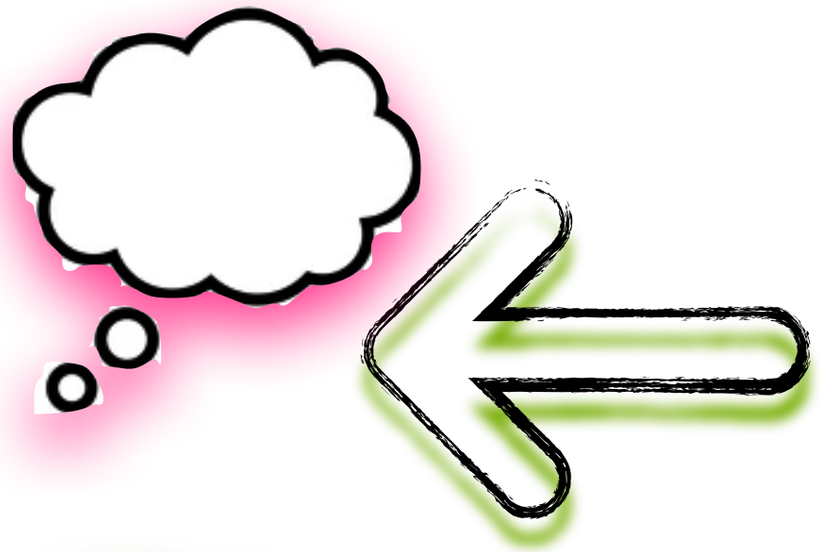
inaccurate deployment p_β

inaccurate both





PRONOUN



$p_{\sigma,\beta}$

p_σ

p_β

$$p_\sigma(\alpha_{num}, \alpha_{subj?}|\text{FORM, CON, MOR}) \propto p(\alpha_{num}, \alpha_{subj?})^{\sigma_\alpha} * p(\text{FORM}|\alpha_{num}, \alpha_{subj?})^{\sigma_{form}} * p(\text{CON}|\alpha_{num}, \alpha_{subj?})^{\sigma_{con}} * p(\text{MOR}|\alpha_{num}, \alpha_{subj?})^{\sigma_{mor}}$$

$$\begin{aligned}
p_\beta(\alpha|\text{FORM, CON, MOR}, \alpha_{num}, \alpha_{subj?}) = \\
&(\beta_{form})(\beta_{con})(\beta_{mor})(\beta_\alpha) * p(\alpha|\text{FORM, CON, MOR}, \alpha_{num}, \alpha_{subj?}) + \\
&(\beta_{form})(\beta_{con})(\beta_{mor})(1-\beta_\alpha) * p_{\text{UNIF}}(\alpha|\text{FORM, CON, MOR}, \alpha_{num}, \alpha_{subj?}) + \\
&(1-\beta_{form})(\beta_{con})(\beta_{mor})(\beta_\alpha) * p(\alpha|\text{CON, MOR}, \alpha_{num}, \alpha_{subj?}) + \\
&(1-\beta_{form})(\beta_{con})(\beta_{mor})(1-\beta_\alpha) * p_{\text{UNIF}}(\alpha|\text{CON, MOR}, \alpha_{num}, \alpha_{subj?}) + \\
&(\beta_{form})(1-\beta_{con})(\beta_{mor})(\beta_\alpha) * p(\alpha|\text{FORM, MOR}, \alpha_{num}, \alpha_{subj?}) + \\
&(\beta_{form})(1-\beta_{con})(\beta_{mor})(1-\beta_\alpha) * p_{\text{UNIF}}(\alpha|\text{FORM, MOR}, \alpha_{num}, \alpha_{subj?}) + \\
&(\beta_{form})(\beta_{con})(1-\beta_{mor})(\beta_\alpha) * p(\alpha|\text{FORM, CON}, \alpha_{num}, \alpha_{subj?}) + \\
&(\beta_{form})(\beta_{con})(1-\beta_{mor})(1-\beta_\alpha) * p_{\text{UNIF}}(\alpha|\text{FORM, CON}, \alpha_{num}, \alpha_{subj?}) + \\
&(1-\beta_{form})(1-\beta_{con})(\beta_{mor})(\beta_\alpha) * p(\alpha|\text{MOR}, \alpha_{num}, \alpha_{subj?}) + \\
&(1-\beta_{form})(1-\beta_{con})(\beta_{mor})(1-\beta_\alpha) * p_{\text{UNIF}}(\alpha|\text{MOR}, \alpha_{num}, \alpha_{subj?}) + \\
&(\beta_{form})(1-\beta_{con})(1-\beta_{mor})(\beta_\alpha) * p(\alpha|\text{FORM}, \alpha_{num}, \alpha_{subj?}) + \\
&(\beta_{form})(1-\beta_{con})(1-\beta_{mor})(1-\beta_\alpha) * p_{\text{UNIF}}(\alpha|\text{FORM}, \alpha_{num}, \alpha_{subj?}) + \\
&(1-\beta_{form})(\beta_{con})(1-\beta_{mor})(\beta_\alpha) * p(\alpha|\text{CON}, \alpha_{num}, \alpha_{subj?}) + \\
&(1-\beta_{form})(\beta_{con})(1-\beta_{mor})(1-\beta_\alpha) * p_{\text{UNIF}}(\alpha|\text{CON}, \alpha_{num}, \alpha_{subj?}) + \\
&(1-\beta_{form})(1-\beta_{con})(1-\beta_{mor})(\beta_\alpha) * p(\alpha_{num}, \alpha_{subj?}) + \\
&(1-\beta_{form})(1-\beta_{con})(1-\beta_{mor})(1-\beta_\alpha) * p(\text{UNIF})
\end{aligned}$$

We allow $0.01 \leq \sigma \leq 4$ and $0 \leq \beta \leq 1$, and see which σ and β value combinations best predict child and adult pronoun interpretation behavior.

Forsythe & Pearl 2019, in prep

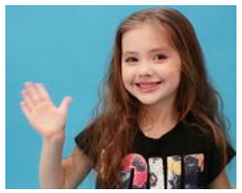
Input to the modeled listener

Bayesian inference

inaccurate representations p_σ

inaccurate deployment p_β

inaccurate both $p_{\sigma,\beta}$



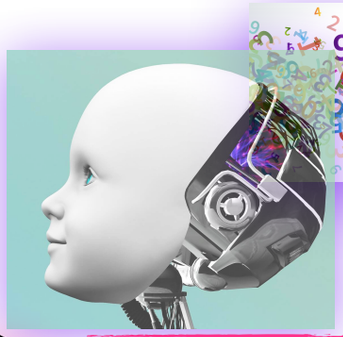
$\approx$ **PRONOUN** $=$

$$p(\alpha_{subj.\text{SG}}|\text{FORM}, \text{CON}, \text{MOR}) \propto p(\alpha_{subj.\text{SG}}) * p(\text{FORM}|\alpha_{subj.\text{SG}}) * p(\text{CON}|\alpha_{subj.\text{SG}}) * p(\text{MOR}|\alpha_{subj.\text{SG}})$$

What input is the modeled listener using to represent the various information types?

Forsythe & Pearl 2019, in prep

Input to the modeled listener

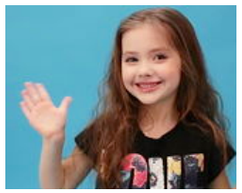


Bayesian inference

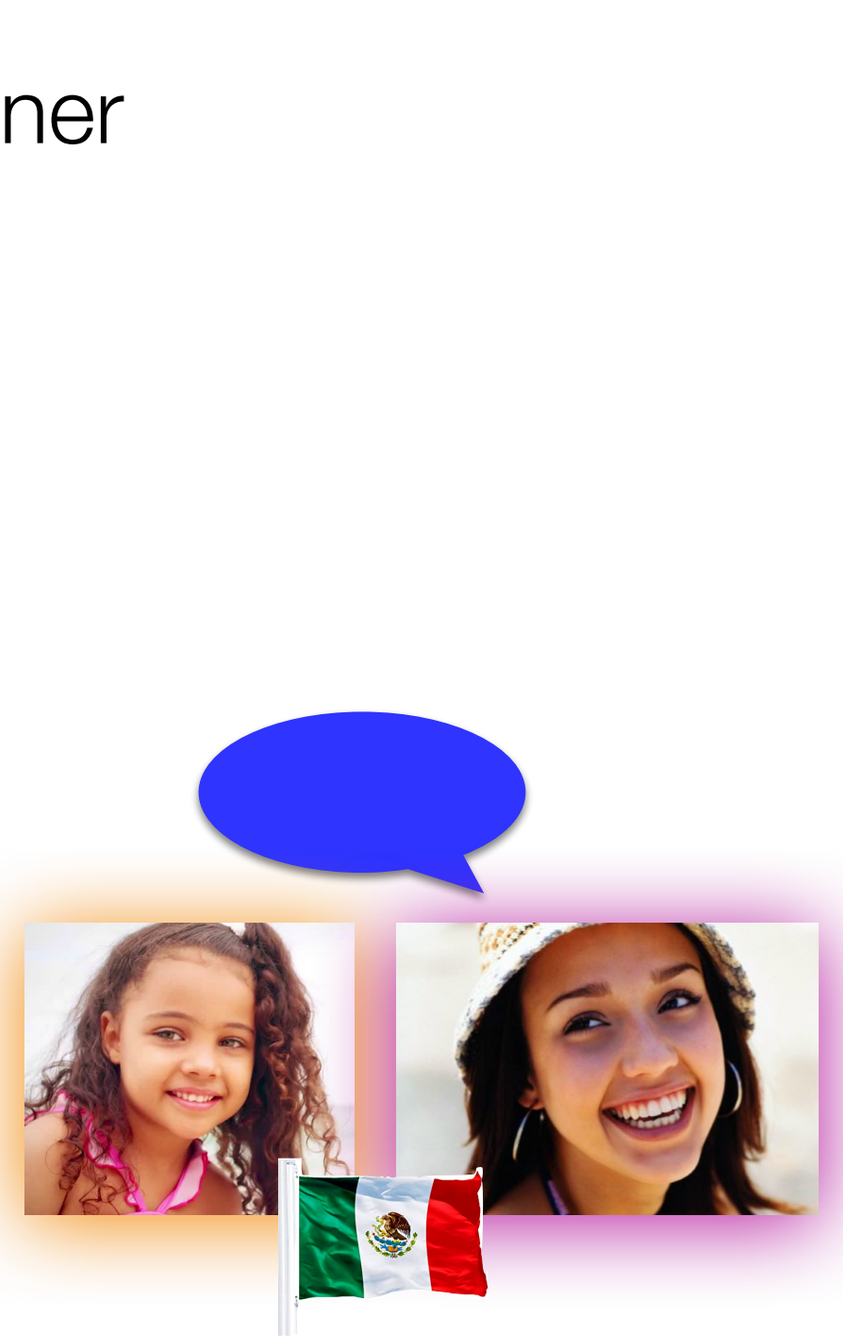
inaccurate representations p_σ

inaccurate deployment p_β

inaccurate both $p_{\sigma,\beta}$



≈ PRONOUN =



$$p(\alpha_{subj.\text{SG}}|\text{FORM}, \text{CON}, \text{MOR}) \propto p(\alpha_{subj.\text{SG}}) * p(\text{FORM}|\alpha_{subj.\text{SG}}) * p(\text{CON}|\alpha_{subj.\text{SG}}) * p(\text{MOR}|\alpha_{subj.\text{SG}})$$

54,757 utterances of Mexico City spontaneous child-directed speech to children 1;6-5;11 from the Schmitt-Miller corpus (Miller & Schmitt 2012).

Forsythe & Pearl 2019, in prep

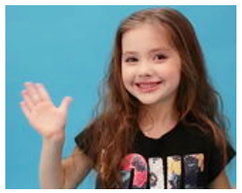
Input to the modeled listener

Bayesian inference

inaccurate representations p_σ

inaccurate deployment p_β

inaccurate both $p_{\sigma,\beta}$



≈ PRONOUN =

$$p(\alpha_{subj.\text{SG}}|\text{FORM}, \text{CON}, \text{MOR}) \propto p(\alpha_{subj.\text{SG}}) * p(\text{FORM}|\alpha_{subj.\text{SG}}) * p(\text{CON}|\alpha_{subj.\text{SG}}) * p(\text{MOR}|\alpha_{subj.\text{SG}})$$

antecedent type		prior $p(\alpha)$	likelihoods $p(\text{FORM}\|\alpha)$		$p(\text{CON}\|\alpha)$		$p(\text{MOR}\|\alpha)$	
			ø	overt	*después*	*porque*	SG	PL
SUBJ	SG	0.362	0.938	0.062	0.324	0.676	0.998	0.002
	PL	0.071	0.984	0.016	0.750	0.250	0.005	0.995
¬SUBJ	SG	0.438	0.817	0.183	0.132	0.868	0.998	0.002
	PL	0.129	0.959	0.041	0.394	0.606	0.005	0.995

From this, we estimate the relevant priors and likelihoods.

Forsythe & Pearl 2019, in prep

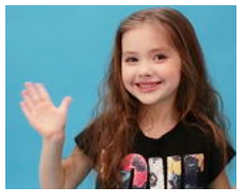
Input to the modeled listener

Bayesian inference

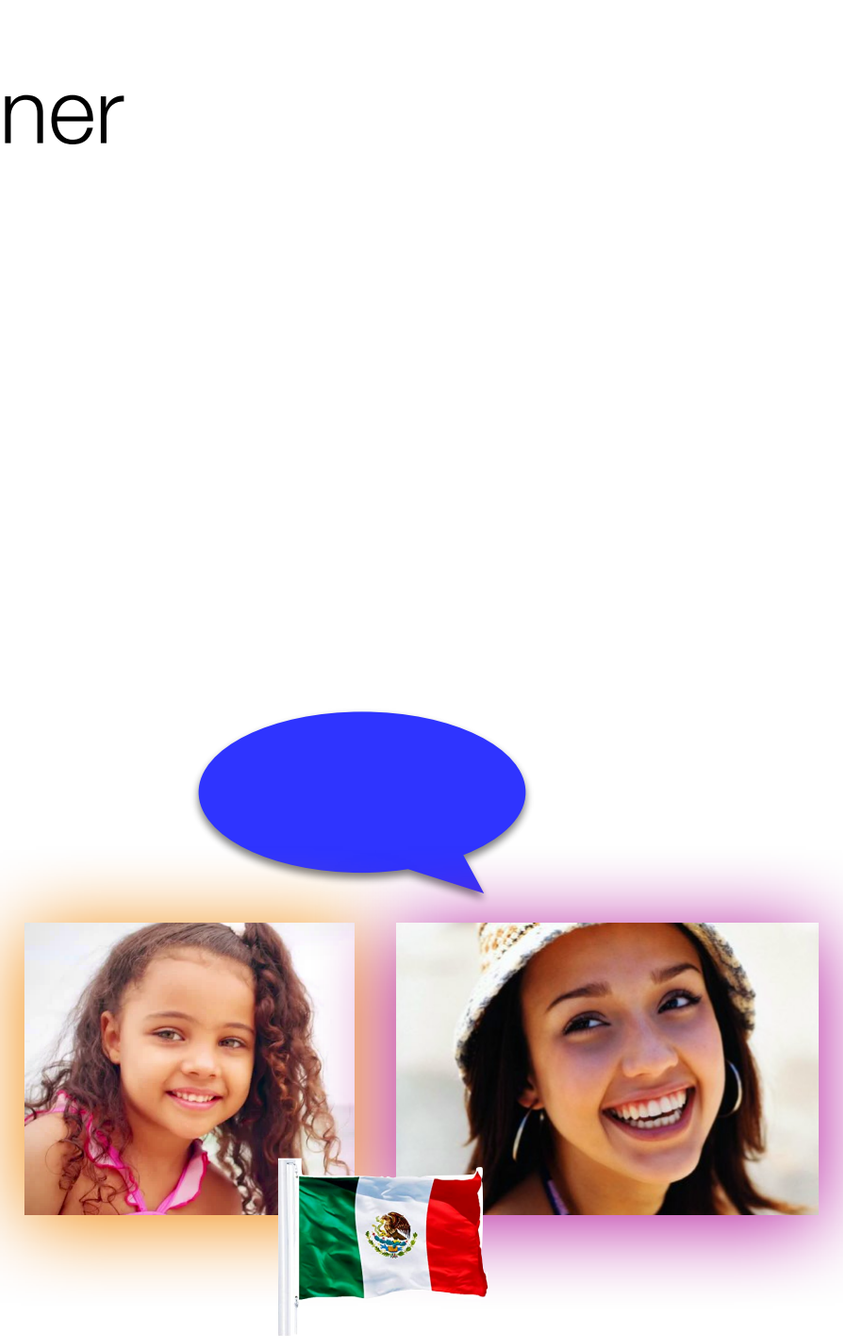
inaccurate representations p_σ

inaccurate deployment p_β

inaccurate both $p_{\sigma,\beta}$



≈ **PRONOUN** =



$$p(\alpha_{subj.\text{SG}}|\text{FORM}, \text{CON}, \text{MOR}) \propto p(\alpha_{subj.\text{SG}}) * p(\text{FORM}|\alpha_{subj.\text{SG}}) * p(\text{CON}|\alpha_{subj.\text{SG}}) * p(\text{MOR}|\alpha_{subj.\text{SG}})$$

antecedent type		prior $p(\alpha)$	likelihoods $p(\text{FORM}\|\alpha)$		$p(\text{CON}\|\alpha)$		$p(\text{MOR}\|\alpha)$	
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SUBJ	SG	0.362	0.938	0.062	0.324	0.676	0.998	0.002
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	PL	0.129	0.959	0.041	0.394	0.606	0.005	0.995

Singular antecedents generally occur more often.

Forsythe & Pearl 2019, in prep

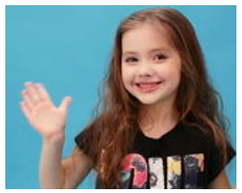
Input to the modeled listener

Bayesian inference

inaccurate representations p_σ

inaccurate deployment p_β

inaccurate both $p_{\sigma,\beta}$



$\approx$ PRONOUN $=$

$$p(\alpha_{subj.\mathrm{SG}}|\mathrm{FORM}, \mathrm{CON}, \mathrm{MOR}) \propto p(\alpha_{subj.\mathrm{SG}}) * p(\mathrm{FORM}|\alpha_{subj.\mathrm{SG}}) * p(\mathrm{CON}|\alpha_{subj.\mathrm{SG}}) * p(\mathrm{MOR}|\alpha_{subj.\mathrm{SG}})$$

antecedent type		prior $p(\alpha)$	likelihoods $p(\mathrm{FORM}\|\alpha)$ ø	$p(\mathrm{FORM}\|\alpha)$ overt	$p(\mathrm{CON}\|\alpha)$ *después*	$p(\mathrm{CON}\|\alpha)$ *porque*	$p(\mathrm{MOR}\|\alpha)$ SG	$p(\mathrm{MOR}\|\alpha)$ PL
SUBJ	SG	0.362	0.938	0.062	0.324	0.676	0.998	0.002
	PL	0.071	0.984	0.016	0.750	0.250	0.005	0.995
¬SUBJ	SG	0.438	0.817	0.183	0.132	0.868	0.998	0.002
	PL	0.129	0.959	0.041	0.394	0.606	0.005	0.995

$\approx$

The null pronoun form is generally used, though some antecedent types use it more often.

Forsythe & Pearl 2019, in prep

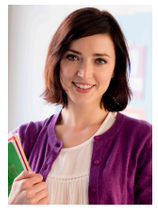
Input to the modeled listener

Bayesian inference

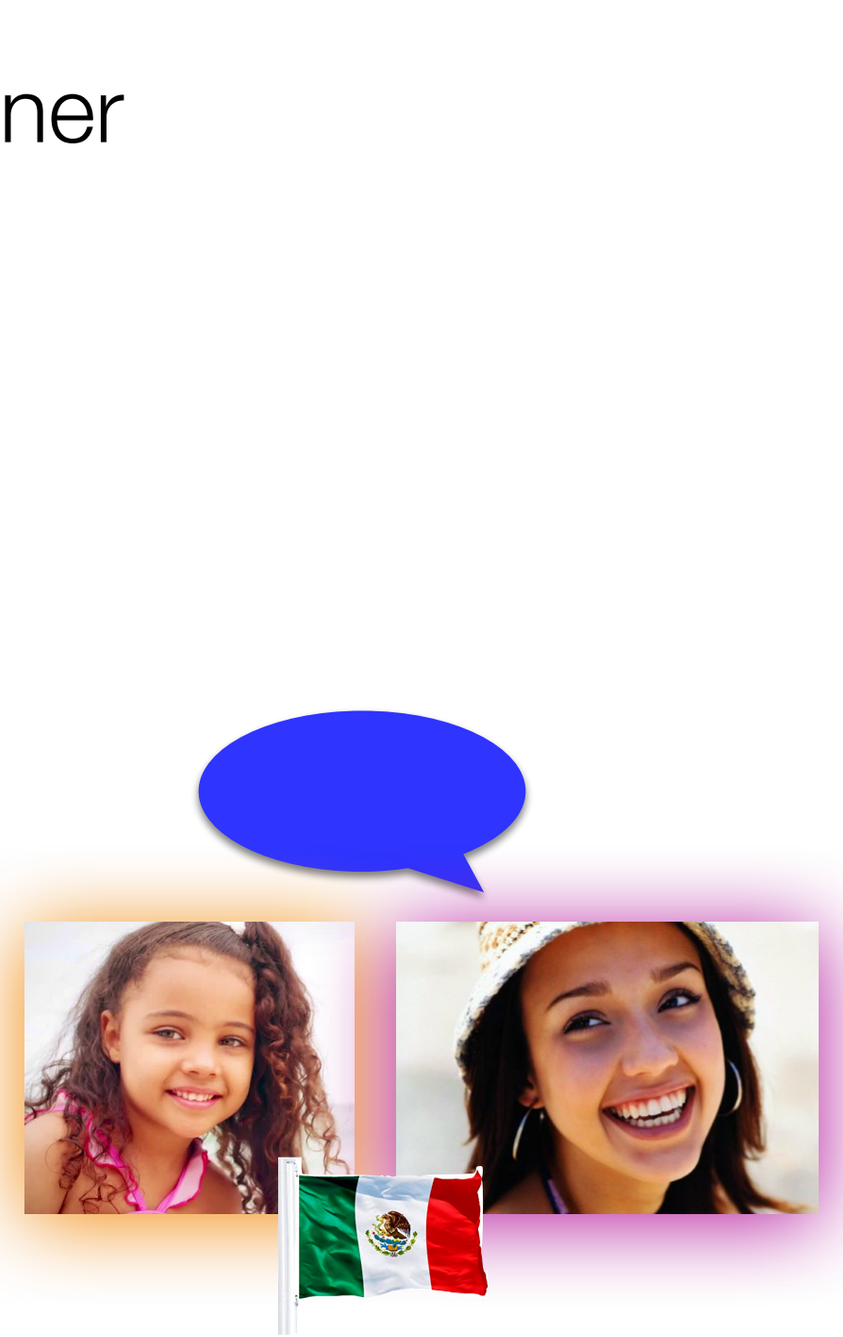
inaccurate representations p_σ

inaccurate deployment p_β

inaccurate both $p_{\sigma,\beta}$



PRONOUN =



$$p(\alpha_{subj.\text{SG}}|\text{FORM}, \text{CON}, \text{MOR}) \propto p(\alpha_{subj.\text{SG}}) * p(\text{FORM}|\alpha_{subj.\text{SG}}) * p(\text{CON}|\alpha_{subj.\text{SG}}) * p(\text{MOR}|\alpha_{subj.\text{SG}})$$

antecedent type		prior $p(\alpha)$	likelihoods $p(\text{FORM}\|\alpha)$ ø	overt	$p(\text{CON}\|\alpha)$ *después*	*porque*	$p(\text{MOR}\|\alpha)$ SG	PL
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	PL	0.071	0.984	0.016	0.750	0.250	0.005	0.995
¬SUBJ	SG	0.438	0.817	0.183	0.132	0.868	0.998	0.002
	PL	0.129	0.959	0.041	0.394	0.606	0.005	0.995

≈ ≈

The connective *porque* is used more often for antecedents that aren't plural subjects, though how much more often varies.

Forsythe & Pearl 2019, in prep

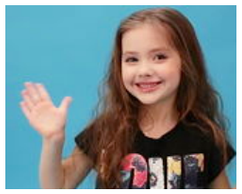
Input to the modeled listener

Bayesian inference

inaccurate representations p_σ

inaccurate deployment p_β

inaccurate both $p_{\sigma,\beta}$



PRONOUN

$$p(\alpha_{subj.\text{SG}}|\text{FORM}, \text{CON}, \text{MOR}) \propto p(\alpha_{subj.\text{SG}}) * p(\text{FORM}|\alpha_{subj.\text{SG}}) * p(\text{CON}|\alpha_{subj.\text{SG}}) * p(\text{MOR}|\alpha_{subj.\text{SG}})$$

antecedent type		prior $p(\alpha)$	likelihoods $p(\text{FORM}\|\alpha)$ ø	overt	$p(\text{CON}\|\alpha)$ *después*	*porque*	$p(\text{MOR}\|\alpha)$ SG	PL
SUBJ	SG	0.362	0.938	0.062	0.324	0.676	0.998	0.002
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	PL	0.129	0.959	0.041	0.394	0.606	0.005	0.995

≈ ≈ =

Agreement morphology is nearly categorical, with a very strong preference for matching morphology.

Forsythe & Pearl 2019, in prep

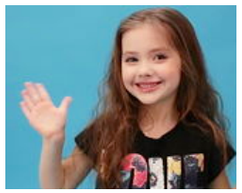
Understanding the development of pronoun interpretation

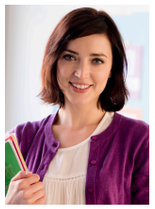
Bayesian inference

inaccurate representations p_σ

inaccurate deployment p_β

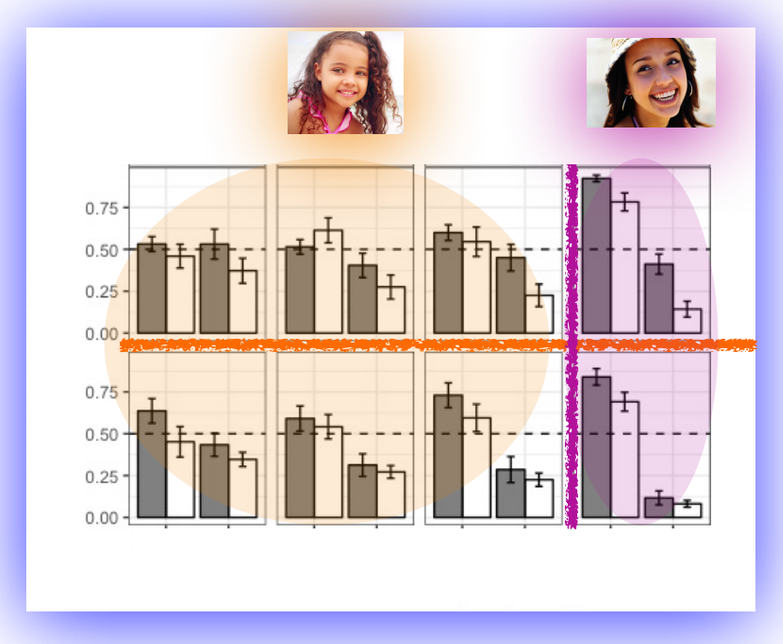
inaccurate both $p_{\sigma,\beta}$





≈ PRONOUN =

The plan, part 2: Use the computational cognitive model to identify the specific differences leading to child and adult pronoun interpretation in context.



Forsythe & Pearl 2019, in prep

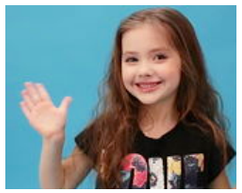
Understanding the development of pronoun interpretation

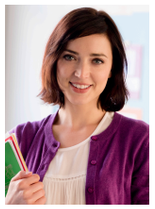
Bayesian inference

inaccurate representations p_σ

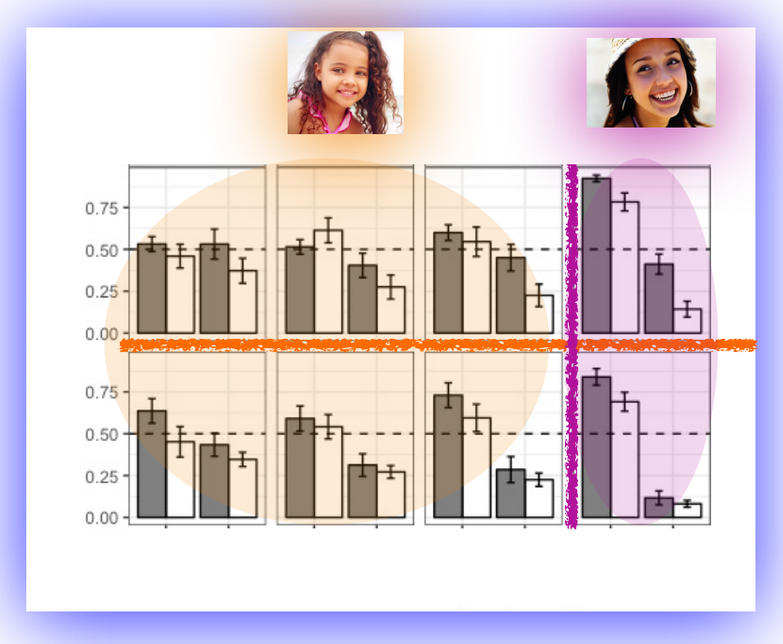
inaccurate deployment p_β

inaccurate both $p_{\sigma,\beta}$





≈ PRONOUN =



Which modeled listener variant best matches the observed pronoun interpretation behavior?

Forsythe & Pearl 2019, in prep

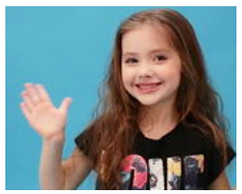
Understanding the development of pronoun interpretation

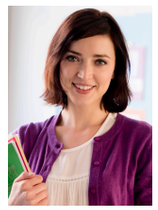
Bayesian inference

inaccurate representations p_σ

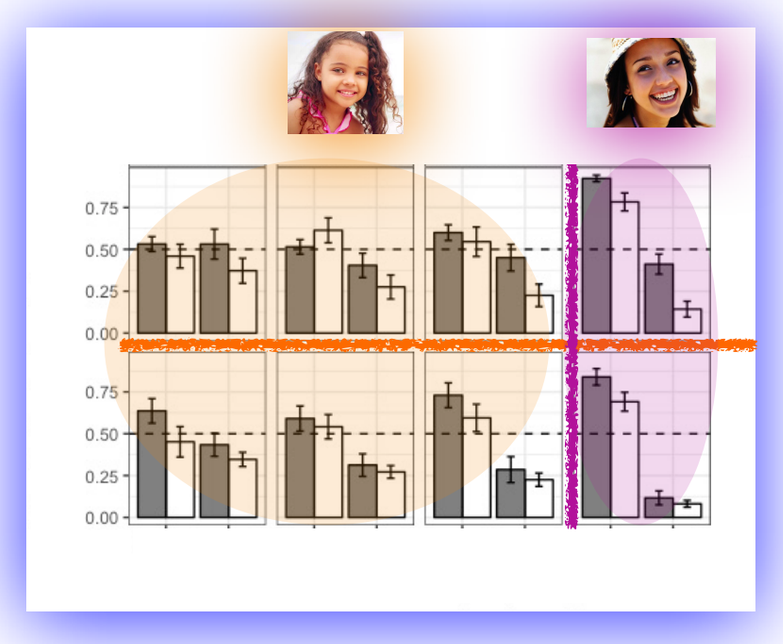
inaccurate deployment p_β

inaccurate both $p_{\sigma,\beta}$





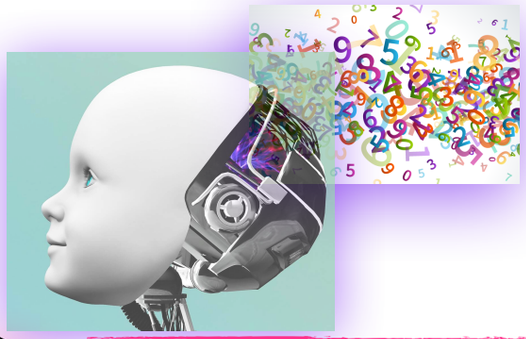
≈ PRONOUN =



Important: Model variants with more parameters have an easier time fitting the data because they have more degrees of freedom.

Forsythe & Pearl 2019, in prep

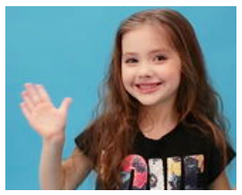
Understanding the development of pronoun interpretation

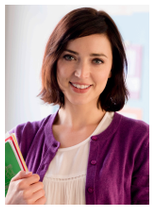


inaccurate representations p_σ

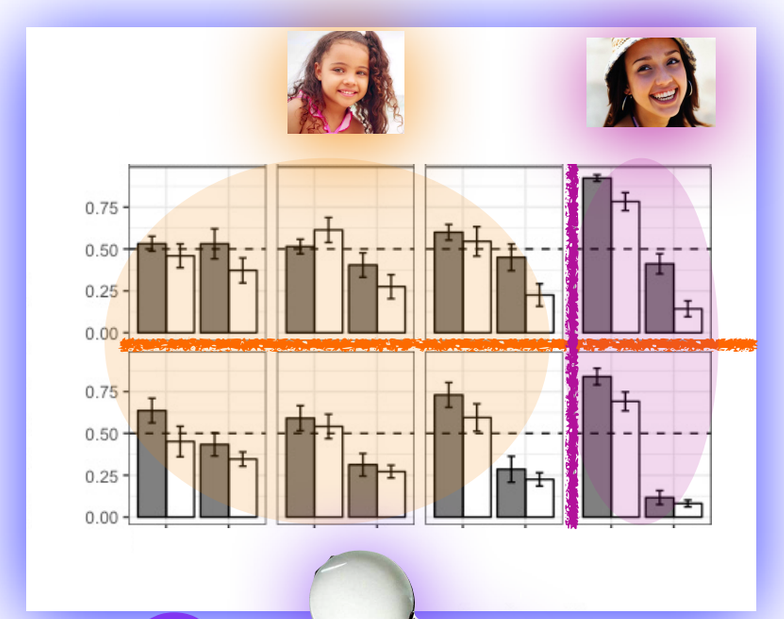
inaccurate deployment p_β

inaccurate both $p_{\sigma,\beta}$





≈ PRONOUN =



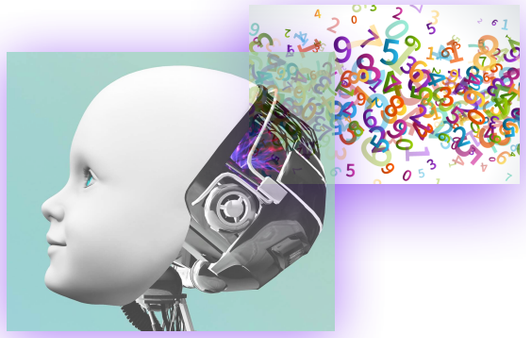
baseline: accurate representations and deployment p

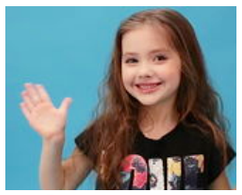
$$p(\alpha_{subj.\text{SG}}|\text{FORM}, \text{CON}, \text{MOR}) \propto p(\alpha_{subj.\text{SG}}) * p(\text{FORM}|\alpha_{subj.\text{SG}}) * p(\text{CON}|\alpha_{subj.\text{SG}}) * p(\text{MOR}|\alpha_{subj.\text{SG}})$$

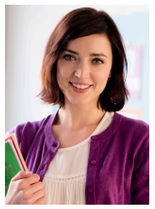
0 free parameters

Forsythe & Pearl 2019, in prep

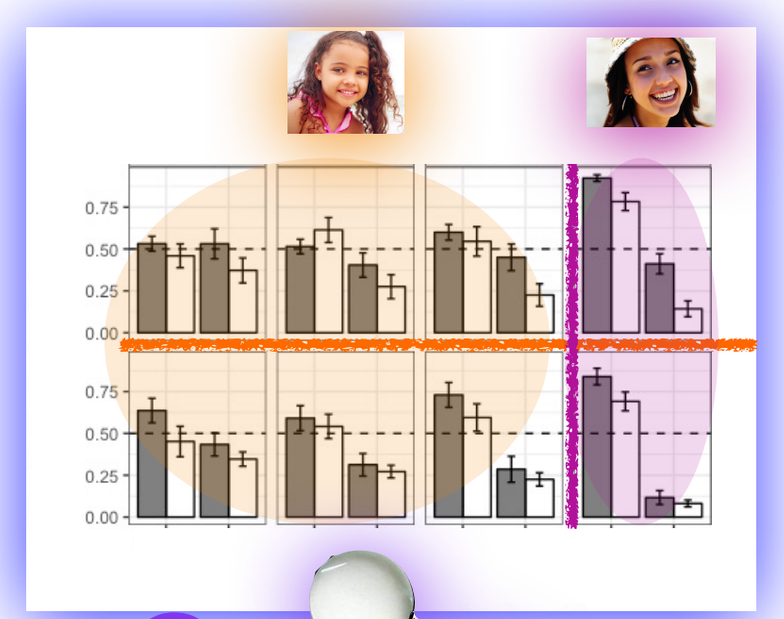
Understanding the development of pronoun interpretation







≈ PRONOUN =



inaccurate deployment p_β

inaccurate both $p_{\sigma,\beta}$

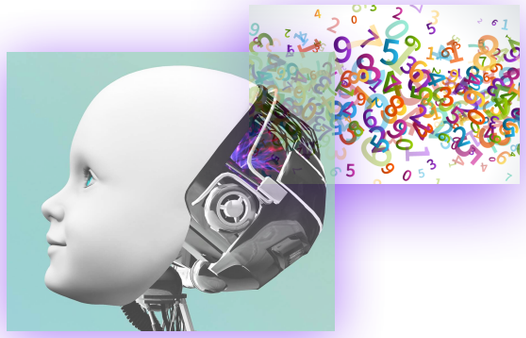
baseline: accurate representations and deployment p 0 free parameters

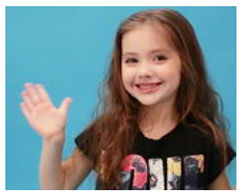
inaccurate representations p_σ

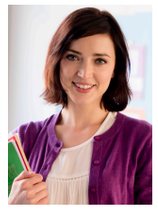
4 free parameters: σ_α, σ_{form}, σ_{con}, σ_{mor}

Forsythe & Pearl 2019, in prep

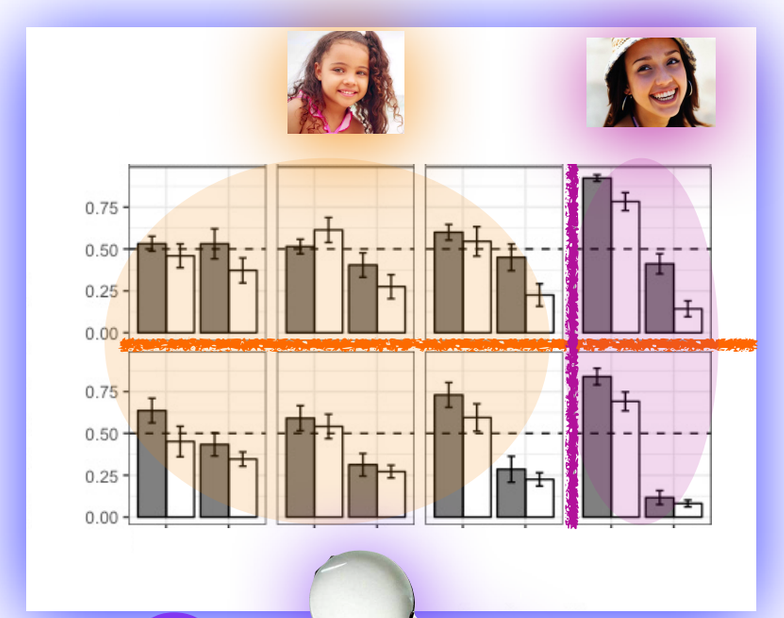
Understanding the development of pronoun interpretation







≈ PRONOUN =



inaccurate both $p_{\sigma,\beta}$

baseline: accurate representations and deployment p 0 free parameters

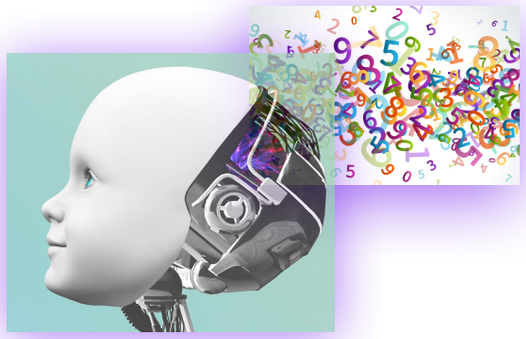
inaccurate representations p_{σ} 4 free parameters: σ_{α}, σ_{form}, σ_{con}, σ_{mor}

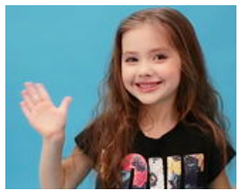
inaccurate deployment p_{β}

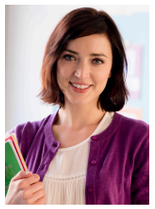
4 free parameters: β_{α}, β_{form}, β_{con}, β_{mor}

Forsythe & Pearl 2019, in prep

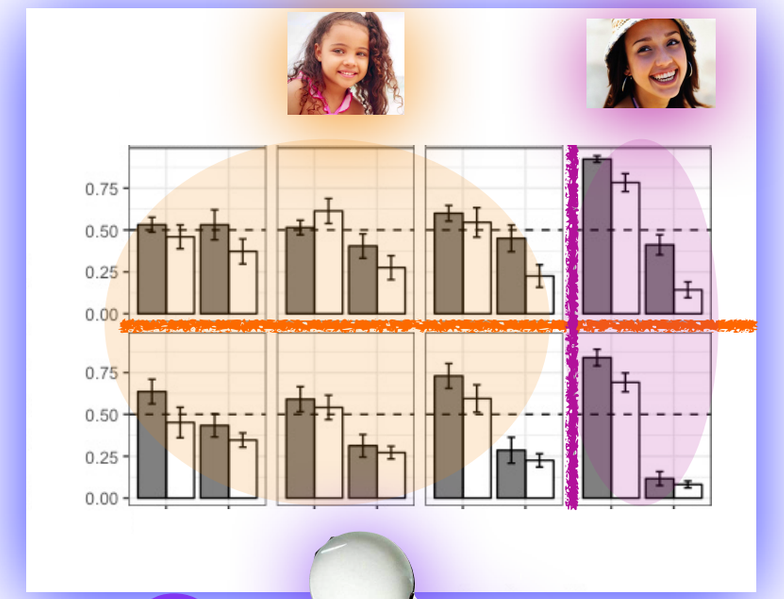
Understanding the development of pronoun interpretation







PRONOUN



baseline: accurate representations and deployment p 0 free parameters

inaccurate representations p_σ 4 free parameters: σ_α, σ_{form}, σ_{con}, σ_{mor}

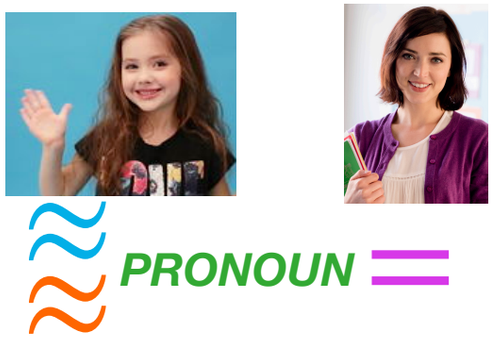
inaccurate deployment p_β 4 free parameters: β_α, β_{form}, β_{con}, β_{mor}

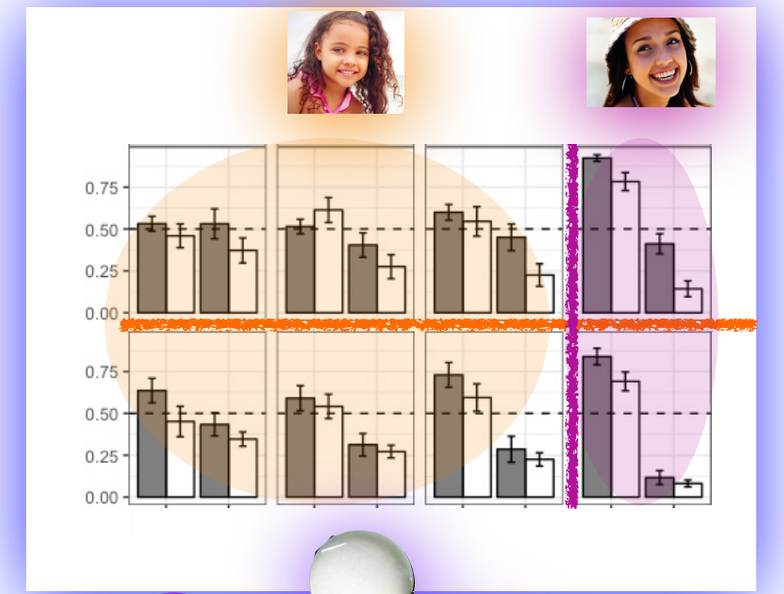
inaccurate both $p_{\sigma,\beta}$

8 free parameters: σ_α, σ_{form}, σ_{con}, σ_{mor}, β_α, β_{form}, β_{con}, β_{mor}

Forsythe & Pearl 2019, in prep

Understanding the development of pronoun interpretation





We want variants with more parameters to have a substantially better fit in order to favor them over variants with fewer parameters.

baseline: accurate representations and deployment p 0 free parameters

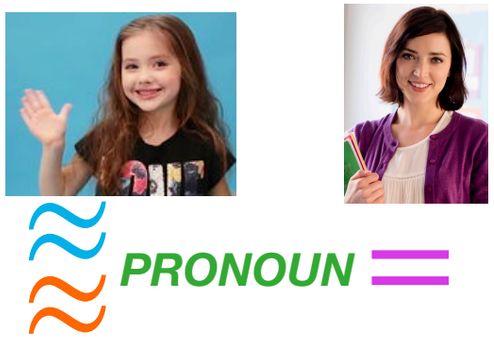
inaccurate representations p_σ 4 free parameters: σ_α, σ_{form}, σ_{con}, σ_{mor}

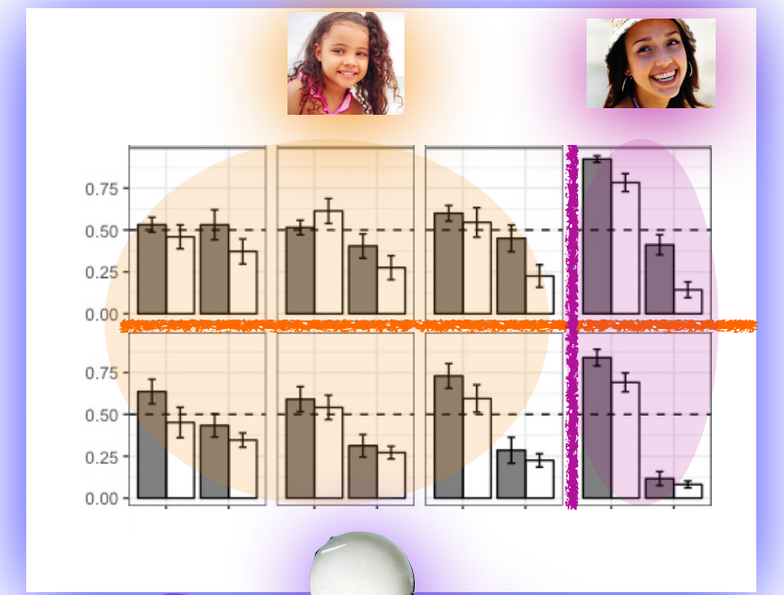
inaccurate deployment p_β 4 free parameters: β_α, β_{form}, β_{con}, β_{mor}

inaccurate both $p_{\sigma,\beta}$ 8 free parameters: σ_α, σ_{form}, σ_{con}, σ_{mor}, β_α, β_{form}, β_{con}, β_{mor}

Forsythe & Pearl 2019, in prep

Understanding the development of pronoun interpretation





The Bayesian Information Criterion (BIC) is one way to quantify this preference (Schwarz 1978).

baseline: accurate representations and deployment p 0 free parameters

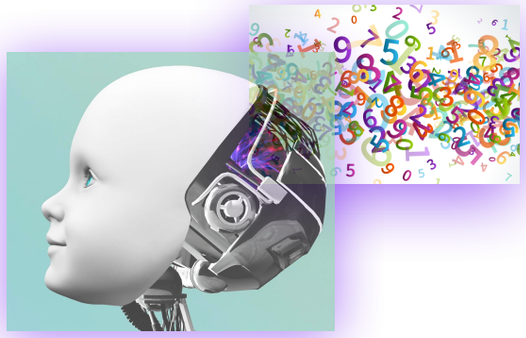
inaccurate representations p_σ 4 free parameters: σ_α, σ_{form}, σ_{con}, σ_{mor}

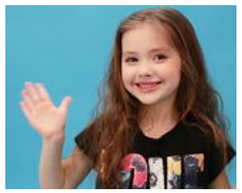
inaccurate deployment p_β 4 free parameters: β_α, β_{form}, β_{con}, β_{mor}

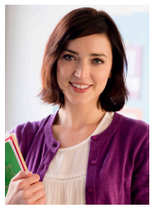
inaccurate both $p_{\sigma,\beta}$ 8 free parameters: σ_α, σ_{form}, σ_{con}, σ_{mor}, β_α, β_{form}, β_{con}, β_{mor}

Forsythe & Pearl 2019, in prep

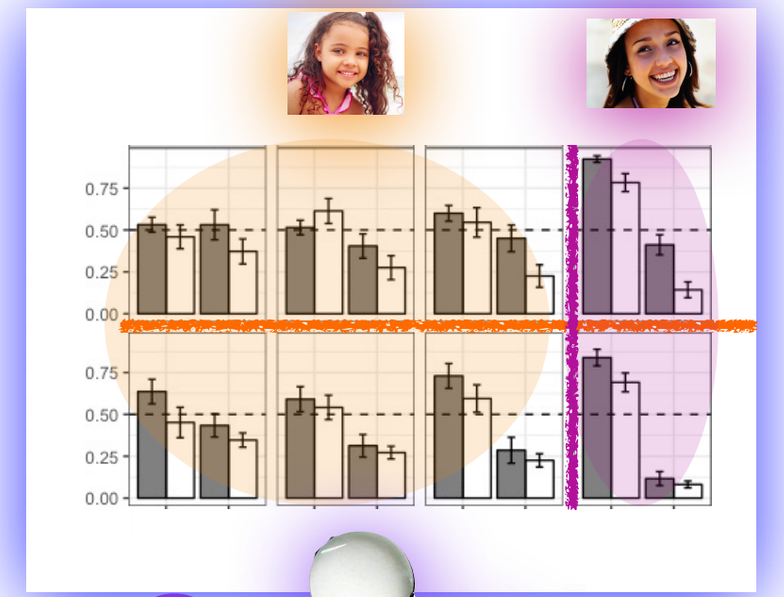
Understanding the development of pronoun interpretation







PRONOUN



BIC = # parameters · log(|data|) – 2 · log(model fit)

$0 \leq \text{BIC} \leq \infty$ (closer to 0 is better)

baseline: accurate representations and deployment p 0 free parameters

inaccurate representations p_σ 4 free parameters: σ_α, σ_{form}, σ_{con}, σ_{mor}

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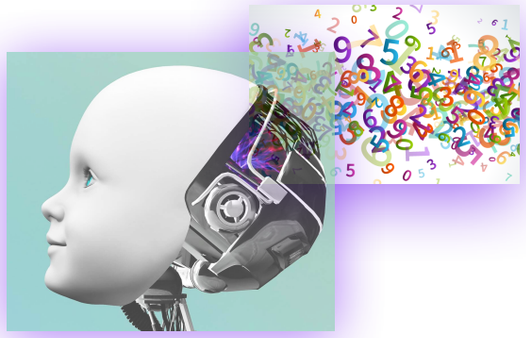
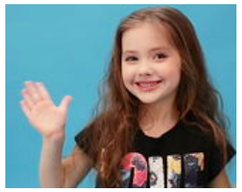
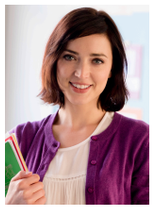
inaccurate both $p_{\sigma,\beta}$ 8 free parameters: σ_α, σ_{form}, σ_{con}, σ_{mor}, β_α, β_{form}, β_{con}, β_{mor}

Forsythe & Pearl 2019, in prep

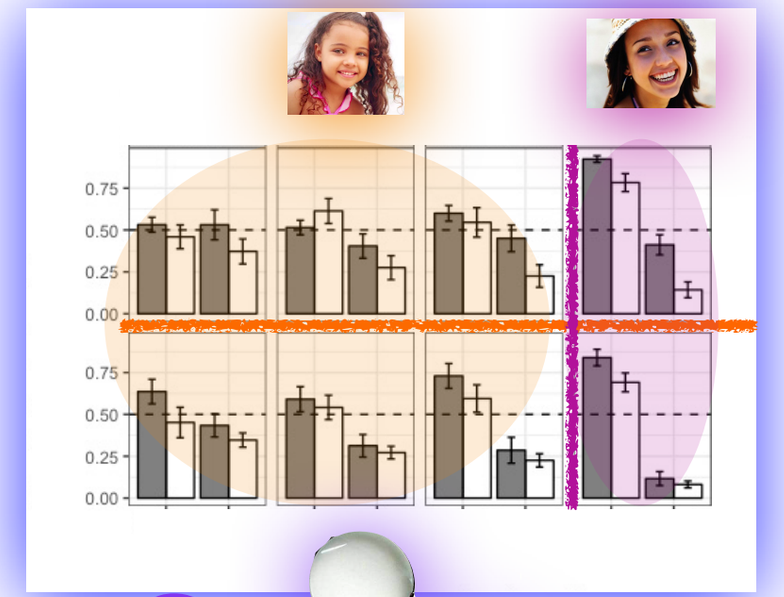
Understanding the development of pronoun interpretation







≈ PRONOUN =



more parameters = higher score,
closer to 0 is better

BIC = # parameters · log(|data|) – 2 · log(model fit)

$0 \leq \text{BIC} \leq \infty$ (closer to 0 is better)

baseline: accurate representations and deployment p 0 free parameters

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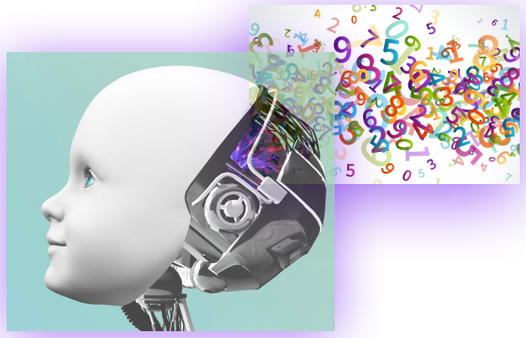
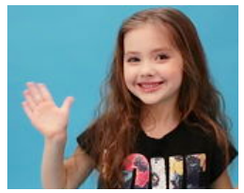
Forsythe & Pearl 2019, in prep

Understanding the development of pronoun interpretation



model fit = likelihood of data, given model with best-fitting parameter values



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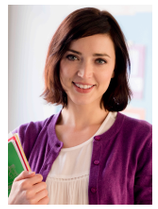

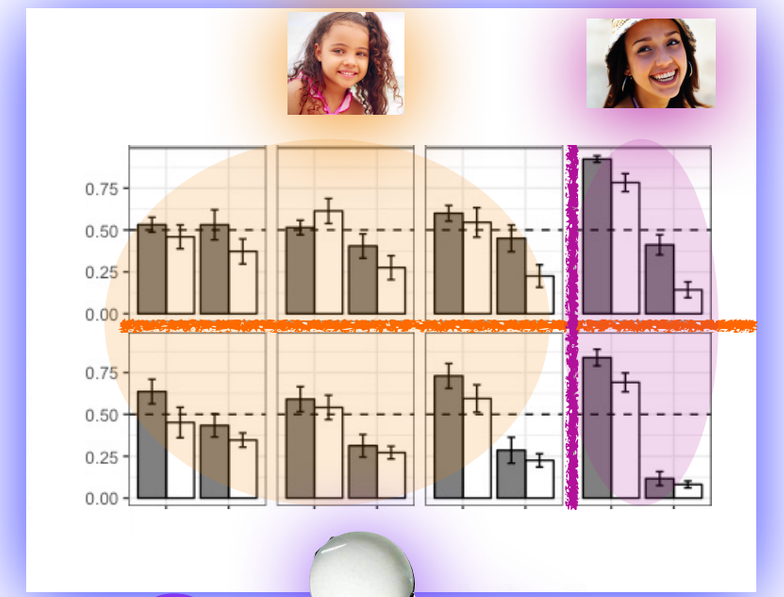

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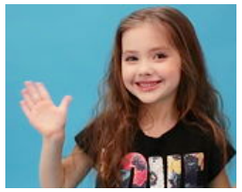
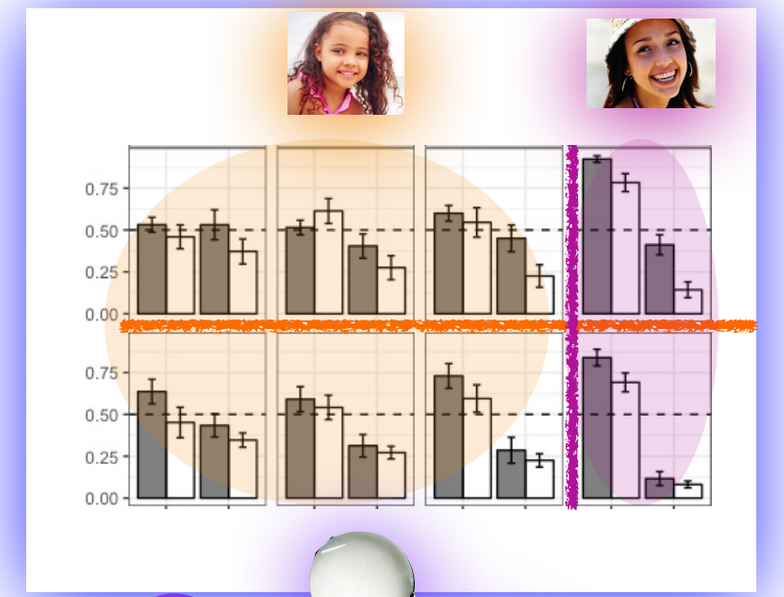
Forsythe & Pearl 2019, in prep

Understanding the development of pronoun interpretation



$-\infty \leq \log(\text{likelihood}) \leq 0$, closer to 0 is better

≈ **PRONOUN** =



$\text{BIC} = \#\text{ parameters} \cdot \log(|\text{data}|) - 2 \cdot \log(\text{model fit})$

$0 \leq \text{BIC} \leq \infty$ (closer to 0 is better)

baseline: accurate representations and deployment p 0 free parameters

inaccurate representations p_σ 4 free parameters: σ_α, σ_{form}, σ_{con}, σ_{mor}

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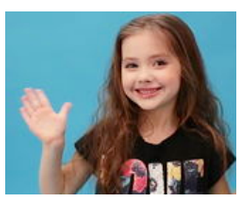
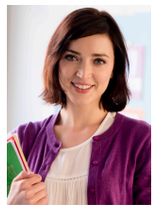
Forsythe & Pearl 2019, in prep

Understanding the development of pronoun interpretation





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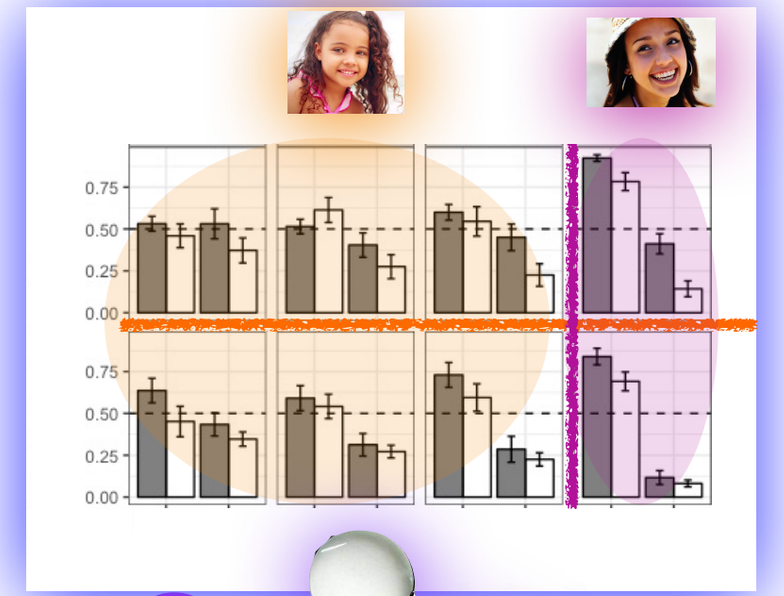
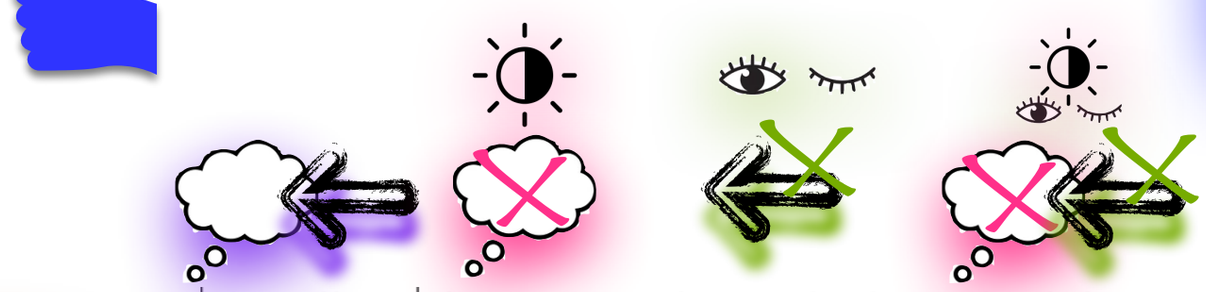


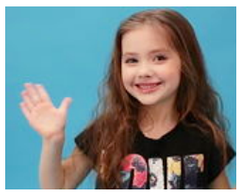
0 ≤ BIC ≤ ∞ (closer to 0 is better)

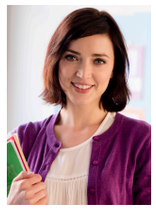


age	baseline	inacc rep	inacc deploy	both inacc
≤ 3				
4				
≥ 5				
adults				

Forsythe & Pearl 2019, in prep

Understanding the development of pronoun interpretation





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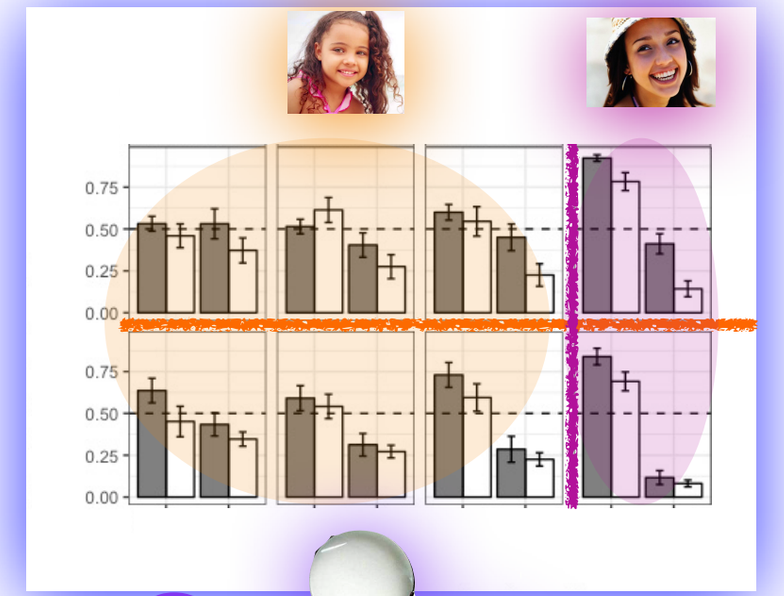
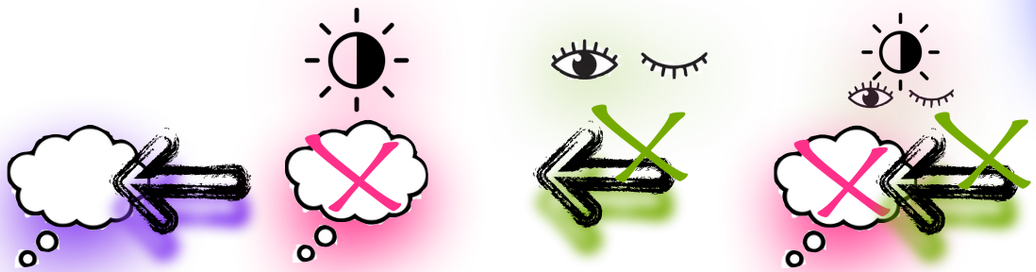


0 ≤ BIC ≤ ∞ (closer to 0 is better)

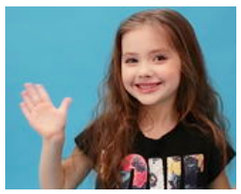


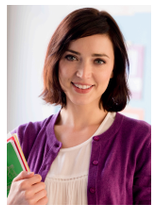
age	baseline	inacc rep	inacc deploy	both inacc
≤ 3	3548.40	**1450.67**	1453.05	1473.04
4				
≥ 5				
adults				

3-year-old pronoun interpretation behavior is best captured by children having inaccurate representations, but accurate deployment

Forsythe & Pearl 2019, in prep

Understanding the development of pronoun interpretation





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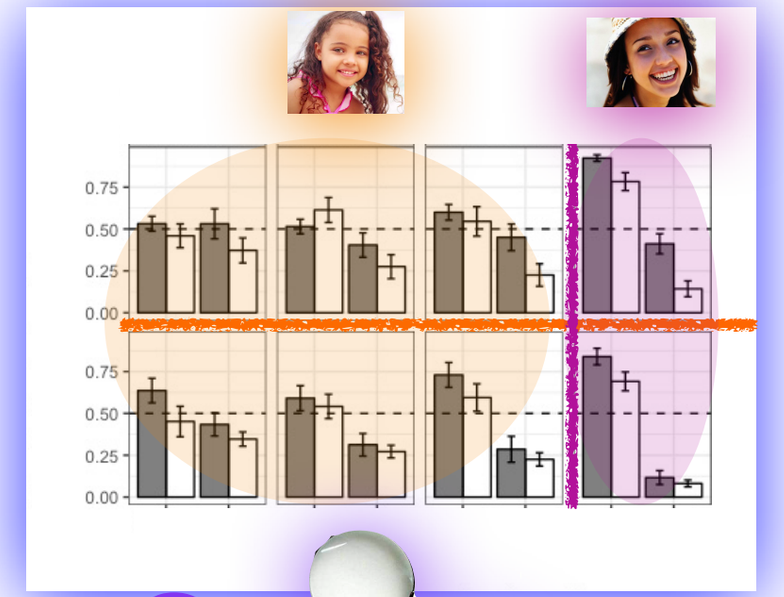
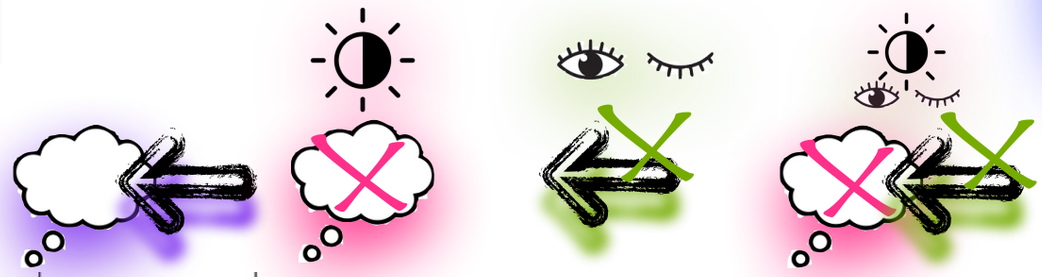


0 ≤ BIC ≤ ∞ (closer to 0 is better)



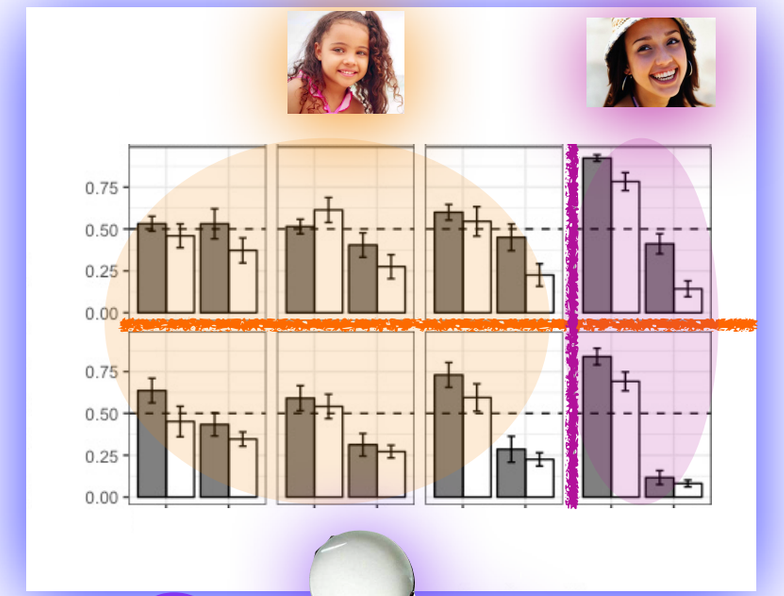
age	baseline	inacc rep	inacc deploy	both inacc
≤ 3	3548.40	**1450.67**	1453.05	1473.04
4				
≥ 5				
adults				

…though all 3 inaccurate variants are far better than the baseline of both accurate representations and accurate deployment.

Forsythe & Pearl 2019, in prep

Understanding the development of pronoun interpretation

≈≈ PRONOUN =



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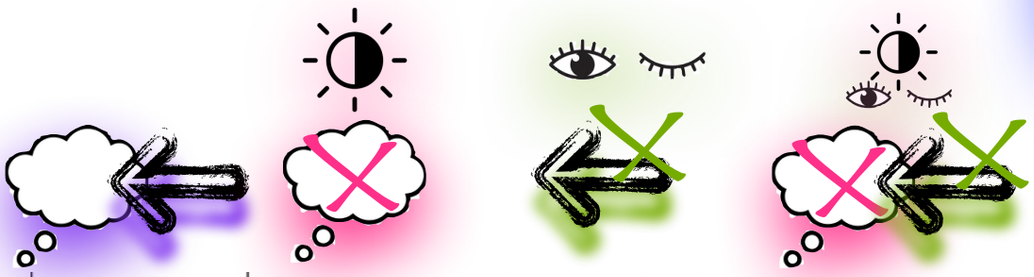
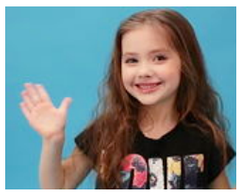


age	baseline	inacc rep	inacc deploy	both inacc
≤ 3	3548.40	**1450.67**	1453.05	1473.04
4	3497.57	**1510.55**	1515.28	1532.71
≥ 5	2528.07	**1216.34**	1219.04	1239.78
adults				

This same pattern holds for 4-year-olds and 5-year-olds, too.

Forsythe & Pearl 2019, in prep

Understanding the development of pronoun interpretation



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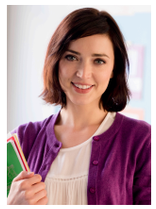

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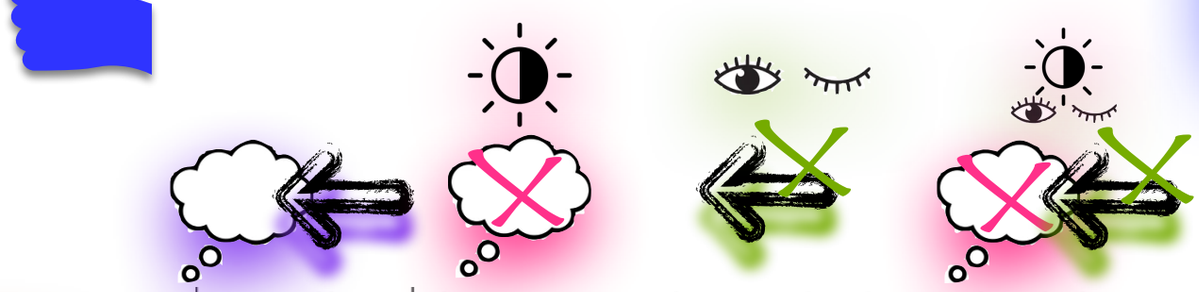
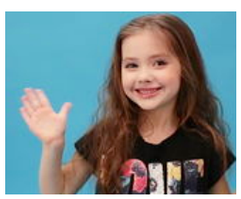


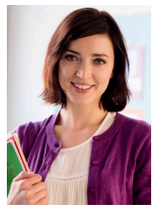
age	baseline	inacc rep	inacc deploy	both inacc
≤ 3	3548.40	**1450.67**	1453.05	1473.04
4	3497.57	**1510.55**	1515.28	1532.71
≥ 5	2528.07	**1216.34**	1219.04	1239.78
adults	2402.53	1637.24	1612.84	**1277.71**

Adult pronoun interpretation behavior is best captured by the model that has both inaccurate representations and inaccurate deployment.

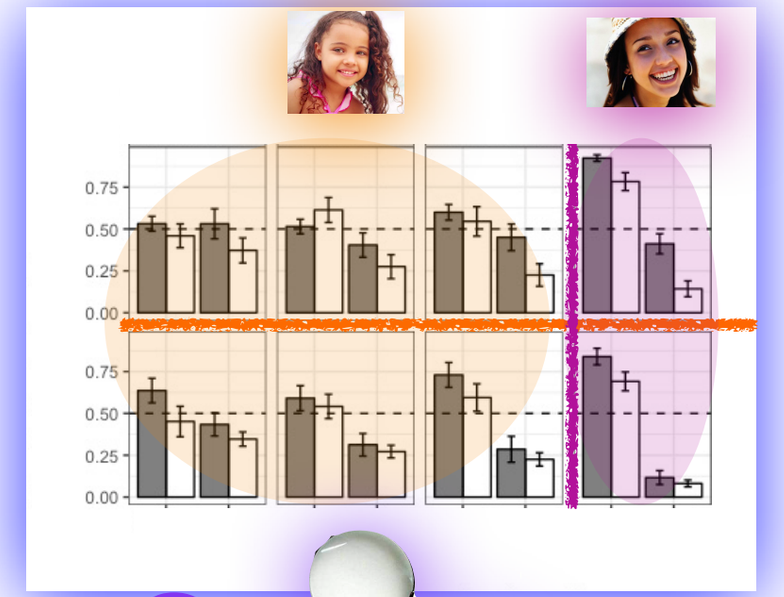
Forsythe & Pearl 2019, in prep

Understanding the development of pronoun interpretation

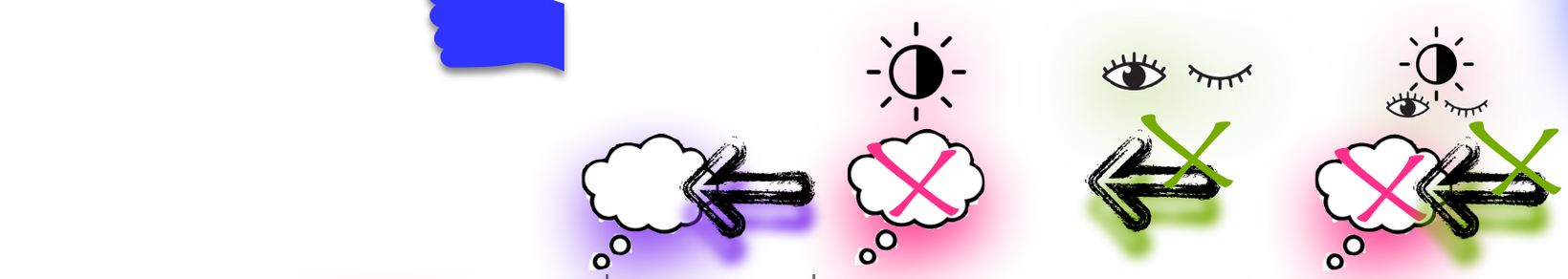




≈≈ PRONOUN =



0 ≤ BIC ≤ ∞ (closer to 0 is better)



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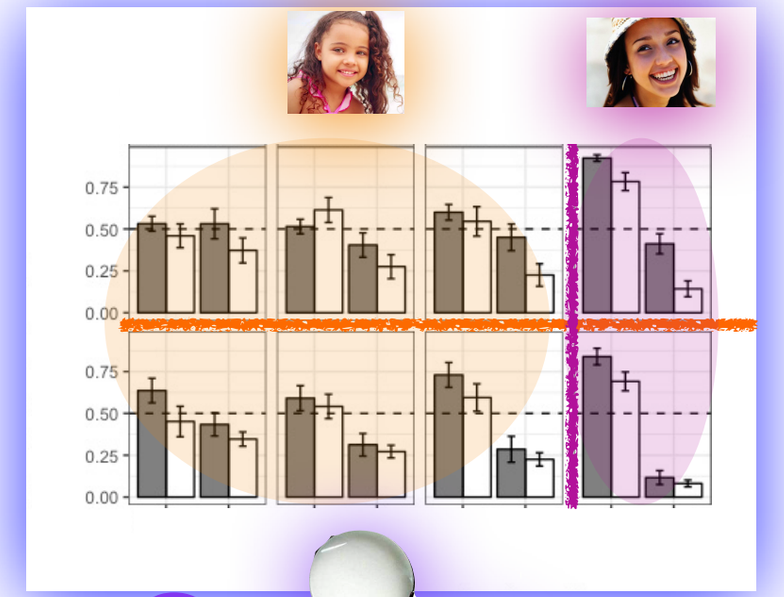
≥ 5	2528.07	**1216.34**	1219.04	1239.78
adults	2402.53	1637.24	1612.84	**1277.71**

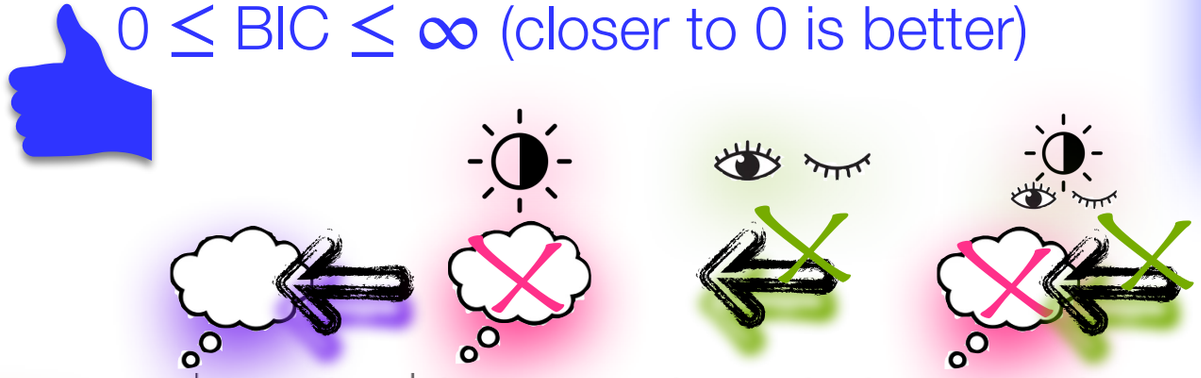
Like the child models, all inaccurate variants are far better than the baseline that has both accurate representations and accurate deployment.

Forsythe & Pearl 2019, in prep

Understanding the development of pronoun interpretation

≈ PRONOUN =





0 ≤ BIC ≤ ∞ (closer to 0 is better)

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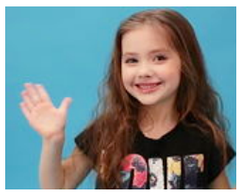
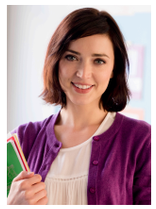
4	3497.57	**1510.55**	1515.28	1532.71
≥ 5	2528.07	**1216.34**	1219.04	1239.78
adults	2402.53	1637.24	1612.84	**1277.71**

…but within the inaccurate variants, the both inaccurate variant is much better than the other two.

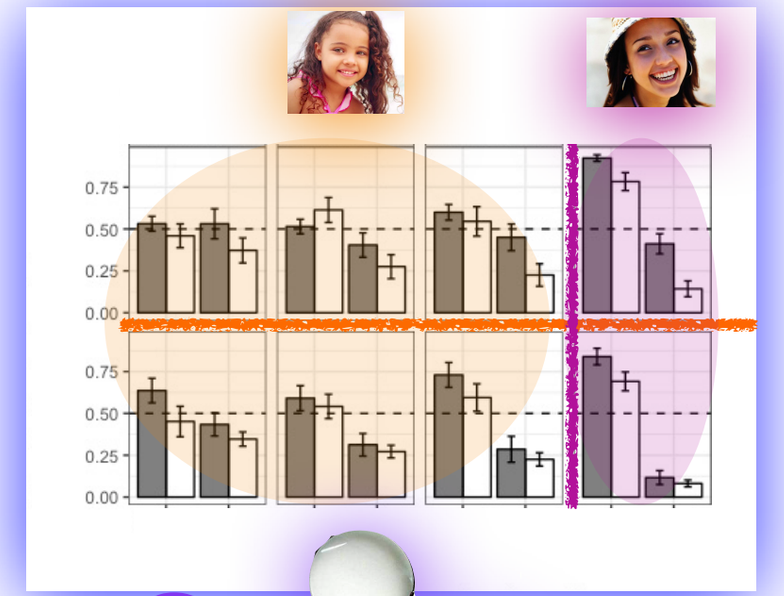
Forsythe & Pearl 2019, in prep

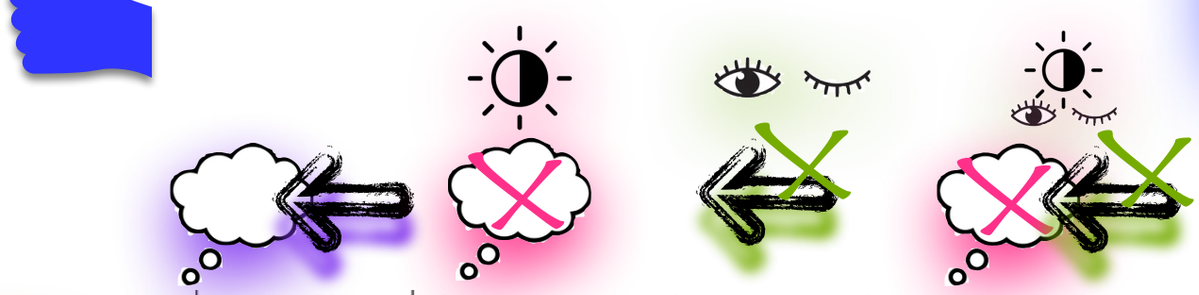
Understanding the development of pronoun interpretation





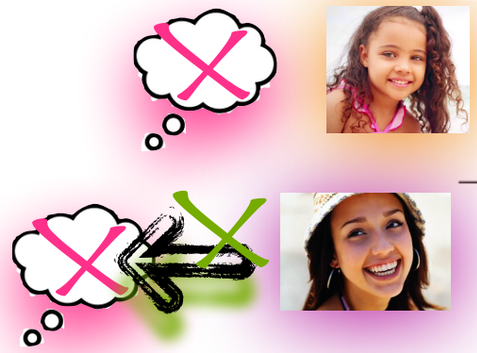
≈ PRONOUN =





0 ≤ BIC ≤ ∞ (closer to 0 is better)

age	baseline	inacc rep	inacc deploy	both inacc
≤ 3	3548.40	**1450.67**	1453.05	1473.04
4	3497.57	**1510.55**	1515.28	1532.71
≥ 5	2528.07	**1216.34**	1219.04	1239.78
adults	2402.53	1637.24	1612.84	**1277.71**



Takeaway: Both child and adult pronoun interpretation behavior are captured by modeled listeners that are inaccurate in some way.

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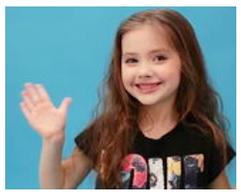

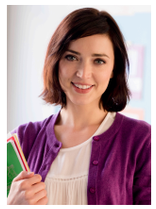

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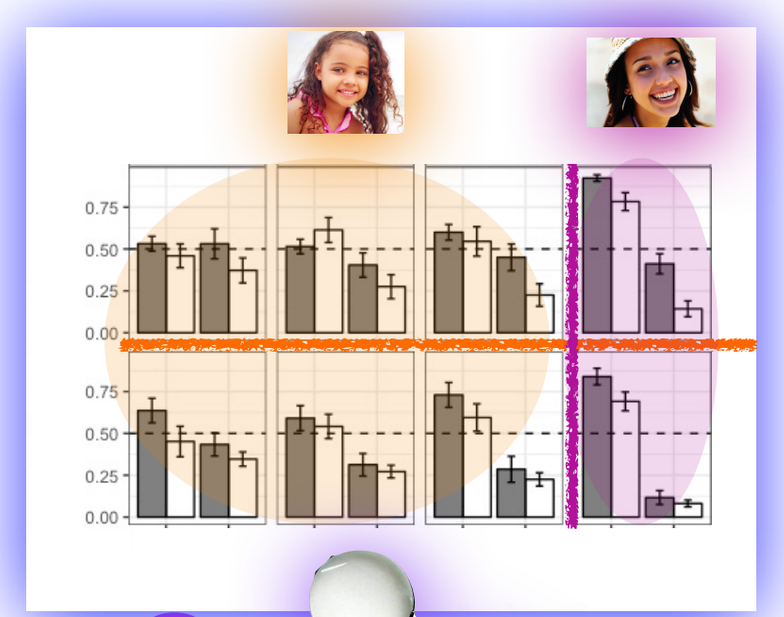

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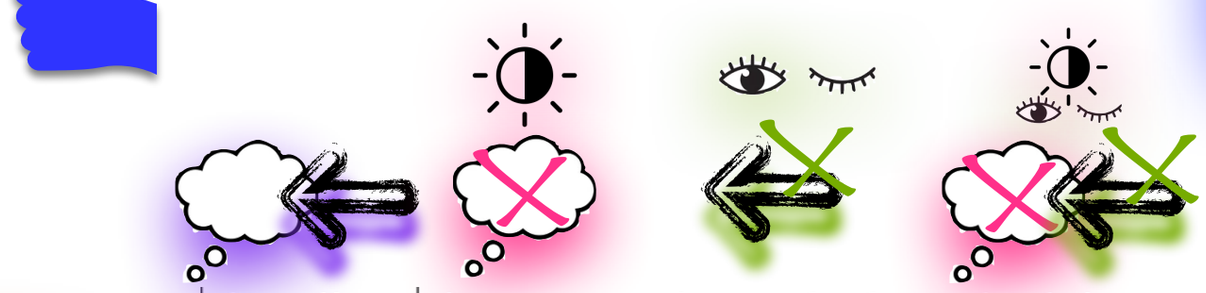

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Becoming adult-like doesn't mean becoming more accurate!

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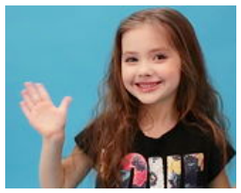

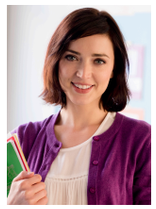

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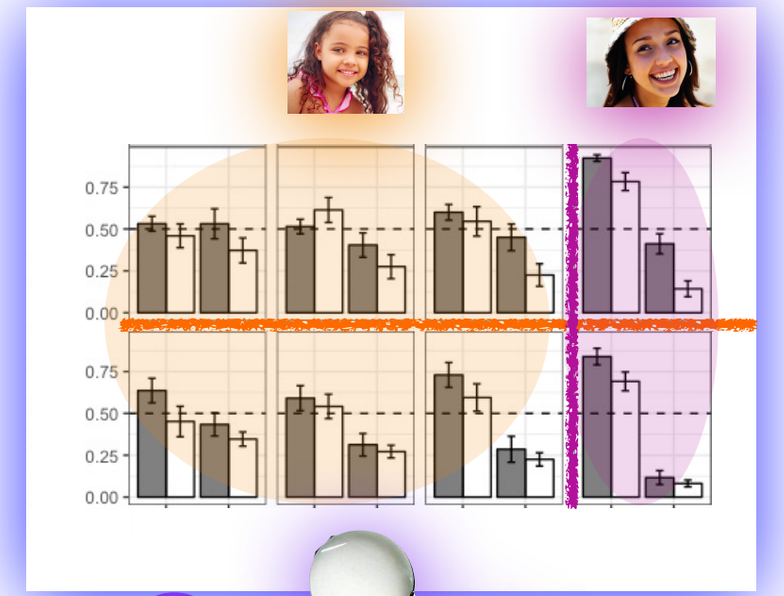

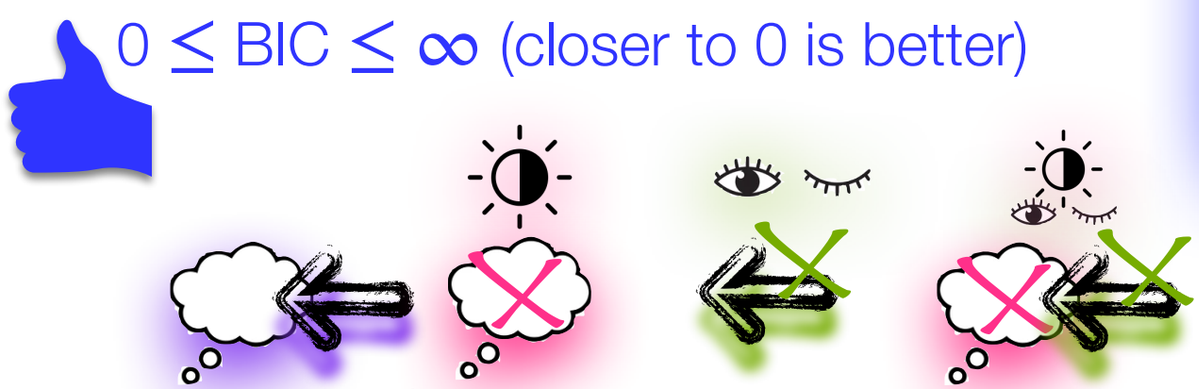

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But what does it mean?
It means learning to become inaccurate in adult-like ways.

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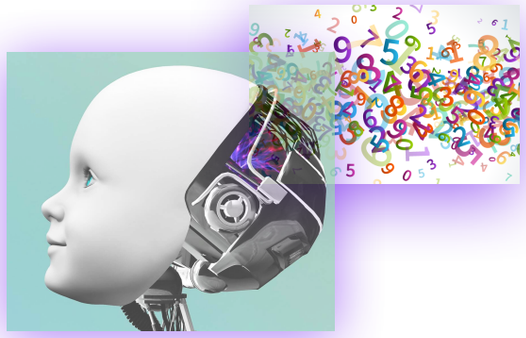

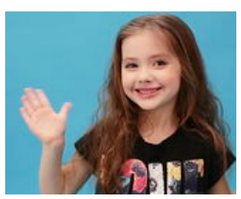

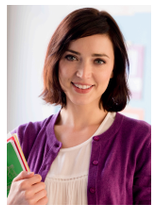

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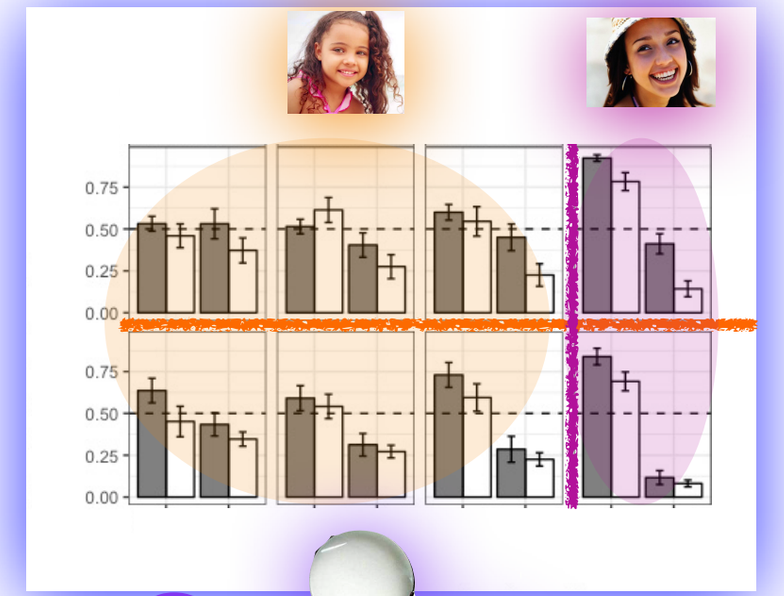

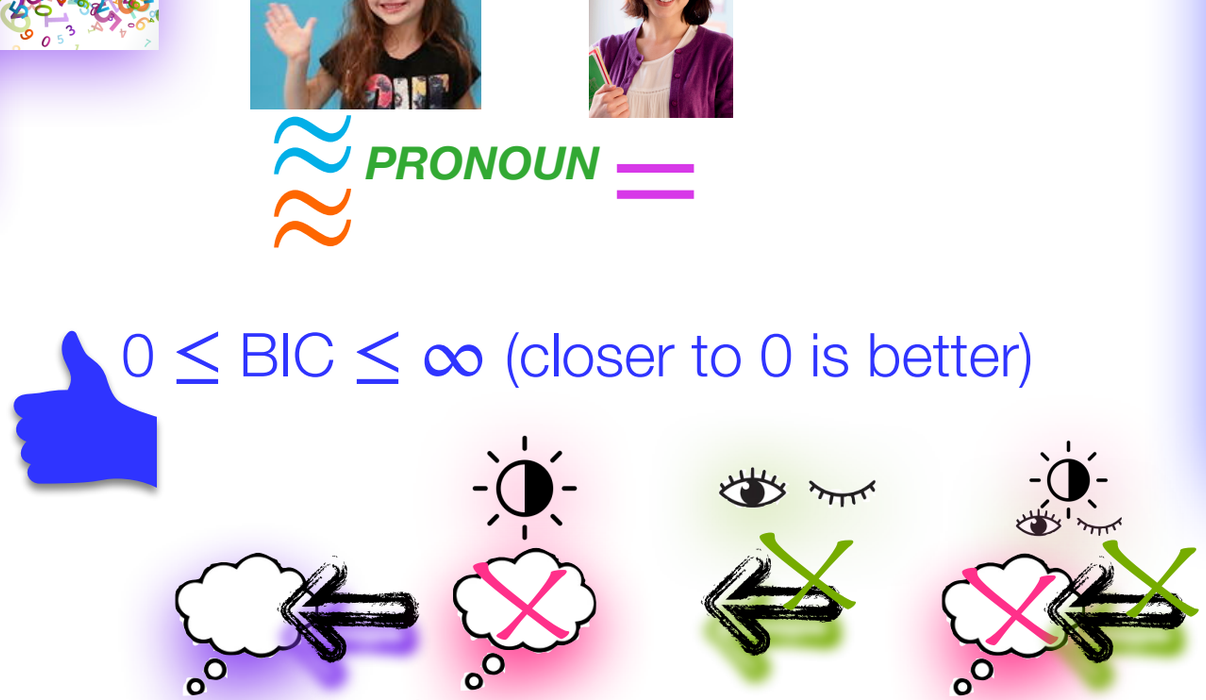

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We know that adults inaccurately deploy their representations.

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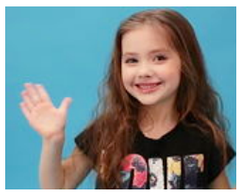

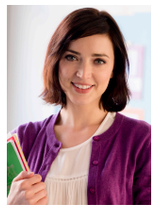

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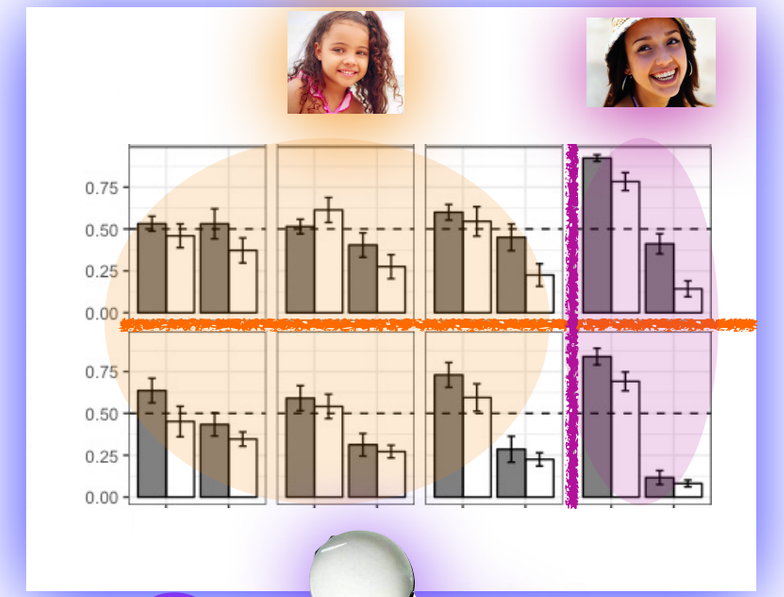

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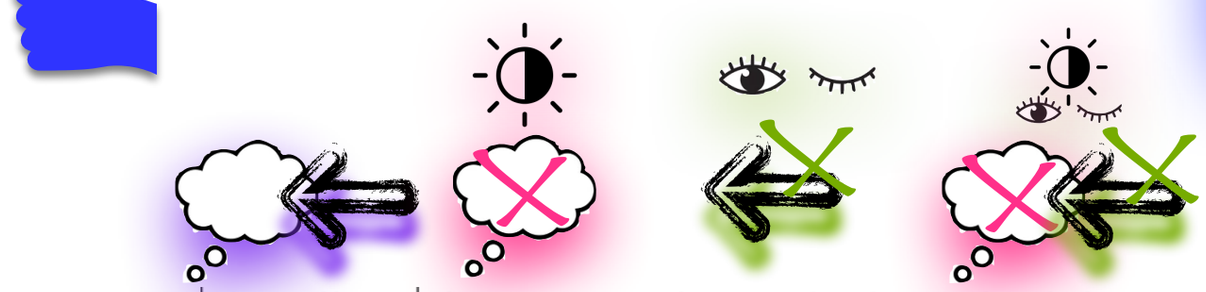

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So we can look at the β values to see which information is being ignored and how often it's being ignored.

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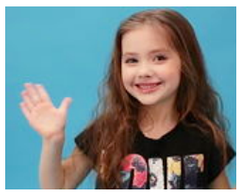

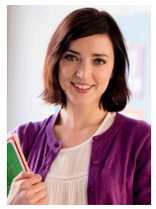

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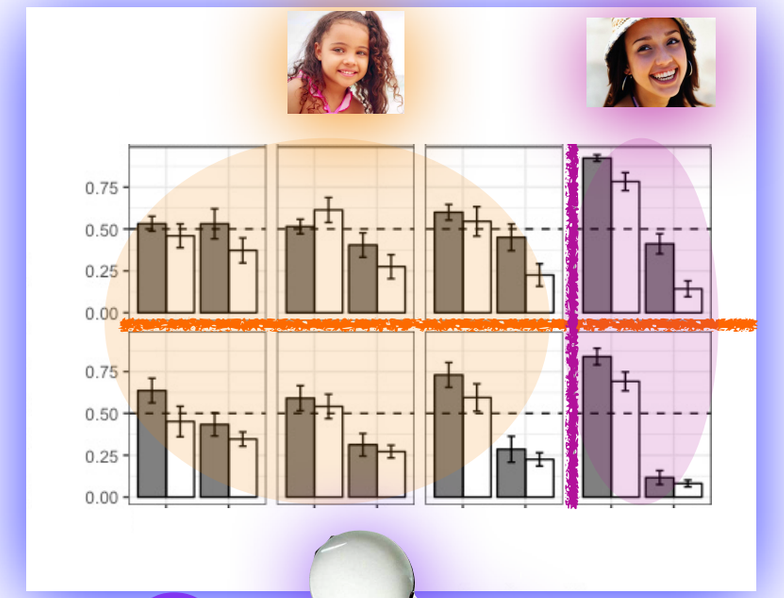

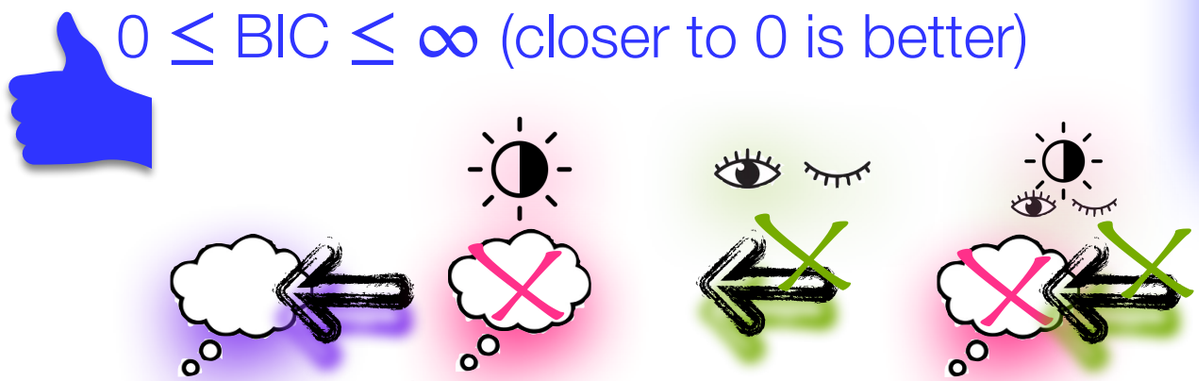

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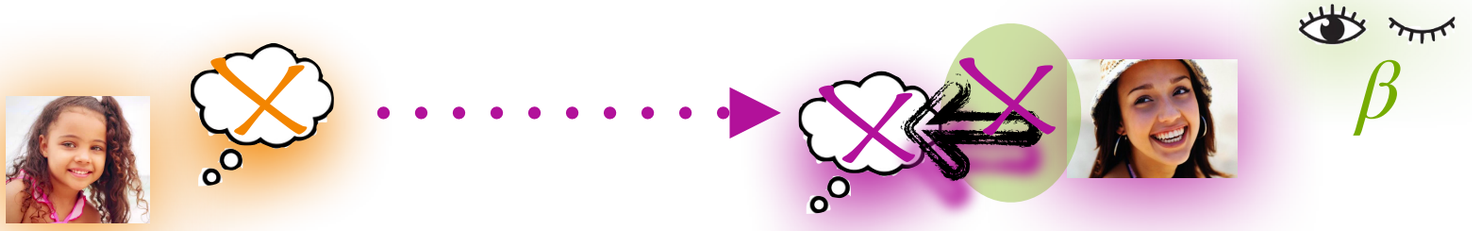
We can also look at the σ values to see how the inaccurate representations are inaccurate — are they too smooth or too sharp?



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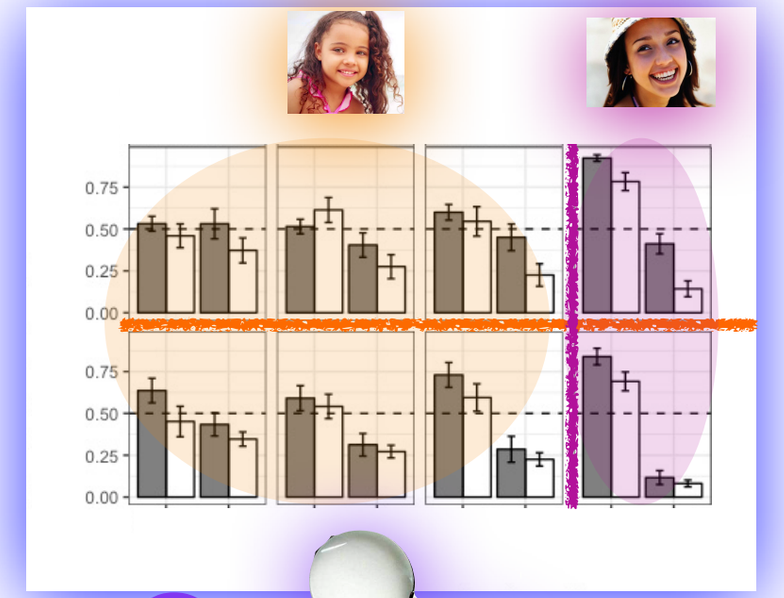

$0.01 \leq \sigma \leq 4.00$

$0 \leq \beta \leq 1$

σ_{for}	σ_{con}	σ_{mor}	σ_{α}	β_{for}	β_{con}	β_{mor}	β_{α}
children: inaccurate representations							
≤3				1	1	1	1
4				1	1	1	1
≥5				1	1	1	1
adults: both inaccurate							
adults							

All children are best represented by accurate deployment, which is equivalent to always paying attention to all information (β=1).

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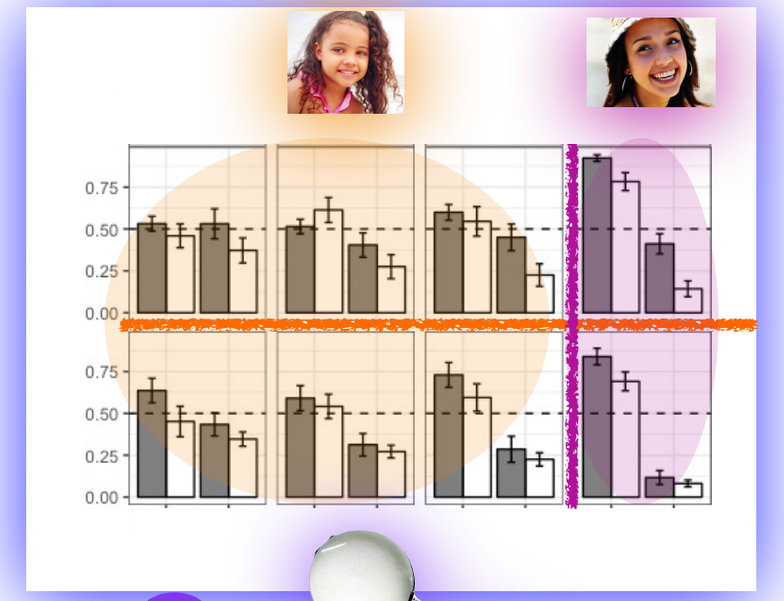

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σ_{for}	σ_{con}	σ_{mor}	σ_{α}	β_{for}	β_{con}	β_{mor}	β_{α}
children: inaccurate representations							
≤3				1	1	1	1
4				1	1	1	1
≥5				1	1	1	1
adults: both inaccurate							
adults				0.25	0.40	0.80	0.98

Adults pay much more attention to the prior over possible antecedents (β_{α}) and agreement morphology (β_{mor})…

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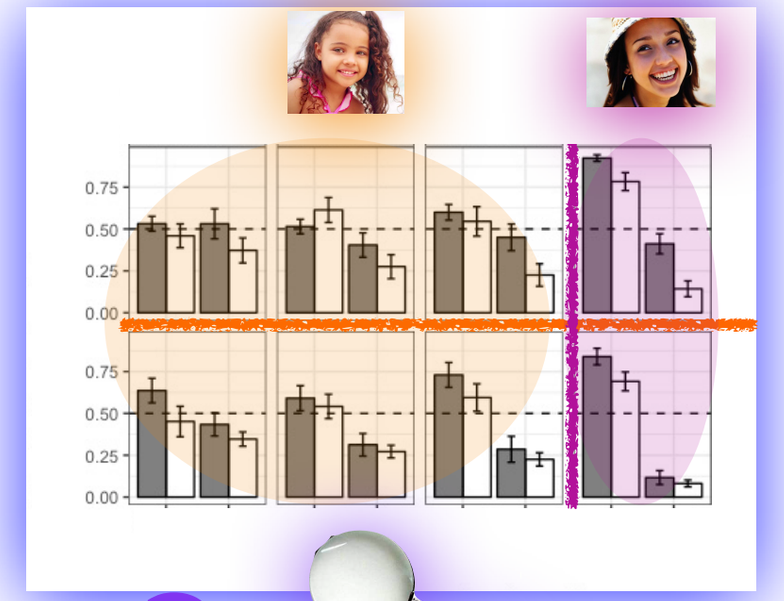

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children: inaccurate representations							
≤3				1	1	1	1
4				1	1	1	1
≥5				1	1	1	1
adults: both inaccurate							
adults				0.25	0.40	0.80	0.98

…and much less attention to the pronoun form (β_{α}) and the connective (β_{con}).

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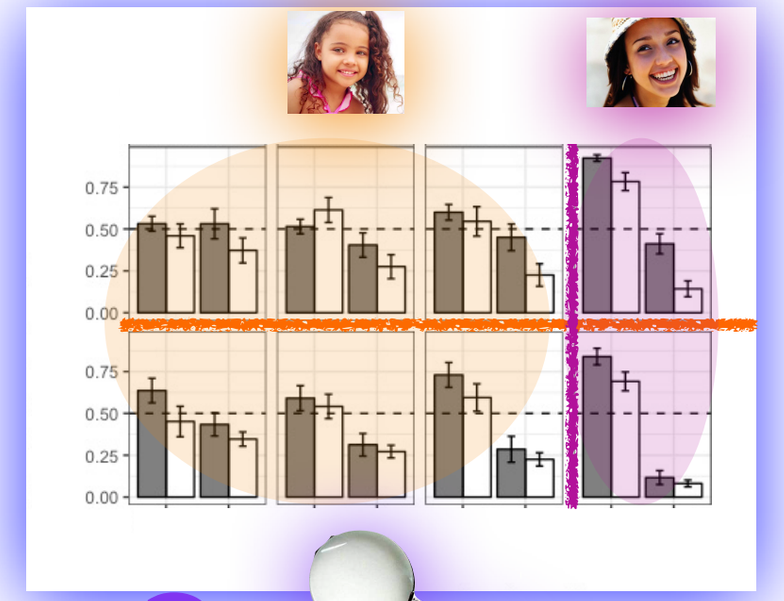

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children: inaccurate representations							
≤3				1	1	1	1
4				1	1	1	1
≥5				1	1	1	1
adults: both inaccurate							
adults				0.25	0.40	0.80	0.98

Becoming adult-like:

Learn how much to ignore certain information

(the pronoun form and connective more often, sometimes the agreement morphology, and occasionally even the prior).

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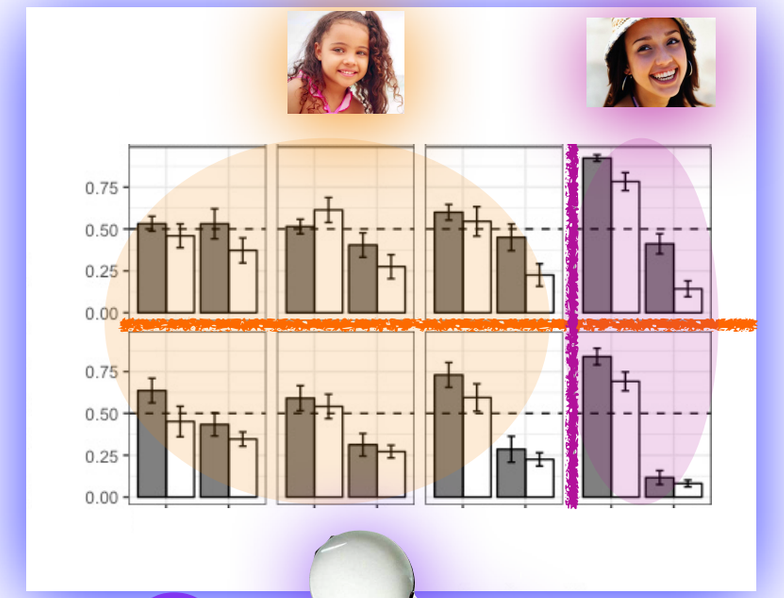

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σ_{for}	σ_{con}	σ_{mor}	σ_{α}	β_{for}	β_{con}	β_{mor}	β_{α}
children: inaccurate representations							
≤3				1	1	1	1
4				1	1	1	1
≥5				1	1	1	1
adults: both inaccurate							
adults				0.25	0.4	.89	0.98

What about the representations? Both child and adult representations are inaccurate, but *how* are they inaccurate?

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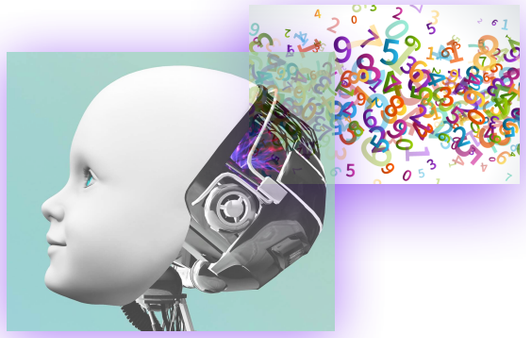

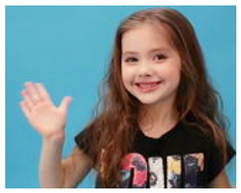

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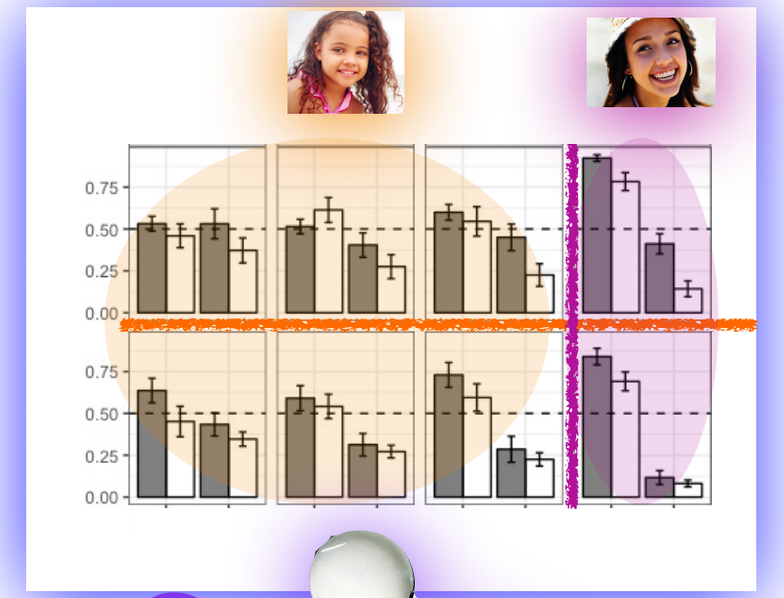

?

$0.01 \leq \sigma \leq 4.00$

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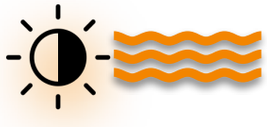
	σ_{for}	σ_{con}	σ_{mor}	σ_{α}	β_{for}	β_{con}	β_{mor}	β_{α}
children: inaccurate representations								
≤3	0.01	0.23	0.02	0.01	1	1	1	1
4	0.01	0.07	0.10	0.01	1	1	1	1
≥5	0.01	0.11	0.10	0.01	1	1	1	1
adults: both inaccurate								
adults					0.25	0.4	.8	0.98

Child representations, with σ values often much < 1, seem to smooth away probability differences, effectively turning down the contrast.



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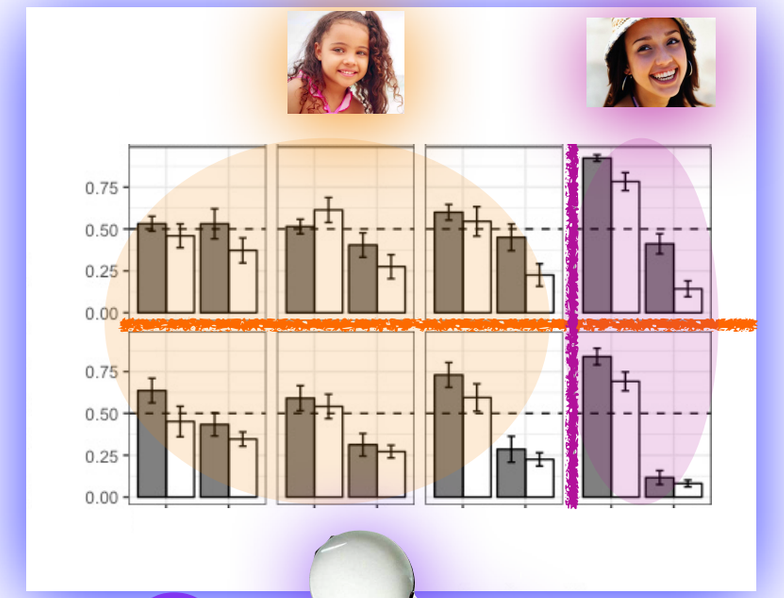

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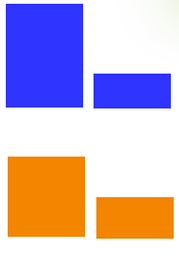
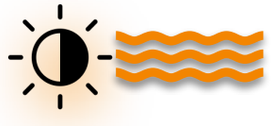
	σ_{for}	σ_{con}	σ_{mor}	σ_{α}	β_{for}	β_{con}	β_{mor}	β_{α}
children: inaccurate representations								
≤3	0.01	0.23	0.02	0.01	1	1	1	1
4	0.01	0.07	0.10	0.01	1	1	1	1
≥5	0.01	0.11	0.10	0.01	1	1	1	1
adults: both inaccurate								
adults					0.25	0.4	.8	0.98

.75 vs. .25

σ = .23

.56 vs. .44





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Understanding the development of pronoun interpretation

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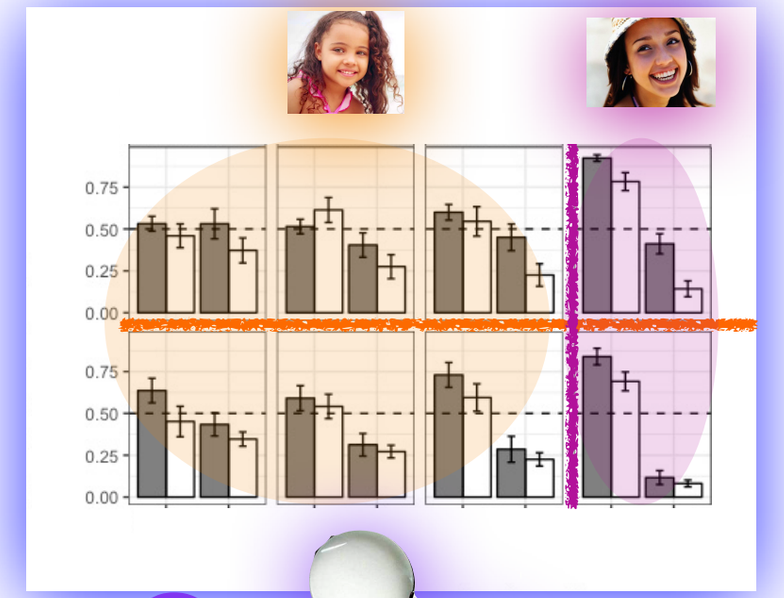


$0.01 \leq \sigma \leq 4.00$

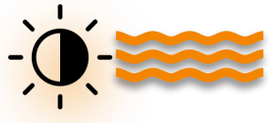
$0 \leq \beta \leq 1$

	σ_{for}	σ_{con}	σ_{mor}	σ_{α}	β_{for}	β_{con}	β_{mor}	β_{α}
children: inaccurate representations								
≤3	0.01	0.23	0.02	0.01	1	1	1	1
4	0.01	0.07	0.10	0.01	1	1	1	1
≥5	0.01	0.11	0.10	0.01	1	1	1	1
adults: both inaccurate								
adults					0.25	0.48	.89	0.98

.75 vs. .25

σ = .23 .56 vs. .44

σ = .10 .53 vs. .47



Forsythe & Pearl 2019, in prep

Understanding the development of pronoun interpretation

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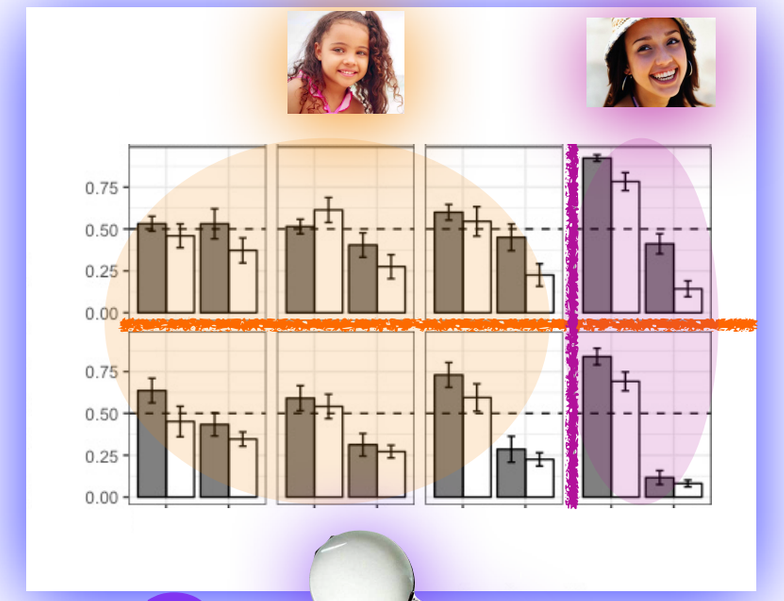

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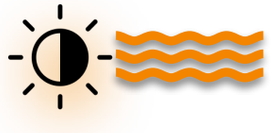

Forsythe & Pearl 2019, in prep

Understanding the development of pronoun interpretation

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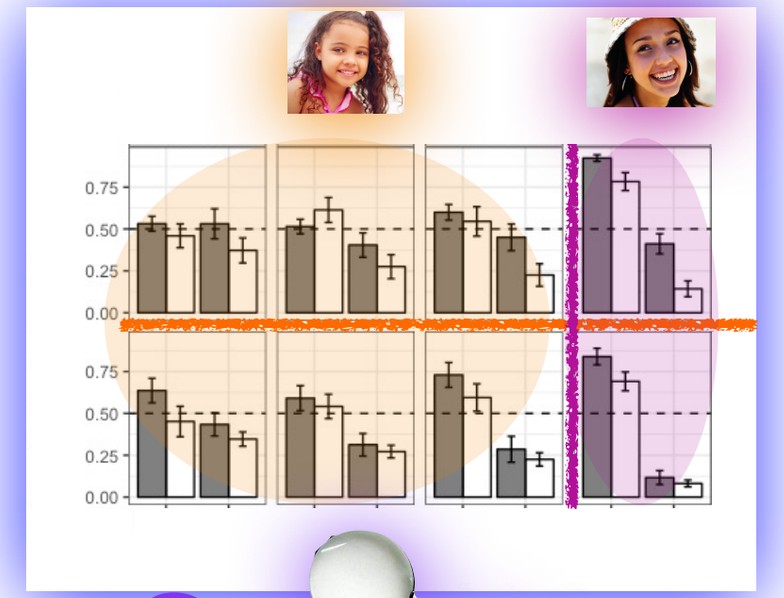

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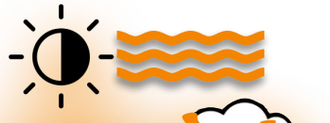

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adults: both inaccurate								
adults	4.00	3.00	4.00	0.01	0.25	0.4	.8	0.98

Adults do this same extreme smoothing for the prior information.

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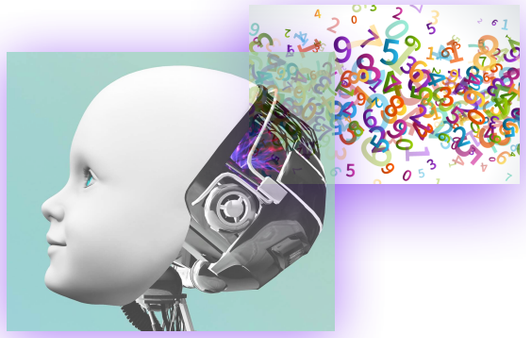
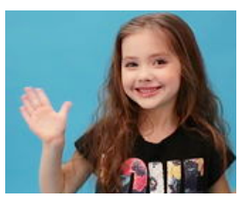
Understanding the development of pronoun interpretation





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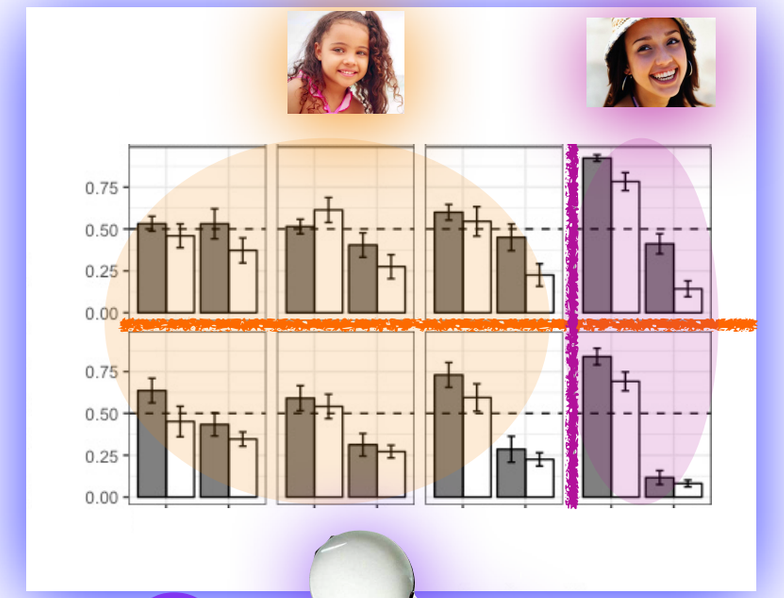

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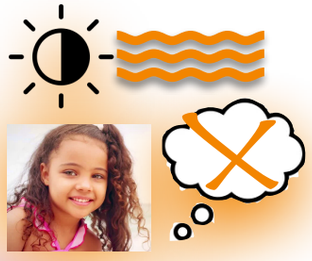

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adults: both inaccurate								
adults	4.00	3.00	4.00	0.01	0.25	0.48	0.89	0.98

But adults substantially sharpen all the other information (σ = 3.00, 4.00)

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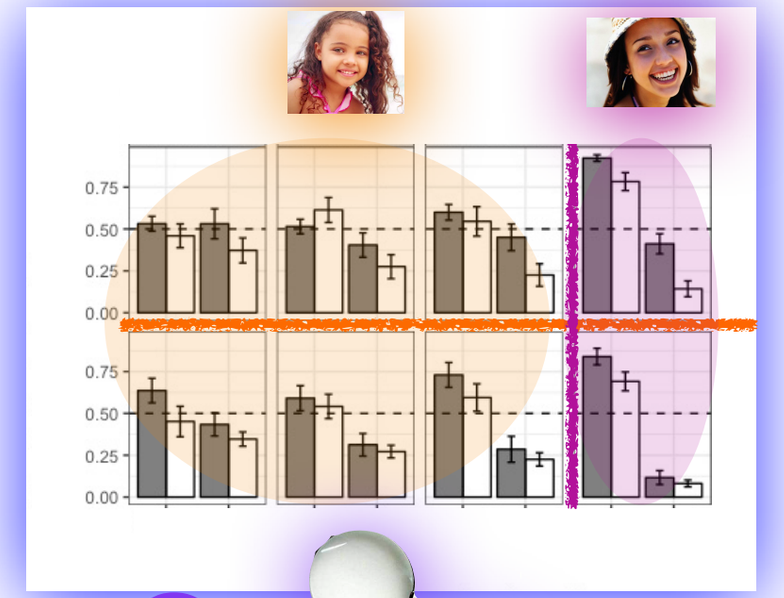
Understanding the development of pronoun interpretation

≈≈ PRONOUN =



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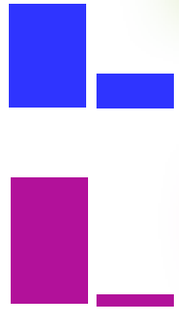
adults: both inaccurate								
adults	4.00	3.00	4.00	0.01	0.25	0.4[illegible]	[illegible]	0.98

.75 vs. .25

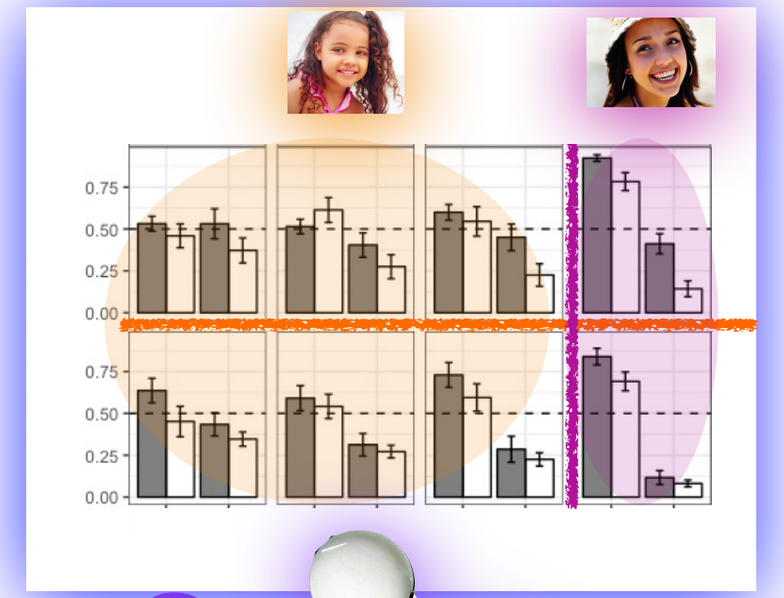
$\sigma = 3.00$ .96 vs. .04



Forsythe & Pearl 2019, in prep

Understanding the development of pronoun interpretation

≈≈ PRONOUN =



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$\sigma = 3.00$ .96 vs. .04

$\sigma = 4.00$ .99 vs. .01

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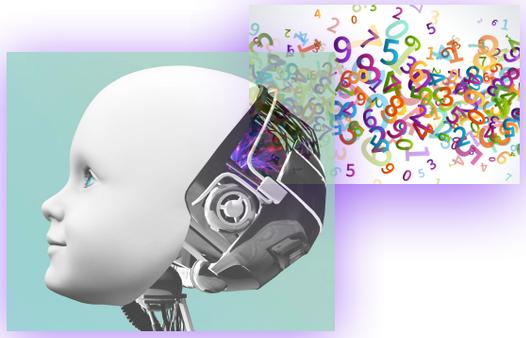
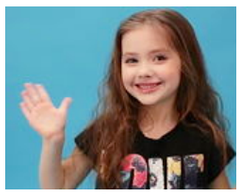
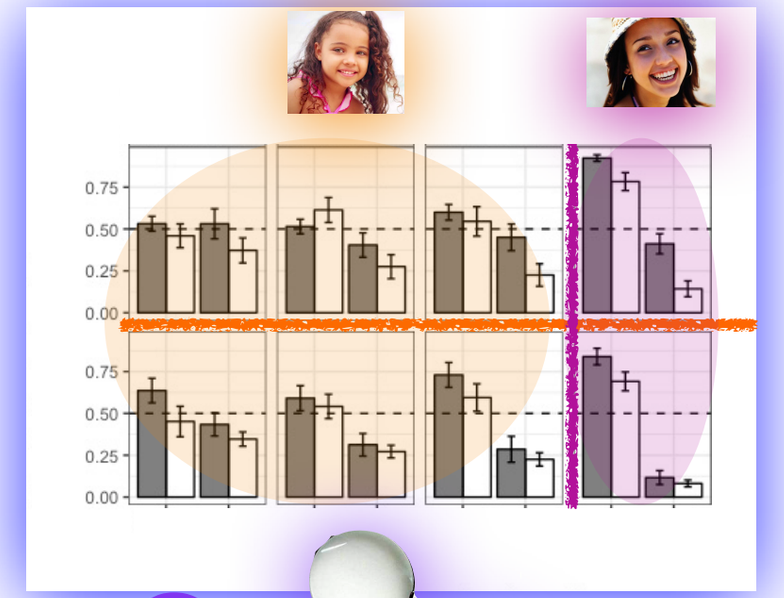
Understanding the development of pronoun interpretation





≈≈ PRONOUN =



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Becoming adult-like: Children need to learn to sharpen certain perceived representations, rather than smooth away probability differences.

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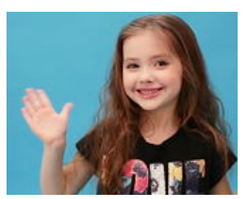
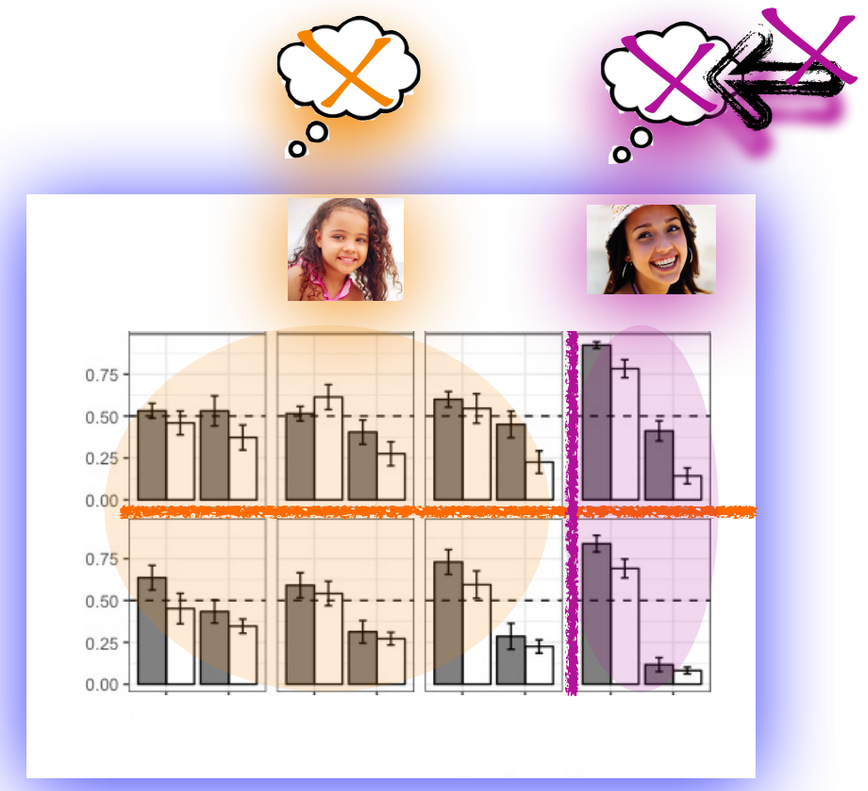
Understanding the development of pronoun interpretation



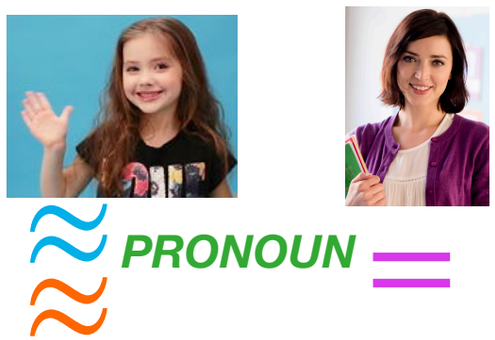
≈ PRONOUN =

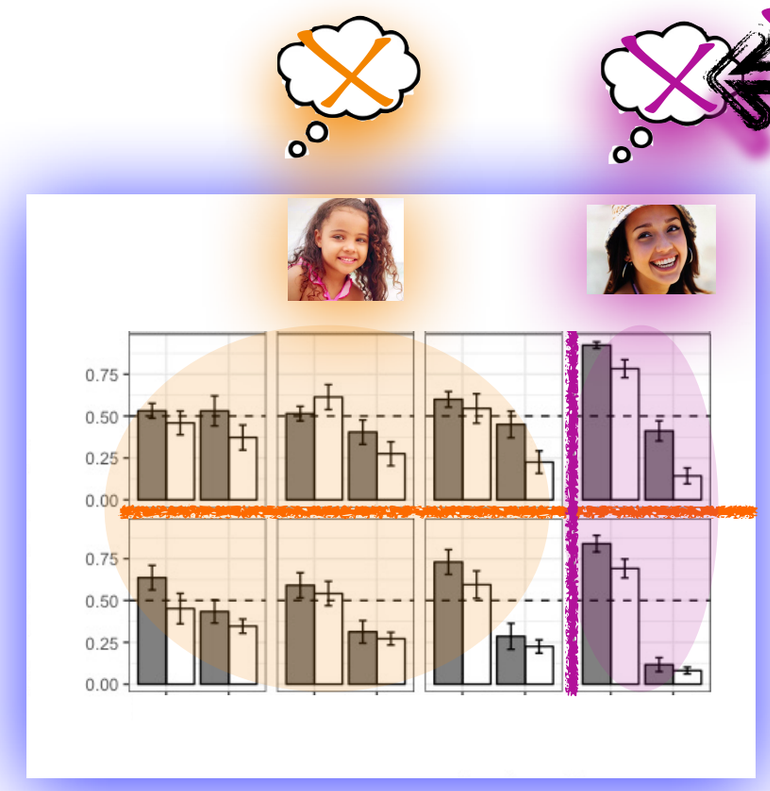
Takeaway:
To generate adult-like pronoun interpretation behavior in context, children need to change both how they represent relevant information from their input and how they deploy those representations.



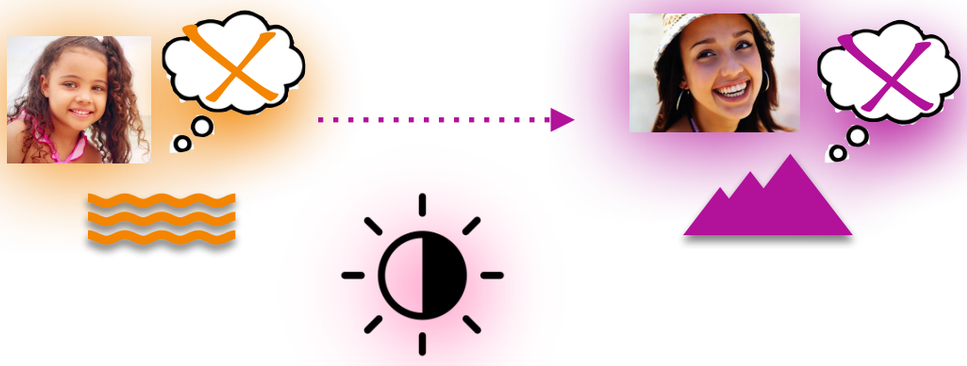
Forsythe & Pearl 2019, in prep

Understanding the development of pronoun interpretation





Takeaway:
Child representations are overly smooth — to become adult-like, many representations must sharpen perceived probability differences.



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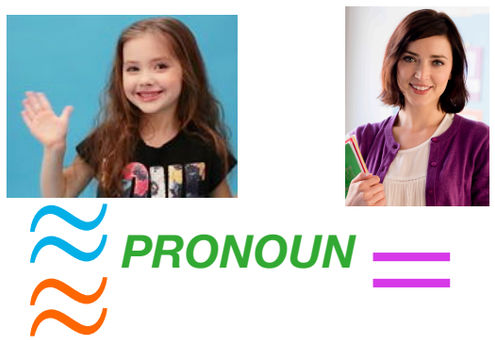
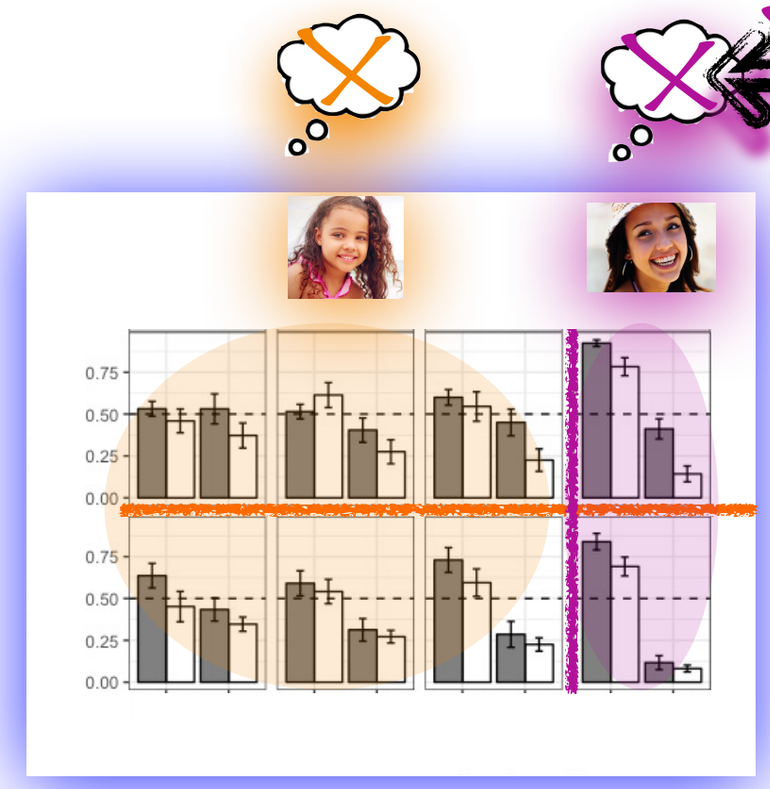
Understanding the development of pronoun interpretation





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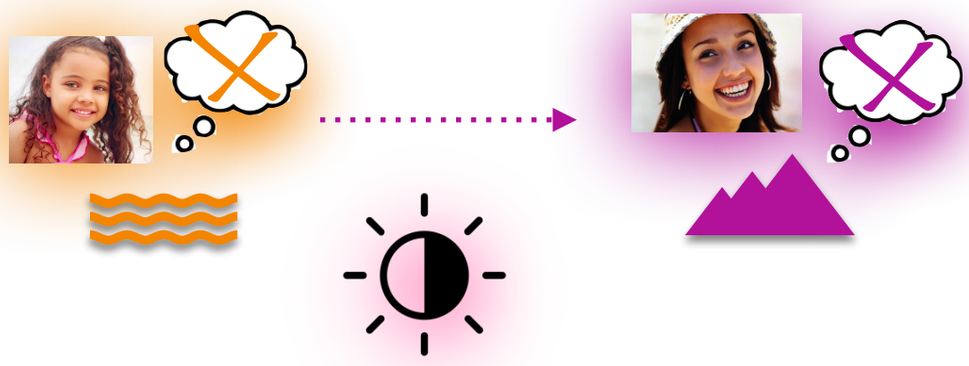

Important: Being adult-like doesn't mean being accurate!

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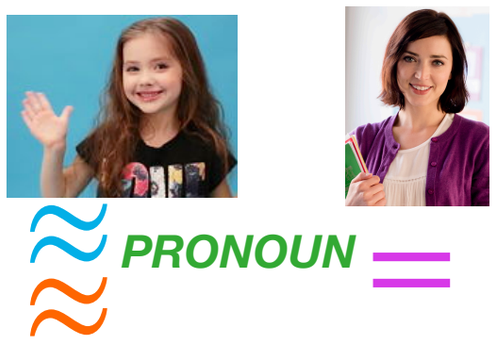
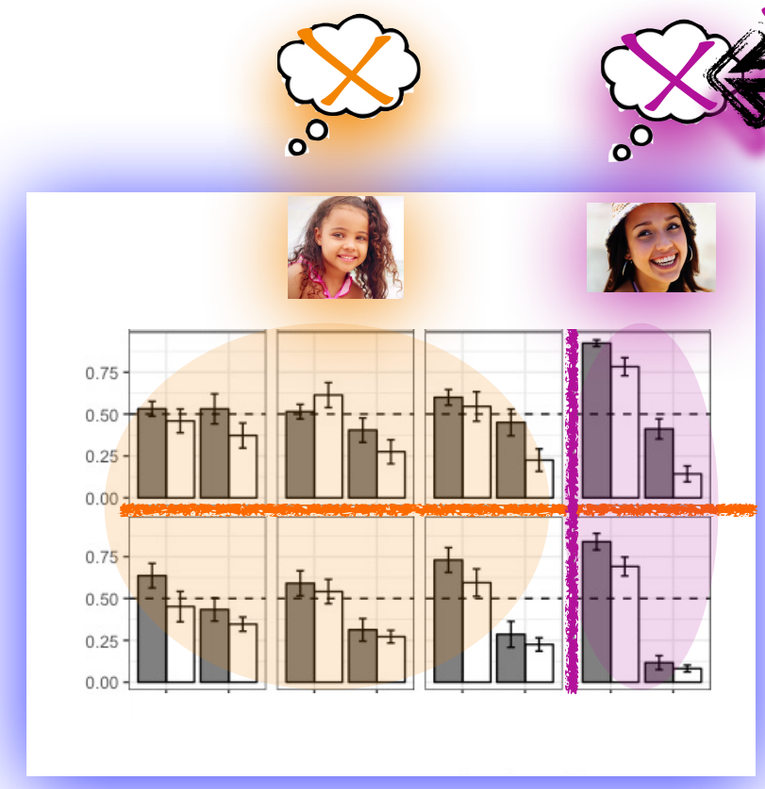
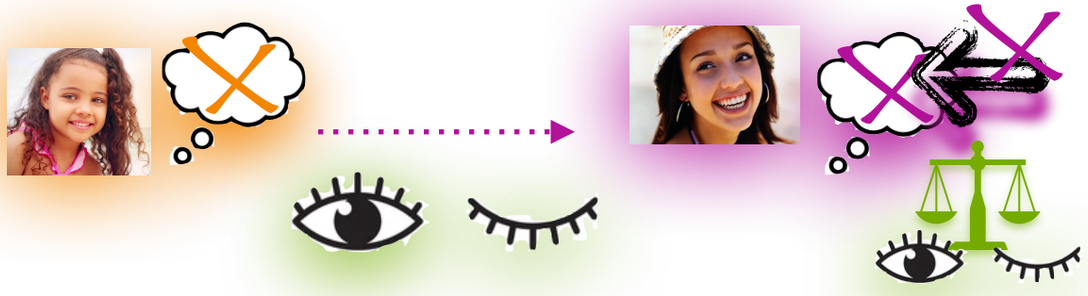
Understanding the development of pronoun interpretation





Takeaway:
Adult deployment is selective — to become adult-like, children must learn how to selectively ignore information like adults.



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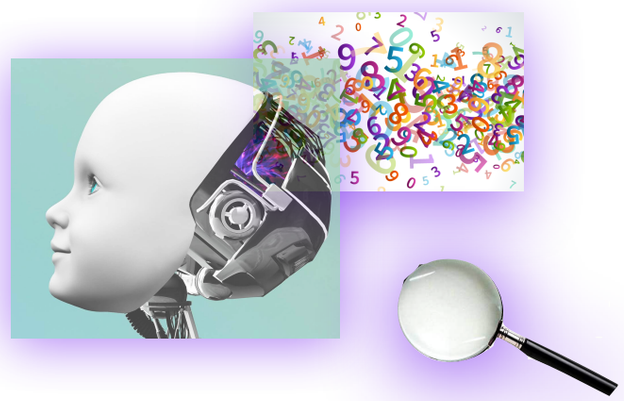
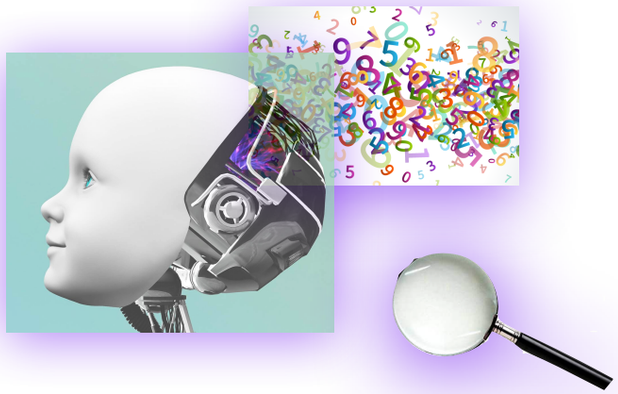
The big picture

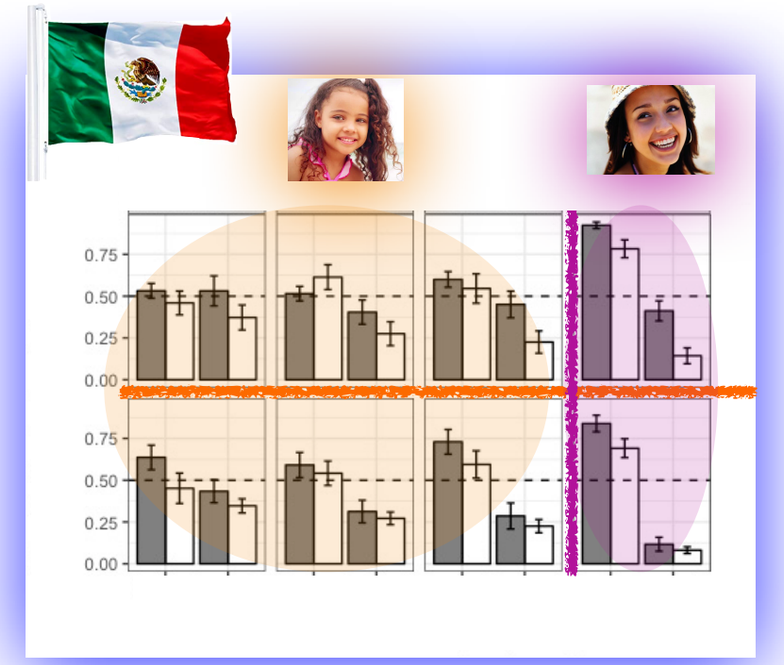


More generally, this case study demonstrates how we can use computational cognitive modeling…

Forsythe & Pearl 2019, in prep

The big picture





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Forsythe & Pearl 2019, in prep

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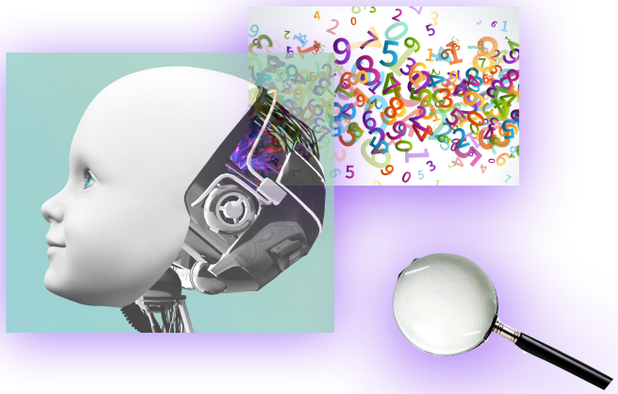

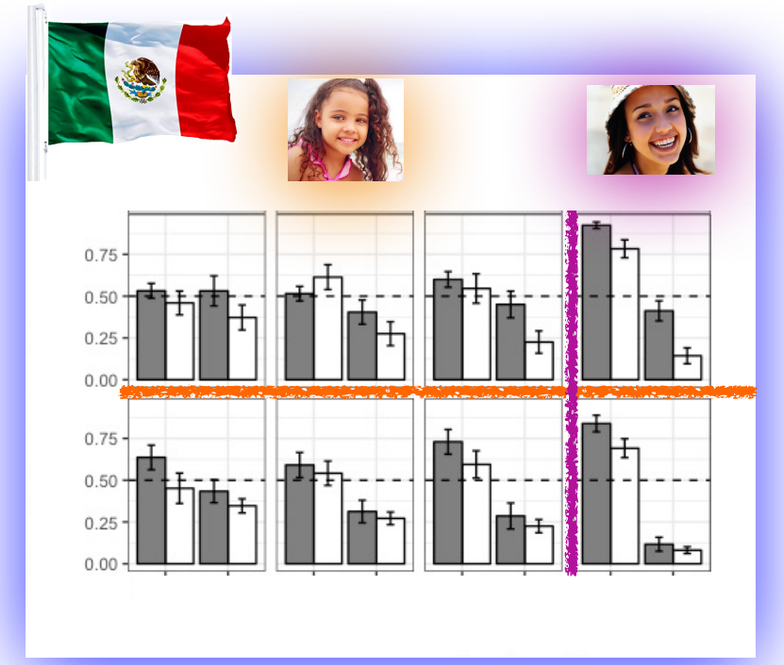

More generally, this case study demonstrates how we can use computational cognitive modeling, grounded in empirical data, to better understand how children and adults…

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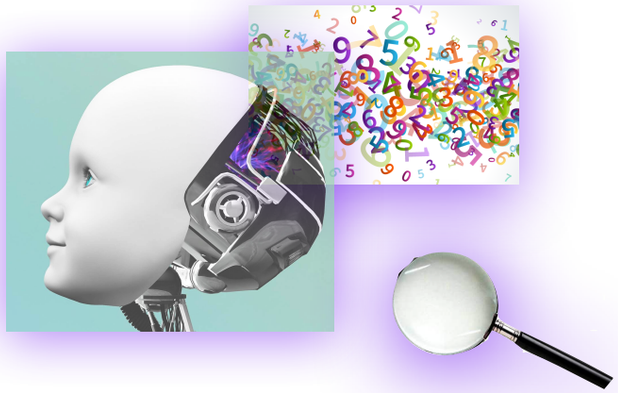
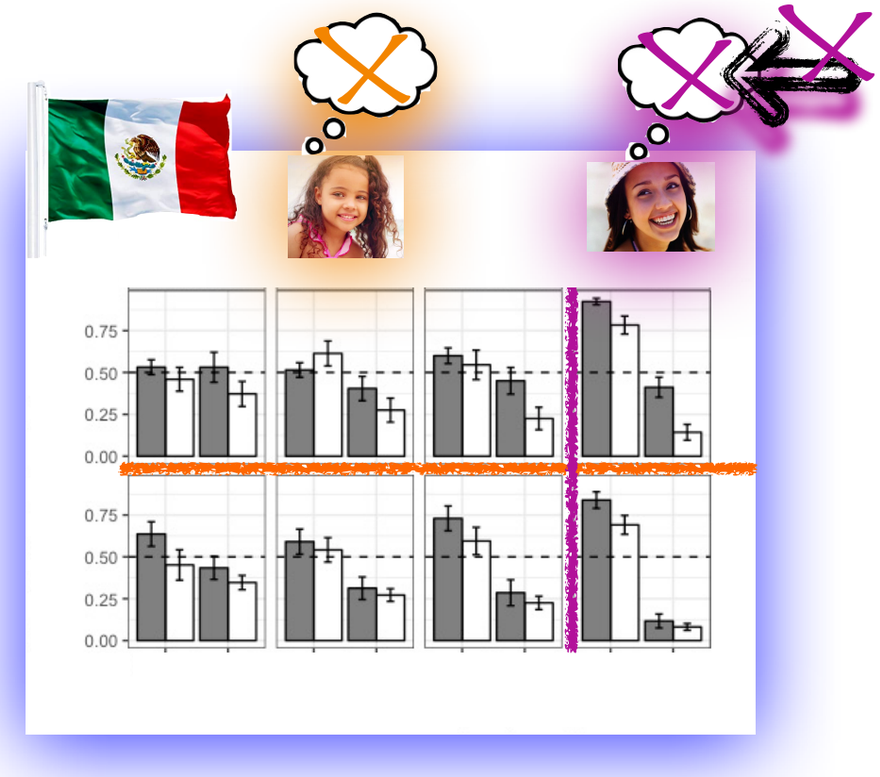
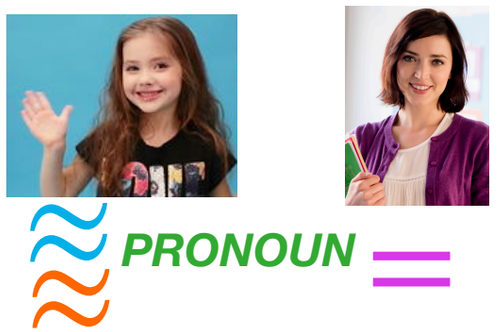
The big picture



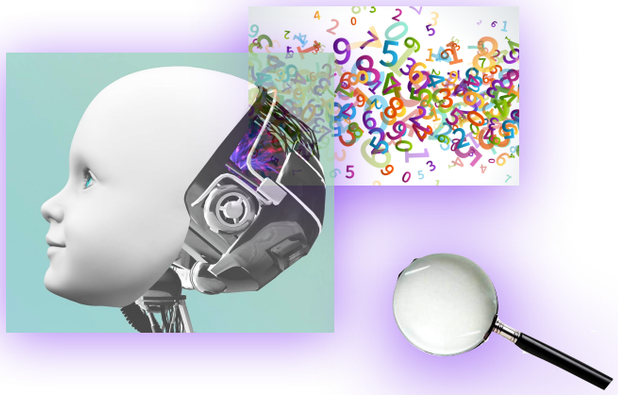


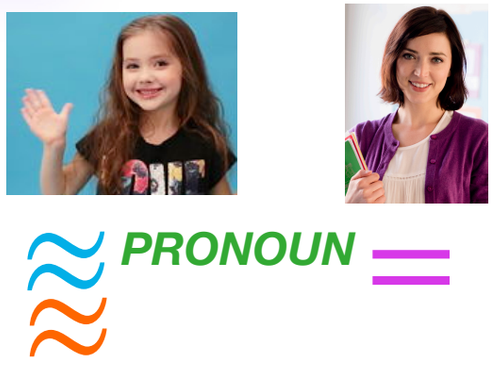
More generally, this case study demonstrates how we can use computational cognitive modeling, grounded in empirical data, to better understand how children and adults can solve complex linguistic tasks (like interpreting pronouns in a context with multiple, potentially conflicting, cues).

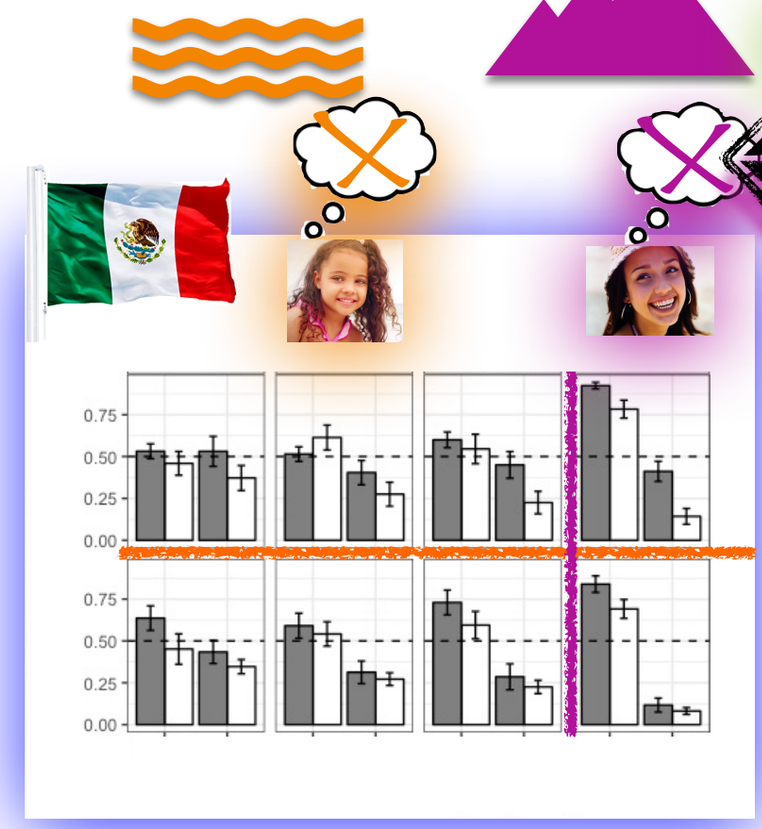


Forsythe & Pearl 2019, in prep

The big picture







This helps us better understand what children need to do to become adult-like (and it seems to be about learning the right helpful biases).

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Thank you!

Hannah Forsythe

UCI QuantLang Collective

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