How children are and aren't like adults when interpreting pronouns: A computational cognitive 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 in this context.

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

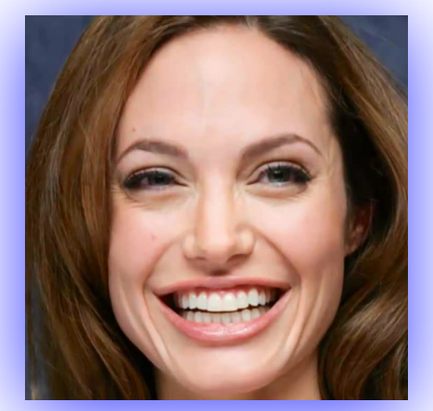
The girls wave at the teacher…

≈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

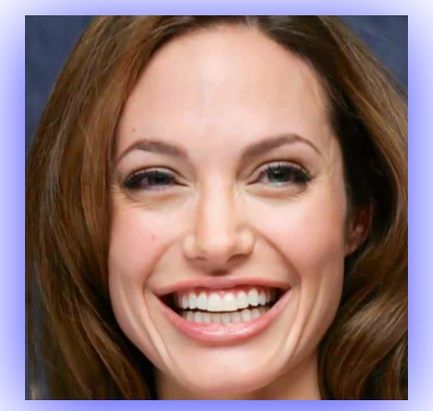
The girls wave at the teacher…

≈subject pl sg

???

…and then **she** leaves.

sg



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

Pronoun interpretation

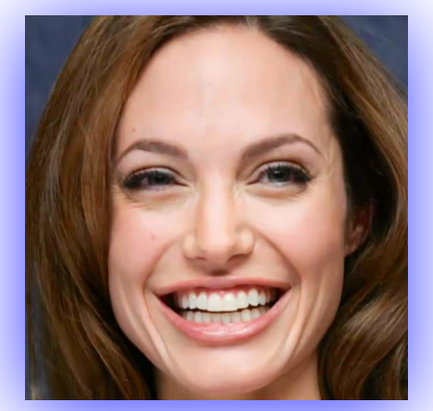
The girls wave at the teacher…

≈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

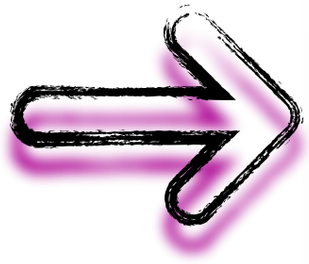
PRONOUN

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

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


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.

Case study: Mexican Spanish

Forsythe & Pearl 2019, Pearl & Forsythe under review

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.

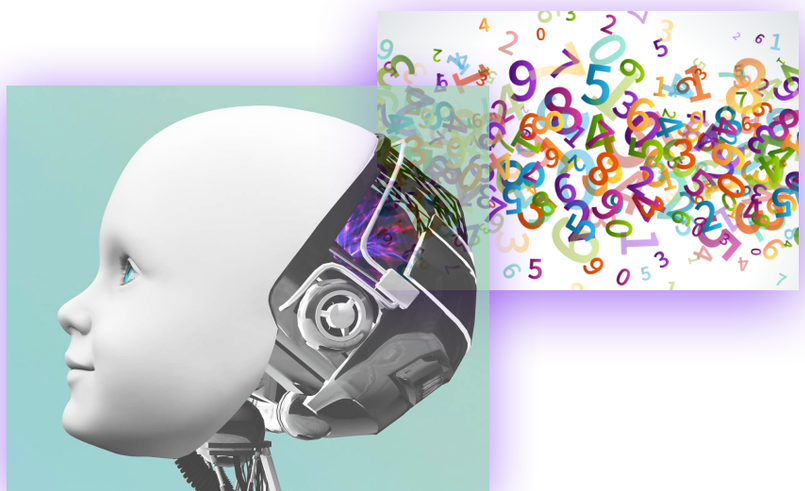
Forsythe & Pearl 2019, Pearl & Forsythe under review

Understanding pronoun interpretation development

≈ PRONOUN =

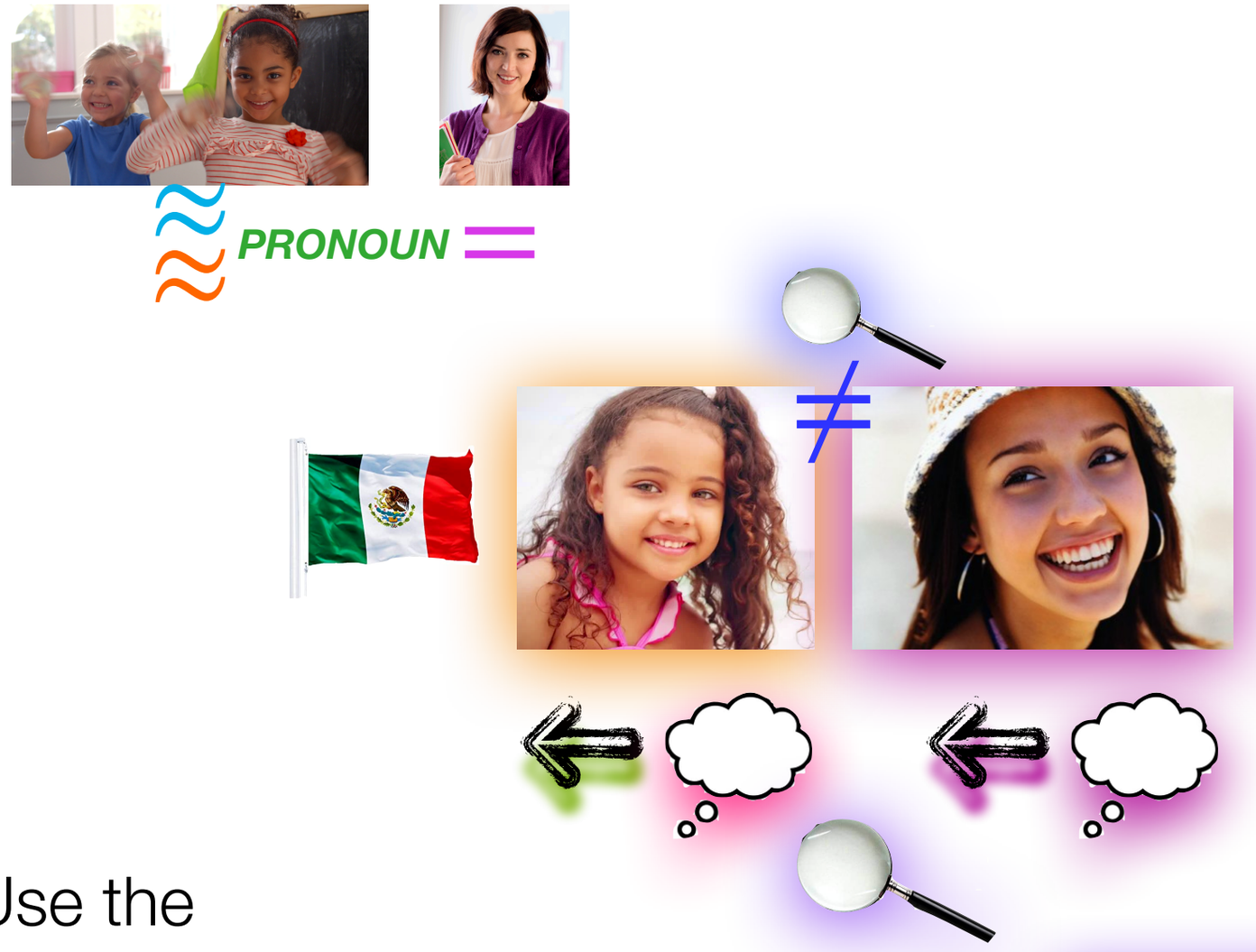
≠

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



Forsythe & Pearl 2019, Pearl & Forsythe under review

Understanding pronoun interpretation development



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

Forsythe & Pearl 2019, Pearl & Forsythe under review

Empirical data on pronoun interpretation

Forsythe & Pearl 2019, Pearl & Forsythe under review

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, Pearl & Forsythe under review

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, Pearl & Forsythe under review

Empirical data on pronoun interpretation

Las niñas saludan a la maestra…

The girls wave at the teacher…

subject pl ≠ sg ??? Ø

…y después 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, Pearl & Forsythe under review

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, Pearl & Forsythe under review

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

Rate of subject responses

Context:
Does agreement favor the subject or the object?

subject object

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Las niñas saludan a la maestra…

The girls wave at the teacher…

pl ≠ sg

???

…y después Ø sale.

… and then ***PRONOUN*** *leaves.*

sg

≠

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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

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

subject object

Favored by agreement

Forsythe & Pearl 2019, Pearl & Forsythe under review

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, Pearl & Forsythe under review

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, Pearl & Forsythe under review

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 respon

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, Pearl & Forsythe under review

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)

Favored by form

(favors subject) overt (favors object)

subject object

Favored by agreement

Forsythe & Pearl 2019, Pearl & Forsythe under review

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)

Favored by form

(favors subject) overt (favors object)

subject object

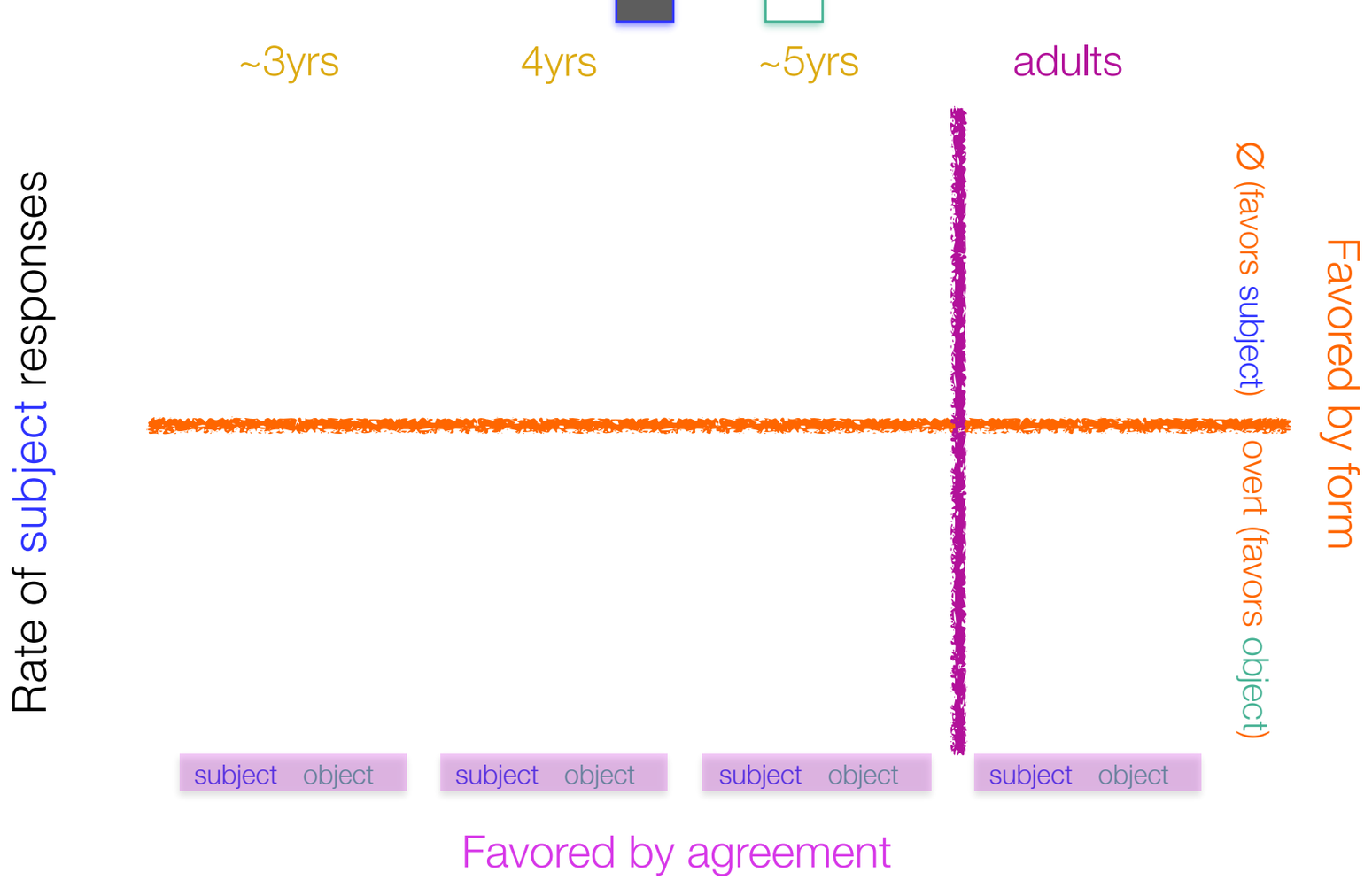
Favored by agreement

Forsythe & Pearl 2019, Pearl & Forsythe under review

Empirical data on pronoun interpretation

Favored by connective

y después (favors subject) porque (favors object)



Forsythe & Pearl 2019, Pearl & Forsythe under review

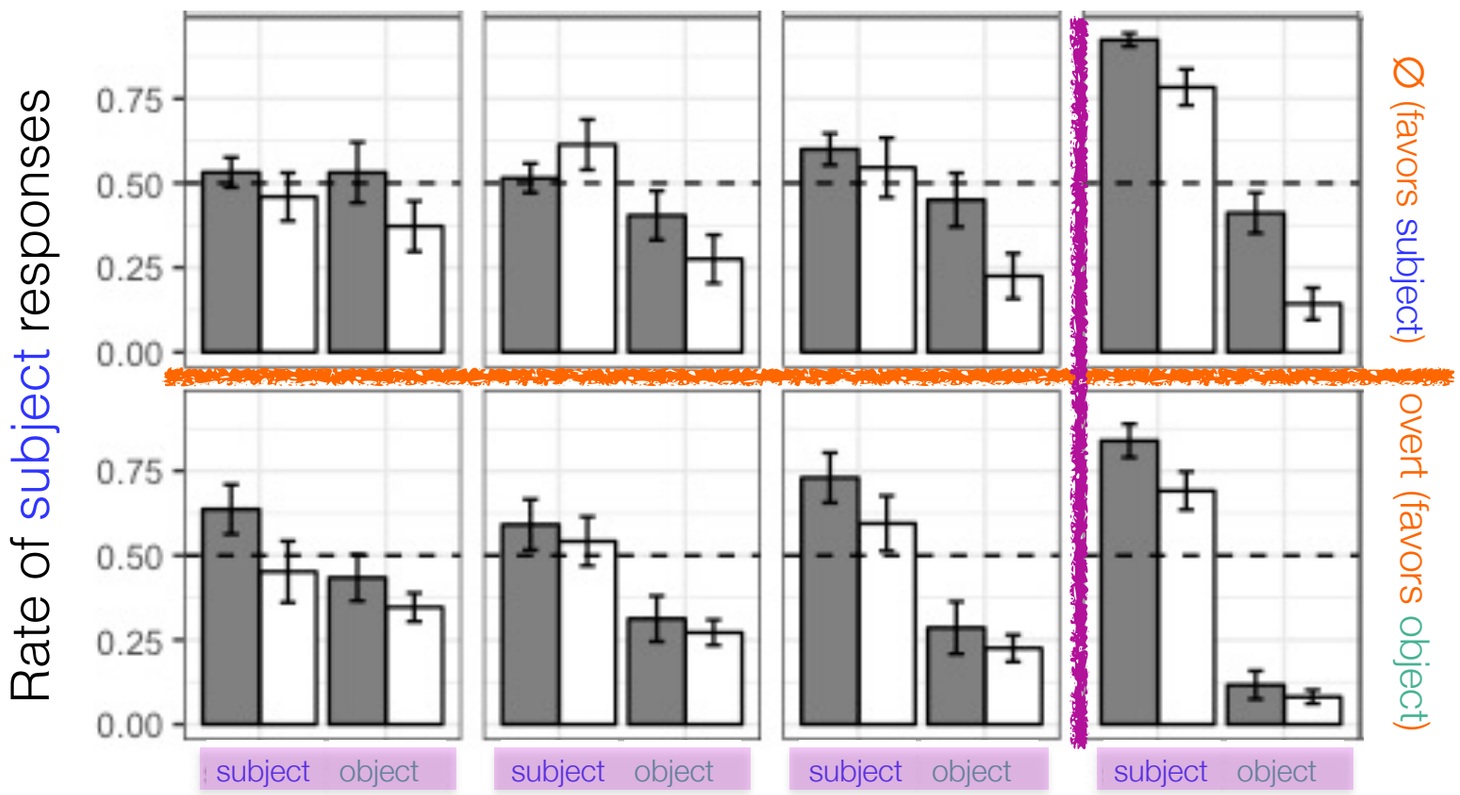
Empirical data on pronoun interpretation

≠

Favored by connective

y después (favors subject) porque (favors object)

~3yrs 4yrs ~5yrs adults

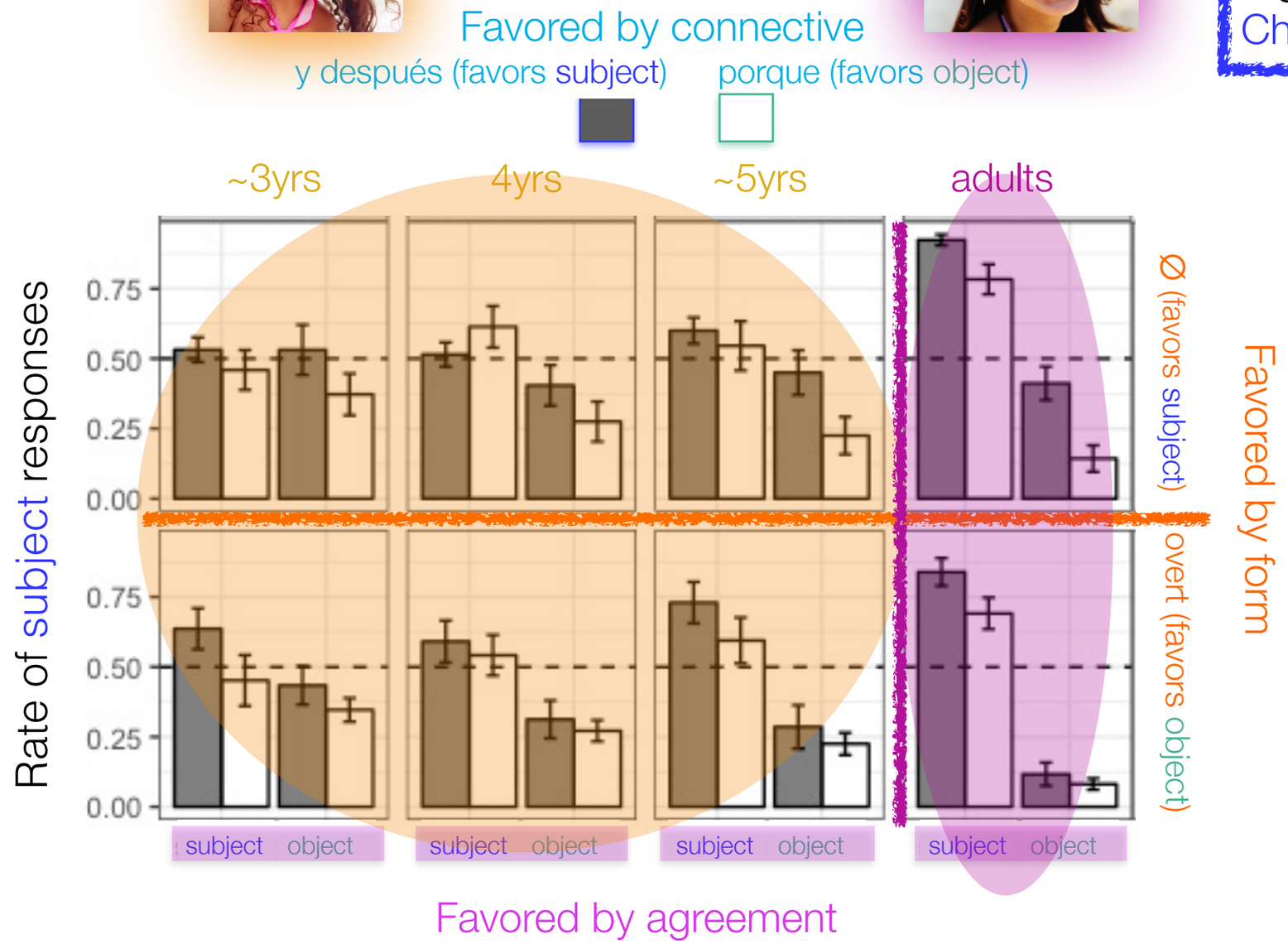


Favored by agreement

Forsythe & Pearl 2019, Pearl & Forsythe under review

Empirical data on pronoun interpretation

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

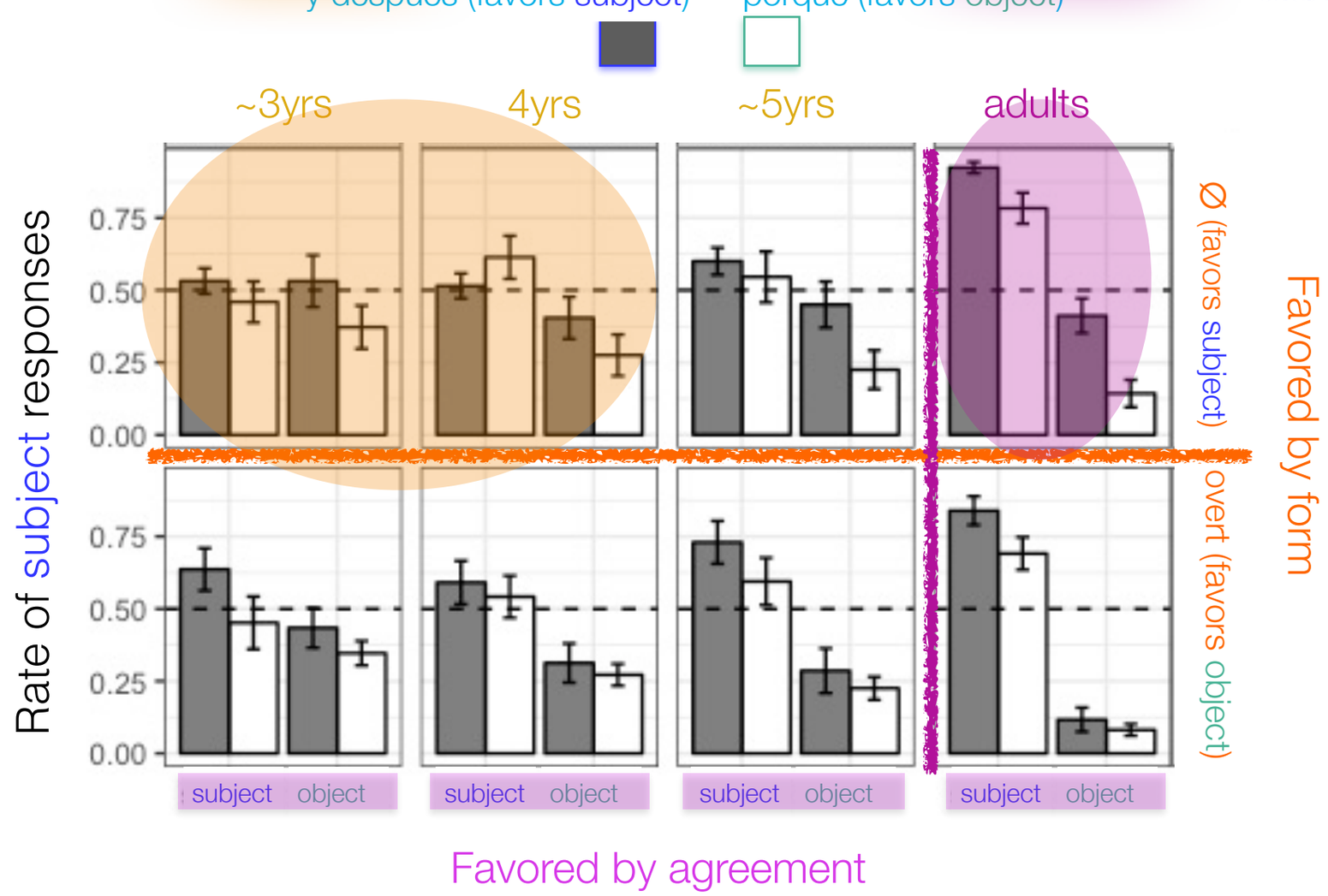


Forsythe & Pearl 2019, Pearl & Forsythe under review

Empirical data on pronoun interpretation

Favored by connective

y después (favors subject) porque (favors object)



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

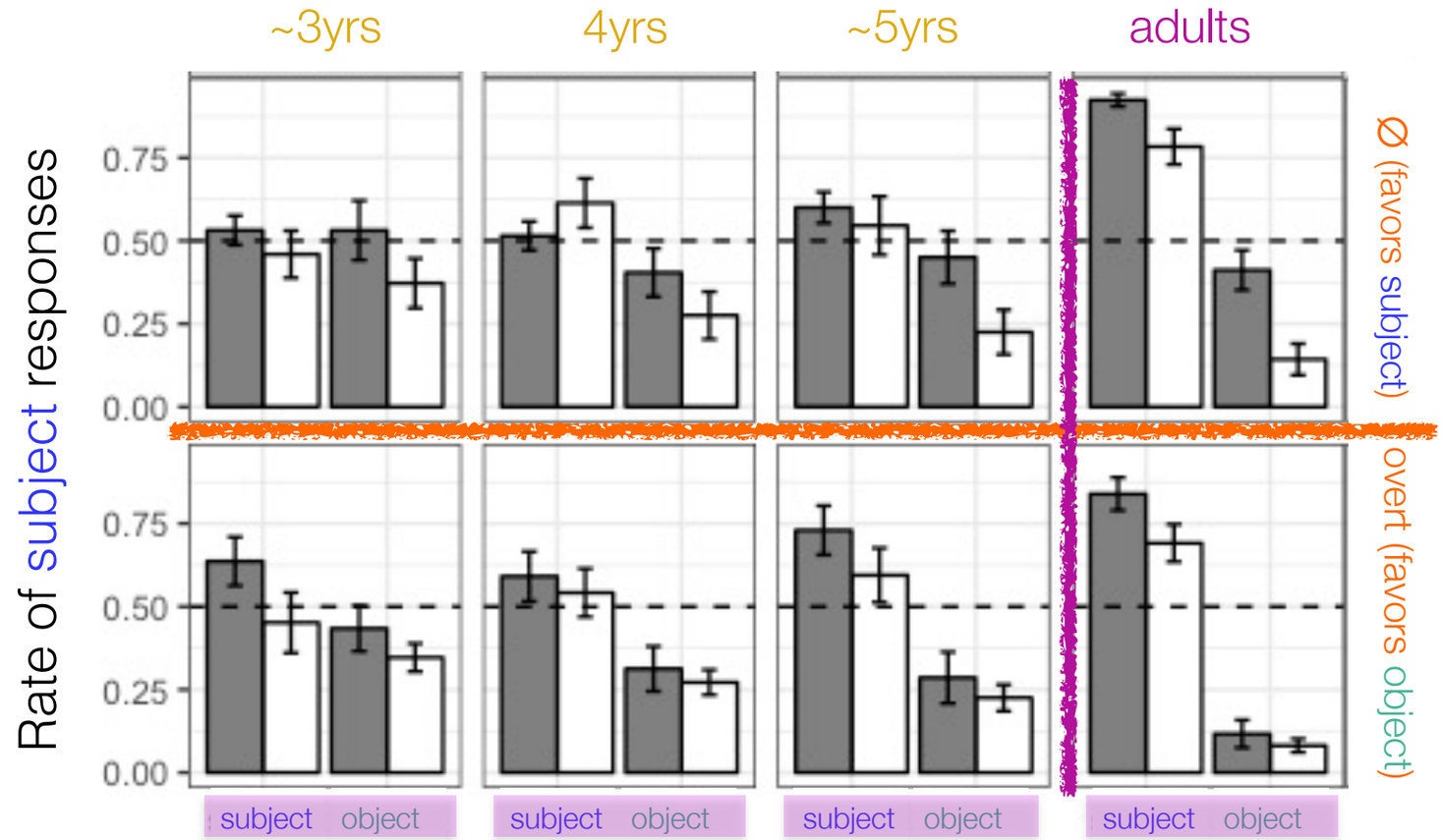
Some nuances:
Younger children seem to differ more, especially in certain contexts.

Forsythe & Pearl 2019, Pearl & Forsythe under review

Empirical data on pronoun interpretation

Favored by connective

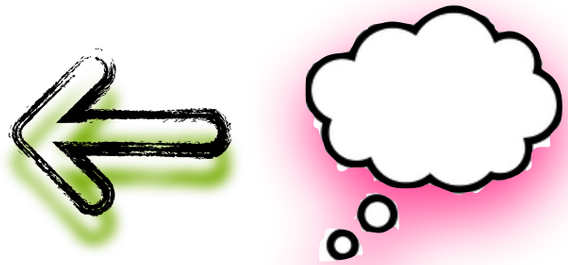
y después (favors subject) porque (favors object)



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

Forsythe & Pearl 2019, Pearl & Forsythe under review

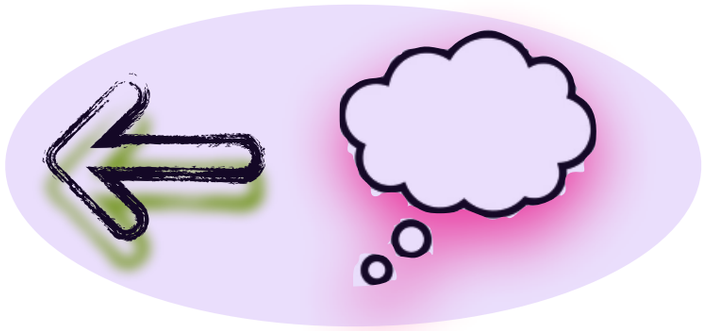
Understanding pronoun interpretation development



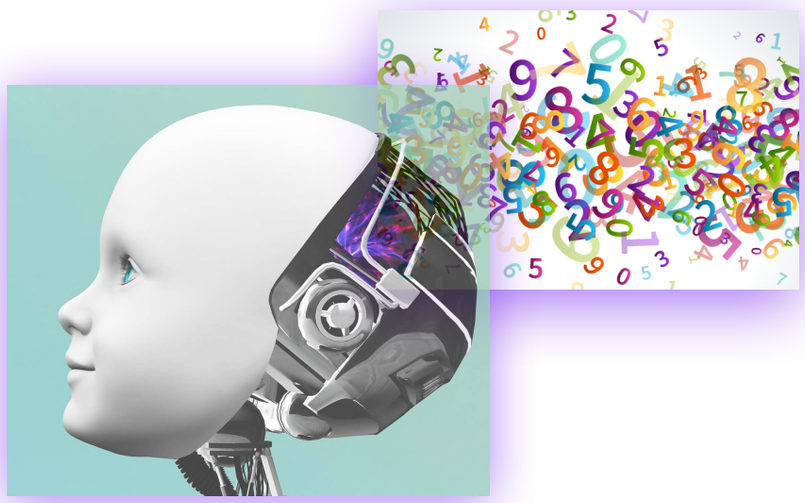
The plan, part 2:
Use computational cognitive modeling to formally articulate the potential process of pronoun interpretation in the context of these multiple cues.

Forsythe & Pearl 2019, Pearl & Forsythe under review

Understanding pronoun interpretation development



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



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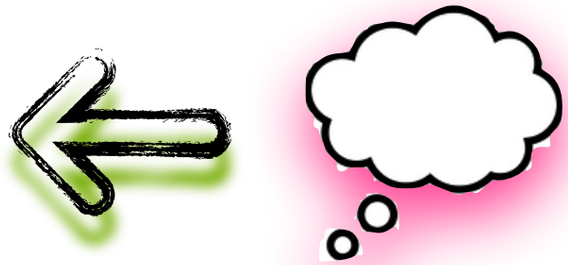
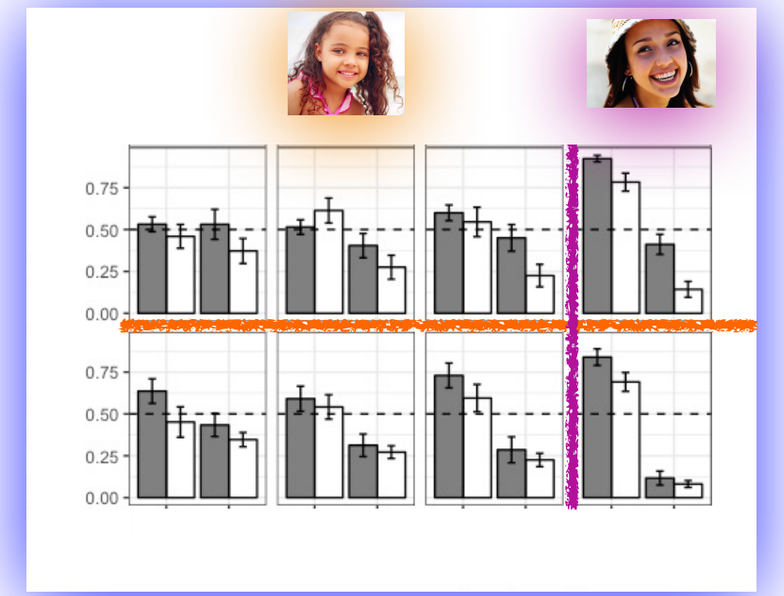
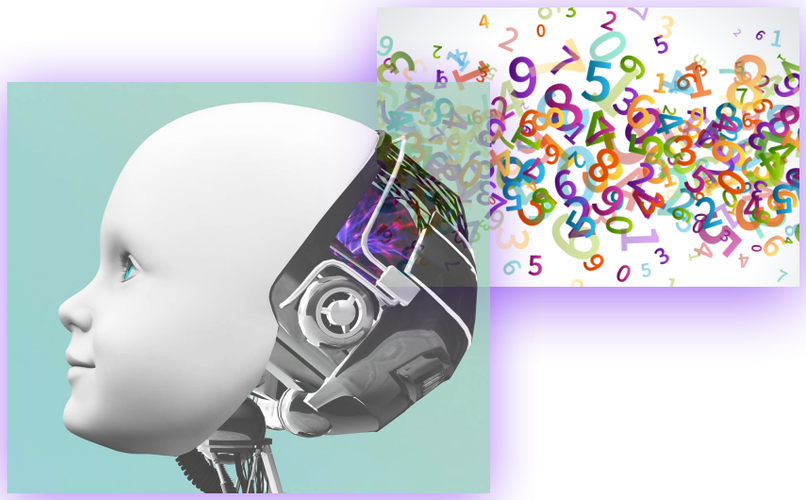
Understanding pronoun interpretation development



PRONOUN =

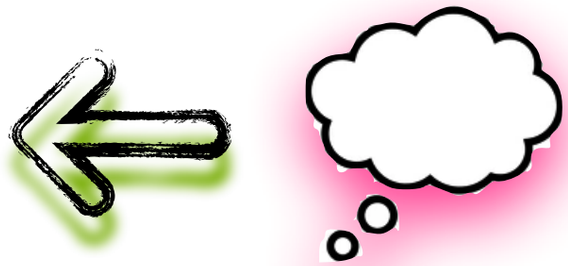
Here: Implement how a modeled listener represents pronoun information and deploys that information in order to predict the probability of a particular interpretation in context.





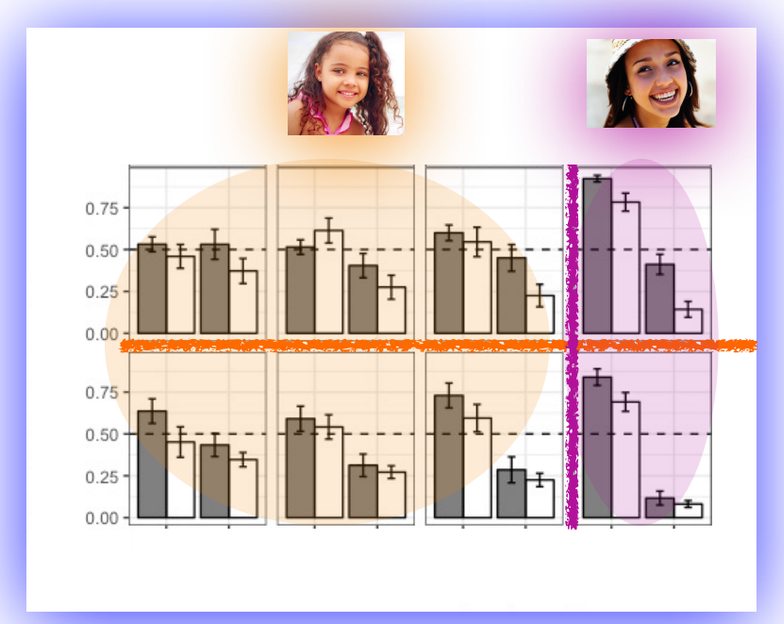
Forsythe & Pearl 2019, Pearl & Forsythe under review

Understanding pronoun interpretation development



≈ PRONOUN =

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



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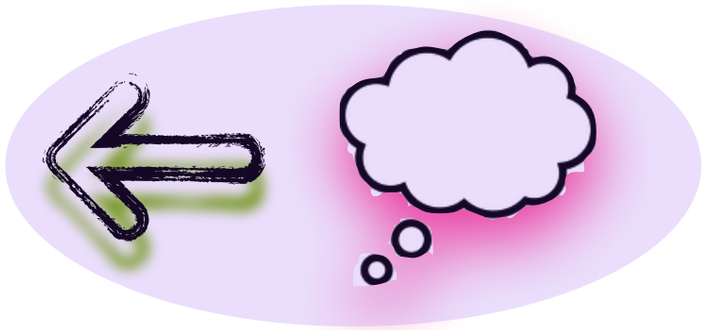
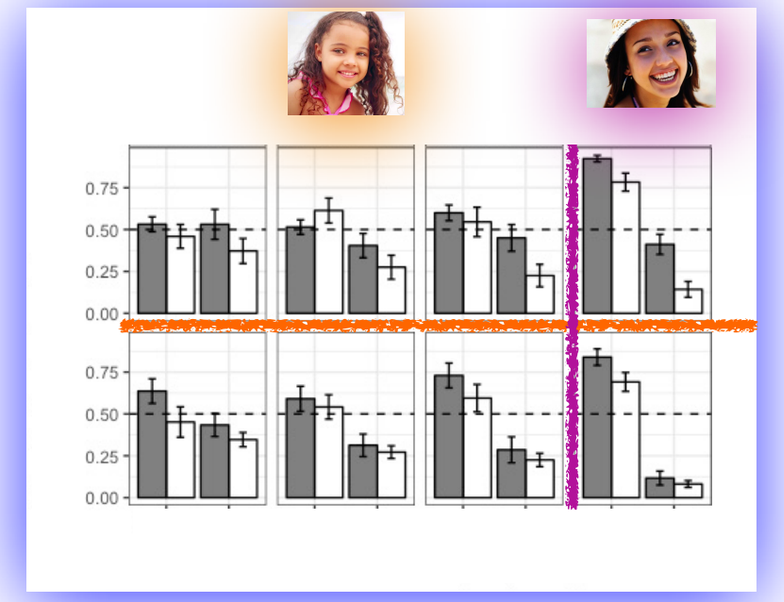
Understanding pronoun interpretation development



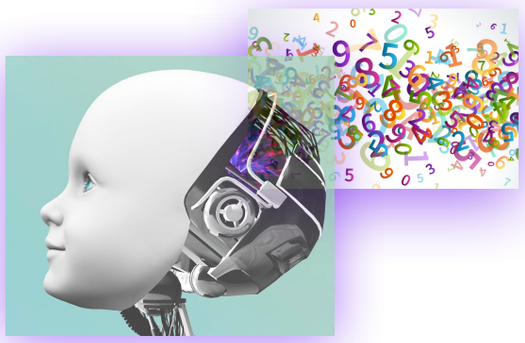
≈ PRONOUN =

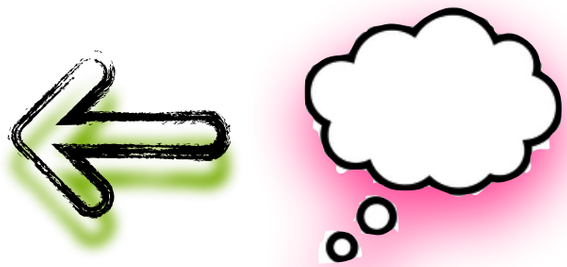
This will articulate how children (potentially) differ from adults, and what needs to develop in children for them to become adult-like.



Forsythe & Pearl 2019, Pearl & Forsythe under review

Modeling pronoun interpretation in context





PRONOUN

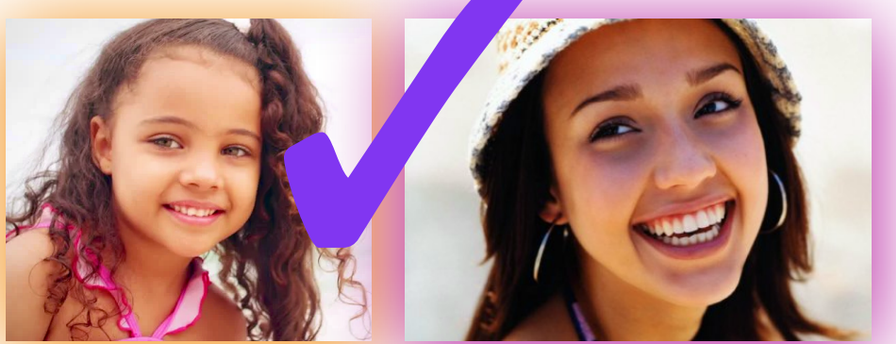
The model uses Bayesian inference to implement the cognitive mechanism that combines information to generate a particular interpretation in context.

Forsythe & Pearl 2019, Pearl & Forsythe under review

Modeling pronoun interpretation in context

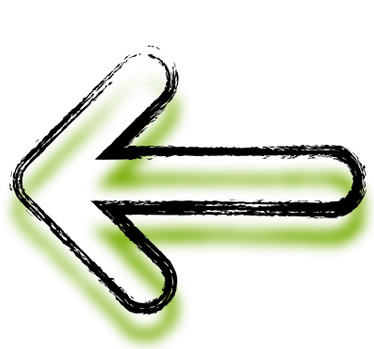
Bayesian inference is commonly used to model human cognition in general and language development in particular, since it matches human behavior quite well (see Pearl in press and b for recent reviews).

PRONOUN



Forsythe & Pearl 2019, Pearl & Forsythe under review

Modeling pronoun interpretation in context



Bayesian inference

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, Pearl & Forsythe under review

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, Pearl & Forsythe under review

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, Pearl & Forsythe under review

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, Pearl & Forsythe under review

Modeling pronoun interpretation in context

Bayesian inference

PRONOUN

interpretation context

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

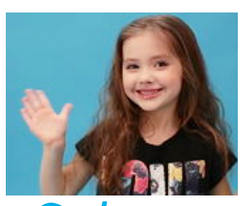
sg *pl*

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

Forsythe & Pearl 2019, Pearl & Forsythe under review

Modeling pronoun interpretation in context

Bayesian inference



PRONOUN

interpretation context

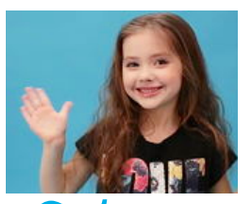
$$p(\alpha_{subj.\text{SG}}|\text{FORM}, \text{CON}, \text{MOR}) \propto p(\alpha_{subj.\text{SG}}) * p(\text{FORM}, \text{CON}, \text{MOR}|\alpha_{subj.\text{SG}})$$

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

Forsythe & Pearl 2019, Pearl & Forsythe under review

Modeling pronoun interpretation in context

Bayesian inference



PRONOUN

interpretation context

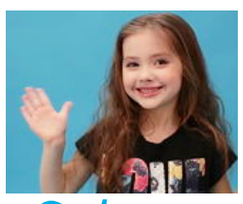
$$p(\alpha_{subj.\text{SG}}|\text{FORM}, \text{CON}, \text{MOR}) \propto p(\alpha_{subj.\text{SG}}) * p(\text{FORM}, \text{CON}, \text{MOR}|\alpha_{subj.\text{SG}})$$

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

Forsythe & Pearl 2019, Pearl & Forsythe under review

Modeling pronoun interpretation in context

Bayesian inference



PRONOUN

interpretation context

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

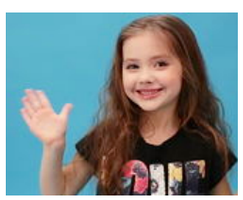
Here, we assume these context values are independent, so we can calculate the likelihood this way.

Not implausible: In visual perception, human behavior is best captured by models assuming features are independent (Vul & Rich 2010).

Forsythe & Pearl 2019, Pearl & Forsythe under review

Modeling pronoun interpretation in context

Bayesian inference



PRONOUN

interpretation context

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

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

Forsythe & Pearl 2019, Pearl & Forsythe under review

Modeling pronoun interpretation in context

Bayesian inference

PRONOUN

interpretation context

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

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, Pearl & Forsythe under review

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, Pearl & Forsythe under review

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, Pearl & Forsythe under review

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, Pearl & Forsythe under review

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. *0.324 vs. 0.676*

σ = 2: probability differences are sharpened. 0.187 vs. 0.813

Forsythe & Pearl 2019, Pearl & Forsythe under review

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, Pearl & Forsythe under review

Modeling pronoun interpretation in context

Bayesian inference

PRONOUN

probability$^{\sigma}$

interpretation context

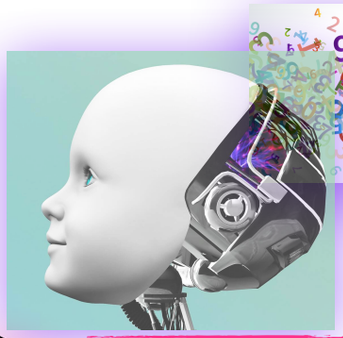
$$p_\sigma(\alpha_{num}, \alpha_{subj?} | \text{FORM}, \text{CON}, \text{MOR}) \propto p(\alpha_{num}, \alpha_{subj?})^{\sigma_\alpha} * p(\text{FORM} | \alpha_{num}, \alpha_{subj?})^{\sigma_{form}} * p(\text{CON} | \alpha_{num}, \alpha_{subj?})^{\sigma_{con}} * p(\text{MOR} | \alpha_{num}, \alpha_{subj?})^{\sigma_{mor}}$$

inaccurate representations

We allow $0.00 \leq \sigma \leq 4.00$, and see which σ value combinations best predict child and adult pronoun interpretation behavior.

Forsythe & Pearl 2019, Pearl & Forsythe under review

Modeling pronoun interpretation in context

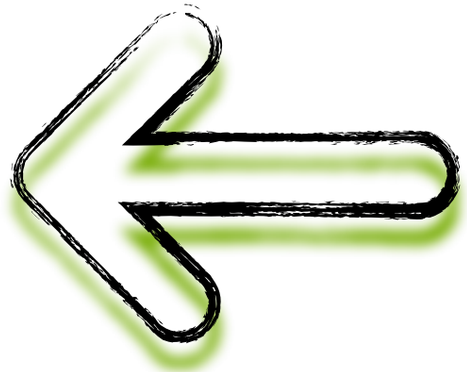


Bayesian inference

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, Pearl & Forsythe under review

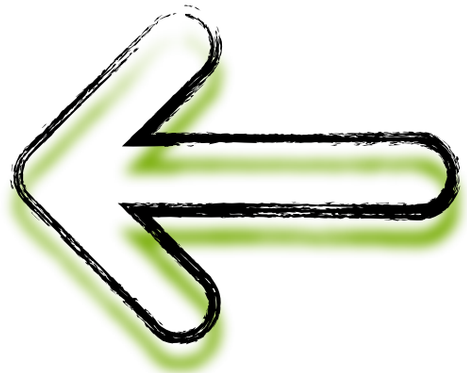
Modeling pronoun interpretation in context

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

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.

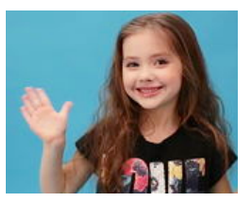
Forsythe & Pearl 2019, Pearl & Forsythe under review

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, Pearl & Forsythe under review

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 (uninformative) prior.

Forsythe & Pearl 2019, Pearl & Forsythe under review

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, Pearl & Forsythe under review

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.

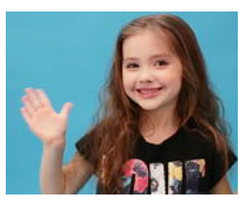
Forsythe & Pearl 2019, Pearl & Forsythe under review

Modeling pronoun interpretation in context

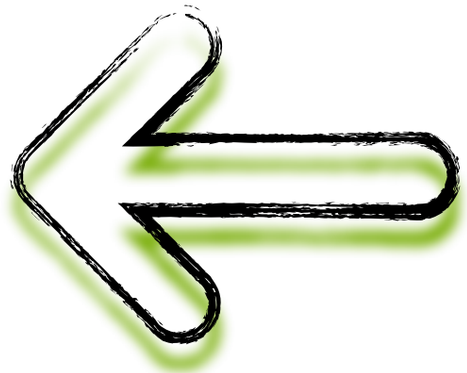
Bayesian inference

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

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.

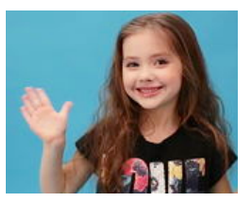
Forsythe & Pearl 2019, Pearl & Forsythe under review

Modeling pronoun interpretation in context

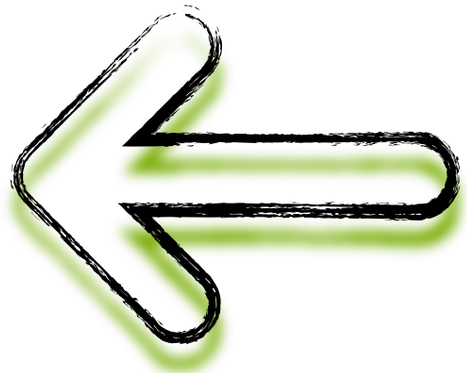
Bayesian inference

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}

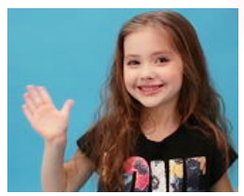
Forsythe & Pearl 2019, Pearl & Forsythe under review

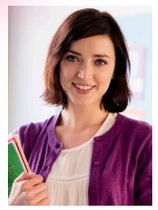
Modeling pronoun interpretation in context

Bayesian inference

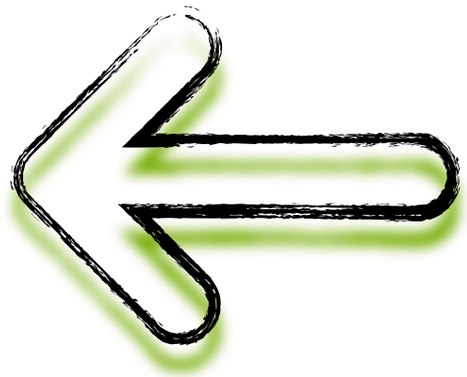
inaccurate representations p_σ

inaccurate deployment





PRONOUN



β_{form} β_{con} β_{mor} β_α

interpretation context

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

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

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

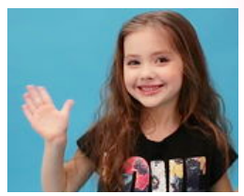
Forsythe & Pearl 2019, Pearl & Forsythe under review

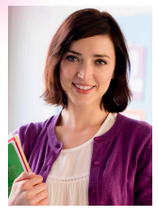
Modeling pronoun interpretation in context

Bayesian inference

inaccurate representations p_σ

inaccurate deployment



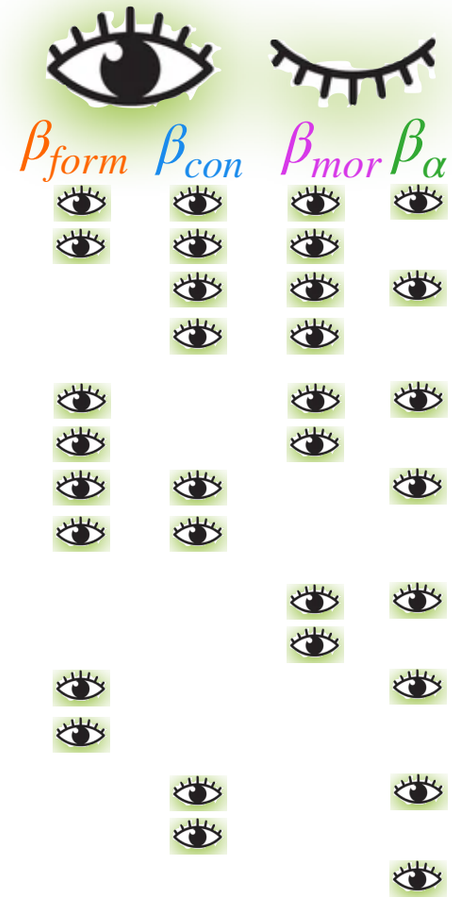


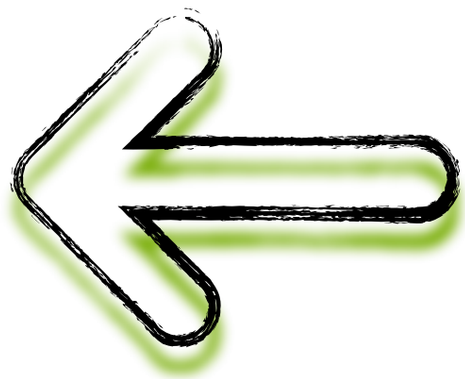
$\approx$ PRONOUN $=$

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.

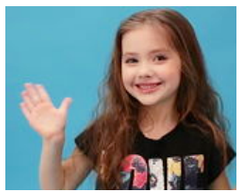
Forsythe & Pearl 2019, Pearl & Forsythe under review

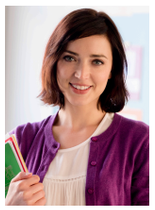
Modeling pronoun interpretation in context

Bayesian inference

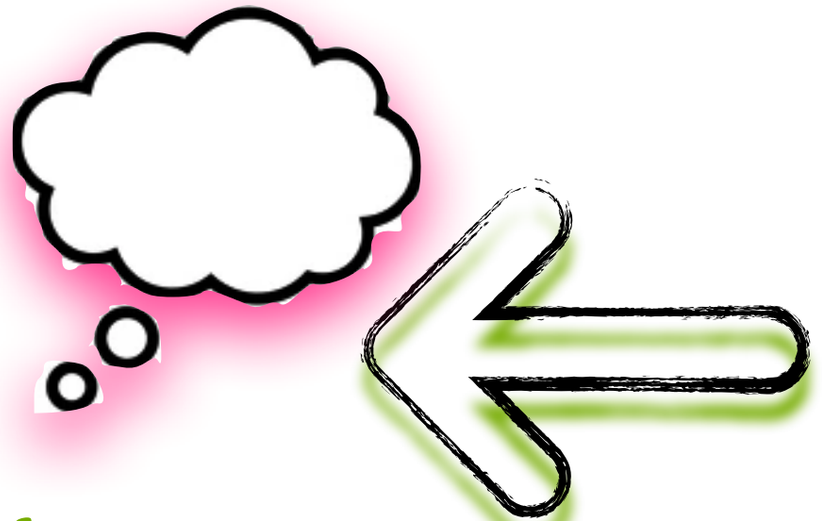
inaccurate representations p_σ

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?

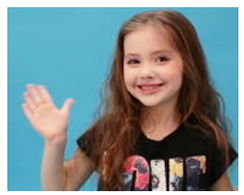
Forsythe & Pearl 2019, Pearl & Forsythe under review

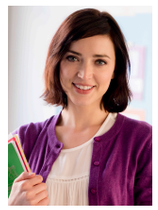
Modeling pronoun interpretation in context

Bayesian inference

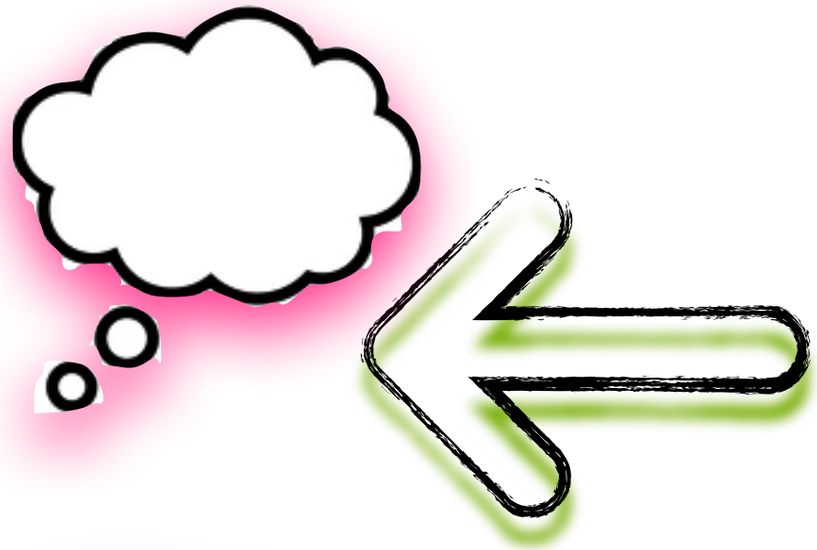
inaccurate representations p_σ

inaccurate deployment p_β





PRONOUN



inaccurate both

$p_{\sigma,\beta}$

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_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.

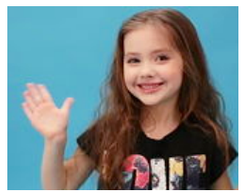
Forsythe & Pearl 2019, Pearl & Forsythe under review

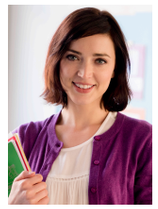
Modeling pronoun interpretation in context

Bayesian inference

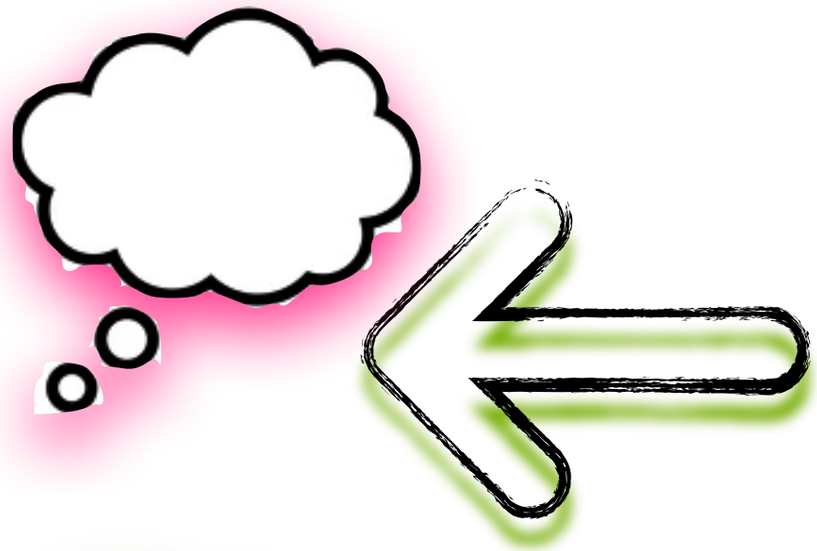
inaccurate representations p_σ

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, Pearl & Forsythe under review

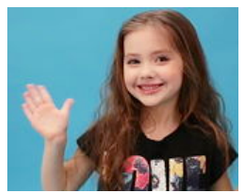
Modeling pronoun interpretation in context

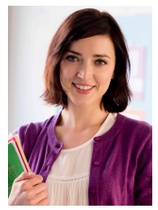
Bayesian inference

inaccurate representations p_σ

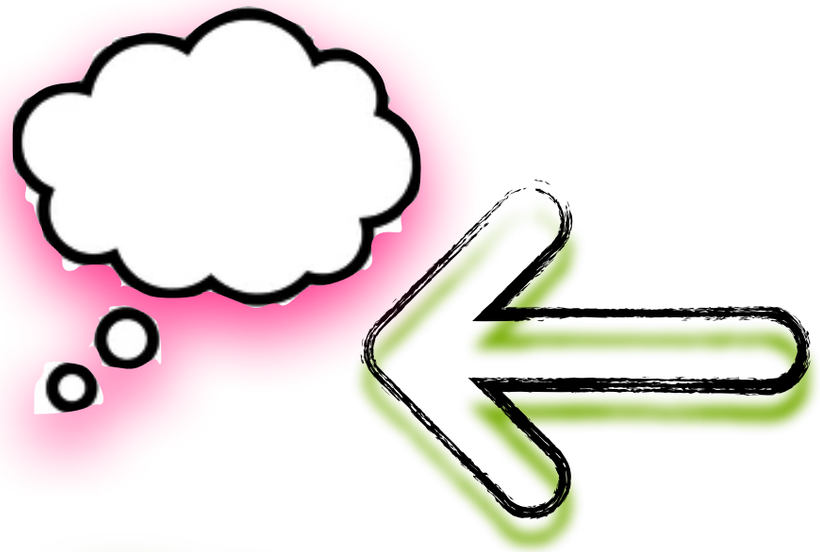
inaccurate deployment p_β

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}$$

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, Pearl & Forsythe under review

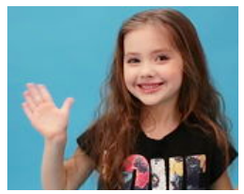
Modeling pronoun interpretation in context

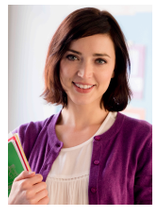
Bayesian inference

inaccurate representations p_σ

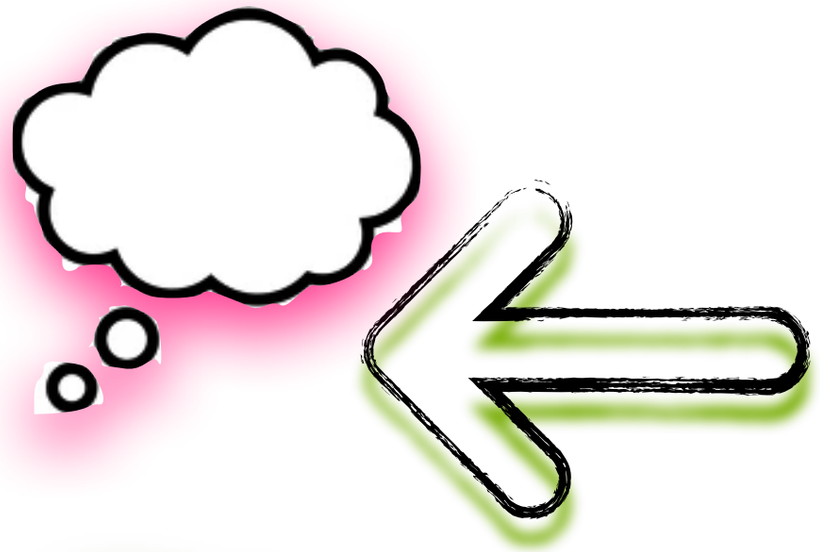
inaccurate deployment p_β

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?}) + \\
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(\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 $0.00 \leq \sigma \leq 4.00$ 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, Pearl & Forsythe under review

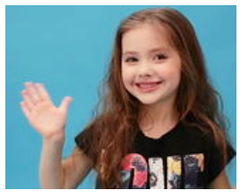
Input to the modeled listener

Bayesian inference

inaccurate representations p_σ

inaccurate deployment p_β

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



PRONOUN

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

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

Forsythe & Pearl 2019, Pearl & Forsythe under review

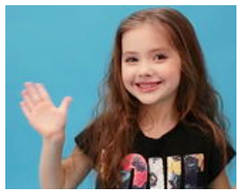
Input to the modeled listener

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, Pearl & Forsythe under review

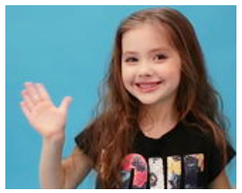
Input to the modeled listener

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
	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, Pearl & Forsythe under review

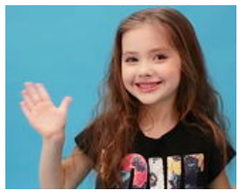
Input to the modeled listener

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
	PL	0.071	0.984	0.016	0.750	0.250	0.005	0.995
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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, Pearl & Forsythe under review

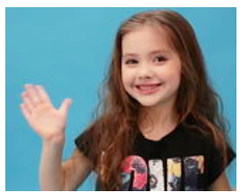
Input to the modeled listener

Bayesian inference

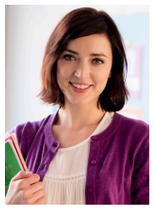
inaccurate representations p_σ

inaccurate deployment p_β

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



$\approx$



PRONOUN $=$

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

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
	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, Pearl & Forsythe under review

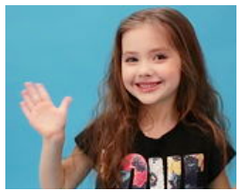
Input to the modeled listener

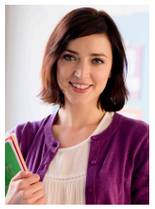
Bayesian inference

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	0.129	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, Pearl & Forsythe under review

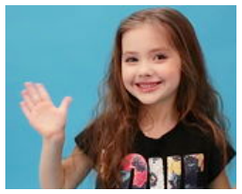
Input to the modeled listener

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, Pearl & Forsythe under review

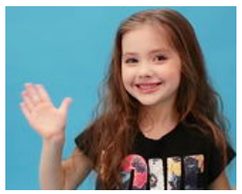
Understanding the development of pronoun interpretation

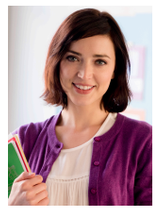
Bayesian inference

inaccurate representations p_σ

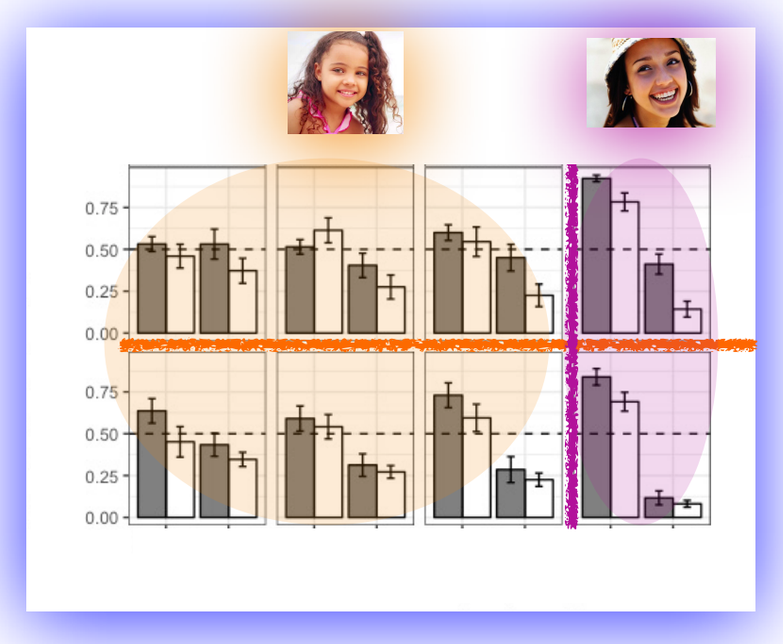
inaccurate deployment p_β

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





≈ PRONOUN =



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

Forsythe & Pearl 2019, Pearl & Forsythe under review

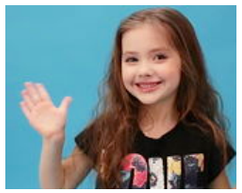
Understanding the development of pronoun interpretation

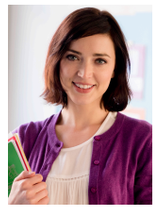
Bayesian inference

inaccurate representations p_σ

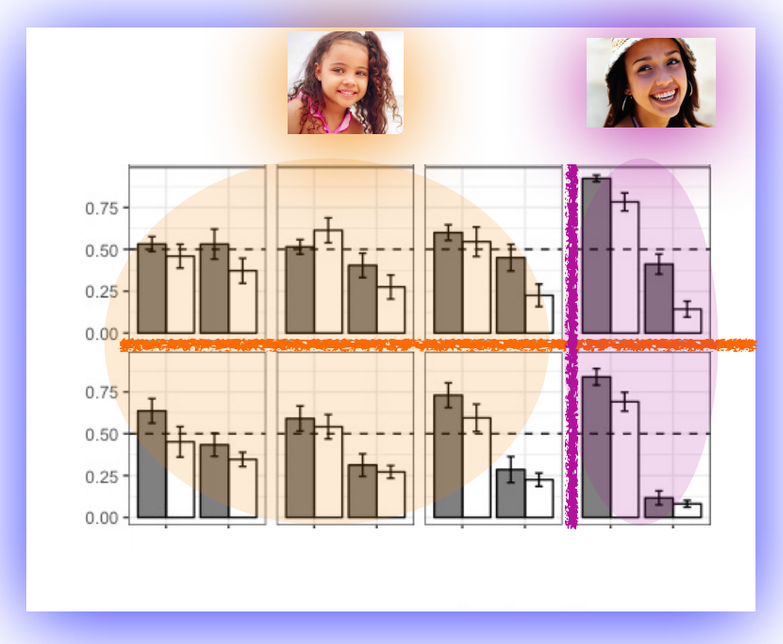
inaccurate deployment p_β

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





≈ PRONOUN =



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

Forsythe & Pearl 2019, Pearl & Forsythe under review

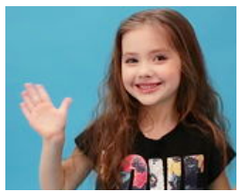
Understanding the development of pronoun interpretation

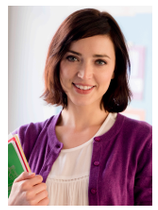
Bayesian inference

inaccurate representations p_σ

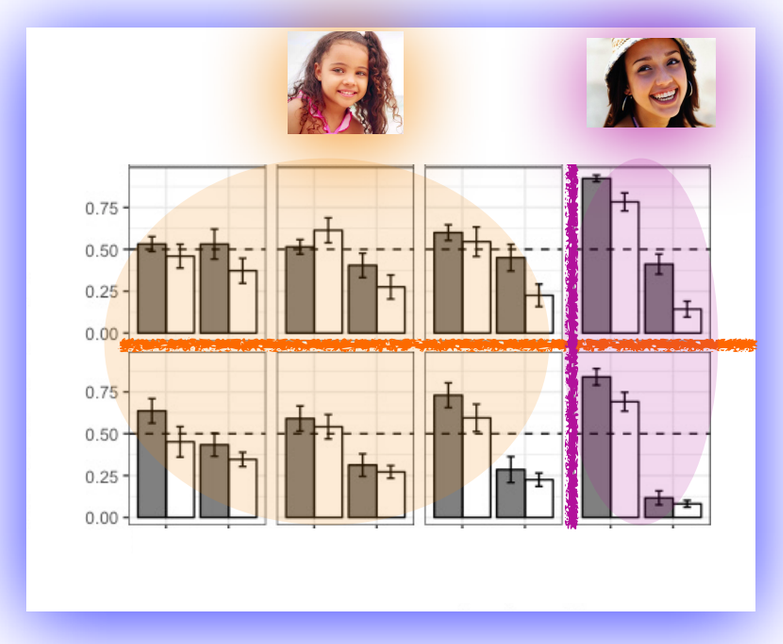
inaccurate deployment p_β

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





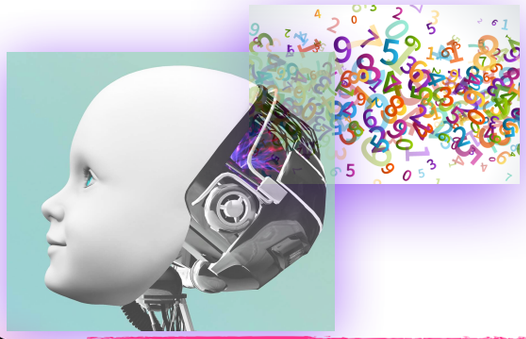
≈ PRONOUN =



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

Forsythe & Pearl 2019, Pearl & Forsythe under review

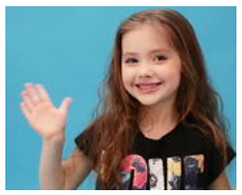
Understanding the development of pronoun interpretation

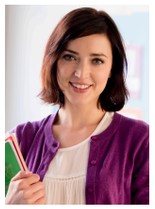


inaccurate representations p_σ

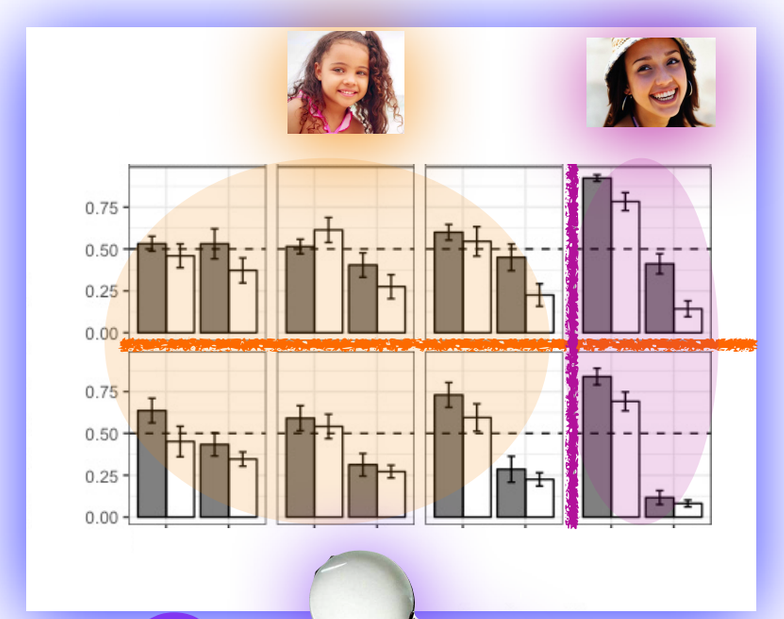
inaccurate deployment p_β

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





≈ PRONOUN =



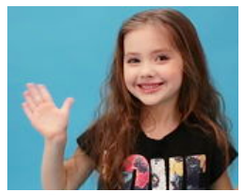
baseline: accurate representations and deployment p

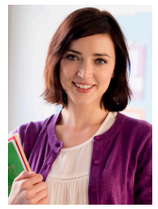
$$p(\alpha_{subj.\text{SG}}|\text{FORM}, \text{CON}, \text{MOR}) \propto p(\alpha_{subj.\text{SG}}) * p(\text{FORM}|\alpha_{subj.\text{SG}}) * p(\text{CON}|\alpha_{subj.\text{SG}}) * p(\text{MOR}|\alpha_{subj.\text{SG}})$$

0 free parameters

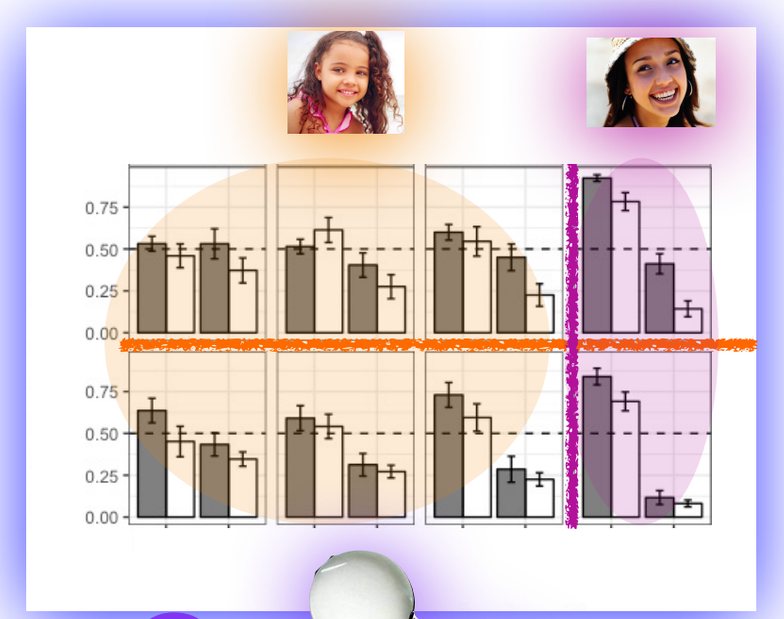
Forsythe & Pearl 2019, Pearl & Forsythe under review

Understanding the development of pronoun interpretation





≈ PRONOUN =



inaccurate deployment p_β

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

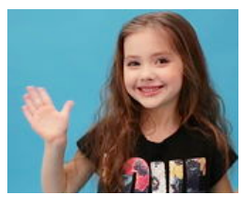
baseline: accurate representations and deployment p 0 free parameters

inaccurate representations p_σ

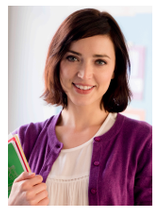
4 free parameters: σ_α, σ_{form}, σ_{con}, σ_{mor}

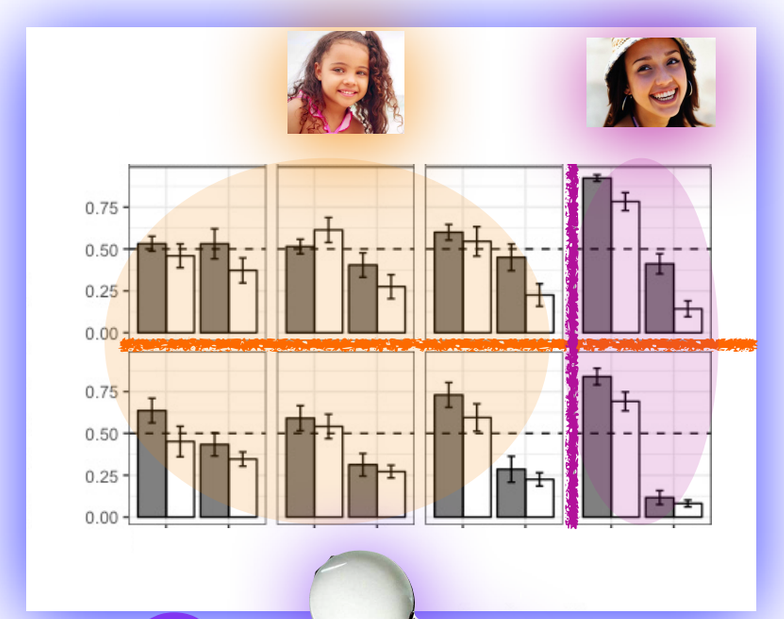
Forsythe & Pearl 2019, Pearl & Forsythe under review

Understanding the development of pronoun interpretation



≈ PRONOUN =





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

baseline: accurate representations and deployment p 0 free parameters

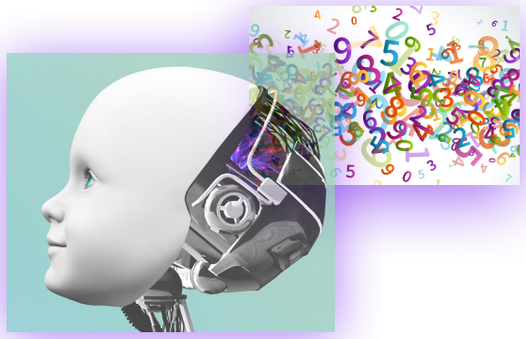
inaccurate representations p_{σ} 4 free parameters: σ_{α}, σ_{form}, σ_{con}, σ_{mor}

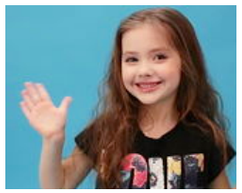
inaccurate deployment p_{β}

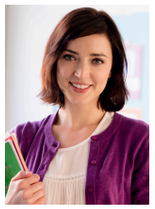
4 free parameters: β_{α}, β_{form}, β_{con}, β_{mor}

Forsythe & Pearl 2019, Pearl & Forsythe under review

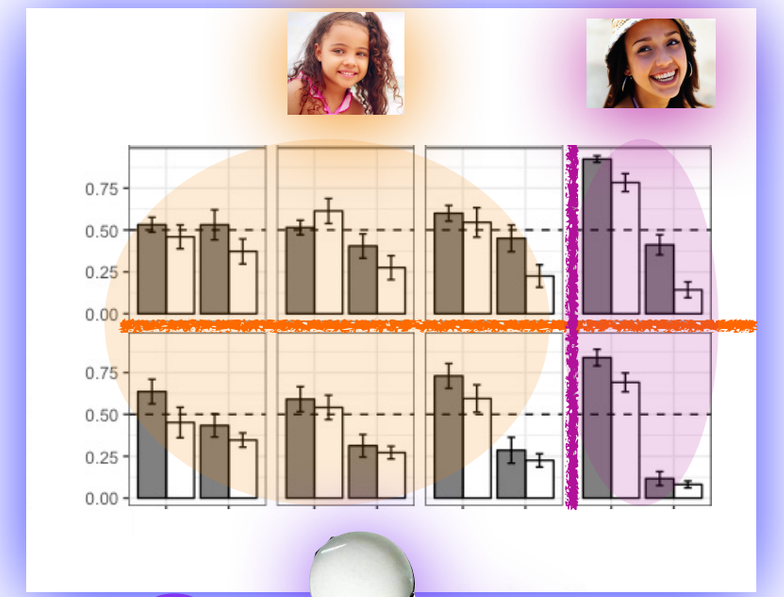
Understanding the development of pronoun interpretation







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}

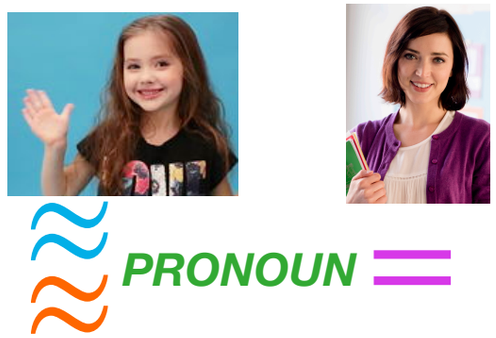
inaccurate deployment p_β 4 free parameters: β_α, β_{form}, β_{con}, β_{mor}

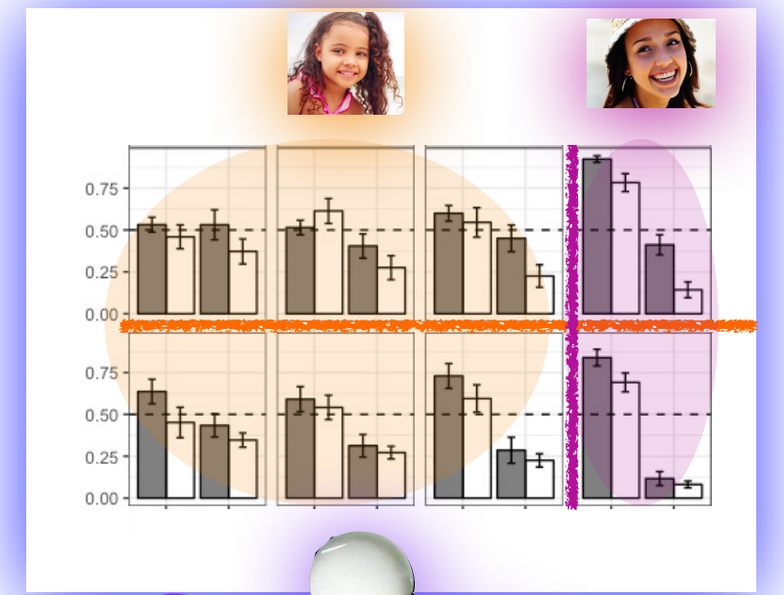
inaccurate both $p_{\sigma,\beta}$

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

Forsythe & Pearl 2019, Pearl & Forsythe under review

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

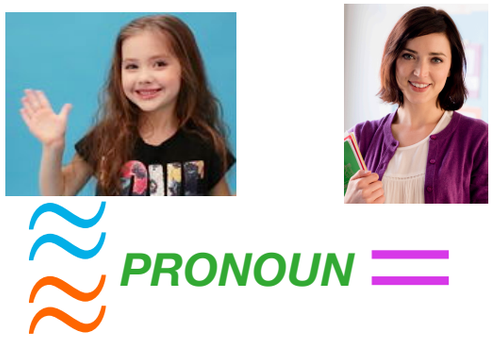
inaccurate representations p_σ 4 free parameters: σ_α, σ_{form}, σ_{con}, σ_{mor}

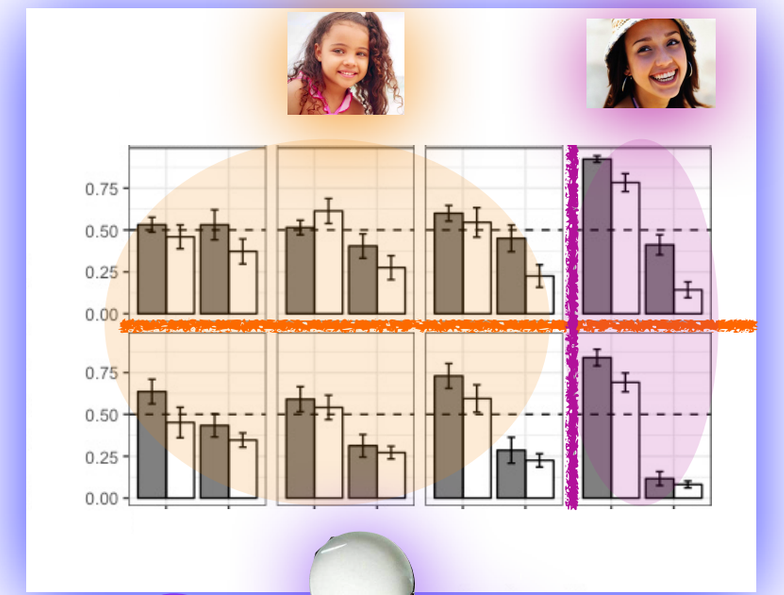
inaccurate deployment p_β 4 free parameters: β_α, β_{form}, β_{con}, β_{mor}

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, Pearl & Forsythe under review

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

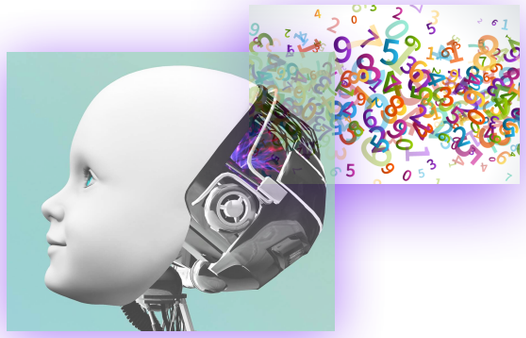
inaccurate representations p_σ 4 free parameters: σ_α, σ_{form}, σ_{con}, σ_{mor}

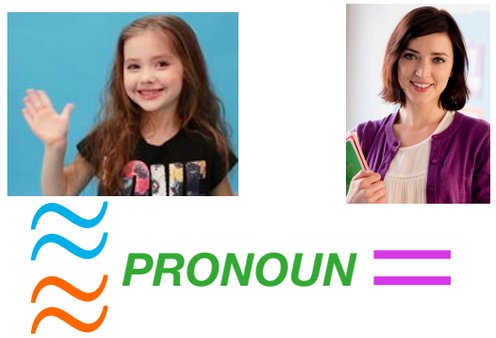
inaccurate deployment p_β 4 free parameters: β_α, β_{form}, β_{con}, β_{mor}

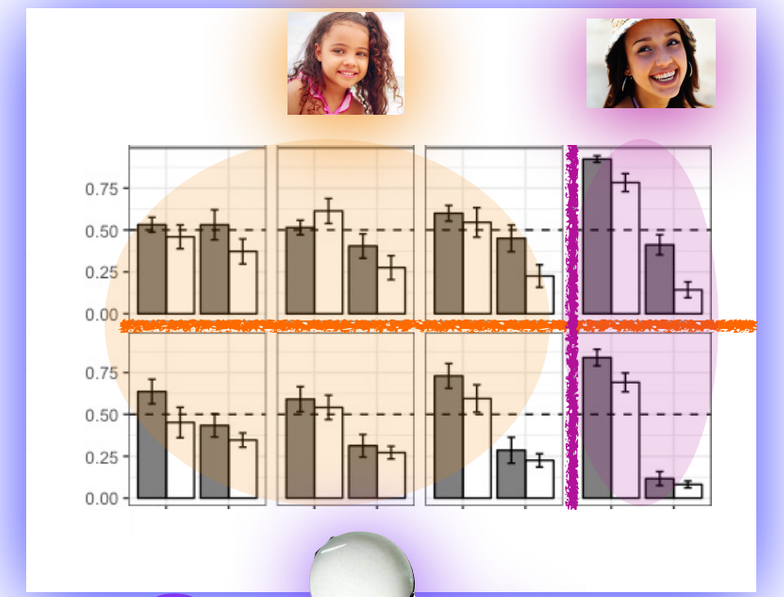
inaccurate both $p_{\sigma,\beta}$ 8 free parameters: σ_α, σ_{form}, σ_{con}, σ_{mor}, β_α, β_{form}, β_{con}, β_{mor}

Forsythe & Pearl 2019, Pearl & Forsythe under review

Understanding the development of pronoun interpretation







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

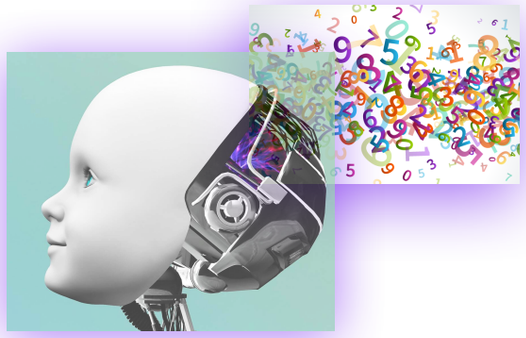
inaccurate representations p_σ 4 free parameters: σ_α, σ_{form}, σ_{con}, σ_{mor}

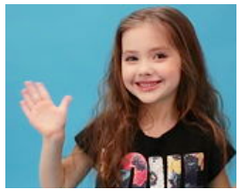
inaccurate deployment p_β 4 free parameters: β_α, β_{form}, β_{con}, β_{mor}

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

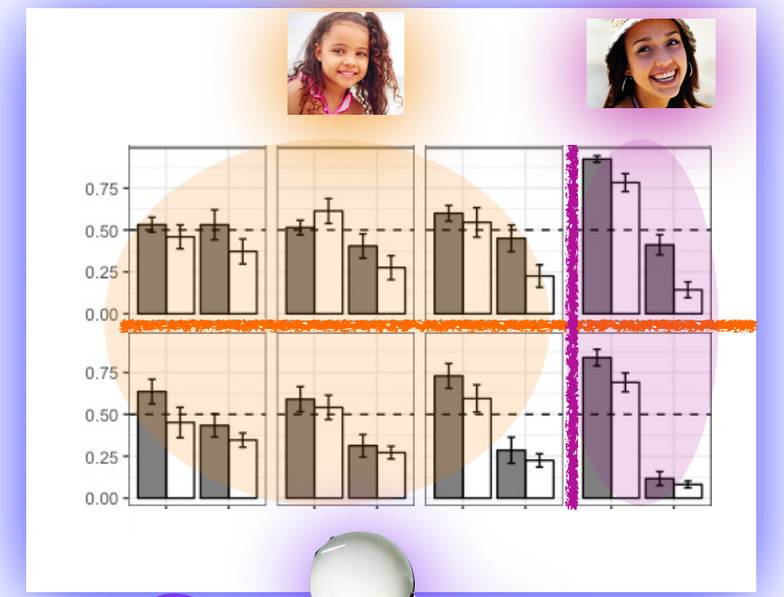
Forsythe & Pearl 2019, Pearl & Forsythe under review

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

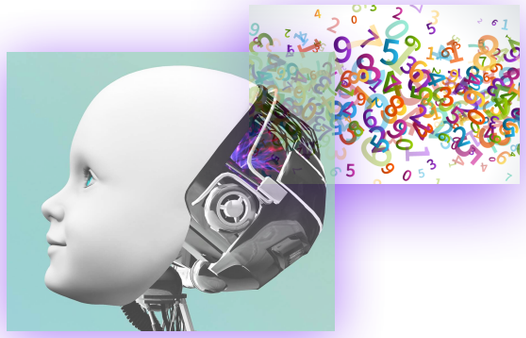
inaccurate representations p_σ 4 free parameters: σ_α, σ_{form}, σ_{con}, σ_{mor}

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

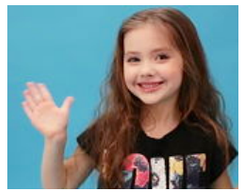
inaccurate both $p_{\sigma,\beta}$ 8 free parameters: σ_α, σ_{form}, σ_{con}, σ_{mor}, β_α, β_{form}, β_{con}, β_{mor}

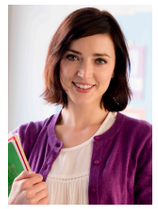
Forsythe & Pearl 2019, Pearl & Forsythe under review

Understanding the development of pronoun interpretation

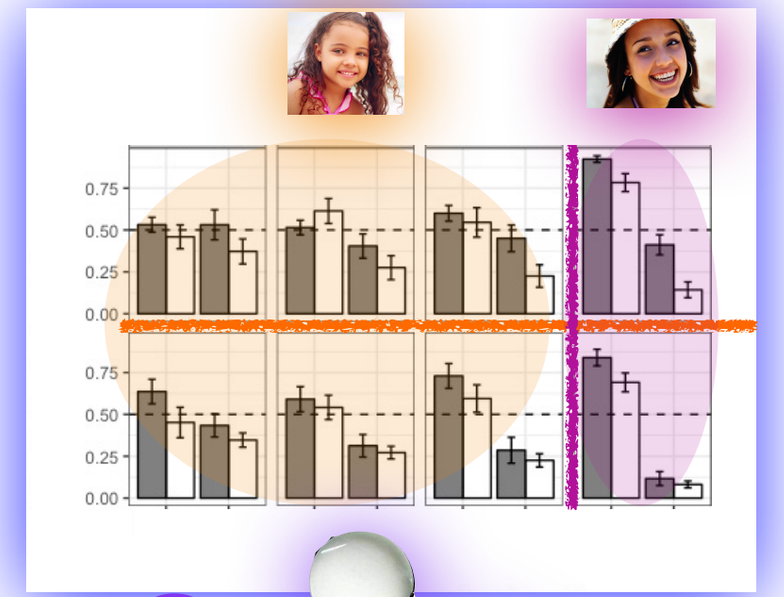


model fit = likelihood of data, given model with best-fitting parameter values





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

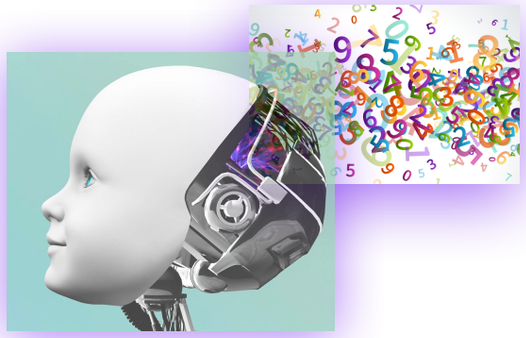
inaccurate representations p_{σ} 4 free parameters: σ_{α}, σ_{form}, σ_{con}, σ_{mor}

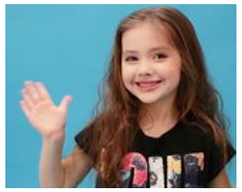
inaccurate deployment p_{β} 4 free parameters: β_{α}, β_{form}, β_{con}, β_{mor}

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, Pearl & Forsythe under review

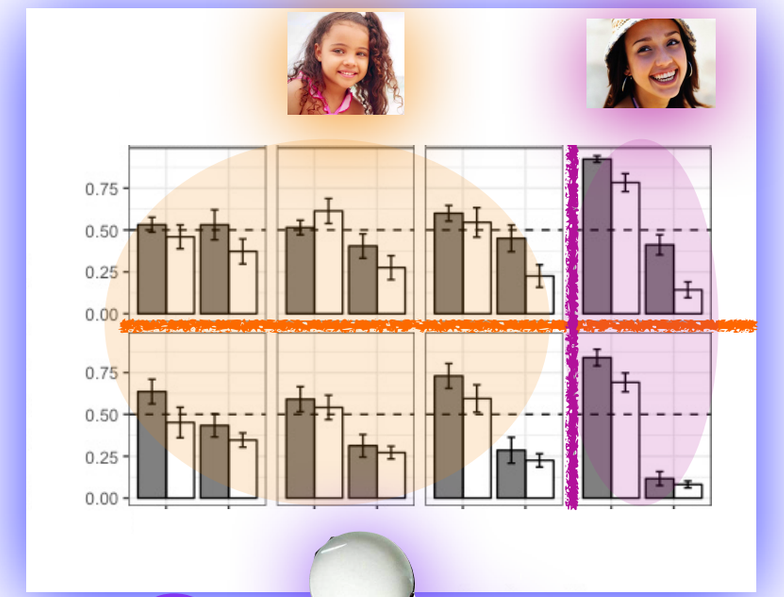
Understanding the development of pronoun interpretation





$-\infty \leq \log(\text{likelihood}) \leq 0$, 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

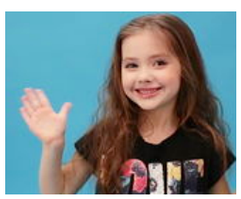
inaccurate representations p_σ 4 free parameters: σ_α, σ_{form}, σ_{con}, σ_{mor}

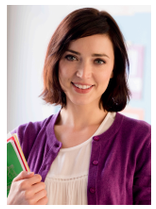
inaccurate deployment p_β 4 free parameters: β_α, β_{form}, β_{con}, β_{mor}

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

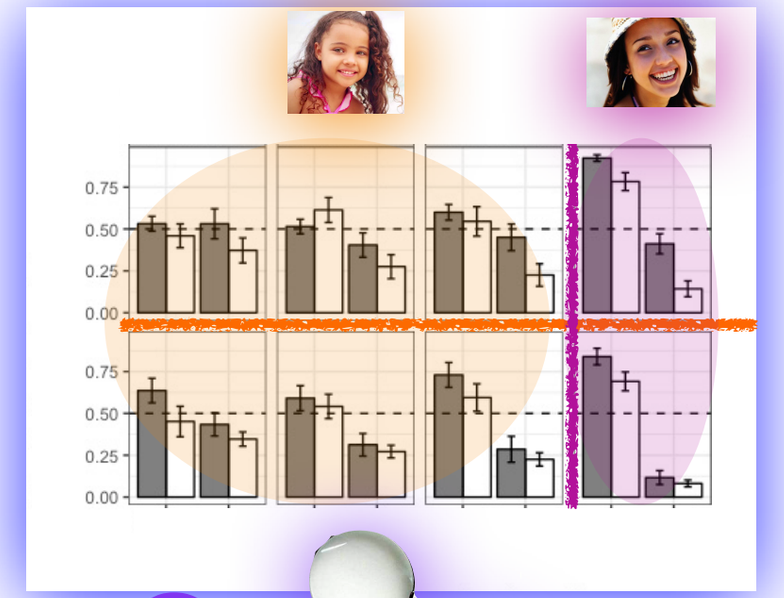
Forsythe & Pearl 2019, Pearl & Forsythe under review

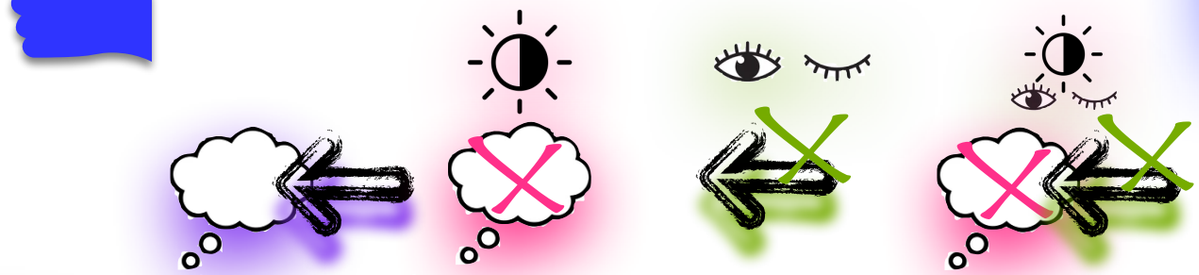
Understanding the development of pronoun interpretation





≈≈ PRONOUN =



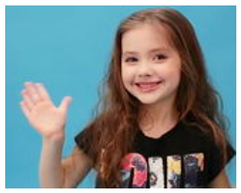


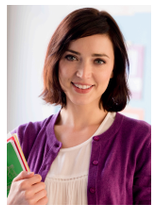
age	baseline	inacc rep	inacc deploy	both inacc
≤ 3				
4				
≥ 5				
adults				

0 ≤ BIC ≤ ∞ (closer to 0 is better)

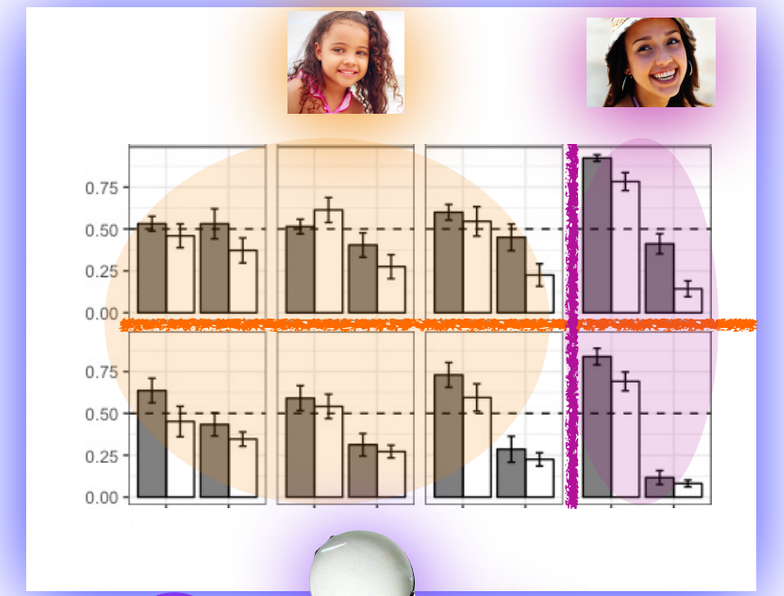
Forsythe & Pearl 2019, Pearl & Forsythe under review

Understanding the development of pronoun interpretation

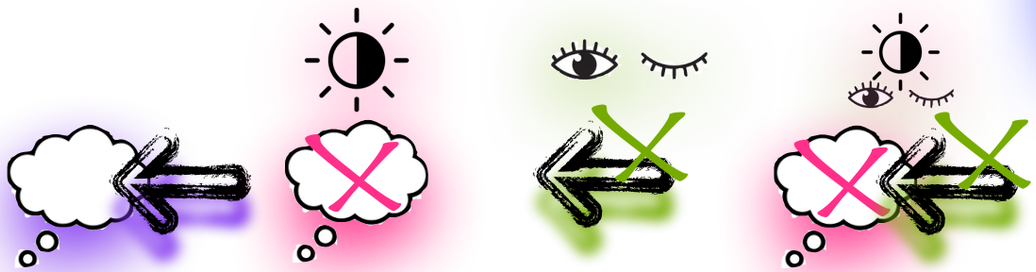




≈≈ PRONOUN =



0 ≤ BIC ≤ ∞ (closer to 0 is better)



age	baseline	inacc rep	inacc deploy	both inacc
≤ 3	2913.00	**735.99**	**735.17**	758.11
4				
≥ 5				
adults				

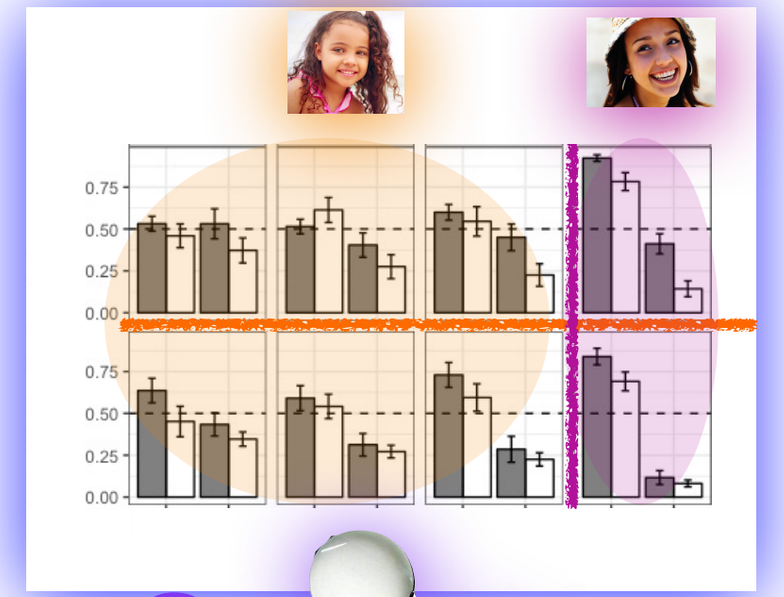
Kass & Raferty 1995: BIC scores within 2.0 are equivalent

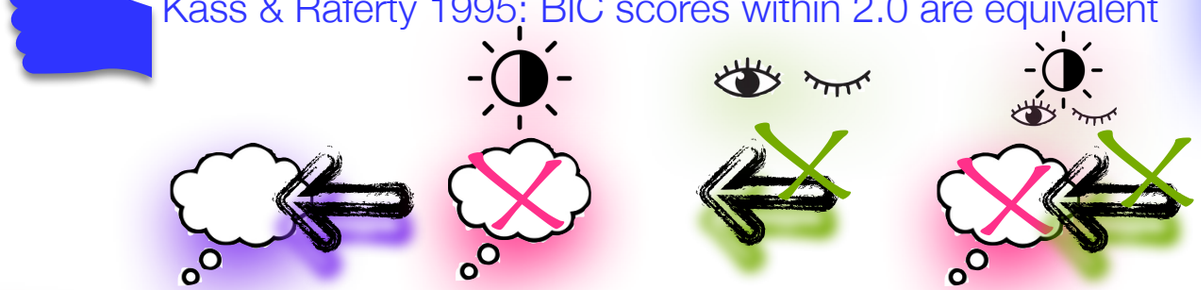
3-year-old pronoun interpretation behavior is best captured by children having inaccurate representations, or inaccurate deployment, but not both inaccurate representations and inaccurate deployment of those representations.

Forsythe & Pearl 2019, Pearl & Forsythe under review

Understanding the development of pronoun interpretation

≈ PRONOUN =





0 ≤ BIC ≤ ∞ (closer to 0 is better)

Kass & Raferty 1995: BIC scores within 2.0 are equivalent

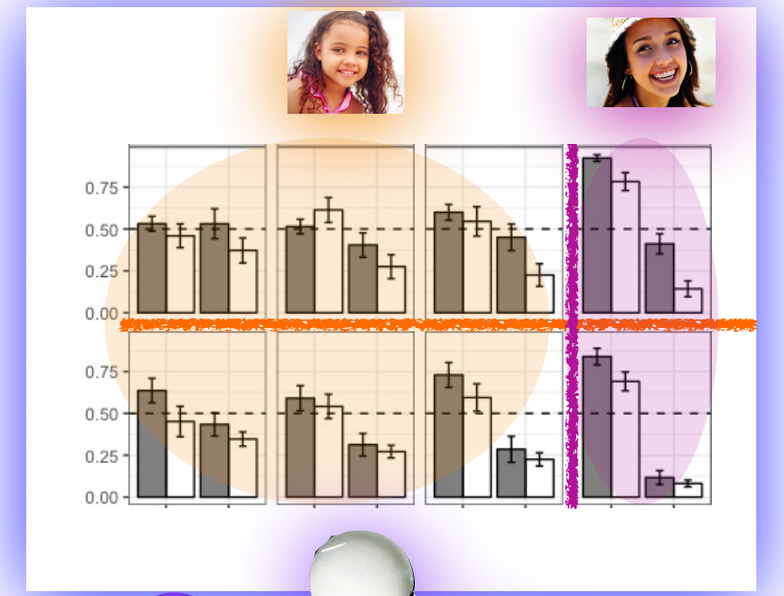
age	baseline	inacc rep	inacc deploy	both inacc
≤ 3	2913.00	**735.99**	**735.17**	758.11
4				
≥ 5				
adults				

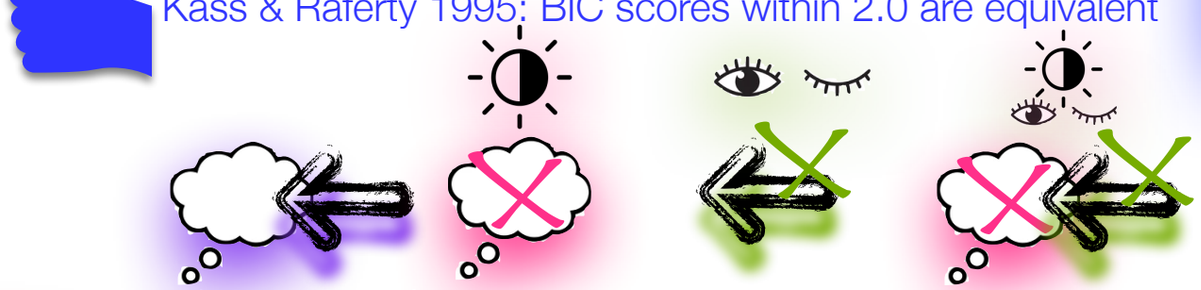
…though all 3 inaccurate variants are far better than the baseline of both accurate representations and accurate deployment.

Forsythe & Pearl 2019, Pearl & Forsythe under review

Understanding the development of pronoun interpretation

≈ PRONOUN =





0 ≤ BIC ≤ ∞ (closer to 0 is better)

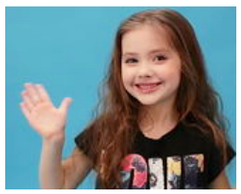
Kass & Raferty 1995: BIC scores within 2.0 are equivalent

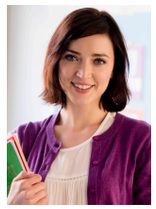
age	baseline	inacc rep	inacc deploy	both inacc
≤ 3	2913.00	**735.99**	**735.17**	758.11
4	2784.61	**752.89**	**754.06**	773.65
≥ 5	1931.33	**590.04**	**590.70**	607.12
adults				

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

Forsythe & Pearl 2019, Pearl & Forsythe under review

Understanding the development of pronoun interpretation





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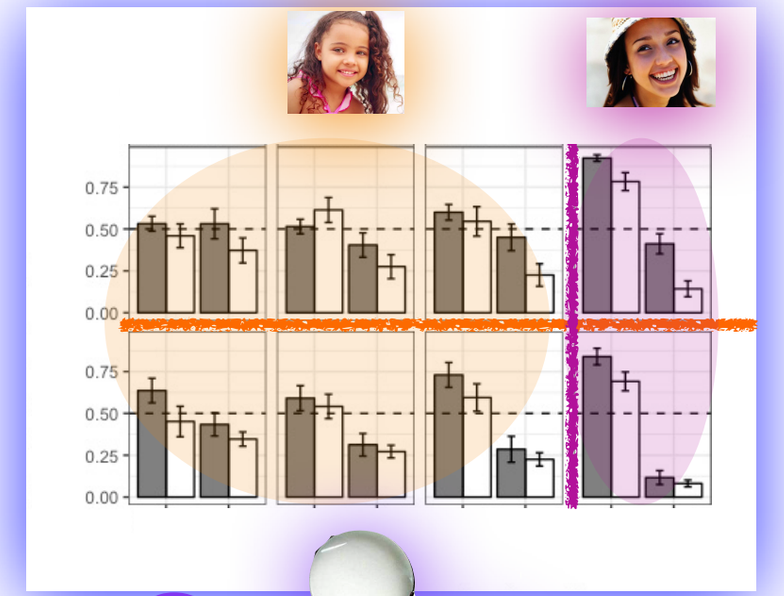
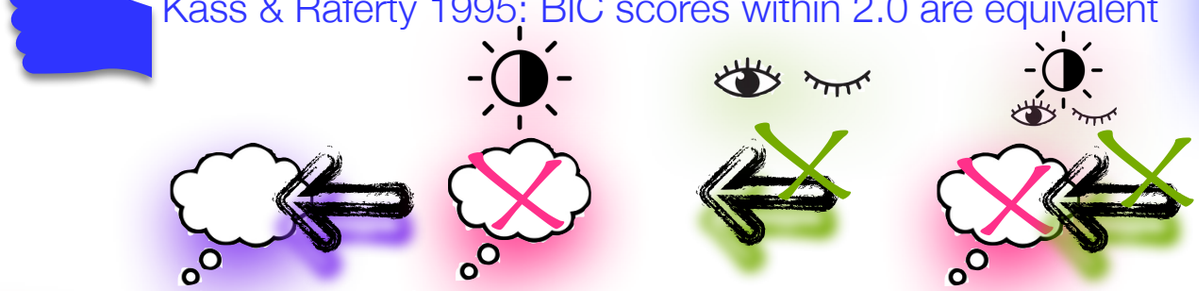




0 ≤ BIC ≤ ∞ (closer to 0 is better)

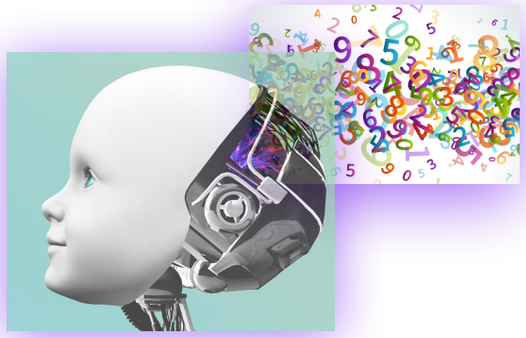
Kass & Raferty 1995: BIC scores within 2.0 are equivalent

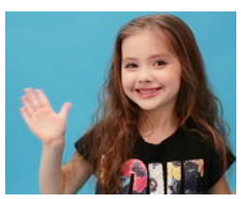
age	baseline	inacc rep	inacc deploy	both inacc
≤ 3	2913.00	**735.99**	**735.17**	758.11
4	2784.61	**752.89**	**754.06**	773.65
≥ 5	1931.33	**590.04**	**590.70**	607.12
adults	1323.82	**642.48**	646.96	668.58

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

Forsythe & Pearl 2019, Pearl & Forsythe under review

Understanding the development of pronoun interpretation





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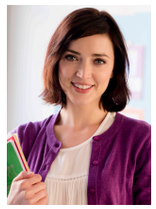

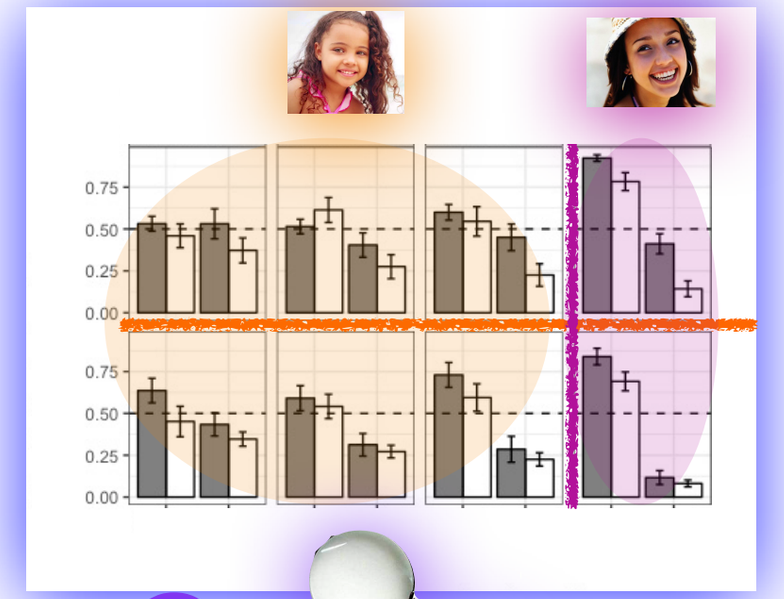

$0 \leq BIC \leq \infty$ (closer to 0 is better)

Kass & Raferty 1995: BIC scores within 2.0 are equivalent

age	baseline	inacc rep	inacc deploy	both inacc
≤ 3	2913.00	**735.99**	**735.17**	758.11
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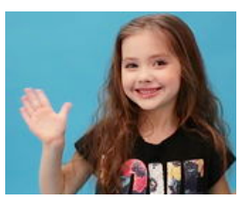
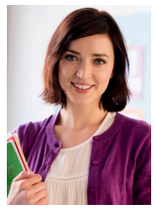
≥ 5	1931.33	**590.04**	**590.70**	607.12
adults	1323.82	**642.48**	646.96	668.58

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

Forsythe & Pearl 2019, Pearl & Forsythe under review

Understanding the development of pronoun interpretation





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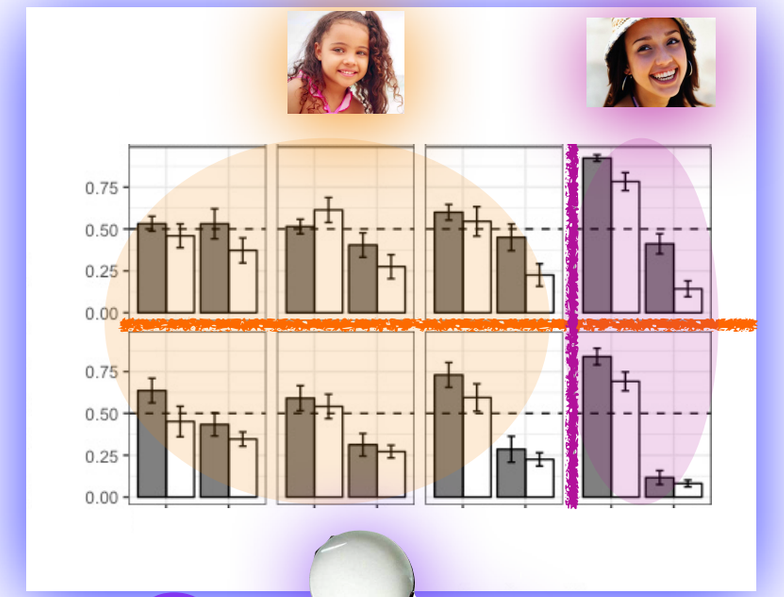
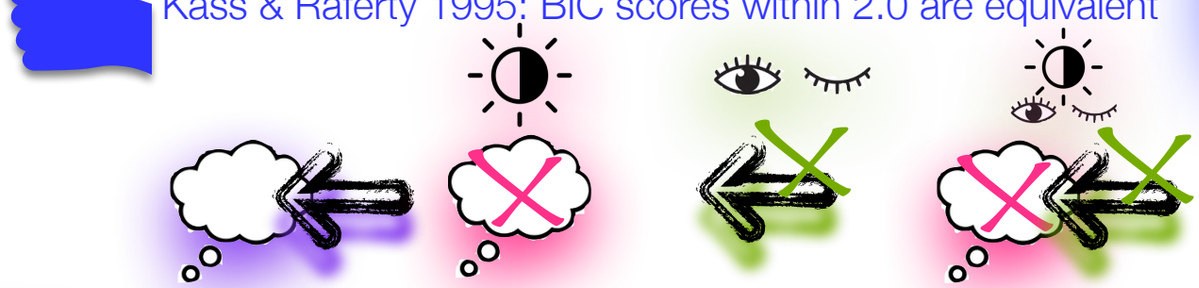




0 ≤ BIC ≤ ∞ (closer to 0 is better)

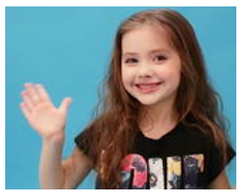
Kass & Raferty 1995: BIC scores within 2.0 are equivalent

age	baseline	inacc rep	inacc deploy	both inacc
≤ 3	2913.00	**735.99**	**735.17**	758.11
4	2784.61	**752.89**	**754.06**	773.65
≥ 5	1931.33	**590.04**	**590.70**	607.12
adults	1323.82	**642.48**	646.96	668.58

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

Forsythe & Pearl 2019, Pearl & Forsythe under review

Understanding the development of pronoun interpretation



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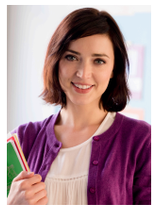

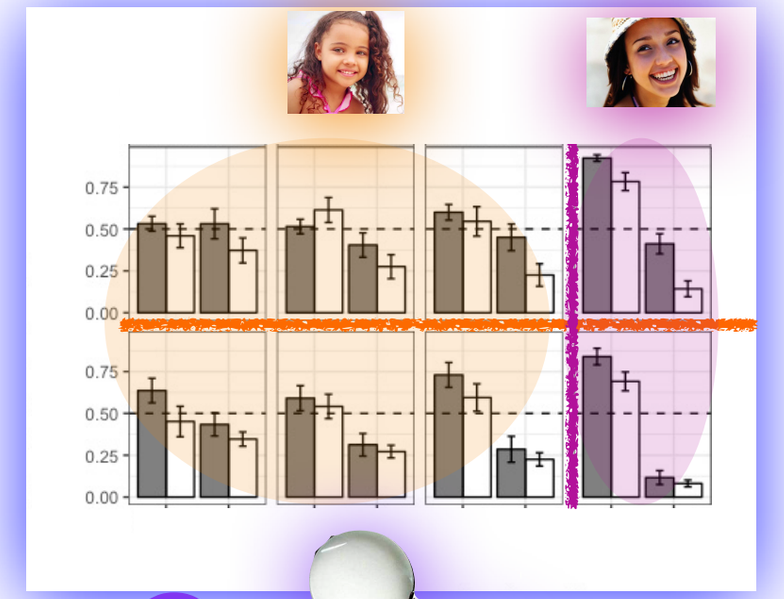

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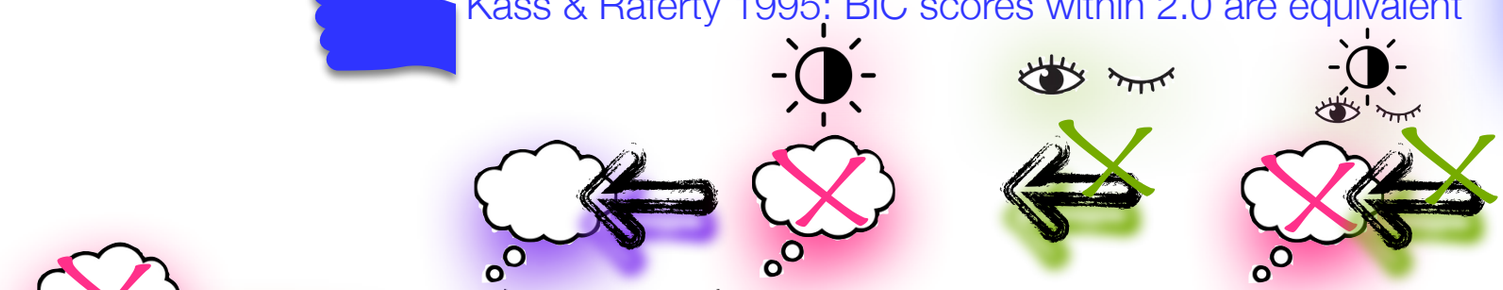

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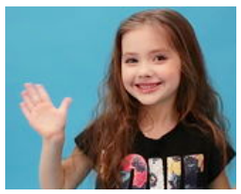
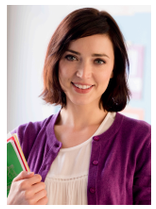
adults	1323.82	**642.48**	646.96	668.58

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

Forsythe & Pearl 2019, Pearl & Forsythe under review

Understanding the development of pronoun interpretation





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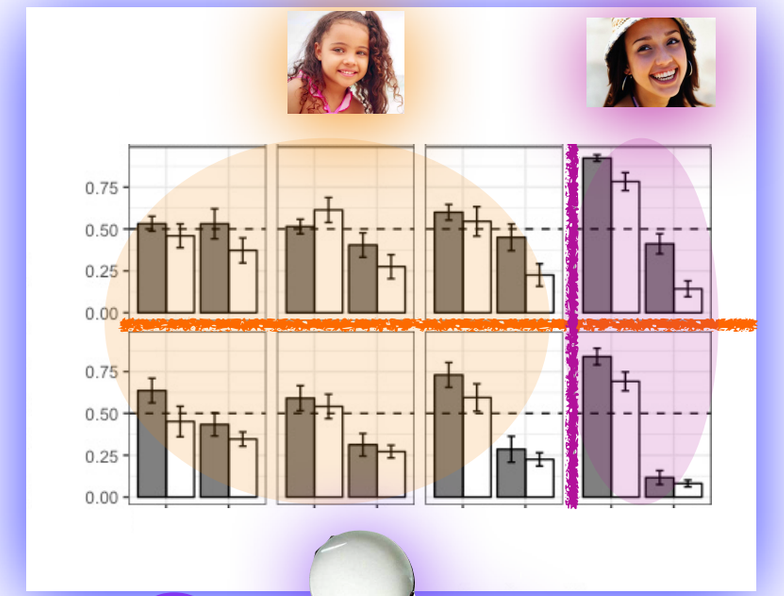

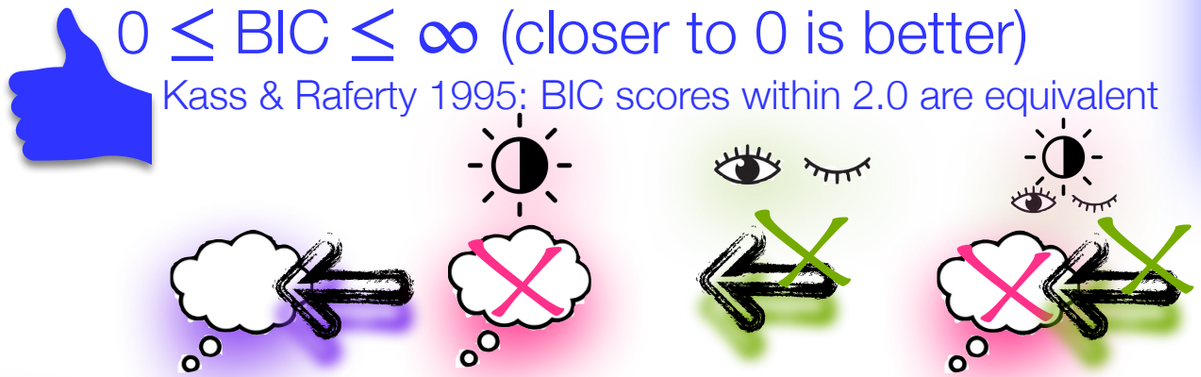

0 ≤ BIC ≤ ∞ (closer to 0 is better)

Kass & Raferty 1995: BIC scores within 2.0 are equivalent

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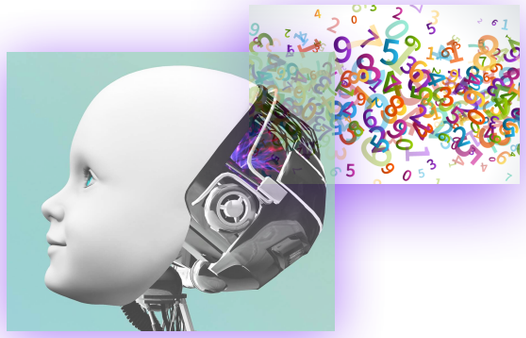
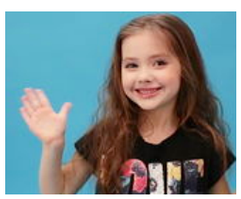
adults	1323.82	**642.48**	646.96	668.58

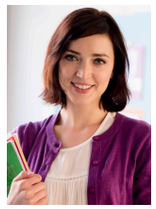
Becoming adult-like doesn't mean becoming accurate!

Forsythe & Pearl 2019, Pearl & Forsythe under review

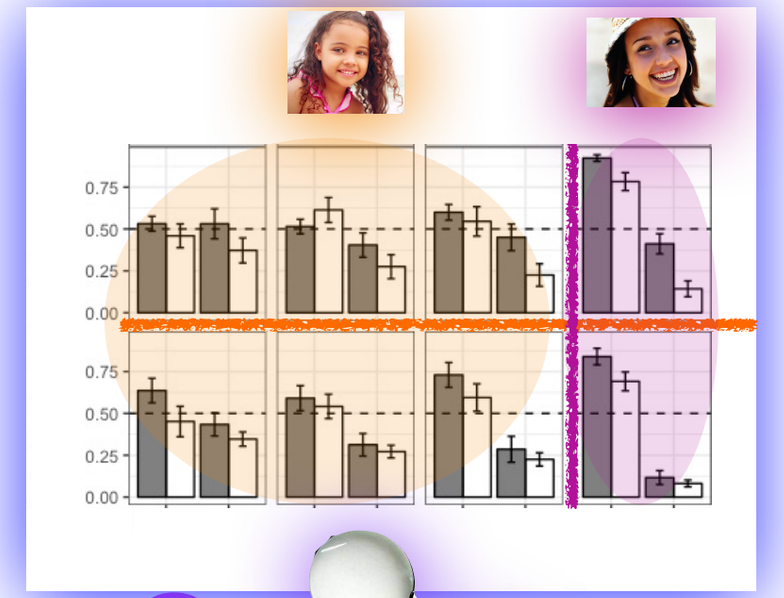
Understanding the development of pronoun interpretation

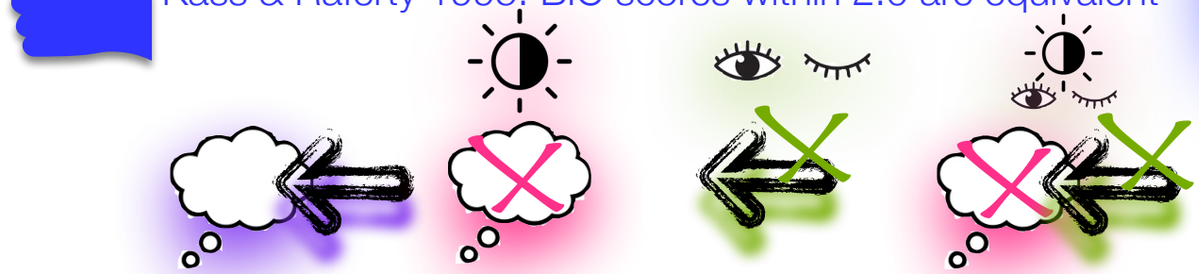






≈ PRONOUN =





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

Kass & Raferty 1995: BIC scores within 2.0 are equivalent

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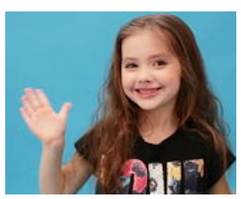
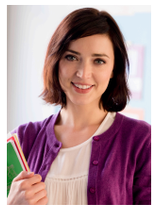
But what does it mean?

It means learning to become inaccurate in adult-like ways.

Forsythe & Pearl 2019, Pearl & Forsythe under review

Understanding the development of pronoun interpretation





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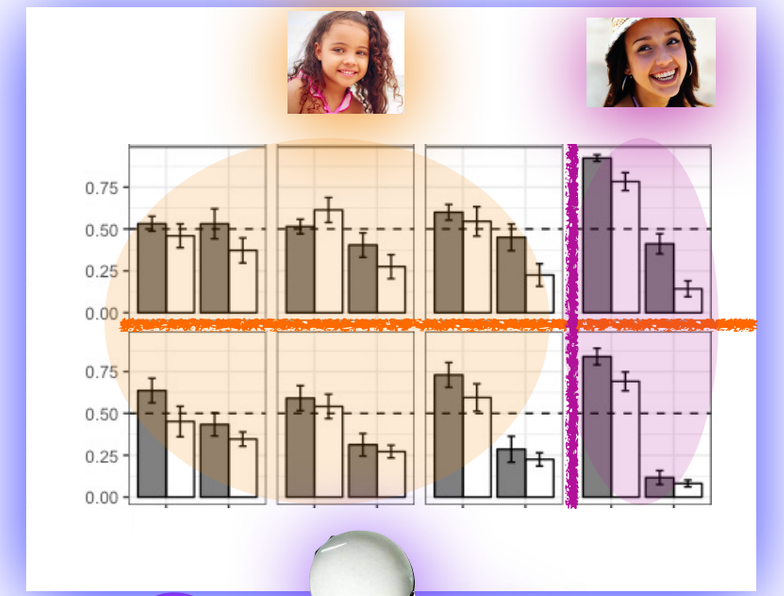

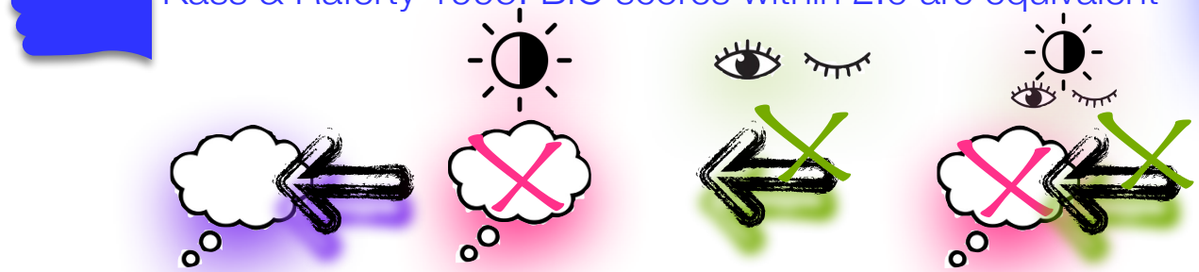

0 ≤ BIC ≤ ∞ (closer to 0 is better)

Kass & Raferty 1995: BIC scores within 2.0 are equivalent

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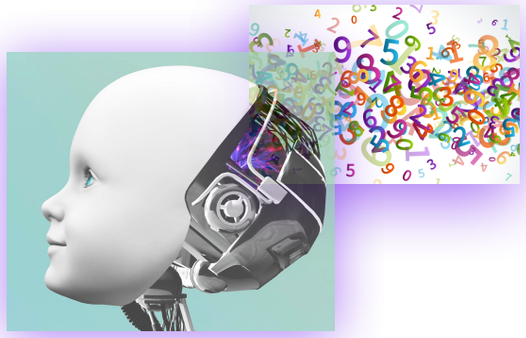
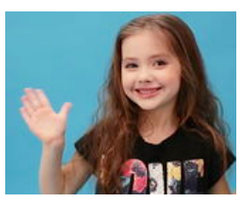
≤ 3	2913.00	**735.99**	**735.17**	758.11
4	2784.61	**752.89**	**754.06**	773.65
≥ 5	1931.33	**590.04**	**590.70**	607.12
adults	1323.82	**642.48**	646.96	668.58

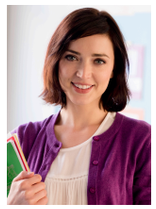
We know that adults inaccurately represent the available information.

Forsythe & Pearl 2019, Pearl & Forsythe under review

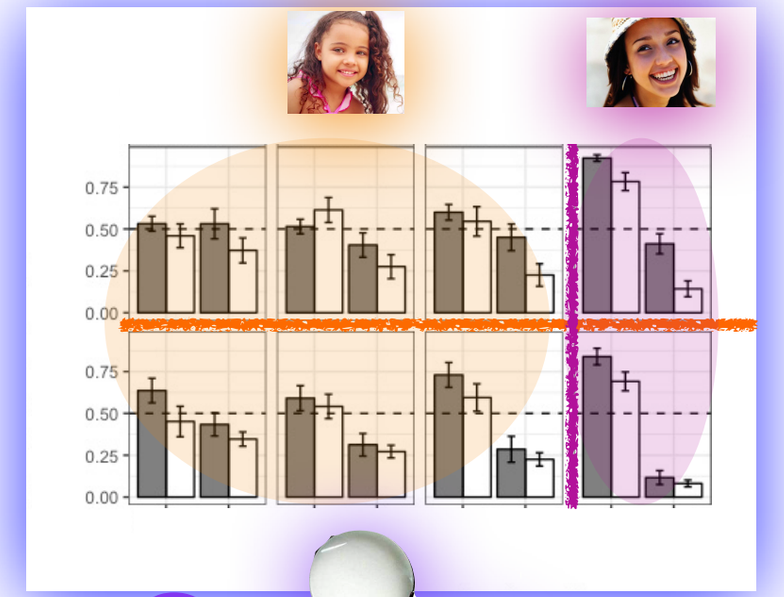
Understanding the development of pronoun interpretation

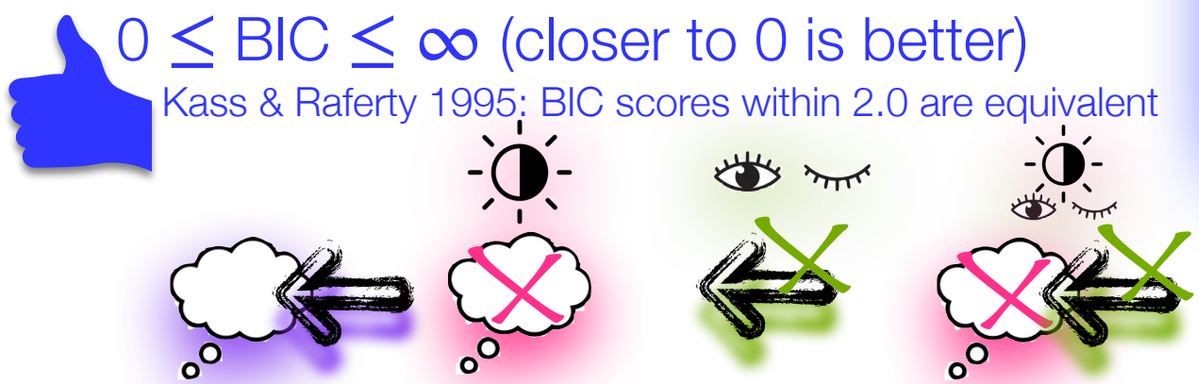






≈ PRONOUN =





0 ≤ BIC ≤ ∞ (closer to 0 is better)

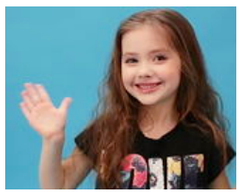
Kass & Raferty 1995: BIC scores within 2.0 are equivalent

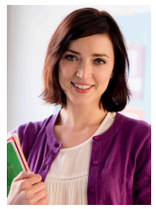
age	baseline	inacc rep	inacc deploy	both inacc
≤ 3	2913.00	**735.99**	**735.17**	758.11
4	2784.61	**752.89**	**754.06**	773.65
≥ 5	1931.33	**590.04**	**590.70**	607.12
adults	1323.82	**642.48**	646.96	668.58

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

Forsythe & Pearl 2019, Pearl & Forsythe under review

Understanding the development of pronoun interpretation





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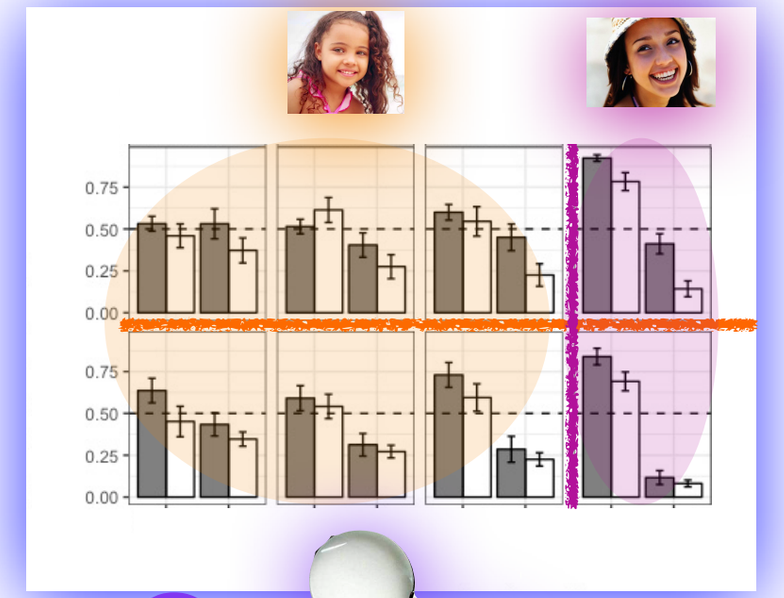

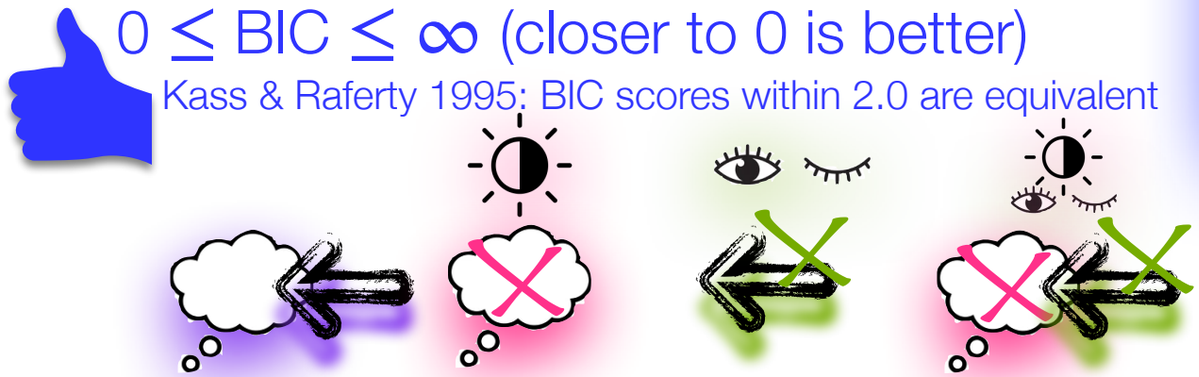

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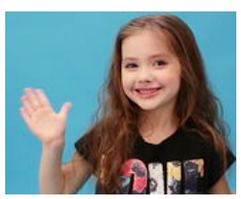
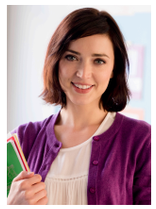
Development: How do these σ values compare to those that the best-fitting child model used that relied on inaccurate representations?

Forsythe & Pearl 2019, Pearl & Forsythe under review

Understanding the development of pronoun interpretation





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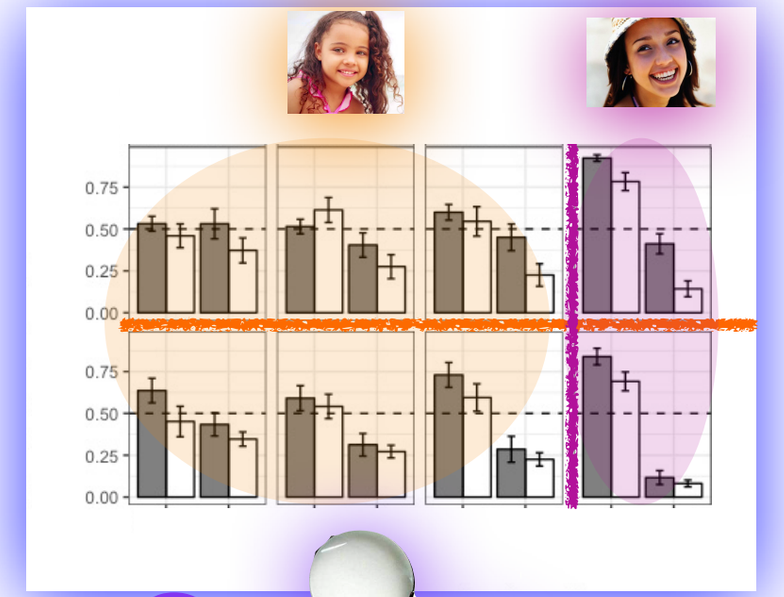

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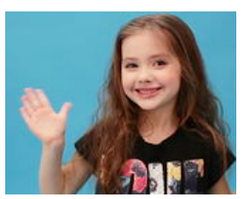
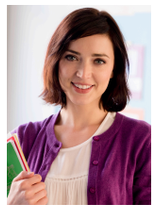
We know that adults accurately deploy their representations.

Forsythe & Pearl 2019, Pearl & Forsythe under review

Understanding the development of pronoun interpretation





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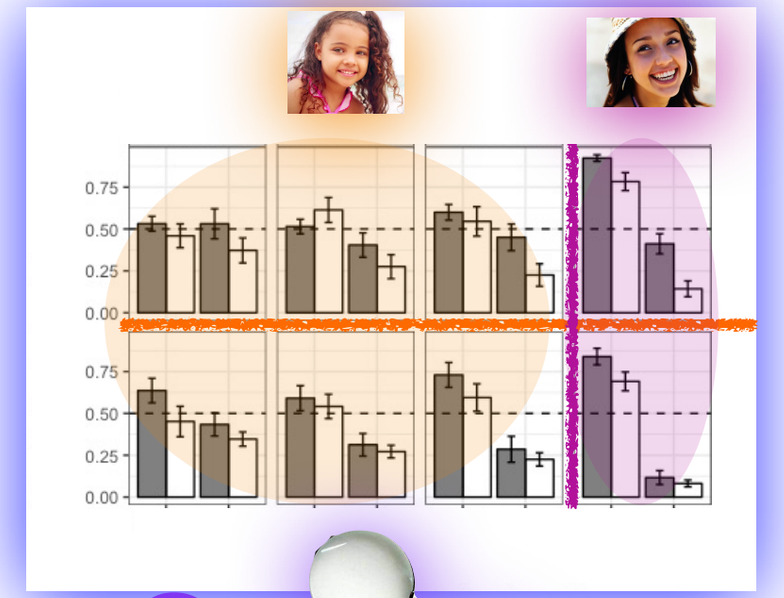

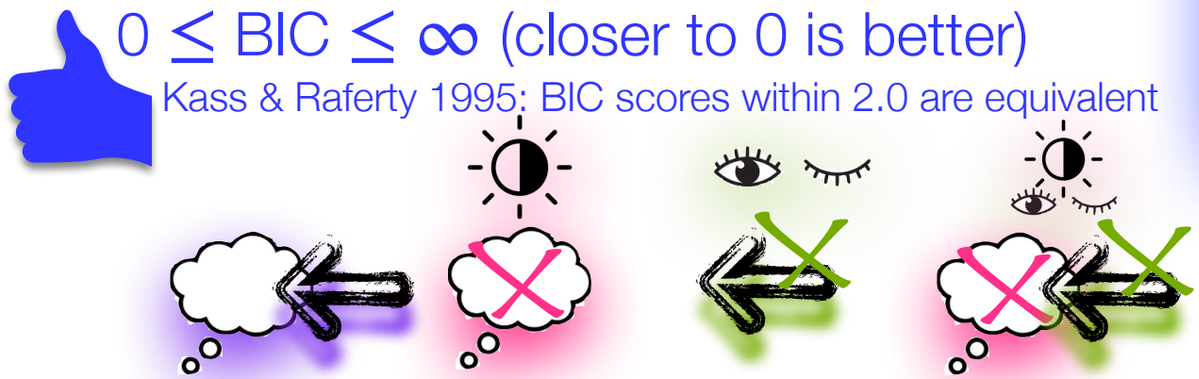

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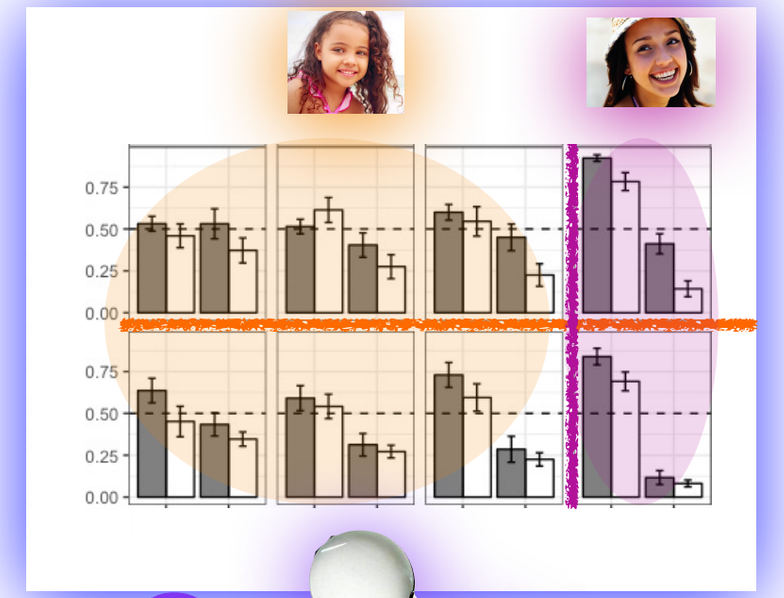
Development: How much <1 are the β values that the best-fitting child model used that relied on inaccurate deployment?

Forsythe & Pearl 2019, Pearl & Forsythe under review

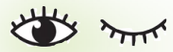
Understanding the development of pronoun interpretation

≈≈ PRONOUN =



$0.00 \leq \sigma \leq 4.00$

$0 \leq \beta \leq 1$

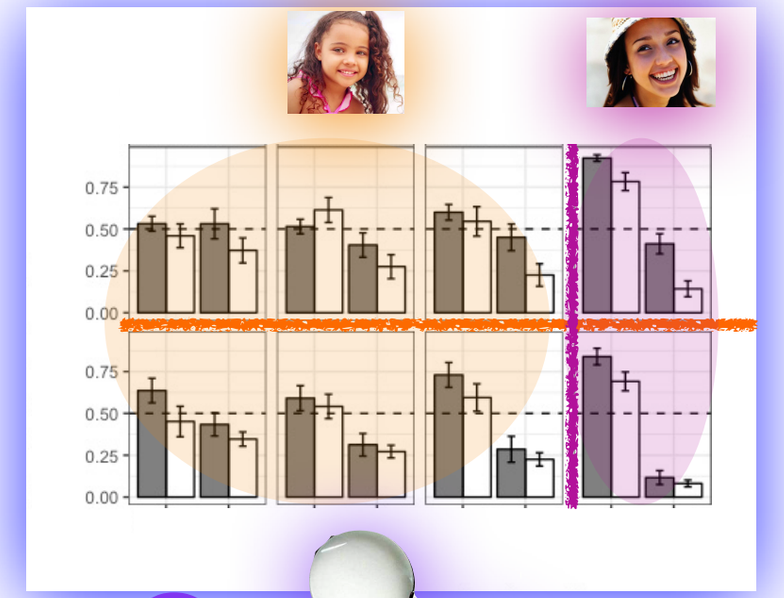


σ_{for}	σ_{con}	σ_{mor}	σ_{α}	β_{for}	β_{con}	β_{mor}	β_{α}
children: inaccurate representations							
≤3							
4							
≥5							
children: inaccurate deployment							
≤3							
4							
≥5							
adults: inaccurate representations							
adults							

Forsythe & Pearl 2019, Pearl & Forsythe under review

Understanding the development of pronoun interpretation

≈≈ PRONOUN =



$0.00 \leq \sigma \leq 4.00$

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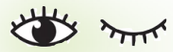


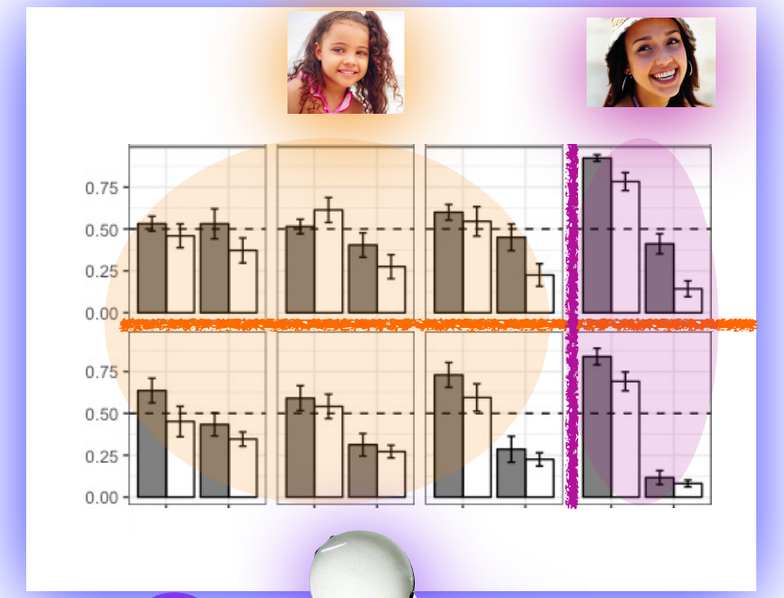
	σ_{for}	σ_{con}	σ_{mor}	σ_{α}	β_{for}	β_{con}	β_{mor}	β_{α}
children: inaccurate representations								
≤3					1	1	1	1
4					1	1	1	1
≥5					1	1	1	1
children: inaccurate deployment								
≤3								
4								
≥5								
adults: inaccurate representations								
adults					1	1	1	1

Inaccurate representations, but accurate deployment: equivalent to always paying attention to all information (β=1).

Forsythe & Pearl 2019, Pearl & Forsythe under review

Understanding the development of pronoun interpretation

≈≈ PRONOUN =



$0.00 \leq \sigma \leq 4.00$

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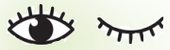


	σ_{for}	σ_{con}	σ_{mor}	σ_{α}	β_{for}	β_{con}	β_{mor}	β_{α}
children: inaccurate representations								
≤3	0.00	0.11	0.04	0.00	1	1	1	1
4	0.00	0.01	0.09	0.00	1	1	1	1
≥5	0.02	0.28	0.11	0.00	1	1	1	1
children: inaccurate deployment								
≤3								
4								
≥5								
adults: inaccurate representations								
adults	0.25	0.33	0.28	0.00	1	1	1	1

Both adults and children completely smooth away information about the prior over possible antecedents (σ_{α}).

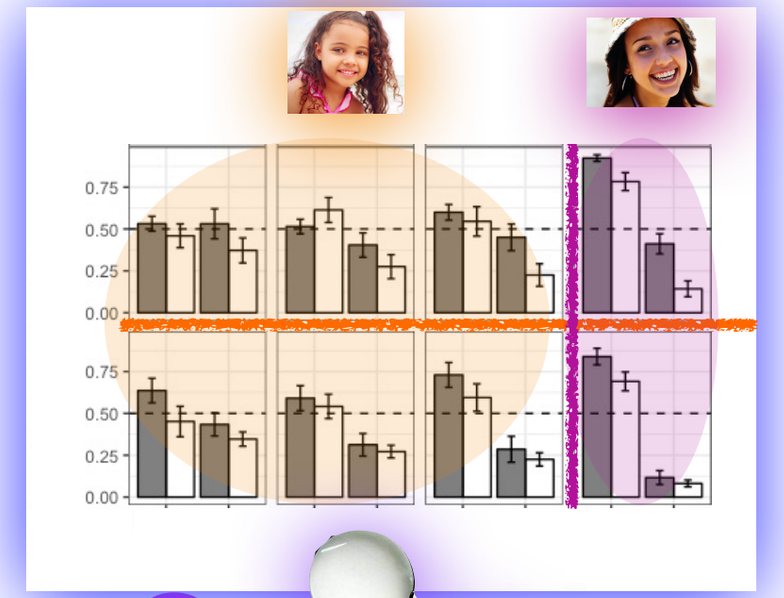
No change needed!

Note: This is functionally the same as never using this information (as if $\beta_{\alpha} = 0.00$).

Forsythe & Pearl 2019, Pearl & Forsythe under review

Understanding the development of pronoun interpretation

≈≈ PRONOUN =



$0.00 \leq \sigma \leq 4.00$

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	σ_{for}	σ_{con}	σ_{mor}	σ_{α}	β_{for}	β_{con}	β_{mor}	β_{α}
children: inaccurate representations								
≤3	0.00	0.11	0.04	0.00	1	1	1	1
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≥5	0.02	0.28	0.11	0.00	1	1	1	1
children: inaccurate deployment								
≤3								
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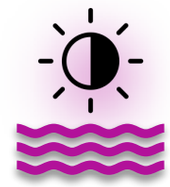
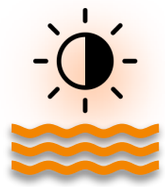


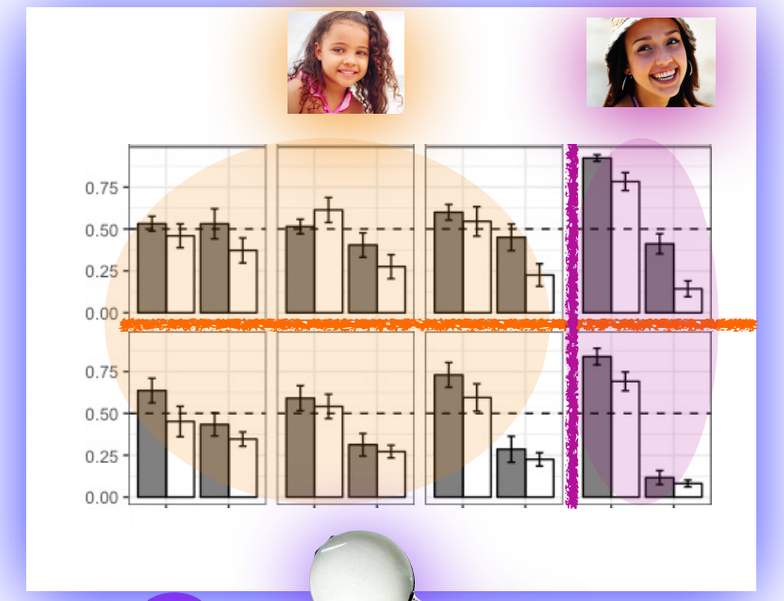


Qualitative similarity:
Both adults and children smooth away information about the form, connective, and agreement morphology ($\sigma < 1$), effectively turning down the contrast.

Forsythe & Pearl 2019, Pearl & Forsythe under review

Understanding the development of pronoun interpretation

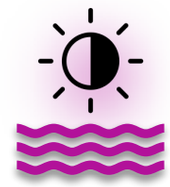
≈≈ PRONOUN =

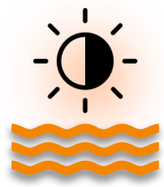


$0.00 \leq \sigma \leq 4.00$

$0 \leq \beta \leq 1$

	σ_{for}	σ_{con}	σ_{mor}	σ_{α}	β_{for}	β_{con}	β_{mor}	β_{α}
children: inaccurate representations								
≤3	0.00	0.11	0.04	0.00	1	1	1	1
4	0.00	0.01	0.09	0.00	1	1	1	1
≥5	0.02	0.28	0.11	0.00	1	1	1	1
children: inaccurate deployment								
≤3								
4								
≥5								
adults: inaccurate representations								
adults	0.25	0.33	0.28	0.00	1	1	1	1





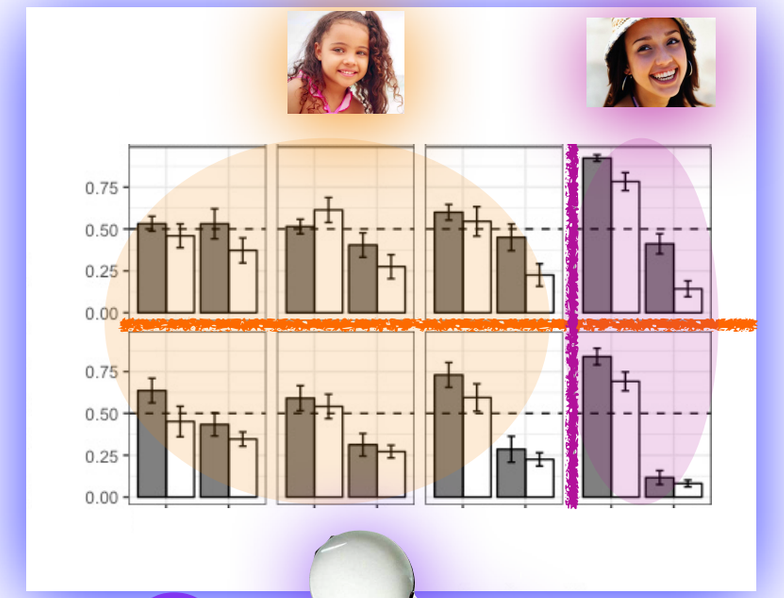
Quantitative differences:
Children smooth more overall (σ = 0.00-0.28) compared to adults (σ = 0.25-0.33)

How much difference does this make?

Forsythe & Pearl 2019, Pearl & Forsythe under review

Understanding the development of pronoun interpretation

≈≈ PRONOUN =



$0.00 \leq \sigma \leq 4.00$

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	σ_{for}	σ_{con}	σ_{mor}	σ_{α}	β_{for}	β_{con}	β_{mor}	β_{α}
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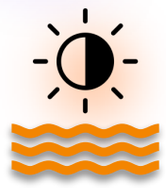
≥5	0.02	0.28	0.11	0.00	1	1	1	1
children: inaccurate deployment								
≤3								
4								
≥5								
adults: inaccurate representations								
adults	0.25	0.33	0.28	0.00	1	1	1	1

σ = 0.25-0.33



σ = 0.00-0.28

How much difference does this make?

σ = .33

.75 vs. .25

.59 vs. .41

Forsythe & Pearl 2019, Pearl & Forsythe under review

Understanding the development of pronoun interpretation

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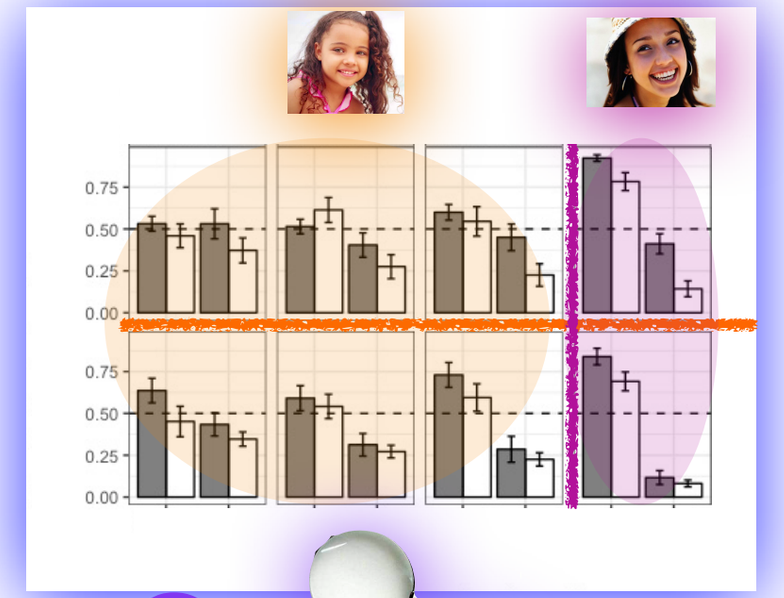

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children: inaccurate deployment								
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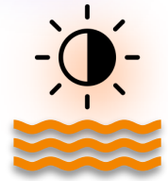
adults: inaccurate representations								
adults	0.25	0.33	0.28	0.00	1	1	1	1

σ = 0.25-0.33



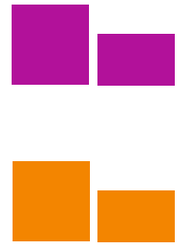
σ = 0.00-0.28

Not a lot for the higher values.

σ = .33 .75 vs. .25

.59 vs. .41

σ = .28 .58 vs. .42



Forsythe & Pearl 2019, Pearl & Forsythe under review

Understanding the development of pronoun interpretation

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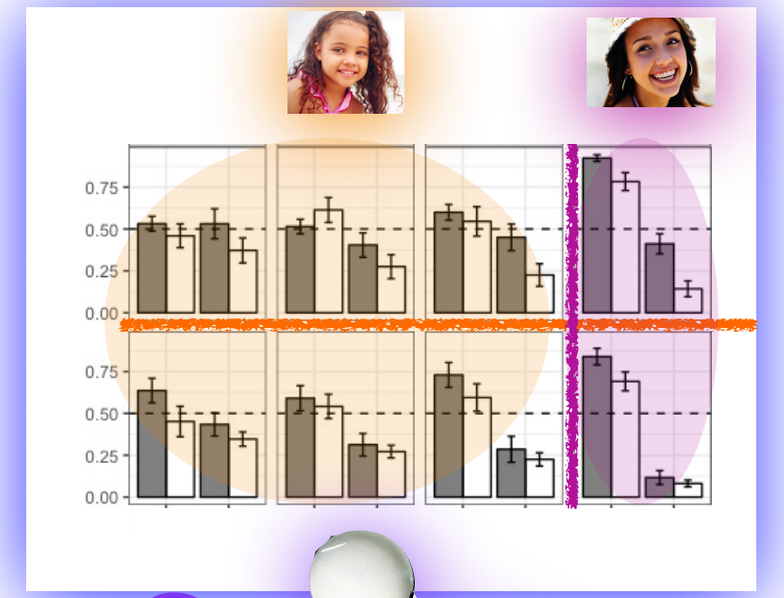
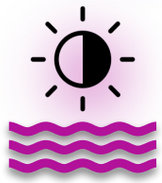
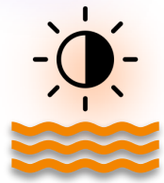


$0.00 \leq \sigma \leq 4.00$

$0 \leq \beta \leq 1$



σ = 0.25-0.33



σ = 0.00-0.28

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children: inaccurate representations								
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≥5	0.02	0.28	0.11	0.00	1	1	1	1
children: inaccurate deployment								
≤3								
4								
≥5								
adults: inaccurate representations								
adults	0.25	0.33	0.28	0.00	1	1	1	1

More for lower values.

σ = .33

.75 vs. .25

.59 vs. .41

σ = .11

.53 vs. .47

Forsythe & Pearl 2019, Pearl & Forsythe under review

Understanding the development of pronoun interpretation

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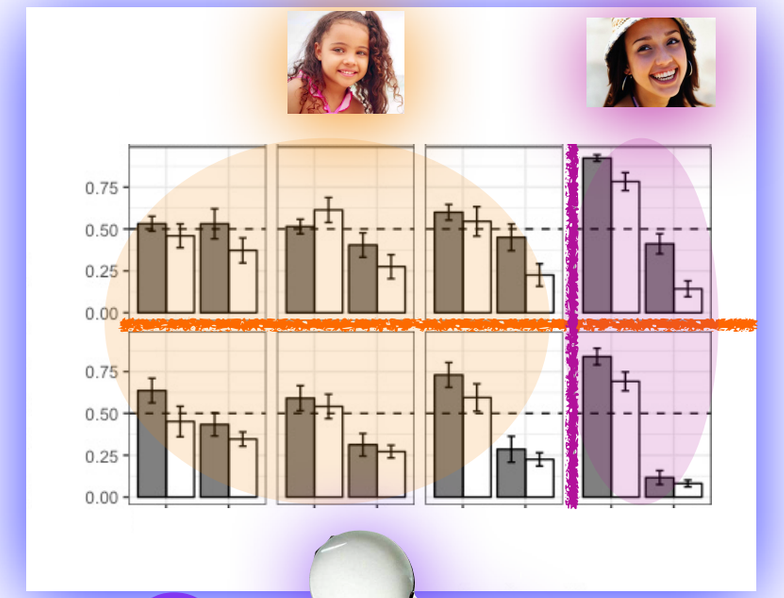

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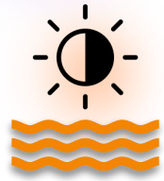
children: inaccurate deployment								
≤3								
4								
≥5								
adults: inaccurate representations								
adults	0.25	0.33	0.28	0.00	1	1	1	1

σ = 0.25-0.33



σ = 0.00-0.28

More for lower values.

σ = .33

.75 vs. .25

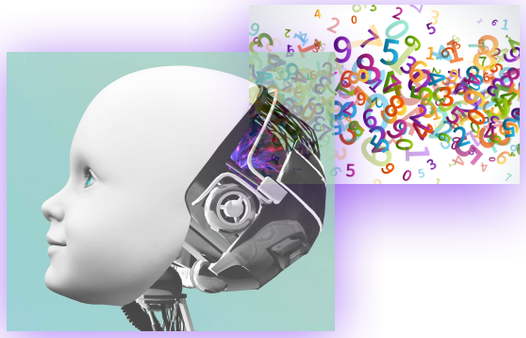
.59 vs. .41

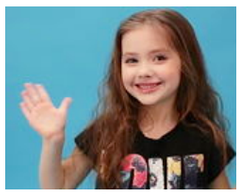
σ = .02

.505 vs. .495

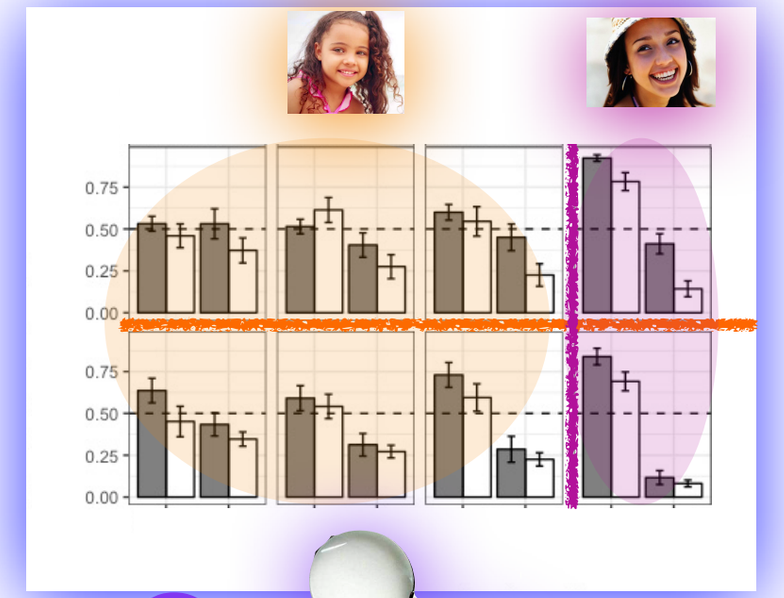
Forsythe & Pearl 2019, Pearl & Forsythe under review

Understanding the development of pronoun interpretation



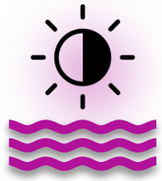


≈≈ PRONOUN =



$0.00 \leq \sigma \leq 4.00$

$0 \leq \beta \leq 1$



σ = 0.25-0.33

σ = 0.00-0.28

	σ_{for}	σ_{con}	σ_{mor}	σ_{α}	β_{for}	β_{con}	β_{mor}	β_{α}
children: inaccurate representations								
≤3	0.00	0.11	0.04	0.00	1	1	1	1
4	0.00	0.01	0.09	0.00	1	1	1	1
≥5	0.02	0.28	0.11	0.00	1	1	1	1
children: inaccurate deployment								
≤3								
4								
≥5								
adults: inaccurate representations								
adults	0.25	0.33	0.28	0.00	1	1	1	1

Takeaway:
Though both adults and children may smooth away information (turn down the contrast)…

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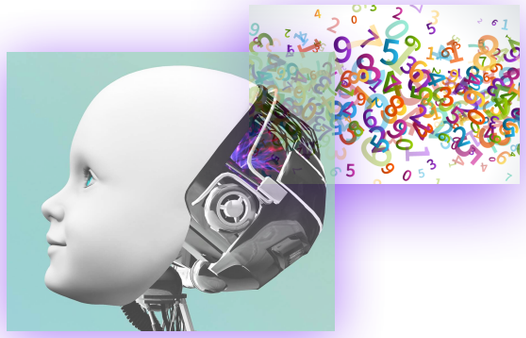
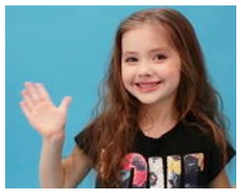
Understanding the development of pronoun interpretation





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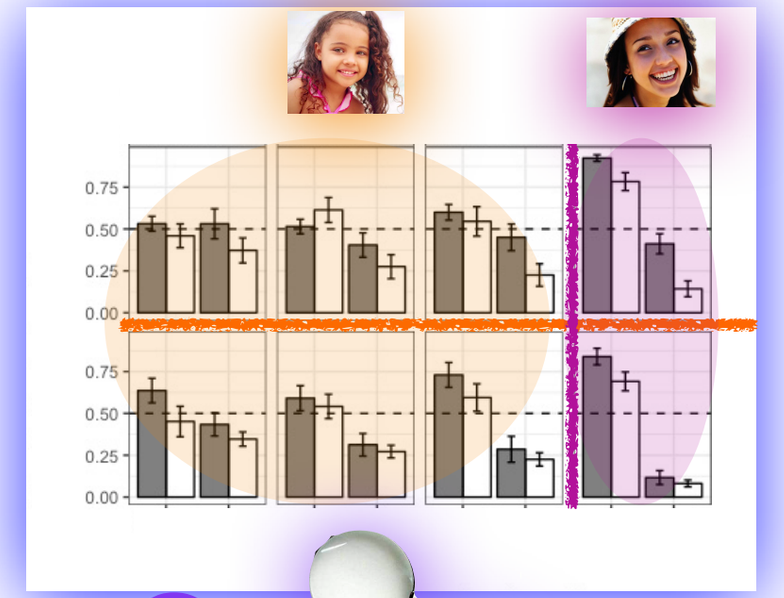

$0.00 \leq \sigma \leq 4.00$

$0 \leq \beta \leq 1$

σ = 0.25-0.33 σ = 0.00-0.28

	σ_{for}	σ_{con}	σ_{mor}	σ_{α}	β_{for}	β_{con}	β_{mor}	β_{α}
children: inaccurate representations								
≤3	0.00	0.11	0.04	0.00	1	1	1	1
4	0.00	0.01	0.09	0.00	1	1	1	1
≥5	0.02	0.28	0.11	0.00	1	1	1	1
children: inaccurate deployment								
≤3								
4								
≥5								
adults: inaccurate representations								
adults	0.25	0.33	0.28	0.00	1	1	1	1

Takeaway:
…children may need to learn to smooth away less (turn up the contrast) for pronoun form, connective, and agreement morphology information…

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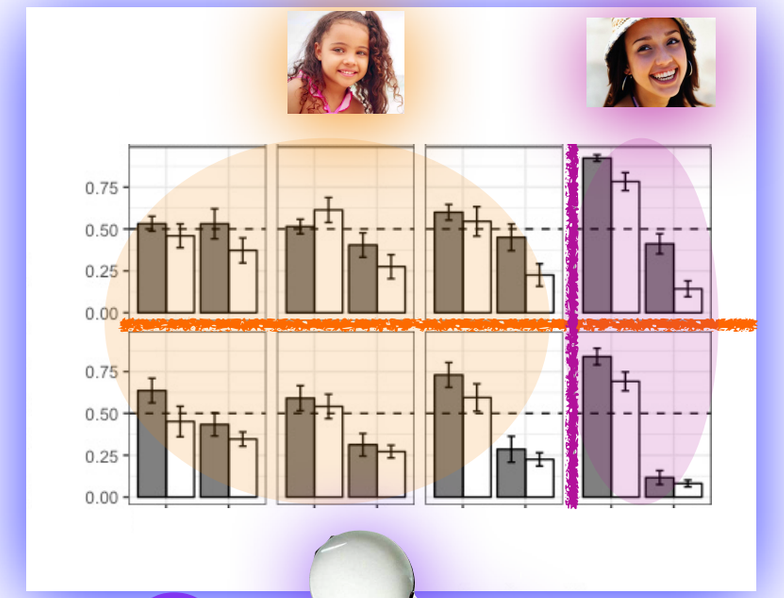
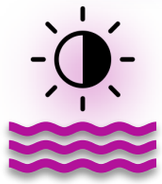
Understanding the development of pronoun interpretation

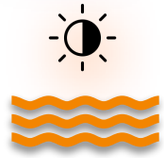
≈≈ PRONOUN =



$0.00 \leq \sigma \leq 4.00$

$0 \leq \beta \leq 1$





σ = 0.25-0.33 σ = 0.00-0.28

	σ_{for}	σ_{con}	σ_{mor}	σ_{α}	β_{for}	β_{con}	β_{mor}	β_{α}
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≤3	0.00	0.11	0.04	0.00	1	1	1	1
4	0.00	0.01	0.09	0.00	1	1	1	1
≥5	0.02	0.28	0.11	0.00	1	1	1	1
children: inaccurate deployment								
≤3								
4								
≥5								
adults: inaccurate representations								
adults	0.25	0.33	0.28	0.00	1	1	1	1

Takeaway:
…and children may need to learn to smooth away about the same amount (0.25-0.33), rather than unevenly (e.g., ≥5: 0.02 for form, 0.11 for morphology, and 0.28 for connective).

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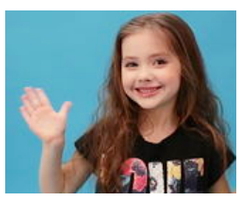
Understanding the development of pronoun interpretation



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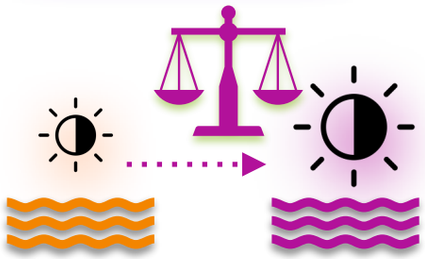

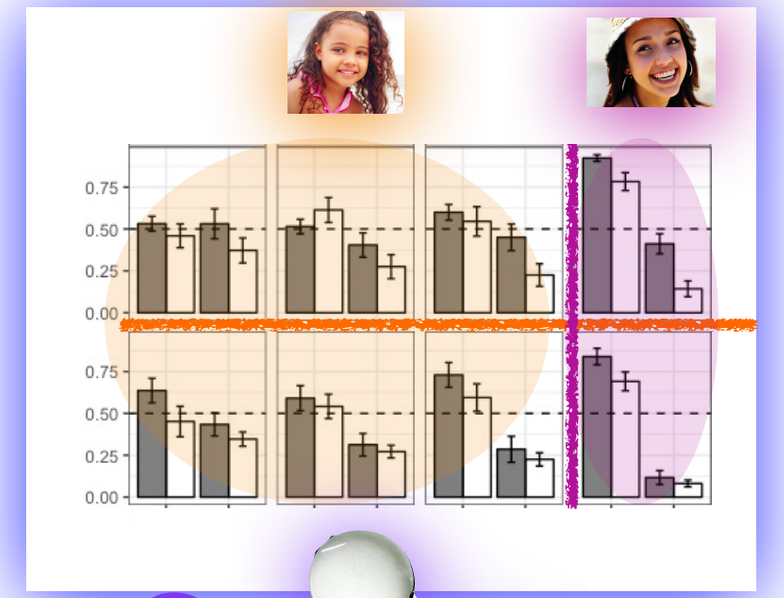

$0.00 \leq \sigma \leq 4.00$

$0 \leq \beta \leq 1$

	σ_{for}	σ_{con}	σ_{mor}	σ_{α}	β_{for}	β_{con}	β_{mor}	β_{α}
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4	0.00	0.01	0.09	0.00	1	1	1	1
≥5	0.02	0.28	0.11	0.00	1	1	1	1
children: inaccurate deployment								
≤3								
4								
≥5								
adults: inaccurate representations								
adults	0.25	0.33	0.28	0.00	1	1	1	1

Or… it could be that children have accurate representations, but inaccurate deployment.

This would be a qualitative difference from adults.

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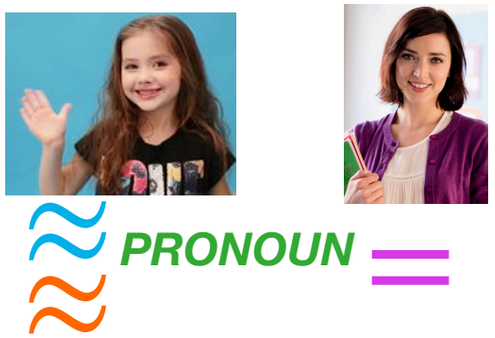
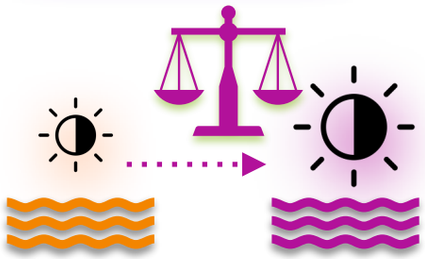
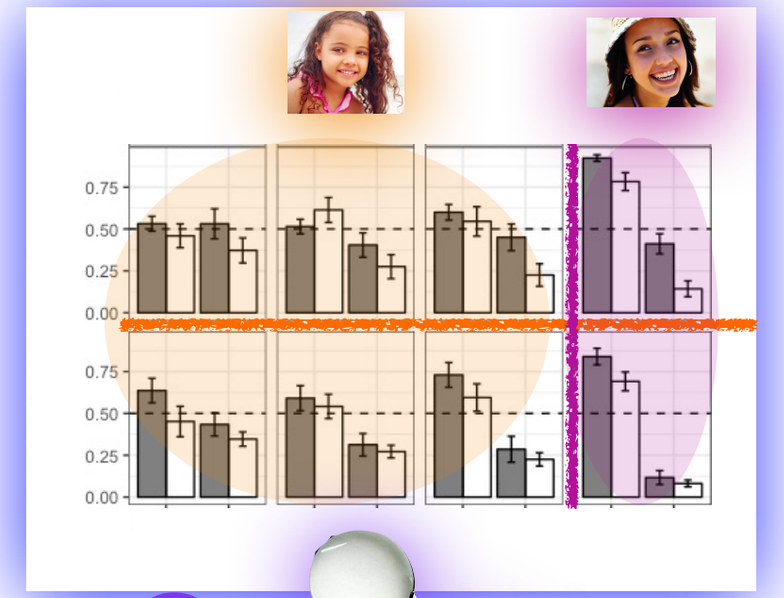
Understanding the development of pronoun interpretation







$0.00 \leq \sigma \leq 4.00$

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	σ_{for}	σ_{con}	σ_{mor}	σ_{α}	β_{for}	β_{con}	β_{mor}	β_{α}
children: inaccurate representations								
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4	0.00	0.01	0.09	0.00	1	1	1	1
≥5	0.02	0.28	0.11	0.00	1	1	1	1
children: inaccurate deployment								
≤3	1	1	1	1				
4	1	1	1	1				
≥5	1	1	1	1				
adults: inaccurate representations								
adults	0.25	0.33	0.28	0.00	1	1	1	1

Accurate representations have σ=1.

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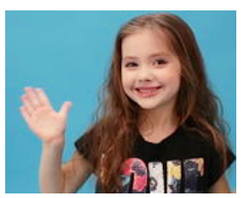
Understanding the development of pronoun interpretation



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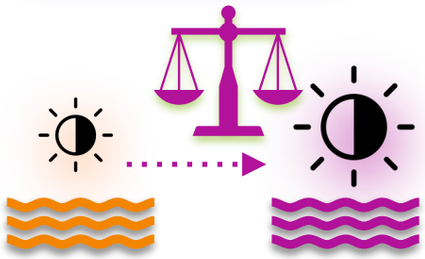

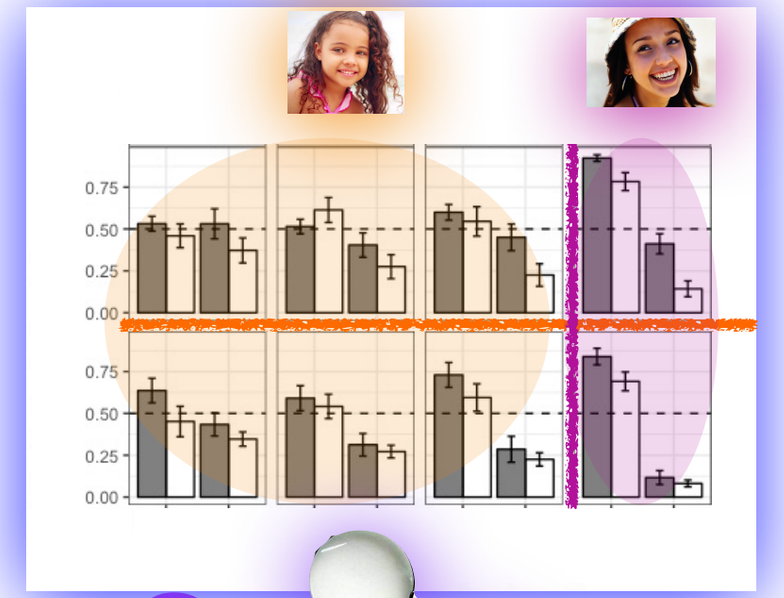

$0.00 \leq \sigma \leq 4.00$

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	σ_{for}	σ_{con}	σ_{mor}	σ_{α}	β_{for}	β_{con}	β_{mor}	β_{α}
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4	0.00	0.01	0.09	0.00	1	1	1	1
≥5	0.02	0.28	0.11	0.00	1	1	1	1
children: inaccurate deployment								
≤3	1	1	1	1	0.00	0.18	0.10	0.00
4	1	1	1	1	0.00	0.08	0.24	0.00
≥5	1	1	1	1	0.00	0.43	0.30	0.00
adults: inaccurate representations								
adults	0.25	0.33	0.28	0.00	1	1	1	1

Inaccurate deployment varies across information types, though all are used <50%.

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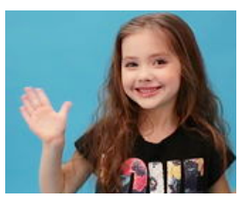
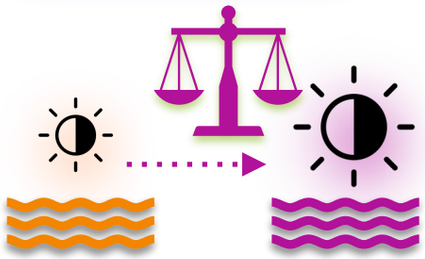
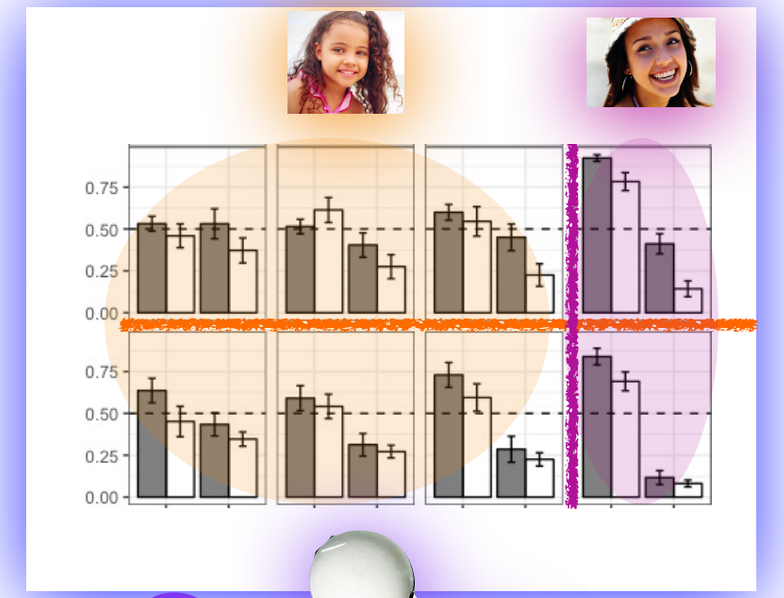


PRONOUN





$0.00 \leq \sigma \leq 4.00$

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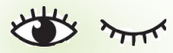

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children: inaccurate deployment								
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≥5	1	1	1	1	0.00	0.43	0.30	0.00
adults: inaccurate representations								
adults	0.25	0.33	0.28	0.00	1	1	1	1

The connective and agreement morphology are heeded varying amounts.

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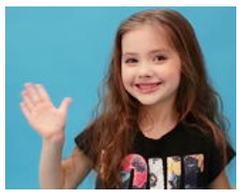
Understanding the development of pronoun interpretation



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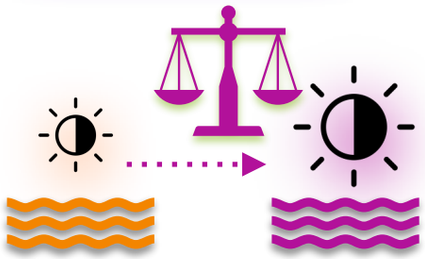

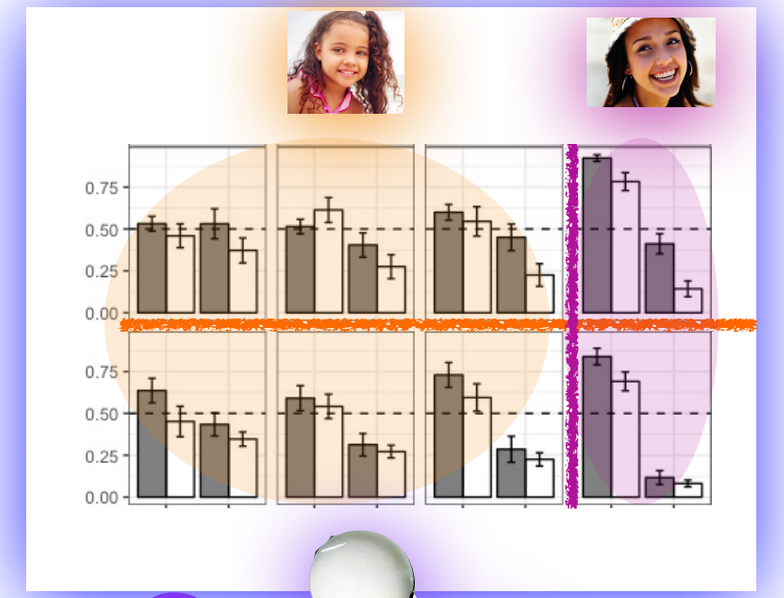

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	σ_{for}	σ_{con}	σ_{mor}	σ_{α}	β_{for}	β_{con}	β_{mor}	β_{α}
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≥5	0.02	0.28	0.11	0.00	1	1	1	1
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≤3	1	1	1	1	0.00	0.18	0.10	0.00
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≥5	1	1	1	1	0.00	0.43	0.30	0.00
adults: inaccurate representations								
adults	0.25	0.33	0.28	0.00	1	1	1	1

The prior over antecedents and form are completely ignored (β=0.00).

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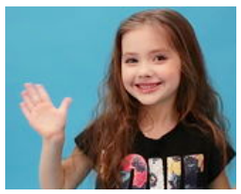

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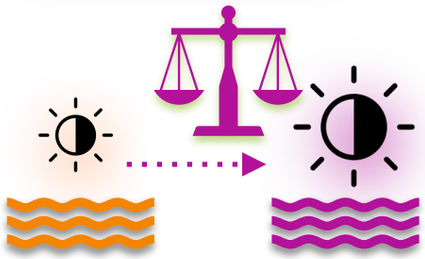

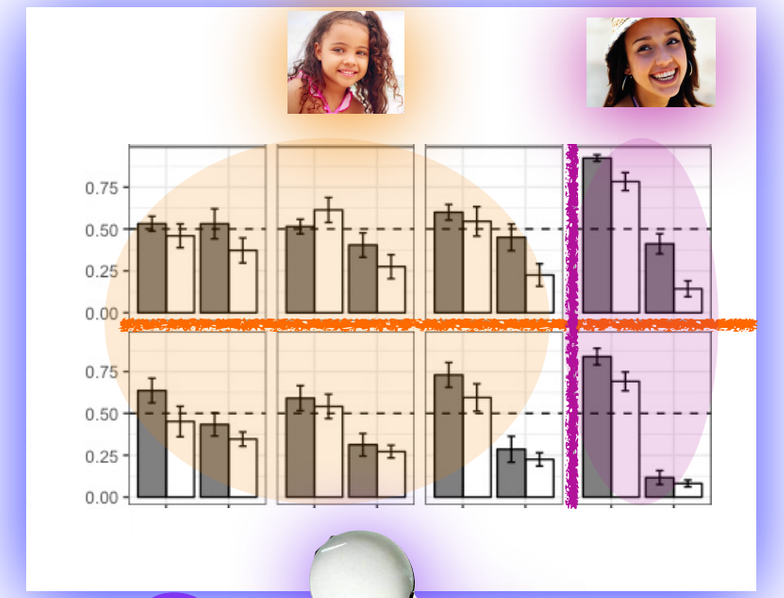

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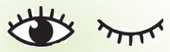

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4	1	1	1	1	0.00	0.08	0.24	0.00
≥5	1	1	1	1	0.00	0.43	0.30	0.00
adults: inaccurate representations								
adults	0.25	0.33	0.28	0.00	1	1	1	1

Note: This is equivalent to smoothing away all information in the representation.

So, a β_{α}=0.00 accomplishes the same thing as a σ_{α}=0.00, which is adult-like. Similarity!

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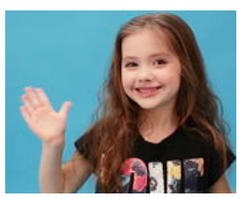

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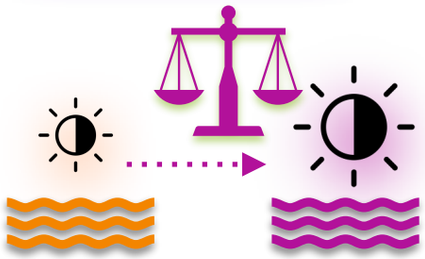

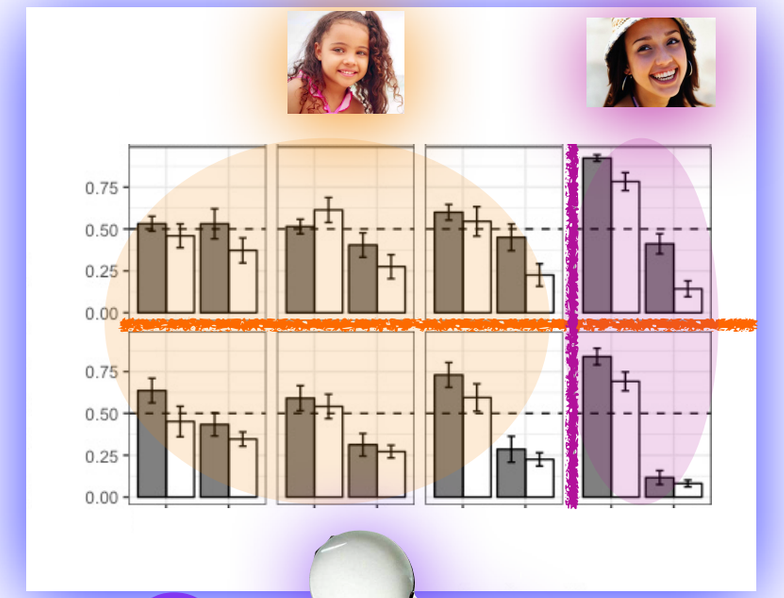

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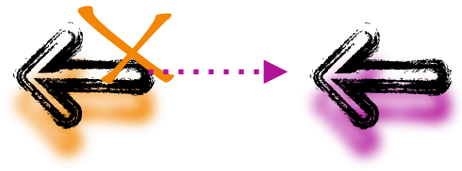
4	1	1	1	1	0.00	0.08	0.24	0.00
≥5	1	1	1	1	0.00	0.43	0.30	0.00
adults: inaccurate representations								
adults	0.25	0.33	0.28	0.00	1	1	1	1

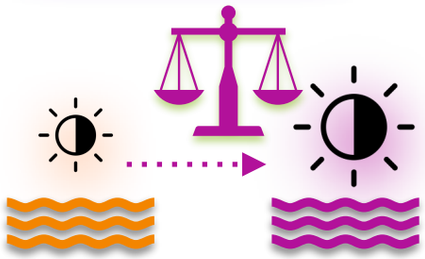
Takeaway:
To become adult-like, children would need to switch to using most of their representations accurately (all the time)…

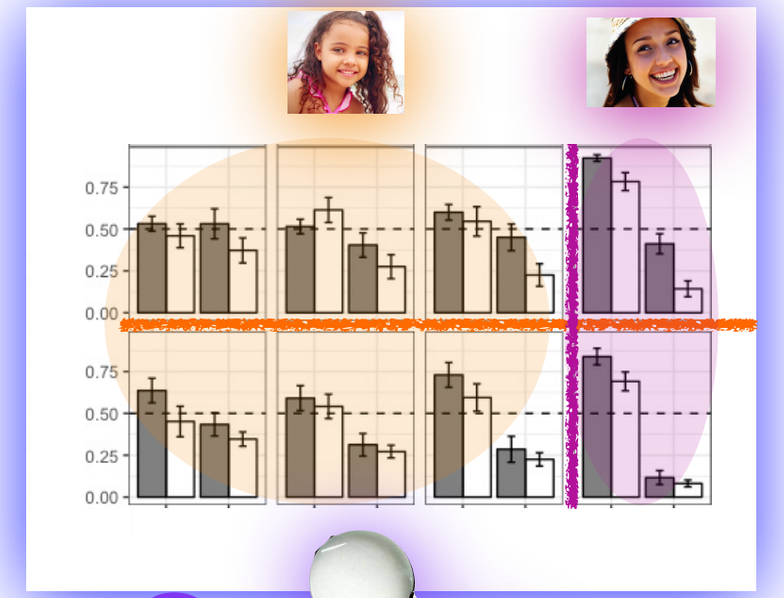


Forsythe & Pearl 2019, Pearl & Forsythe under review

Understanding the development of pronoun interpretation

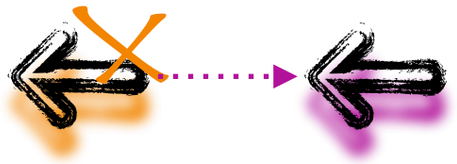
≈≈ PRONOUN =





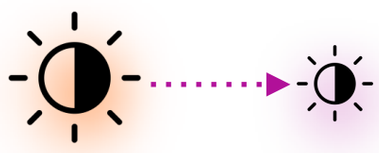
$0.00 \leq \sigma \leq 4.00$

$0 \leq \beta \leq 1$



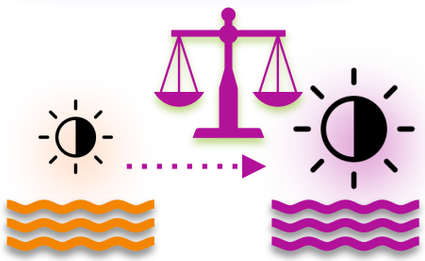
	σ_{for}	σ_{con}	σ_{mor}	σ_{α}	β_{for}	β_{con}	β_{mor}	β_{α}
children: inaccurate representations								
≤3	0.00	0.11	0.04	0.00	1	1	1	1
4	0.00	0.01	0.09	0.00	1	1	1	1
≥5	0.02	0.28	0.11	0.00	1	1	1	1
children: inaccurate deployment								
≤3	1	1	1	1	0.00	0.18	0.10	0.00
4	1	1	1	1	0.00	0.08	0.24	0.00
≥5	1	1	1	1	0.00	0.43	0.30	0.00
adults: inaccurate representations								
adults	0.25	0.33	0.28	0.00	1	1	1	1

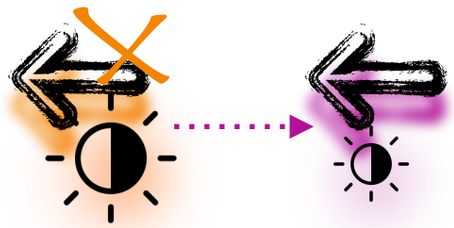
Takeaway:
…and smooth away information (turn down the contrast) for pronoun form, connective, and agreement morphology.



Forsythe & Pearl 2019, Pearl & Forsythe under review

Understanding the development of pronoun interpretation

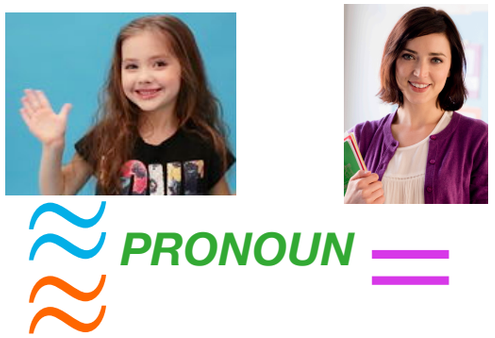


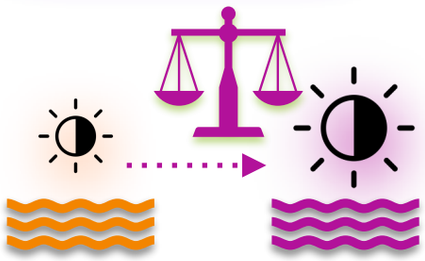


Takeaway:
To generate adult-like pronoun interpretation behavior in context, children may need to change both how they represent relevant information from their input and how they deploy those representations.

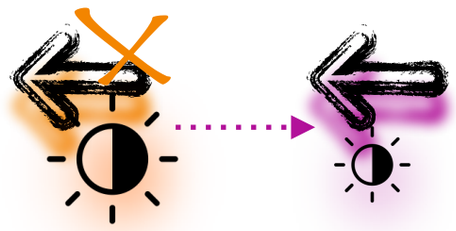
Forsythe & Pearl 2019, Pearl & Forsythe under review

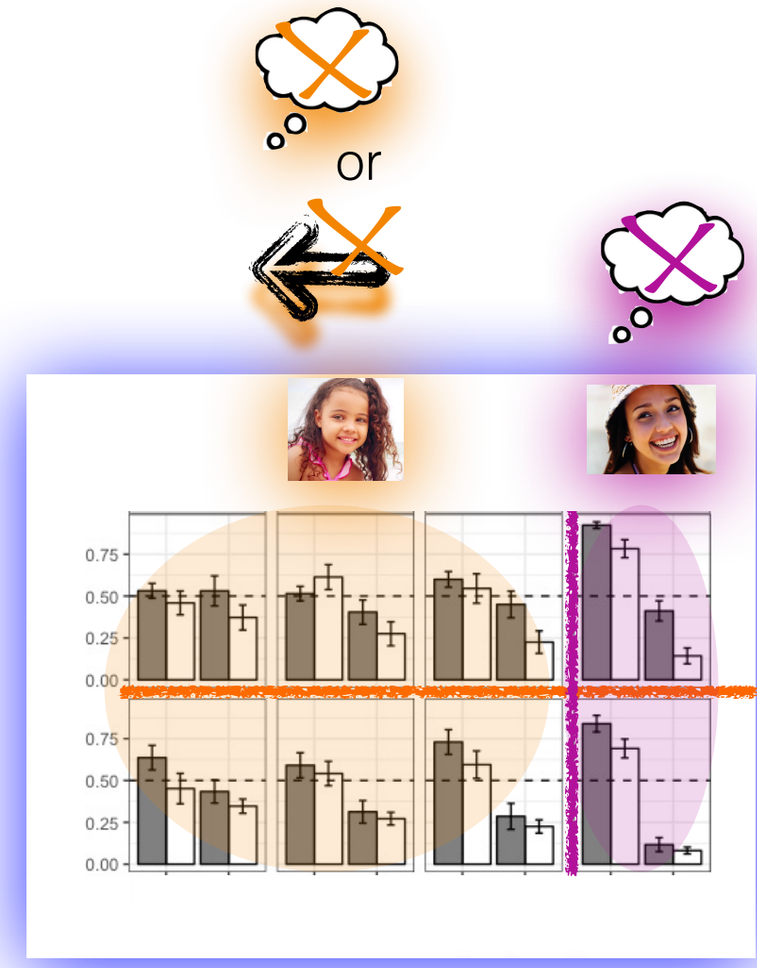
Understanding the development of pronoun interpretation





Takeaway:
In one case, children are qualitatively different from adults in two basic ways:
(1) They use accurate representations
(2) They deploy those representations inaccurately

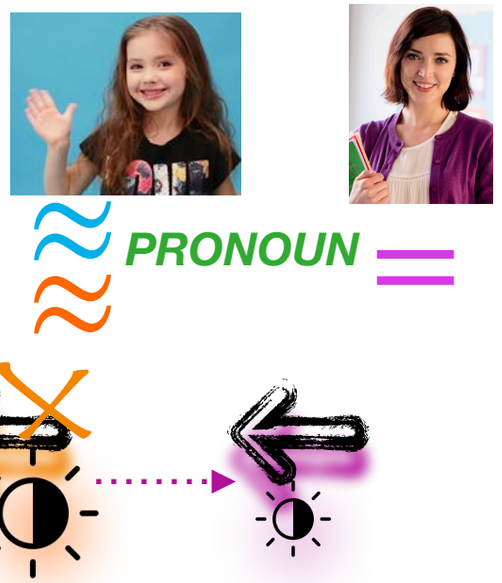


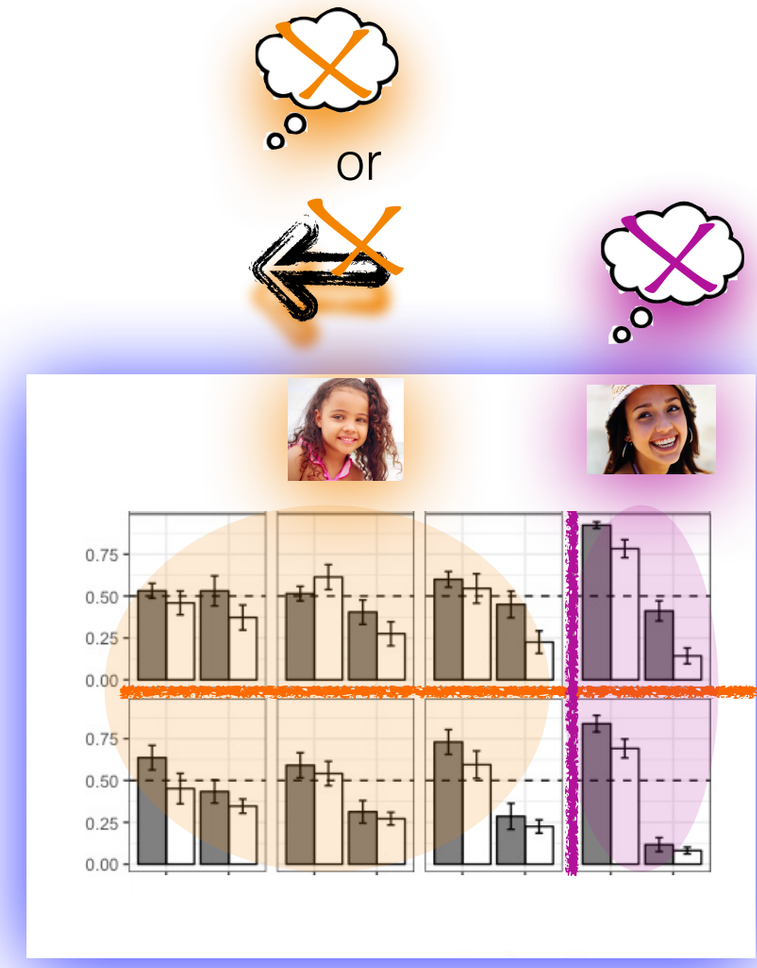


Development means changing both of these to be adult-like
(turning down the contrast, always deploying information)

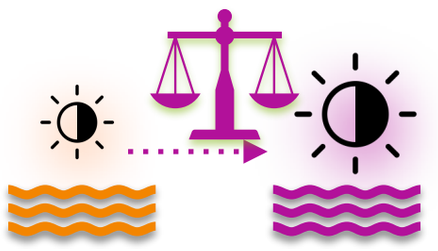
Forsythe & Pearl 2019, Pearl & Forsythe under review

Understanding the development of pronoun interpretation





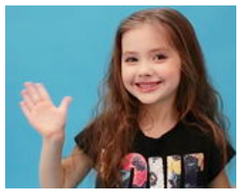
Takeaway:
In another case, children are qualitatively similar to adults:
(1) They use inaccurate representations
(2) They deploy those representations accurately

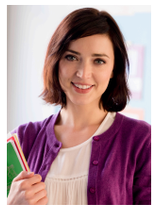


Development means learning to represent information inaccurately in an adult-like way (turning up the contrast equally)

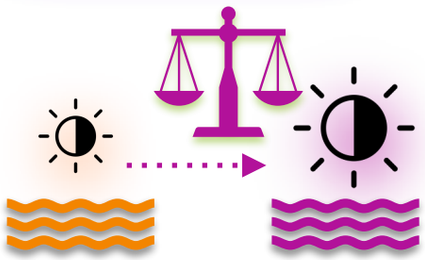
Forsythe & Pearl 2019, Pearl & Forsythe under review

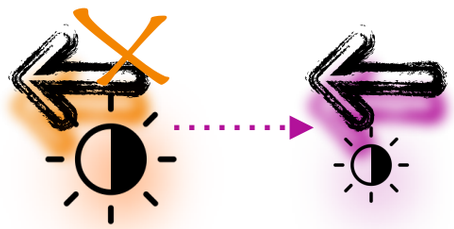
Understanding the development of pronoun interpretation



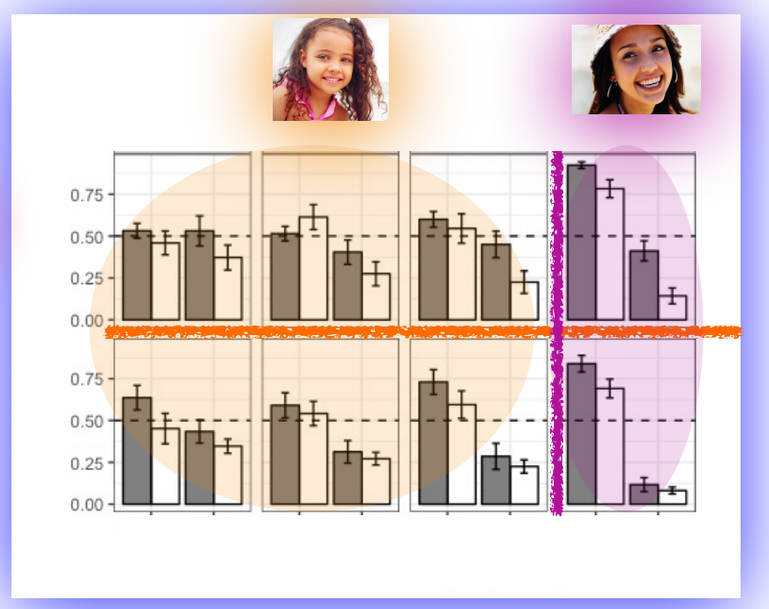


PRONOUN

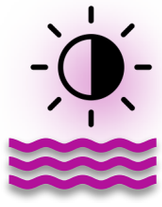




or



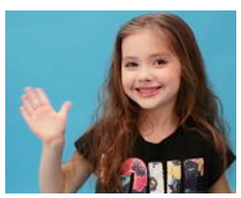
Takeaway:
Being adult-like doesn't mean being accurate!
Here, the best explanation for adult behavior is representations that are inaccurate because they smooth away information.

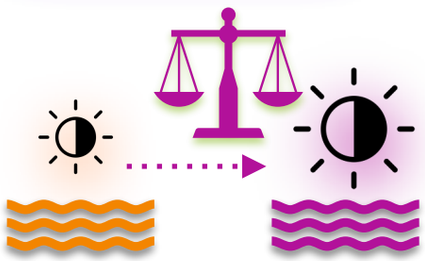


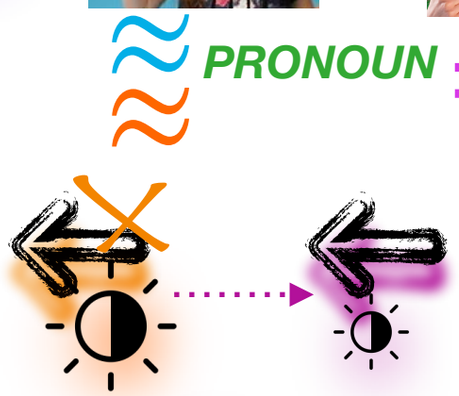
How plausible is this?

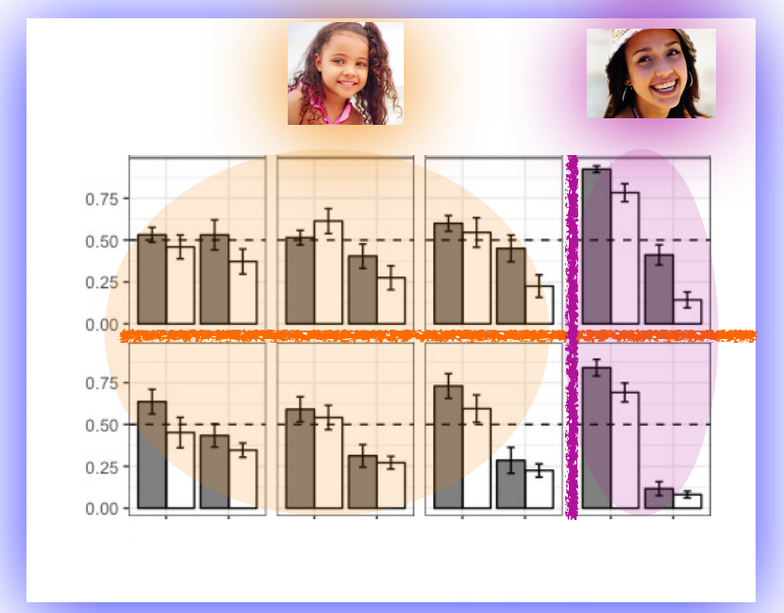
Forsythe & Pearl 2019, Pearl & Forsythe under review

Understanding the development of pronoun interpretation









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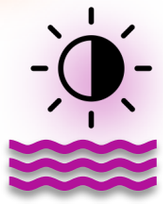
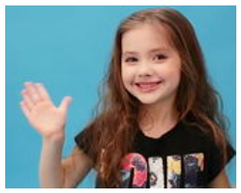


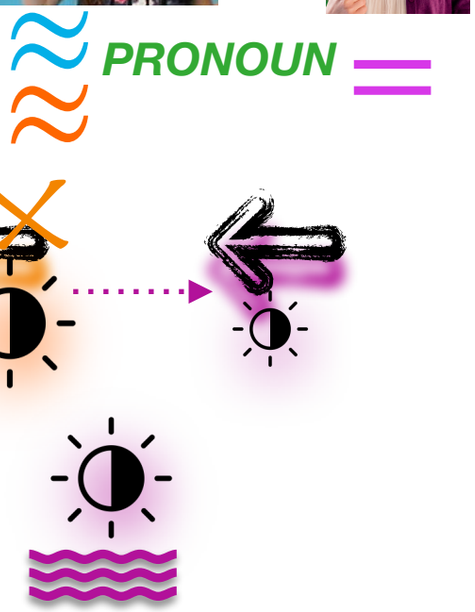
Adults smoothing away information:

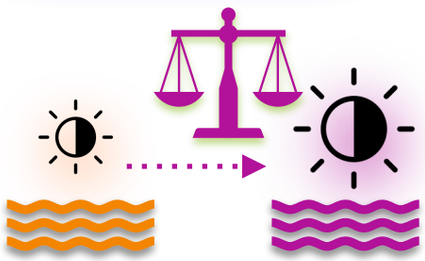
In adult decision-making studies (Kahneman & Tversky 1979), adults "interpret" representations, rather than using them accurately

Forsythe & Pearl 2019, Pearl & Forsythe under review

Understanding the development of pronoun interpretation



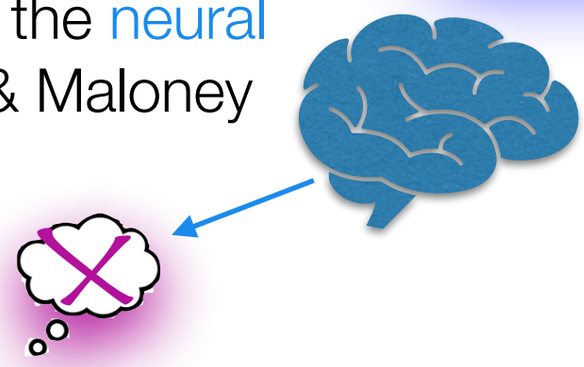




How plausible is this?

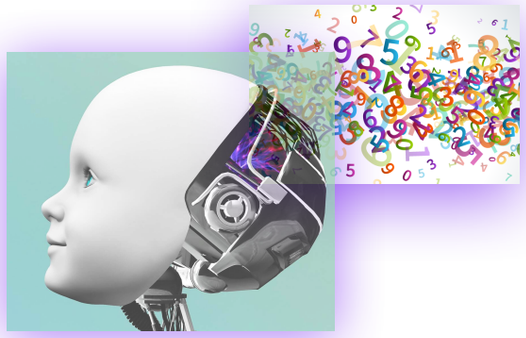
Adults smoothing away information:

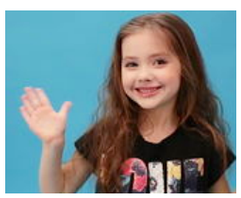
More recently, adult decision-making studies have found limits on the “dynamic range of the neural representation of probability” (Zhang & Maloney 2012, Zhang et al. 2020)

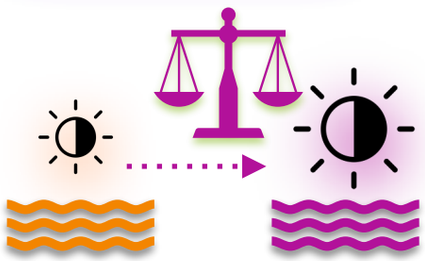


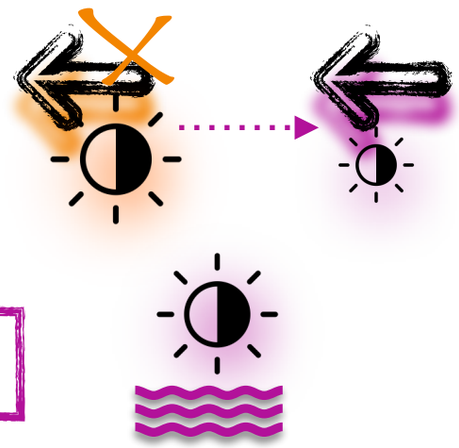
Forsythe & Pearl 2019, Pearl & Forsythe under review

Understanding the development of pronoun interpretation









How plausible is this?

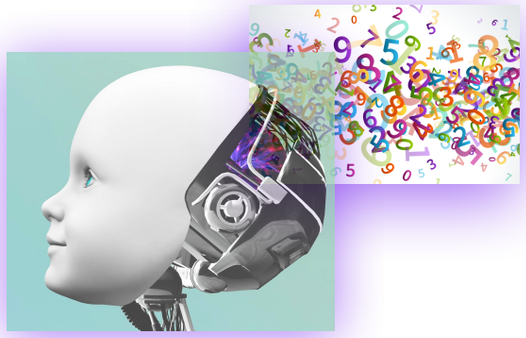
Adults smoothing away information:

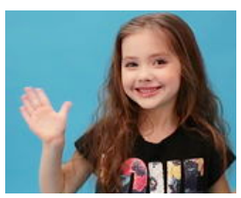
Zhang & Maloney 2012, Zhang et al. 2020:
This neural limitation causes endpoints (near 0 and 1) to get smoothed away into something between 0.16 to 0.80

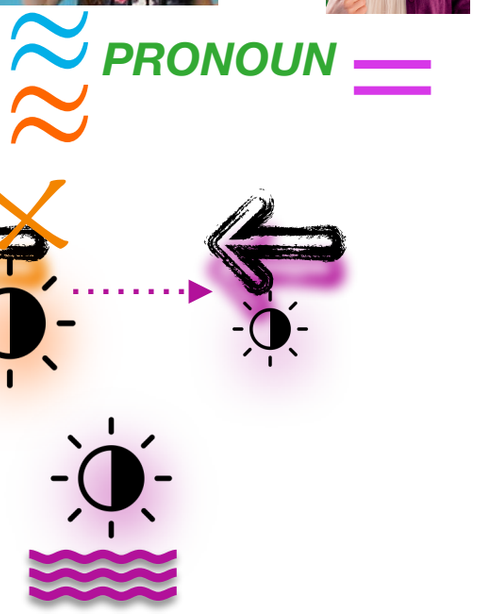
antecedent type		prior $p(\alpha)$	$p(\text{FORM}\|\alpha)$ ø	overt	*des*	*que*	$p(\text{MOR}\|\alpha)$ SG	PL
SUBJ	SG	0.362	0.938	0.062	0.324	0.676	0.998	0.002
	PL	0.071	0	016	0.750	0.250	0.005	0.995
¬SUBJ	SG	0.438	0.8	0.183	0.132	0.868	0.998	0.002
	PL	0.129	0.959	0.041	0.394	0.606	0.005	0.995

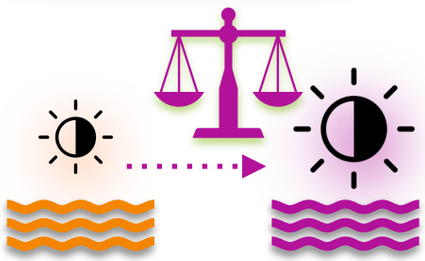
Forsythe & Pearl 2019, Pearl & Forsythe under review

Understanding the development of pronoun interpretation

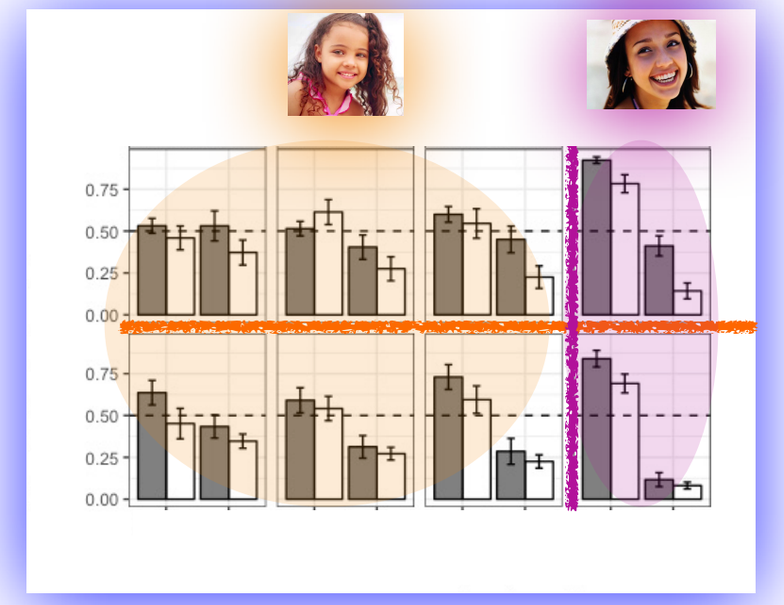








How plausible is this?



Adults smoothing away information:

Zhang & Maloney 2012, Zhang et al. 2020:
…which is what these sigma values do.

	σ_{for}	σ_{con}	σ_{mor}
adults	0.25	0.33	0.28

antecedent type		prior $p(\alpha)$	$p(\text{FORM}\|\alpha)$ ø	overt	*desque*	$p(\text{MOR}\|\alpha)$ SG	PL
SUBJ	SG	0.362	0.938	0.062	0.324	0.676	0.998	0.002
	PL	0.071	0.[illegible]	016	0.750	0.250	0.005	0.995
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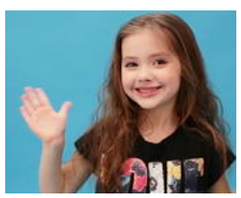
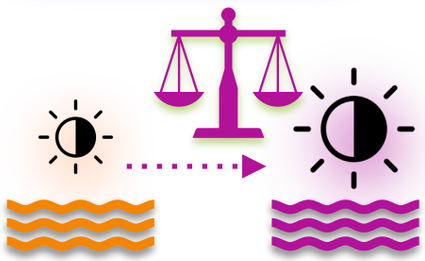
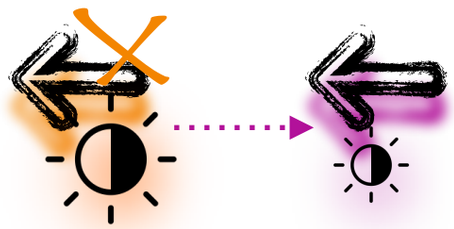
Forsythe & Pearl 2019, Pearl & Forsythe under review

Understanding the development of pronoun interpretation







So actually, adults having inaccurate representations where they smooth away information this amount is pretty plausible!

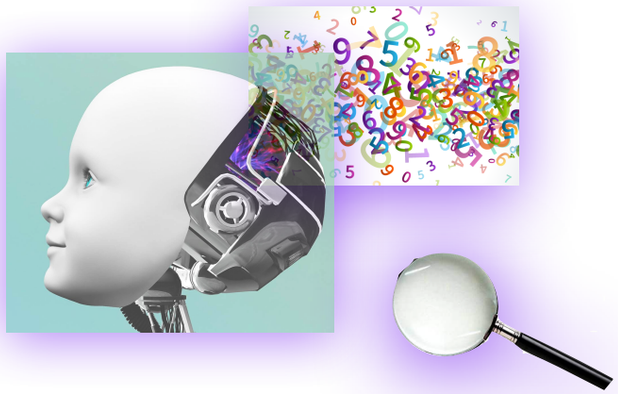
Forsythe & Pearl 2019, Pearl & Forsythe under review

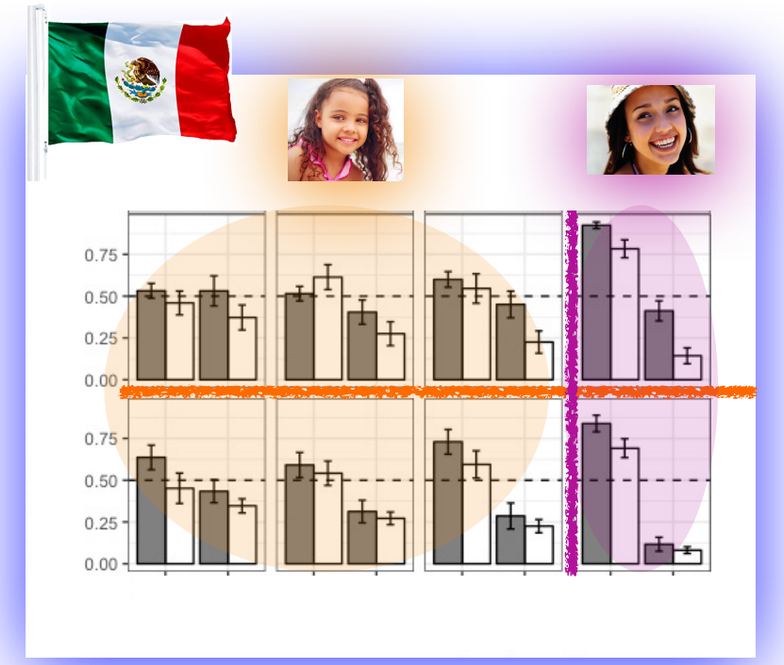
The big picture

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

Forsythe & Pearl 2019, Pearl & Forsythe under review

The big picture

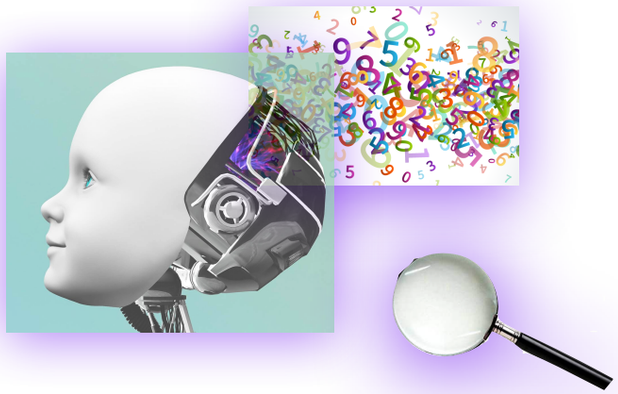


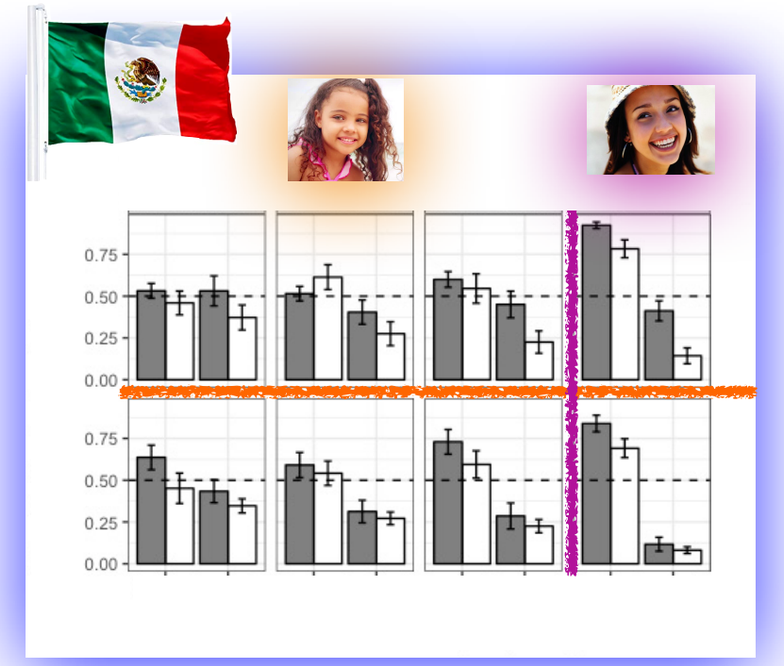


More generally, this case study demonstrates how we can use computational cognitive modeling, grounded in empirical data…

Forsythe & Pearl 2019, Pearl & Forsythe under review

The big picture

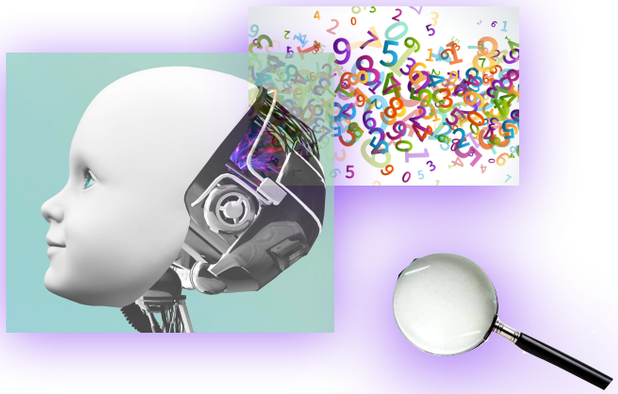




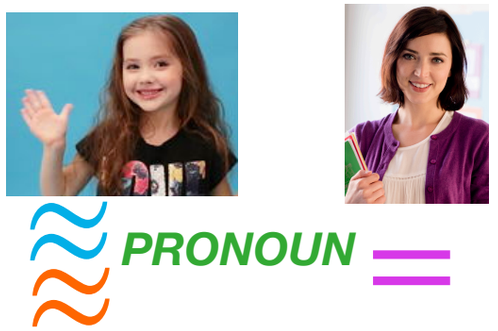
More generally, this case study demonstrates how we can use computational cognitive modeling, grounded in empirical data, to better understand how children and adults…

Forsythe & Pearl 2019, Pearl & Forsythe under review

The big picture

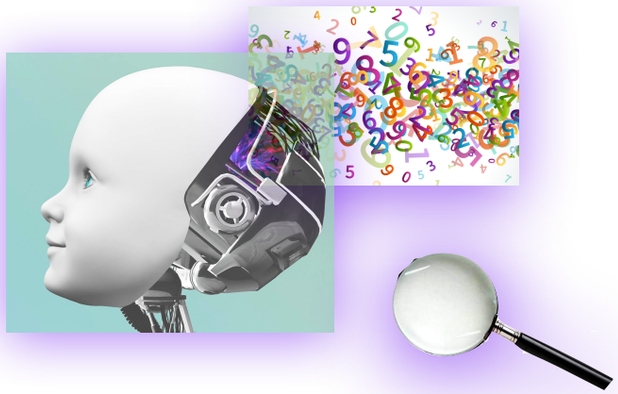


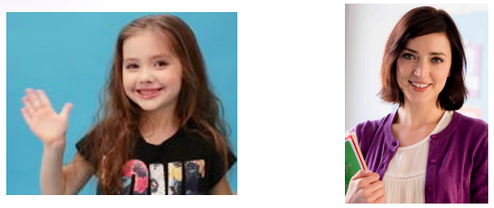
More generally, this case study demonstrates how we can use computational cognitive modeling, grounded in empirical data, to better understand how children and adults can solve complex linguistic tasks (like interpreting pronouns in a context with multiple, potentially conflicting, cues).



Forsythe & Pearl 2019, Pearl & Forsythe under review

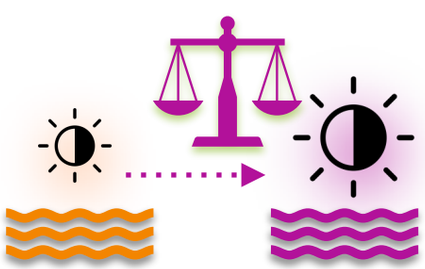
The big picture

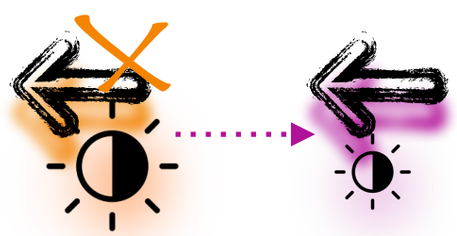




≈ *PRONOUN* =

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





Forsythe & Pearl 2019, Pearl & Forsythe under review

Thank you!

Hannah Forsythe

UMaryland CLIP Colloquium 2021

UCI QuantLang Collective

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