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…

…and then **she** leaves.

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

The girls wave at the teacher…

…and then she leaves.

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

The girls wave at the teacher...

...and then she leaves.

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…

…and then she leaves.

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

The girl waves at the teacher...

...and then she leaves.

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

The girl waves at the teacher…

...and then she leaves.

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…

...and then she leaves.

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…

...and then she leaves.

What about when interpretation cues conflict?
Pronoun interpretation

The girls wave at the teacher…

\[ \approx_{\text{subject}} \text{pl} \quad \text{sg} \quad ??? \]

…and then she leaves.

\[ \text{sg} \]

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…

...and then she leaves.

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...

\( \approx \text{subject} \quad \text{pl} \quad \text{sg} \quad ??? \)

...and then she leaves.

\( \text{sg} \)

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

The need to integrate multiple cues to interpretation doesn’t just happen in English, of course.
Las niñas saludan a la maestra…

...y después ella sale.

Here’s the same sentence in Spanish.
Las niñas saludan a la maestra…

The girls wave at the teacher…

…y después sale.

… and then leaves.

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…

…y después sale.

…and then leaves.

Just like English, there are multiple cues available to interpret the pronoun.
Las niñas saludan a la maestra…

The girls wave at the teacher…

...y después sale.

... and then leaves.

Spanish-speaking adults also have interpretation preferences.
Las niñas saludan a la maestra…

The girls wave at the teacher…

y después sale.

...and then PRONOUN leaves.

For Spanish-speaking adults…

...the connective favors the subject.
Las niñas saludan a la maestra…

The girls wave at the teacher…

≈ subject pl

???

sg

…y después sale.

… and then leaves.

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…

...y después ∅ sale.
... and then PRONOUN leaves.

For Spanish-speaking adults…

…the (null) form favors the subject.
Pronoun interpretation

Las niñas saludan a la maestra...

The girls wave at the teacher...

...y después sale.

...and then leaves.

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…

...y después sale.

... and then leaves.

How do Spanish-learning children develop this ability to interpret pronouns in context?
Children’s ability to interpret a pronoun in an adult-like way depends on (at least) two things.
First, children need adult-like knowledge of what each cue signals.
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.
But if we get non-adult-like pronoun interpretation, then it could be due to immature knowledge, immature deployment of that knowledge, or both!
How do we tell what the differences are between child and adult pronoun interpretation? When we understand this better, we’ll understand what children need to do to become adults.
Understanding pronoun interpretation development

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

Case study: Mexican Spanish

Forsythe & Pearl 2019, Pearl & Forsythe under review
Understanding pronoun interpretation development

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

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

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 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…

…y después ∅ sale.
…and then PRONOUN leaves.

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

Children

<=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

Las niñas saludan a la maestra...

The girls wave at the teacher...

...y después sale.

... and then PRONOUN leaves.

~3yrs 4yrs ~5yrs adults

Forsythe & Pearl 2019, Pearl & Forsythe under review
Empirical data on pronoun interpretation

Las niñas saludan a la maestra…

The girls wave at the teacher…

…y después sale.

…and then PRONOUN leaves.

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

Rate of subject responses

We can plot the rate of subject responses.

Forsythe & Pearl 2019, Pearl & Forsythe under review
Empirical data on pronoun interpretation

Context:
Does agreement favor the subject or the object?

Rate of subject responses

~3yrs 4yrs ~5yrs adults

Favored by agreement

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

…y después sale.

… and then LEAVES.

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 ∅ salen.

... and then PRONOUN leave.

pl

Context:
Does agreement favor the subject or the object?

Favored by agreement

Rate of subject responses

~3yrs 4yrs ~5yrs adults

Forsythe & Pearl 2019, Pearl & Forsythe under review
Empirical data on pronoun interpretation

Las niñas saludan a la maestra... The girls wave at the teacher...

...y después sale. ... and then leaves.

Context:
Does agreement favor the subject or the object?

Rate of subject responses

~3yrs 4yrs ~5yrs adults

Favored by agreement

Forsythe & Pearl 2019, Pearl & Forsythe under review
Empirical data on pronoun interpretation

Las niñas saludan a la maestra...

...y después sale.

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

Rate of subject responses

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…

...y después sale.
... and then leaves.

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

Rate of subject responses

≈ subject

∅ (favors subject)

Favored by agreement

Forsythe & Pearl 2019, Pearl & Forsythe under review
Empirical data on pronoun interpretation

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

Las niñas saludan a la maestra...
The girls wave at the teacher...

...y después ella sale.
... and then PRONOUN leaves.

Rate of subject responses

~3yrs  4yrs  ~5yrs  adults

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...

... y después sale. ... and then leaves.

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

Rate of subject responses

~3yrs 4yrs ~5yrs adults

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...

...y después sale.

... and then PRONOUN leaves.

Rate of subject responses

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

~3yrs
4yrs
~5yrs
adults

Forsythe & Pearl 2019, Pearl & Forsythe under review
Empirical data on pronoun interpretation

Las niñas saludan a la maestra...

The girls wave at the teacher...

...porque

... because

porque (favors object)

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

Rate of subject responses

~3yrs 4yrs ~5yrs adults

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)

~3yrs
4yrs
~5yrs
adults

Favored by form

- ø (favors subject)
- overt (favors object)

Favored by agreement

Rate of subject responses

subject object
subject object
subject object
subject object

Forsythe & Pearl 2019, Pearl & Forsythe under review
Empirical data on pronoun interpretation

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

Favored by connective
- y después (favors subject)
- porque (favors object)

Favored by agreement

~3yrs | 4yrs | ~5yrs | adults

Rate of subject responses

Forsythe & Pearl 2019, Pearl & Forsythe under review
Empirical data on pronoun interpretation

Favored by connective:
y después (favors subject)
porque (favors object)

Favored by agreement:

Rate of subject responses

~3yrs 4yrs ~5yrs

Favored by form:

Ø (favors subject)
over (favors object)

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

Forsythe & Pearl 2019, Pearl & Forsythe under review
Empirical data on pronoun interpretation

Favored by form
- Overt (favors object)
- Empty (favors subject)

Favored by agreement
- porque (favors object)
- y después (favors subject)

Rate of subject responses

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 form**
  - Overt (favors object)
  - ∅ (favors subject)

- **Favored by agreement**
  - Rate of subject responses
  - Porque (favors object)
  - Y después (favors subject)

- **Favored by connective**
  - ~3yrs
  - 4yrs
  - ~5yrs
  - Adults

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.

Forsythe & Pearl 2019, Pearl & Forsythe under review
Understanding pronoun interpretation development

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.
Understanding pronoun interpretation development

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

Forsythe & Pearl 2019, Pearl & Forsythe under review
Understanding pronoun interpretation development

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

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
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).
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.
Modeling pronoun interpretation in context

Interpreting the pronoun as the subject, which is singular….
Modeling pronoun interpretation in context

\[ p(\alpha_{subj.sg} | FORM, CON, MOR) \propto p(\alpha_{subj.sg}) \times p(\text{FORM, CON, MOR}|\alpha_{subj.sg}) \]

∅ ella

...given the particular context involving the pronoun’s form,

Forsythe & Pearl 2019, Pearl & Forsythe under review
Modeling pronoun interpretation in context

Bayesian inference


text

interpretation \quad context

\[ p(\alpha_{subj.sg}| FORM, CON, MOR) \propto p(\alpha_{subj.sg}) \cdot p(\text{FORM, CON, MOR}|\alpha_{subj.sg}) \]

...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

...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

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

\[ p(\alpha_{subj,sg}|\text{FORM, CON, MOR}) \propto p(\alpha_{subj,sg}) \times p(\text{FORM, CON, MOR}|\alpha_{subj,sg}) \]

...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

\[ p(\alpha_{subj,SG}|\text{FORM, CON, MOR}) \propto p(\alpha_{subj,SG}) \cdot p(\text{FORM}|\alpha_{subj,SG}) \cdot p(\text{CON}|\alpha_{subj,SG}) \cdot p(\text{MOR}|\alpha_{subj,SG}) \]

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).
Modeling pronoun interpretation in context

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

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

Forsythe & Pearl 2019, Pearl & Forsythe under review
What about a modeled listener who has inaccurate representations? This could involve inaccurately representing the prior or the likelihood information, or both.
Modeling pronoun interpretation in context

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

\[
e^{\sigma \cdot \ln\text{(probability)}} = \text{probability}^\sigma
\]

Forsythe & Pearl 2019, Pearl & Forsythe under review
Modeling pronoun interpretation in context

\[ p(\alpha_{\text{subj.sg}}|\text{FORM, CON, MOR}) \propto p(\alpha_{\text{subj.sg}}) \times p(\text{FORM}|\alpha_{\text{subj.sg}}) \times p(\text{CON}|\alpha_{\text{subj.sg}}) \times p(\text{MOR}|\alpha_{\text{subj.sg}}) \]

\[ \text{probability}^\sigma \]

About \( \sigma \): 
- \( \sigma < 1 \): probability differences are smoothed away.
- \( \sigma = 1 \): probabilities remain accurate.
- \( \sigma > 1 \): probability differences are sharpened.

0.324 vs. 0.676

Forsythe & Pearl 2019, Pearl & Forsythe under review
Modeling pronoun interpretation in context

About $\sigma$:

- $\sigma = 0.5$: probability differences are smoothed away.  
  $0.409$ vs. $0.591$

- $\sigma = 1$: probabilities remain accurate.    
  $0.324$ vs. $0.676$

- $\sigma > 1$: probability differences are sharpened.

Forsythe & Pearl 2019, Pearl & Forsythe under review
Modeling pronoun interpretation in context

About $\sigma$:

- $\sigma < 1$: probability differences are smoothed away.
- $\sigma = 1$: probabilities remain accurate.
- $\sigma = 2$: probability differences are sharpened.

0.324 vs. 0.676

0.187 vs. 0.813

Forsythe & Pearl 2019, Pearl & Forsythe under review
Modeling pronoun interpretation in context

Bayesian inference

One $\sigma$ for each information type:
(in the prior) $\sigma_\alpha$
(in the likelihood) $\sigma_{\text{form}}$, $\sigma_{\text{con}}$, $\sigma_{\text{mor}}$

Forsythe & Pearl 2019, Pearl & Forsythe under review
Modeling pronoun interpretation in context

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

Forsythe & Pearl 2019, Pearl & Forsythe under review
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.
Modeling pronoun interpretation in context

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.

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Forsythe & Pearl 2019, Pearl & Forsythe under review
Modeling pronoun interpretation in context

Bayesian inference

Not using information means not incorporating it into the inference.

\[ p(\alpha_{subj.sg}|\text{FORM, CON, MOR}) \propto p(\alpha_{subj.sg}) \times p(\text{FORM}|\alpha_{subj.sg}) \times p(\text{CON}|\alpha_{subj.sg}) \times p(\text{MOR}|\alpha_{subj.sg}) \]

Forsythe & Pearl 2019, Pearl & Forsythe under review
Modeling pronoun interpretation in context

Bayesian inference

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

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

$\approx \approx =$

inaccurate representations $\Rightarrow p_\sigma$

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

\[
p(\alpha_{subj,SG}|\text{FORM, CON, MOR}) \propto p(\alpha_{subj,SG}) \times p(\text{FORM}|\alpha_{subj,SG}) \times p(\text{CON}|\alpha_{subj,SG}) \times p(\text{MOR}|\alpha_{subj,SG})
\]

For any information, the modeled listener could use or not use it in the moment. **Use parameter** $\beta$ **determines whether a particular information type is used.**
Modeling pronoun interpretation in context

Bayesian inference

inaccurate representations

PRONOUN

interpretation context

\[ p(\alpha_{\text{subj.sg}}|\text{FORM, CON, MOR}) \propto p(\alpha_{\text{subj.sg}}) \times p(\text{FORM}|\alpha_{\text{subj.sg}}) \times p(\text{CON}|\alpha_{\text{subj.sg}}) \times p(\text{MOR}|\alpha_{\text{subj.sg}}) \]

Each of the four information types has its own \( \beta \):

(prior) \( \beta_\alpha \)

(likelihood) \( \beta_{\text{form}}, \beta_{\text{con}}, \beta_{\text{mor}} \)

Forsythe & Pearl 2019, Pearl & Forsythe under review
Modeling pronoun interpretation in context

This yields 16 possible use combinations for any particular moment, implemented with a mixture model $p_\beta$. 

Forsythe & Pearl 2019, Pearl & Forsythe under review
Modeling pronoun interpretation in context

Bayesian inference

inaccurate representations

inaccurate deployment

interpretation context

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

\[ \beta_{\text{form}} \beta_{\text{con}} \beta_{\text{mor}} \beta_{\alpha} \]

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

Forsythe & Pearl 2019, Pearl & Forsythe under review
Modeling pronoun interpretation in context

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

\[
p(\alpha_{\text{subj.sg}} | \text{FORM, CON, MOR}) \propto p(\alpha_{\text{subj.sg}}) \times p(\text{FORM}|\alpha_{\text{subj.sg}}) \times p(\text{CON}|\alpha_{\text{subj.sg}}) \times p(\text{MOR}|\alpha_{\text{subj.sg}})
\]

Forsythe & Pearl 2019, Pearl & Forsythe under review
Modeling pronoun interpretation in context

We implement this as a combination of the previous two modeled listeners, including $\sigma$ values for inaccurate representations and $\beta$ values for inaccurate deployment.

\[
p_{\sigma,\beta}(x_{\text{num}}, x_{\text{subj}} | \text{FORM, CON, MOR}) \propto p(x_{\text{num}}, x_{\text{subj}}) \sigma_{\text{form}} \times p(\text{FORM} | x_{\text{num}}, x_{\text{subj}}) \sigma_{\text{con}} \times p(\text{MOR} | x_{\text{num}}, x_{\text{subj}}) \sigma_{\text{mor}}
\]
Each term of $p_{\beta}$ has $\sigma$ values for all information types that are used.
Modeling pronoun interpretation in context

Bayesian inference

inaccurate representations

inaccurate deployment

inaccurate both

So, \( p_{\alpha,\beta} \) has 8 parameter values:

(in the prior) \( \sigma_\alpha, \beta_\alpha \)

(in the likelihood) \( \sigma_{\text{form}}, \sigma_{\text{con}}, \sigma_{\text{mor}}, \beta_{\text{form}}, \beta_{\text{con}}, \beta_{\text{mor}} \)

\[
p_{\sigma}(\alpha_{\text{num}}, \alpha_{\text{subj}}|\text{FORM, CON, MOR}) \propto p(\alpha_{\text{num}}, \alpha_{\text{subj}}) \sigma_{\alpha}^2
\]

\[
\times p(\text{FORM}|\alpha_{\text{num}}, \alpha_{\text{subj}}) \sigma_{\text{form}}^2
\]

\[
\times p(\text{CON}|\alpha_{\text{num}}, \alpha_{\text{subj}}) \sigma_{\text{con}}^2
\]

\[
\times p(\text{MOR}|\alpha_{\text{num}}, \alpha_{\text{subj}}) \sigma_{\text{mor}}^2
\]

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

\[
(\beta_{\text{form}})(\beta_{\text{con}})(\beta_{\text{mor}})(\beta_{\alpha}) \times p(\alpha|\text{FORM, CON, MOR, } \alpha_{\text{num}}, \alpha_{\text{subj}}) +
\]

\[
(\beta_{\text{form}})(\beta_{\text{con}})(\beta_{\text{mor}})(1 - \beta_{\alpha}) \times p(\alpha|\text{FORM, CON, MOR, } \alpha_{\text{num}}, \alpha_{\text{subj}}) +
\]

\[
(1 - \beta_{\text{form}})(\beta_{\text{con}})(\beta_{\text{mor}})(\beta_{\alpha}) \times p(\alpha|\text{FORM, CON, MOR, } \alpha_{\text{num}}, \alpha_{\text{subj}}) +
\]

\[
(1 - \beta_{\text{form}})(\beta_{\text{con}})(\beta_{\text{mor}})(1 - \beta_{\alpha}) \times p(\alpha|\text{FORM, CON, MOR, } \alpha_{\text{num}}, \alpha_{\text{subj}}) +
\]

\[
(\beta_{\text{form}})(\beta_{\text{con}})(1 - \beta_{\text{mor}})(\beta_{\alpha}) \times p(\alpha|\text{FORM, CON, MOR, } \alpha_{\text{num}}, \alpha_{\text{subj}}) +
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(\beta_{\text{form}})(\beta_{\text{con}})(1 - \beta_{\text{mor}})(1 - \beta_{\alpha}) \times p(\alpha|\text{FORM, CON, MOR, } \alpha_{\text{num}}, \alpha_{\text{subj}}) +
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(\beta_{\text{form}})(\beta_{\text{con}})(1 - \beta_{\text{mor}})(1 - \beta_{\alpha}) \times p(\alpha|\text{FORM, CON, MOR, } \alpha_{\text{num}}, \alpha_{\text{subj}}) +
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(\beta_{\text{form}})(\beta_{\text{con}})(1 - \beta_{\text{mor}})(1 - \beta_{\alpha}) \times p(\alpha|\text{FORM, CON, MOR, } \alpha_{\text{num}}, \alpha_{\text{subj}}) +
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(\beta_{\text{form}})(\beta_{\text{con}})(1 - \beta_{\text{mor}})(1 - \beta_{\alpha}) \times p(\alpha|\text{FORM, CON, MOR, } \alpha_{\text{num}}, \alpha_{\text{subj}}) +
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(\beta_{\text{form}})(\beta_{\text{con}})(1 - \beta_{\text{mor}})(1 - \beta_{\alpha}) \times p(\alpha|\text{FORM, CON, MOR, } \alpha_{\text{num}}, \alpha_{\text{subj}})
\]

\[
\times p(\alpha|\text{FORM, CON, MOR, } \alpha_{\text{num}}, \alpha_{\text{subj}})
\]

Forsythe & Pearl 2019, Pearl & Forsythe under review
We allow $0.00 \leq \sigma \leq 4.00$ and $0 \leq \beta \leq 1$, and see which $\sigma$ and $\beta$ value combinations best predict child and adult pronoun interpretation behavior.
What input is the modeled listener using to represent the various information types?
54,757 utterances of Mexico City spontaneous child-directed speech to children 1;6-5;11 from the Schmitt-Miller corpus (Miller & Schmitt 2012).
Bayesian inference

inaccurate representations

inaccurate deployment

inaccurate both

\[ p(\alpha_{subj,SG}|\text{FORM, CON, MOR}) \propto p(\alpha_{subj,SG}) \times p(\text{FORM}|\alpha_{subj,SG}) \times p(\text{CON}|\alpha_{subj,SG}) \times p(\text{MOR}|\alpha_{subj,SG}) \]

<table>
<thead>
<tr>
<th>antecedent type</th>
<th>prior</th>
<th>likelihoods</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( p(\alpha) )</td>
<td>( p(\text{FORM}</td>
</tr>
<tr>
<td>SUBJ</td>
<td>0.362</td>
<td>0.938 0.062</td>
</tr>
<tr>
<td>PL</td>
<td>0.071</td>
<td>0.984 0.016</td>
</tr>
<tr>
<td>¬SUBJ</td>
<td>0.438</td>
<td>0.817 0.183</td>
</tr>
<tr>
<td>PL</td>
<td>0.129</td>
<td>0.959 0.041</td>
</tr>
</tbody>
</table>

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

inaccurate deployment

inaccurate both

\[ p(\alpha_{subj,SG}|\text{FORM, CON, MOR}) \propto p(\alpha_{subj,SG}) \times p(\text{FORM}|\alpha_{subj,SG}) \times p(\text{CON}|\alpha_{subj,SG}) \times p(\text{MOR}|\alpha_{subj,SG}) \]

Singel antecedents generally occur more often.

Forsythe & Pearl 2019, Pearl & Forsythe under review
The null pronoun form is generally used, though some antecedent types use it more often.
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

inaccurate deployment

inaccurate both

\[
p(\alpha_{\text{subj.SG}}|\text{FORM, CON, MOR}) \propto p(\alpha_{\text{subj.SG}}) \times p(\text{FORM}|\alpha_{\text{subj.SG}}) \times p(\text{CON}|\alpha_{\text{subj.SG}}) \times p(\text{MOR}|\alpha_{\text{subj.SG}})
\]

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

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

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

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

Baseline: accurate representations and deployment

\[ p(\alpha_{\text{subj},SG} | \text{FORM, CON, MOR}) \propto p(\alpha_{\text{subj},SG}) \times p(\text{FORM} | \alpha_{\text{subj},SG}) \times p(\text{CON} | \alpha_{\text{subj},SG}) \times p(\text{MOR} | \alpha_{\text{subj},SG}) \]

0 free parameters

Forsythe & Pearl 2019, Pearl & Forsythe under review
Understanding the development of pronoun interpretation

baseline: accurate representations and deployment

inaccurate deployment

inaccurate both

inaccurate representations

4 free parameters: $\sigma_\alpha$, $\sigma_{form}$, $\sigma_{con}$, $\sigma_{mor}$
Understanding the development of pronoun interpretation

Baseline: accurate representations and deployment

Inaccurate representations

Inaccurate deployment

Forsythe & Pearl 2019, Pearl & Forsythe under review
Understanding the development of pronoun interpretation

Baseline: accurate representations and deployment

\[ p \] 0 free parameters

Inaccurate representations

\[ p_\sigma \] 4 free parameters: \( \sigma_\alpha, \sigma_{\text{form}}, \sigma_{\text{con}}, \sigma_{\text{mor}} \)

Inaccurate deployment

\[ p_\beta \] 4 free parameters: \( \beta_\alpha, \beta_{\text{form}}, \beta_{\text{con}}, \beta_{\text{mor}} \)

Inaccurate both

\[ p_{\sigma, \beta} \] 8 free parameters: \( \sigma_\alpha, \sigma_{\text{form}}, \sigma_{\text{con}}, \sigma_{\text{mor}}, \beta_\alpha, \beta_{\text{form}}, \beta_{\text{con}}, \beta_{\text{mor}} \)

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**
  - $p_\sigma$ 4 free parameters: $\sigma_\alpha$, $\sigma_{\text{form}}$, $\sigma_{\text{con}}$, $\sigma_{\text{mor}}$

- **Inaccurate deployment**
  - $p_\beta$ 4 free parameters: $\beta_\alpha$, $\beta_{\text{form}}$, $\beta_{\text{con}}$, $\beta_{\text{mor}}$

- **Inaccurate both**
  - $p_{\sigma,\beta}$ 8 free parameters: $\sigma_\alpha$, $\sigma_{\text{form}}$, $\sigma_{\text{con}}$, $\sigma_{\text{mor}}$, $\beta_\alpha$, $\beta_{\text{form}}$, $\beta_{\text{con}}$, $\beta_{\text{mor}}$

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

\( p_\sigma \) 4 free parameters: \( \sigma_\alpha, \sigma_{\text{form}}, \sigma_{\text{con}}, \sigma_{\text{mor}} \)

inaccurate deployment

\( p_\beta \) 4 free parameters: \( \beta_\alpha, \beta_{\text{form}}, \beta_{\text{con}}, \beta_{\text{mor}} \)

inaccurate both

\( p_{\sigma,\beta} \) 8 free parameters: \( \sigma_\alpha, \sigma_{\text{form}}, \sigma_{\text{con}}, \sigma_{\text{mor}}, \beta_\alpha, \beta_{\text{form}}, \beta_{\text{con}}, \beta_{\text{mor}} \)

Forsythe & Pearl 2019, Pearl & Forsythe under review
Understanding the development of pronoun interpretation

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

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

Baseline: accurate representations and deployment
\[ p_0 \text{ free parameters} \]

Inaccurate representations
\[ p_\sigma \text{ 4 free parameters: } \sigma_\alpha, \sigma_{\text{form}}, \sigma_{\text{conv}}, \sigma_{\text{mor}} \]

Inaccurate deployment
\[ p_\beta \text{ 4 free parameters: } \beta_\alpha, \beta_{\text{form}}, \beta_{\text{conv}}, \beta_{\text{mor}} \]

Inaccurate both
\[ p_{\sigma,\beta} \text{ 8 free parameters: } \sigma_\alpha, \sigma_{\text{form}}, \sigma_{\text{conv}}, \sigma_{\text{mor}}, \beta_\alpha, \beta_{\text{form}}, \beta_{\text{conv}}, \beta_{\text{mor}} \]

Forsythe & Pearl 2019, Pearl & Forsythe under review
Understanding the development of pronoun interpretation

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

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

baseline: accurate representations and deployment

\[ p \sigma \]

4 free parameters: \( \sigma_{\alpha}, \sigma_{\text{form}}, \sigma_{\text{con}}, \sigma_{\text{mor}} \)

inaccurate representations

\[ p \sigma \]

4 free parameters: \( \sigma_{\alpha}, \sigma_{\text{form}}, \sigma_{\text{con}}, \sigma_{\text{mor}} \)

inaccurate deployment

\[ p \beta \]

4 free parameters: \( \beta_{\alpha}, \beta_{\text{form}}, \beta_{\text{con}}, \beta_{\text{mor}} \)

inaccurate both

\[ p \sigma, \beta \]

8 free parameters: \( \sigma_{\alpha}, \sigma_{\text{form}}, \sigma_{\text{con}}, \sigma_{\text{mor}}, \beta_{\alpha}, \beta_{\text{form}}, \beta_{\text{con}}, \beta_{\text{mor}} \)

more parameters = higher score, closer to 0 is better

\[ \text{BIC} = \# \text{parameters} \cdot \log(|\text{data}|) – 2 \cdot \log(\text{model fit}) \]

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

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

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

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

baseline: accurate representations and deployment

$p_0$ 0 free parameters

inaccurate representations

$p_\sigma$ 4 free parameters: $\sigma_\alpha$, $\sigma_{form}$, $\sigma_{con}$, $\sigma_{mor}$

inaccurate deployment

$p_\beta$ 4 free parameters: $\beta_\alpha$, $\beta_{form}$, $\beta_{con}$, $\beta_{mor}$

inaccurate both

$p_{\sigma,\beta}$ 8 free parameters: $\sigma_\alpha$, $\sigma_{form}$, $\sigma_{con}$, $\sigma_{mor}$, $\beta_\alpha$, $\beta_{form}$, $\beta_{con}$, $\beta_{mor}$

Forsythe & Pearl 2019, Pearl & Forsythe under review
Understanding the development of pronoun interpretation

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

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

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

Baseline: accurate representations and deployment

- $$p_0$$ free parameters

Inaccurate representations

- $$p_\sigma$$ 4 free parameters: $$\sigma_\alpha, \sigma_{\text{form}}, \sigma_{\text{con}}, \sigma_{\text{mor}}$$

Inaccurate deployment

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Inaccurate both

- $$p_{\sigma,\beta}$$ 8 free parameters: $$\sigma_\alpha, \sigma_{\text{form}}, \sigma_{\text{con}}, \sigma_{\text{mor}}, \beta_\alpha, \beta_{\text{form}}, \beta_{\text{con}}, \beta_{\text{mor}}$$

Forsythe & Pearl 2019, Pearl & Forsythe under review
Understanding the development of pronoun interpretation

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

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Forsythe & Pearl 2019, Pearl & Forsythe under review
Understanding the development of pronoun interpretation

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

0 ≤ BIC ≤ ∞ (closer to 0 is better)
Kass & Raferty 1995: BIC scores within 2.0 are equivalent

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...though all 3 inaccurate variants are far better than the baseline of both accurate representations and accurate deployment.
Understanding the development of pronoun interpretation

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

Kass & Raferty 1995: BIC scores within 2.0 are equivalent

This same pattern holds for 4-year-olds and 5-year-olds, too.
Understanding the development of pronoun interpretation

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

Kass & Raferty 1995: BIC scores within 2.0 are equivalent

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

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

Kass & Raferty 1995: BIC scores within 2.0 are equivalent

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

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

Kass & Raferty 1995: BIC scores within 2.0 are equivalent

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…but within the inaccurate variants, the inaccurate representations variant is better than the other two.
Understanding the development of pronoun interpretation

Kass & Raferty 1995: BIC scores within 2.0 are equivalent

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

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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

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

Kass & Raferty 1995: BIC scores within 2.0 are equivalent

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Becoming adult-like doesn’t mean becoming accurate!
Understanding the development of pronoun interpretation

0 \leq \text{BIC} \leq \infty \text{ (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.
Understanding the development of pronoun interpretation

We know that adults inaccurately represent the available information.

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Kass & Raferty 1995: BIC scores within 2.0 are equivalent

0 ≤ BIC ≤ ∞ (closer to 0 is better)
Understanding the development of pronoun interpretation

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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

0 ≤ BIC ≤ ∞ (closer to 0 is better)

Kass & Raferty 1995: BIC scores within 2.0 are equivalent

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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?
Understanding the development of pronoun interpretation

Kass & Raferty 1995: BIC scores within 2.0 are equivalent

<table>
<thead>
<tr>
<th>age</th>
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<th>inacc deploy</th>
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<tbody>
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0 ≤ BIC ≤ ∞ (closer to 0 is better)

We know that adults accurately deploy their representations.

Forsythe & Pearl 2019, Pearl & Forsythe under review
Understanding the development of pronoun interpretation

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

Kass & Raferty 1995: BIC scores within 2.0 are equivalent

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Development: How much < 1 are the $\beta$ values that the best-fitting child model used that relied on inaccurate deployment?
Understanding the development of pronoun interpretation

\[0.00 \leq \sigma \leq 4.00\]
\[0 \leq \beta \leq 1\]

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Forsythe & Pearl 2019, Pearl & Forsythe under review
Understanding the development of pronoun interpretation

Inaccurate representations, but accurate deployment: equivalent to always paying attention to all information ($\beta=1$).
Understanding the development of pronoun interpretation

Both adults and children completely smooth away information about the prior over possible antecedents ($\sigma_\alpha$).

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No change needed!

Note: This is functionally the same as never using this information (as if $\beta_\alpha = 0.00$).
Understanding the development of pronoun interpretation

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

Quantitative differences: Children smooth more overall ($\sigma = 0.00-0.28$) compared to adults ($\sigma = 0.25-0.33$).

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How much difference does this make?

Forsythe & Pearl 2019, Pearl & Forsythe under review
Understanding the development of pronoun interpretation

How much difference does this make?

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Forsythe & Pearl 2019, Pearl & Forsythe under review
Understanding the development of pronoun interpretation

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Not a lot for the higher values.

Forsythe & Pearl 2019, Pearl & Forsythe under review
Understanding the development of pronoun interpretation

More for lower values.

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Forsythe & Pearl 2019, Pearl & Forsythe under review
Understanding the development of pronoun interpretation

More for lower values.

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Forsythe & Pearl 2019, Pearl & Forsythe under review
Understanding the development of pronoun interpretation

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

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σ = 0.00-0.28, σ = 0.25-0.33

Forsythe & Pearl 2019, Pearl & Forsythe under review
Understanding the development of pronoun interpretation

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

Forsythe & Pearl 2019, Pearl & Forsythe under review

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Understanding the development of pronoun interpretation

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

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<tr>
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\( \sigma = 0.25-0.33 \) \( \sigma = 0.00-0.28 \)
Understanding the development of pronoun interpretation

Or... it could be that children have accurate representations, but inaccurate deployment. This would be a qualitative difference from adults.

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Forsythe & Pearl 2019, Pearl & Forsythe under review
Understanding the development of pronoun interpretation

Accurate representations have $\sigma = 1$.  

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Understanding the development of pronoun interpretation

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

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Forsythe & Pearl 2019, Pearl & Forsythe under review
Understanding the development of pronoun interpretation

The connective and agreement morphology are heeded varying amounts.

Forsythe & Pearl 2019, Pearl & Forsythe under review
Understanding the development of pronoun interpretation

The prior over antecedents and form are completely ignored ($\beta=0.00$).

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children: inaccurate deployment

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Forsythe & Pearl 2019, Pearl & Forsythe under review
Understanding the development of pronoun interpretation

\[
\frac{\text{PRONOUN}}{\sim} = \frac{\text{PRONOUN}}{\sim}
\]

\[0.00 \leq \sigma \leq 4.00\]

\[0 \leq \beta \leq 1\]

\[
\begin{array}{c|cccc|cccc}
\sigma_{\text{for}} & \sigma_{\text{con}} & \sigma_{\text{mor}} & \sigma_{\alpha} & \beta_{\text{for}} & \beta_{\text{con}} & \beta_{\text{mor}} & \beta_{\alpha} \\
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\end{array}
\]

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

So, a \(\beta_{\alpha}=0.00\) accomplishes the same thing as a \(\sigma_{\alpha}=0.00\), which is adult-like. Similarity!
Takeaway:
To become adult-like, children would need to switch to using most of their representations accurately (all the time)…
Understanding the development of pronoun interpretation

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

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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)
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)
Understanding the development of pronoun interpretation

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?
Understanding the development of pronoun interpretation

How plausible is this?

Adults smoothing away information:

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

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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
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.

| antecedent type | $p(\alpha)$ | $p(\text{FORM}|\alpha)$ | $p(\text{MOR}|\alpha)$ |
|------------------|-------------|--------------------------|------------------------|
| SUBJ SG          | 0.362       | 0.938                    | 0.998                  |
| SUBJ PL          | 0.071       | 0.016                    | 0.005                  |
| ~SUBJ SG         | 0.438       | 0.183                    | 0.998                  |
| ~SUBJ PL         | 0.129       | 0.041                    | 0.005                  |
Understanding the development of pronoun interpretation

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

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

Hannah Forsythe

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UCI QuantLang Collective

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PRONOUN ≠