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

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Pronoun interpretation

The girls wave at the teacher…

???

…and then she leaves.
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…

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…

...and then she leaves.

How to choose?
Use linguistic knowledge about connectives.

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

The girls wave at the teacher...

\[ \text{subject} \approx \text{pl} \quad \text{sg} \]

...and then she leaves.

\[ \text{sg} \]

What about when interpretation cues conflict?
Pronoun interpretation

What about when interpretation cues conflict?
Here, the connective “and then” signals the subject “the girls”, while the agreement signals the object “the teacher”.

The girls wave at the teacher…

and then she leaves.
Pronoun interpretation

The girls wave at the teacher…

**subject** ≈ \( \text{pl} \) \( \text{sg} \) ???

…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...

...and then she leaves.

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

The girls wave at the teacher…

...and then she leaves.

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…

…y después ella sale.

… and then she leaves.

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.
Pronoun interpretation

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 leaves.

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 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.
For Spanish-speaking adults…

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

Second, children need adult-like ability to deploy that knowledge in real time.
When both of these are adult-like, we should get adult-like pronoun interpretation.
Pronoun interpretation development

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, in prep
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, in prep
Understanding pronoun interpretation development

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

Forsythe & Pearl 2019, in prep
Understanding pronoun interpretation development

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

Forsythe & Pearl 2019, in prep
Empirical data on pronoun interpretation
Empirical data on pronoun interpretation

Las niñas saludan a la maestra…

The girls wave at the teacher…

…y después sale.

… and then leaves.

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

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

Adults (N=47)

Forsythe & Pearl 2019, in prep
Las niñas saludan a la maestra...

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

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

~3yrs  4yrs  ~5yrs  adults

Forsythe & Pearl 2019, in prep
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?

We can plot the rate of subject responses.

Forsythe & Pearl 2019, in prep
Empirical data on pronoun interpretation

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

…y después sale.

… and then PRONOUN leaves.

Rate of subject responses

~3yrs 4yrs ~5yrs adults

Context:
Does agreement favor the subject or the object?

Favored by agreement

Forsythe & Pearl 2019, in prep
Empirical data on pronoun interpretation

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

...y después salen.
... and then PRENOUN leave.

Context:
Does agreement favor the subject or the object?

Rate of subject responses

~3yrs 4yrs ~5yrs adults

Favored by agreement

Forsythe & Pearl 2019, in prep
Empirical data on pronoun interpretation

Las niñas saludan a la maestra...

The girls wave at the teacher...

...y después sale.

... and then PRONOUN leaves.

Rate of subject responses

Context:
Does agreement favor the subject or the object?

~3yrs 4yrs ~5yrs adults

Favored by agreement

Forsythe & Pearl 2019, in prep
Empirical data on pronoun interpretation

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

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

Favored by agreement

Rate of subject responses

~3yrs 4yrs ~5yrs adults

Context:
Does the pronoun form favor the subject or the object?
Empirical data on pronoun interpretation

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

Rate of subject responses

~3yrs 4yrs ~5yrs adults

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

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

Favored by agreement

∅ (favors subject)

≈ subject pl

sg

∅

(subject object)
Empirical data on pronoun interpretation

Las niñas saludan a la maestra... The girls wave at the teacher...
...y después ella sale. ... and then PRONOUN leaves.

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

Rate of subject responses

~3yrs 4yrs ~5yrs adults

Favored by agreement

Forsythe & Pearl 2019, in prep
Empirical data on pronoun interpretation

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

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

Rate of subject responses

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

Favored by agreement

Favored by form

Forsythe & Pearl 2019, in prep
Empirical data on pronoun interpretation

Las niñas saludan a la maestra...

The girls wave at the teacher...

...y después sale.

... and then PRONOUN leaves.

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

Rate of subject responses

~3yrs 4yrs ~5yrs adults

Favored by agreement

∅ (favors subject) overt (favors object)

Forsythe & Pearl 2019, in prep
Empirical data on pronoun interpretation

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

...porque... ... because PRONOUN leaves.

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

Rate of subject responses

Favored by agreement

Favored by form

∅ (favors subject) overt (favors object)

~3yrs 4yrs ~5yrs adults

Forsythe & Pearl 2019, in prep
Empirical data on pronoun interpretation

Favored by form

\(\emptyset\) (favors subject)  overt (favors object)

Favored by connective

\(y\) después (favors subject)  \(porque\) (favors object)

Rate of subject responses

~3yrs  4yrs  ~5yrs  adults

subject  object  subject  object  subject  object  subject  object

Favored by agreement

Forsythe & Pearl 2019, in prep
Empirical data on pronoun interpretation

Favored by form

Favored by connective

Favored by agreement
Empirical data on pronoun interpretation

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

Favored by agreement
- rate of subject responses
  - ~3yrs
  - 4yrs
  - ~5yrs
  - adults

Big qualitative picture:
Children don’t behave like adults.
Empirical data on pronoun interpretation

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

- Favored by agreement:
  - Rate of subject responses

- Favored by form:
  - Over (favors object)

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

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

Forsythe & Pearl 2019, in prep
Empirical data on pronoun interpretation

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

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

Rate of subject responses

Favored by form
- over (favors object)
- subject

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

Forsythe & Pearl 2019, in prep
The plan, part 2:
Use computational cognitive modeling to formally articulate the potential process of pronoun interpretation in the context of these multiple cues.
Understanding pronoun interpretation development

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

Forsythe & Pearl 2019, in prep
Understanding pronoun interpretation development

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, in prep
Understanding pronoun interpretation development

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

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

Bayesian inference

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

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

Forsythe & Pearl 2019, in prep
...given the particular context involving the pronoun’s form,
Modeling pronoun interpretation in context

Bayesian inference

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

\[ y \text{ después} \quad \text{porque} \]

...given the particular context involving the pronoun’s form, the connective,
Modeling pronoun interpretation in context

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

Bayesian inference

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

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

Forsythe & Pearl 2019, in prep
Modeling pronoun interpretation in context

Bayesian inference

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

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

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

$$e^{\sigma \cdot \ln(\text{probability})} = \text{probability}^\sigma$$
Modeling pronoun interpretation in context

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, in prep
Modeling pronoun interpretation in context

PRONOUN "≈ ≈ ≈ ≈"  

Forsythe & Pearl 2019, in prep

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.
Modeling pronoun interpretation in context

Bayesian inference

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

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, in prep
Modeling pronoun interpretation in context

One $\sigma$ for each information type:

(in the prior) $\sigma_\alpha$

(in the likelihood) $\sigma_{\text{form}}$, $\sigma_{\text{con}}$, $\sigma_{\text{mor}}$
Modeling pronoun interpretation in context

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

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.
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.
Modeling pronoun interpretation in context

Bayesian inference

inaccurate representations

interpretation

context

\begin{align*}
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}}) \\
\end{align*}

Not using information means not incorporating it into the inference.

Forsythe & Pearl 2019, in prep
Modeling pronoun interpretation in context

Bayesian inference

inaccurate representations

interpretation

context

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

Not using the prior means relying on a uniform prior.

Forsythe & Pearl 2019, in prep
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.
Modeling pronoun interpretation in context

Bayesian inference

inaccurate representations

PRONOUN

interpretation context

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

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.
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. Accuracy of deployment is inaccurate representations in context.

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

Forsythe & Pearl 2019, in prep.
Modeling pronoun interpretation in context

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, in prep
Modeling pronoun interpretation in context

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

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

Forsythe & Pearl 2019, in prep
Modeling pronoun interpretation in context

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

Forsythe & Pearl 2019, in prep
Modeling pronoun interpretation in context

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

Forsythe & Pearl 2019, in prep
Modeling pronoun interpretation in context

Bayesian inference

inaccurate representations

inaccurate deployment

inaccurate both

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

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

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

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

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

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

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

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

Forsythe & Pearl 2019, in prep
Modeling pronoun interpretation in context

Bayesian inference

inaccurate representations

inaccurate deployment

inaccurate both

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

Forsythe & Pearl 2019, in prep
Input to the modeled listener

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

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

inaccurate representations

inaccurate deployment

inaccurate both

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

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

Forsythe & Pearl 2019, in prep
Input to the modeled listener

From this, we estimate the relevant priors and likelihoods.

Forsythe & Pearl 2019, in prep
Bayesian inference

inaccurate representations

inaccurate deployment

inaccurate both

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

---

| antecedent type | prior $p(\alpha)$ | likelihoods $p(\text{FORM}|\alpha)$ | $p(\text{CON}|\alpha)$ | $p(\text{MOR}|\alpha)$ |
|-----------------|-------------------|-----------------|----------------|----------------|
| SUBJ            |                   |                 |                 |                 |
| SG              | 0.362             | 0.938           | 0.324           | 0.998           |
| PL              | 0.071             | 0.984           | 0.750           | 0.005           |
| −SUBJ           |                   |                 |                 |                 |
| SG              | 0.438             | 0.817           | 0.132           | 0.998           |
| PL              | 0.129             | 0.959           | 0.394           | 0.005           |

Singular antecedents generally occur more often.

Forsythe & Pearl 2019, in prep
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.
Bayesian inference

Input to the modeled listener

PRONOUN

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>prior FORM</th>
<th>prior overt</th>
<th>likelihoods CON</th>
<th>likelihoods MOR</th>
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<td>SUBJ</td>
<td>0.362</td>
<td>0.938</td>
<td>0.062</td>
<td>0.324</td>
<td>0.998</td>
</tr>
<tr>
<td></td>
<td>0.071</td>
<td>0.984</td>
<td>0.016</td>
<td>0.750</td>
<td>0.005</td>
</tr>
<tr>
<td>¬SUBJ</td>
<td>0.438</td>
<td>0.817</td>
<td>0.183</td>
<td>0.132</td>
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<td>0.129</td>
<td>0.959</td>
<td>0.041</td>
<td>0.394</td>
<td>0.005</td>
</tr>
</tbody>
</table>

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

Forsythe & Pearl 2019, in prep
Understanding the development of pronoun interpretation

The plan, part 2: Use the computational cognitive model to identify the specific 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.
Understanding the development of pronoun interpretation

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

0 free parameters

baseline: accurate representations and deployment

\[ p \]

Forsythe & Pearl 2019, in prep
Understanding the development of pronoun interpretation

- inaccurate deployment
- inaccurate both
- inaccurate representations

Baseline: accurate representations and deployment
- $p$ free parameters

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

Forsythe & Pearl 2019, in prep
Understanding the development of pronoun interpretation

- **Inaccurate both:** \( p_{\sigma,\beta} \)
- **Inaccurate representations:** \( p_{\sigma} \) 4 free parameters: \( \sigma_{\alpha}, \sigma_{\text{form}}, \sigma_{\text{conv}}, \sigma_{\text{mor}} \)
- **Inaccurate deployment:** \( p_{\beta} \) 4 free parameters: \( \beta_{\alpha}, \beta_{\text{form}}, \beta_{\text{conv}}, \beta_{\text{mor}} \)

Baseline: accurate representations and deployment \( p \) 0 free parameters

Forsythe & Pearl 2019, in prep
Understanding the development of pronoun interpretation

baseline: accurate representations and deployment $p$ 0 free parameters

inaccurate representations $p_{\sigma}$ 4 free parameters: $\sigma_{\alpha}, \sigma_{\text{form}}, \sigma_{\text{conv}}, \sigma_{\text{mor}}$

inaccurate deployment $p_{\beta}$ 4 free parameters: $\beta_{\alpha}, \beta_{\text{form}}, \beta_{\text{conv}}, \beta_{\text{mor}}$

inaccurate both $p_{\sigma,\beta}$ 8 free parameters: $\sigma_{\alpha}, \sigma_{\text{form}}, \sigma_{\text{conv}}, \sigma_{\text{mor}}, \beta_{\alpha}, \beta_{\text{form}}, \beta_{\text{conv}}, \beta_{\text{mor}}$

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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, in prep
The Bayesian Information Criterion (BIC) is one way to quantify this preference (Schwarz 1978).
Understanding the development of pronoun interpretation

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

0 ≤ BIC ≤ ∞ (closer to 0 is better)

baseline: accurate representations and deployment

$p_0$ free parameters

inaccurate representations

$p_σ$ 4 free parameters: $σ_α$, $σ_{form}$, $σ_{conv}$, $σ_{mor}$

inaccurate deployment

$p_β$ 4 free parameters: $β_α$, $β_{form}$, $β_{conv}$, $β_{mor}$

inaccurate both

$p_{σ,β}$ 8 free parameters: $σ_α$, $σ_{form}$, $σ_{conv}$, $σ_{mor}$, $β_α$, $β_{form}$, $β_{conv}$, $β_{mor}$

Forsythe & Pearl 2019, in prep
Understanding the development of pronoun interpretation

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

0 ≤ BIC ≤ ∞ (closer to 0 is better)

baseline: accurate representations and deployment

$p_0$ 0 free parameters

inaccurate representations

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

inaccurate deployment

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

inaccurate both

$p_{\sigma,\beta}$ 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, in prep
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: $\sigma_\alpha, \sigma_{\text{form}}, \sigma_{\text{con}}, \sigma_{\text{mor}}, \beta_\alpha, \beta_{\text{form}}, \beta_{\text{con}}, \beta_{\text{mor}}$

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

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

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

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

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

$0 \leq \text{BIC} \leq \infty$ (closer to 0 is better)
Understanding the development of pronoun interpretation

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

<table>
<thead>
<tr>
<th>age</th>
<th>baseline</th>
<th>inacc rep</th>
<th>inacc deploy</th>
<th>both inacc</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \leq 3 )</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>4</td>
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</tr>
<tr>
<td>( \geq 5 )</td>
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</table>

Forsythe & Pearl 2019, in prep
3-year-old pronoun interpretation behavior is best captured by children having inaccurate representations, but accurate deployment.
Understanding the development of pronoun interpretation

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

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

Forsythe & Pearl 2019, in prep
Understanding the development of pronoun interpretation

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

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

0 ≤ BIC ≤ ∞ (closer to 0 is better)

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</table>

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

Forsythe & Pearl 2019, in prep
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

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

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

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

\[ \approx \text{PRONOUN} = \approx \]

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

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

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

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

We know that adults inaccurately deploy their representations.

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

Forsythe & Pearl 2019, in prep
Understanding the development of pronoun interpretation

0 ≤ BIC ≤ ∞ (closer to 0 is better)

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So we can look at the β values to see which information is being ignored and how often it’s being ignored.
Understanding the development of pronoun interpretation

\[
\sim PRONOUN \sim
\]

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

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We can also look at the \(\sigma\) values to see how the inaccurate representations are inaccurate — are they too smooth or too sharp?
Understanding the development of pronoun interpretation

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

<table>
<thead>
<tr>
<th>(\sigma_{for})</th>
<th>(\sigma_{con})</th>
<th>(\sigma_{mor})</th>
<th>(\sigma_{a})</th>
<th>(\beta_{for})</th>
<th>(\beta_{con})</th>
<th>(\beta_{mor})</th>
<th>(\beta_{a})</th>
</tr>
</thead>
<tbody>
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<td>children: inaccurate representations</td>
<td></td>
<td></td>
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<tr>
<td>(\leq 3)</td>
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<td>1</td>
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</tbody>
</table>

0.01 \(\leq \sigma \leq 4.00\)

0 \(\leq \beta \leq 1\)

Forsythe & Pearl 2019, in prep
Understanding the development of pronoun interpretation

Adults pay much more attention to the *prior* over possible antecedents ($\beta_\alpha$) and agreement morphology ($\beta_{mor}$)…

<table>
<thead>
<tr>
<th>$\sigma_{for}$</th>
<th>$\sigma_{con}$</th>
<th>$\sigma_{mor}$</th>
<th>$\sigma_\alpha$</th>
<th>$\beta_{for}$</th>
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<tr>
<td>adults</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.25 0.40 0.80 0.98</td>
<td></td>
<td></td>
</tr>
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</table>

$0.01 \leq \sigma \leq 4.00$ $0 \leq \beta \leq 1$
Understanding the development of pronoun interpretation

...and much less attention to the pronoun form ($\beta_\alpha$) and the connective ($\beta_{con}$).

\[
\begin{array}{cccc|cccc}
\sigma_{for} & \sigma_{con} & \sigma_{mor} & \sigma_\alpha & \beta_{for} & \beta_{con} & \beta_{mor} & \beta_\alpha \\
\hline
\leq 3 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
4 & 1 & 1 & 1 & 1 \\
\geq 5 & 1 & 1 & 1 & 1 \\
\hline
\text{adults: both inaccurate} & 0.25 & 0.40 & 0.80 & 0.98 \\
\end{array}
\]
Understanding the development of pronoun interpretation

Becoming adult-like:

Learn how much to ignore certain information
(the pronoun form and connective more often, sometimes the agreement morphology, and occasionally even the prior).

Forsythe & Pearl 2019, in prep
What about the representations? Both child and adult representations are inaccurate, but *how are they inaccurate?*
Understanding the development of pronoun interpretation

Child representations, with $\sigma$ values often much $< 1$, seem to smooth away probability differences, effectively turning down the contrast.
Understanding the development of pronoun interpretation

PRONOUN = .23

σ = .23  .56 vs. .44

σ for σ con σ mor σ α | β for β con β mor β α

children: inaccurate representations

≤3 0.01 0.23 0.02 0.01 | 1 1 1 1

4   0.01 0.07 0.10 0.01 | 1 1 1 1

≥5 0.01 0.11 0.10 0.01 | 1 1 1 1

adults: both inaccurate

σ for σ con σ mor σ α | β for β con β mor β α

adults

0.25 0.48 0.80 0.98

? 0.75 vs. .25

0.01 ≤ σ ≤ 4.00  0 ≤ β ≤ 1

Forsythe & Pearl 2019, in prep
Understanding the development of pronoun interpretation

PRONOUN

$0.01 \leq \sigma \leq 4.00$

$0 \leq \beta \leq 1$

<table>
<thead>
<tr>
<th>$\sigma_\text{for}$</th>
<th>$\sigma_\text{con}$</th>
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$\sigma = .23$ vs. $.25$

$\sigma = .10$ vs. $.44$

$\sigma = .53$ vs. $.47$

Forsythe & Pearl 2019, in prep
Understanding the development of pronoun interpretation

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<tr>
<th></th>
<th>$\sigma_{for}$</th>
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$\sigma = 0.23$ vs. 0.25
$\sigma = 0.56$ vs. 0.44
$\sigma = 0.53$ vs. 0.47
$\sigma = 0.502$ vs. 0.498
Understanding the development of pronoun interpretation

Adults do this same extreme smoothing for the prior information.

<table>
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<tr>
<th></th>
<th>$\sigma_{for}$</th>
<th>$\sigma_{con}$</th>
<th>$\sigma_{mor}$</th>
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<td>0.48</td>
<td>0.30</td>
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</table>

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But adults substantially sharpen all the other information ($\sigma = 3.00, 4.00$)

Forsythe & Pearl 2019, in prep
Understanding the development of pronoun interpretation

Forsythe & Pearl 2019, in prep

\[ 0.01 \leq \sigma \leq 4.00 \]
\[ 0 \leq \beta \leq 1 \]

<table>
<thead>
<tr>
<th>( \sigma_{for} )</th>
<th>( \sigma_{con} )</th>
<th>( \sigma_{mor} )</th>
<th>( \sigma_{\alpha} )</th>
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</table>

children: inaccurate representations

adults: both inaccurate

\[ \sigma = 3.00 \]
\[ 0.75 \text{ vs. } 0.25 \]

\[ \sigma = 3.00 \]
\[ 0.96 \text{ vs. } 0.04 \]
Understanding the development of pronoun interpretation

\[ \begin{align*}
0.01 &\leq \sigma \leq 4.00 \\
0 &\leq \beta \leq 1
\end{align*} \]

<table>
<thead>
<tr>
<th>( \sigma_{for} )</th>
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</table>

\[ \sigma = 3.00 \quad .96 \text{ vs. } .04 \]
\[ \sigma = 4.00 \quad .99 \text{ vs. } .01 \]

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

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

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

Important: Being adult-like doesn’t mean being accurate!
Understanding the development of pronoun interpretation

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

Important: Being adult-like doesn’t mean being accurate!
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).
This helps us better understand what children need to do to become adult-like (and it seems to be about learning the right helpful biases).
Thank you!

Hannah Forsythe

UCI QuantLang Collective

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