Arguments from acquisition for how to solve the linking problem

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The little girl *blinked* the kitten on the stairs.
Linking theories

What is this likely to mean?

The little girl *blicked* the kitten on the stairs.
Linking theories

What is this likely to mean?

The little girl *blicked* the kitten on the stairs.

Event participants
Linking theories

What is this likely to mean?

Syntactic positions

Subject
Object
Oblique Object

The little girl *blicked* the kitten on the stairs.

Event participants
This event is much more likely…

The little girl *blicked* the kitten on the stairs.
The little girl *blicked* the kitten on the stairs. …compared to these.
The little girl *blicked* the kitten on the stairs.
We as adults have linking theories that help us interpret verbs in combination with their arguments.

The little girl blicked the kitten on the stairs.
We as adults have linking theories that help us interpret verbs in combination with their arguments.

We can also use these linking theories to produce verbs in combination with their arguments when we want to express a particular meaning.

Subject
Object
Oblique Object

The little girl blinked the kitten on the stairs.
These linking theories are mental representations that we as adults have developed. They let us link event participants and syntactic positions, so we know how to interpret an utterance — even when we don’t know what the verb means.

**Syntactic positions**

- Subject
- Object
- Oblique Object

**Event participants**

The little girl *blicked* the kitten on the stairs.
Linking theories

The little girl *blicked* the kitten on the stairs.

What does a linking theory look like?
What does a linking theory look like?

Syntax

The little girl *blicked* the kitten on the stairs.

Current proposals involve prior (innate) knowledge

**Event participant roles** = **Thematic roles**

Agent, Experiencer, Patient, Theme, Goal, Source, Location…
What does a linking theory look like?

Syntax

The little girl *blicked* the kitten on the stairs.

Event participant roles

= Thematic roles

Agent, Experiencer, Patient, Theme, Goal, Source, Location…
Linking theories

What does a linking theory look like?

Syntax

The little girl *blicked* the kitten on the stairs.

Subject
Object
Oblique Object

Event participant roles = Thematic roles

Agent, Experiencer, Patient, Theme, Goal, Source, Location…

The Uniformity of Theta Assignment Hypothesis

What does a linking theory look like?

Syntax

Event participant roles = Thematic roles

Agent, Experiencer, Patient, Theme, Goal, Source, Location…

UTAH
Thematic roles map to one of three fixed macro-roles.

proto-Agent
proto-Patient
Other
Linking theories

What does a linking theory look like?

Syntax

The little girl *blicked* the kitten on the stairs.

Event participant roles = Thematic roles

Intermediate representations

Mapping to syntax

UTAH

Thematic roles map to one of three *fixed macro-roles*.

Agent, Experiencer, Patient, Theme, Goal, Source, Location…
What does a linking theory look like?

Syntax

**Mapping to syntax**

The little girl *blicked* the kitten on the stairs.

These map to syntactic positions.

**UTAH**

fixed

**Intermediate representations**

Event participant roles

= Thematic roles

Agent, Experiencer, Patient, Theme, Goal, Source, Location…
What does a linking theory look like?

Syntax

Event participant roles = Thematic roles

Agent, Experiencer, Patient, Theme, Goal, Source, Location…

Mapping to syntax

Intermediate representations

The little girl *blicked* the kitten on the stairs.

These map to syntactic positions.

UTAH fixed
What does a linking theory look like?

**Syntax**

*Mapping to syntax*

*Intermediate representations*

**Event participant roles**

=  

**Thematic roles**

*Subject*  

*Object*  

*Oblique Object*  

The little girl *blicked* the kitten on the stairs.

**UTAH**

*fixed*

The (*relativized*) **UTAH**

Larson 1988, Larson 1990
Linking theories

What does a linking theory look like?

Syntax

Intermediate representations

Mapping to syntax

Event participant roles

Thematic roles

Agent, Experiencer, Patient, Theme, Goal, Source, Location…

The little girl blicked the kitten on the stairs.

Subject

Object

Oblique Object

Subject

Object

Oblique Object
Linking theories

What does a linking theory look like?

Syntax

Event participant roles

Thematic roles

Agent, Experiencer, Patient, Theme, Goal, Source, Location…

Mapping to syntax

Intermediate representations

Subject

Object

Oblique Object

The little girl \textit{blicked} the kitten on the stairs.

UTAH

rUTAH

Thematic roles are ordered relative to each other.

Agent > Experiencer > Theme > Patient > (Source, Goal, Location)
Linking theories

What does a linking theory look like?

Syntax

Mapping to syntax

Intermediate representations

Event participant roles = Thematic roles

UTAH

fixed

rUTAH

relative

The little girl \textit{blicked} the kitten on the stairs.

Whichsoever ones are present map in order to the available syntactic positions.

Agent, Experiencer, Patient, Theme, Goal, Source, Location…
What does a linking theory look like?

Syntax

Event participant roles

\[\text{Agent, Experiencer, Patient, Theme, Goal, Source, Location} \ldots\]

Intermediate representations

Mapping to syntax

Linking theories

The little girl \textit{blicked} the kitten on the stairs.

UTAH

\textit{fixed}

rUTAH

\textit{relative}

Agent \textit{>} Experiencer \textit{>} Theme \textit{>} Patient \textit{>} (Source, Goal, Location)

Whichever ones are present map in order to the available syntactic positions.
What does a linking theory look like?

Syntax
- Mapping to syntax
- Intermediate representations

Event participant roles = Thematic roles
- Agent, Experiencer, Patient, Theme, Goal, Source, Location...

UTAH & rUTAH assume the mapping to syntax is innate.

The little girl blicked the kitten on the stairs.

UTAH & rUTAH assume the mapping to syntax is innate.

Agent > Experiencer > Theme > Patient > (Source, Goal, Location)
Linking theories

What does a linking theory look like?

Syntax

Mapping to syntax

Intermediate representations

Event participant roles = Thematic roles

The little girl *blicked* the kitten on the stairs.

But it could be that this mapping is derived from language experience.

Agent > Experiencer > Theme > Patient > (Source, Goal, Location)

Agent, Experiencer, Patient, Theme, Goal, Source, Location…
What does a linking theory look like?

Syntax

Mapping to syntax

Intermediate representations

Event participant roles = Thematic roles

The little girl *blicked* the kitten on the stairs.

But it could be that this mapping is derived from language experience.
Linking theories

The little girl blicked the kitten on the stairs.

How do we tell which linking theory proposal is likely to be correct?

rUTAH

Agent > Experiencer >
Theme > Patient >
(Source, Goal, Location)

relative

fixed

UTAH
Linking theories

The little girl blicked the kitten on the stairs.

**Argument from acquisition:**
Which linking theory proposals are compatible with the observed development of this knowledge in children?

*Pearl 2017, Pearl et al. 2017*

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**rUTAH**
Agent > Experiencer >
Theme > Patient >
(Source, Goal, Location)

**UTAH**
relative
fixed
The little girl *blicked* the kitten on the stairs.

Good news: These proposals make developmental predictions.
Proposals relying on innate knowledge typically assume early maturation: the knowledge is present as early as we can test for it.

The little girl *blicked* the kitten on the stairs.
The little girl *blicked* the kitten *on* the stairs.

Implication: A modeled learner who has knowledge of the mapping to syntax should always match real children's behavior best.
The little girl *blicked* the kitten on the stairs.

Proposals relying on derived knowledge typically assume it takes some time for children to derive the knowledge from their input.
Linking theories

The little girl *blicked* the kitten on the stairs.

Implication: A modeled learner who has knowledge of the mapping to syntax should *not* always match real children’s behavior best.

A modeled learner *without* this knowledge should match younger children best.
Linking theories

The little girl *blicked* the kitten on the stairs.

The same evaluation can be done for modeled learners who use a fixed thematic system vs. a relative thematic system. Which ones match real children's behavior best?

**rUTAH**
- Agent > Experiencer > Theme > Patient > (Source, Goal, Location)

**UTAH**
- fixed

**relative**
Linking theories

The little girl *blicked* the kitten on the stairs.

So what behavior should we look at that would leverage linking theory knowledge?
The little girl *blicked* the kitten on the stairs.

One answer: The development of **verb classes** — how children cluster verbs together in order to generalize about verb linguistic behavior.
Linking theories

The little girl *blicked* the kitten on the stairs.

Why **verb classes**? Linking theories are precisely about one key aspect of verb behavior: how **verb arguments** are interpreted.

So, linking theory knowledge could affect how children cluster verbs together into **verb classes**.
How does linking knowledge affect verb clustering in children?

The kitten was *blicked* by the little girl.
How does linking knowledge affect verb clustering in children?

The kitten was *blicked* by the little girl.
Linking theories

How does linking knowledge affect verb clustering in children?

If children expect a mapping already, it’s salient when the mapping doesn’t hold.

Interpretation: movement, which is used to cluster verbs.

The kitten was *blicked* by the little girl.
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Linking theories

How does linking knowledge affect verb clustering in children?

If children don’t expect a mapping already, they may track the details of where certain thematic representations appear and use that to cluster verbs.

The kitten was *blicked* by the little girl.
Linking theories

How does linking knowledge affect verb clustering in children?

If children don’t expect a mapping already, they may track the details of where certain thematic representations appear and use that to cluster verbs.

The kitten was *blicked* by the little girl.

*blick:*
Subject/Highest-Syn = 2nd-Highest
Oblique/2nd-Highest-Syn = Highest

Agent > Experiencer >
Theme > Patient >
(Source, Goal, Location)
Linking theories

The little girl *blicked* the kitten on the stairs.

**Strong empirical foundation:**
We have a lot of empirical data about the development of **verb classes**: experimental studies of children’s behavior (output of acquisition) and corpus studies of their input.

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**rUTAH**
Agent > Experiencer >
Theme > Patient >
(Source, Goal, Location)

**relative**

**UTAH**

**fixed**
1. Evaluating different linking theory proposals using acquisition modeling

The little girl *blicked* the kitten on the stairs.
1. Evaluating different linking theory proposals using acquisition modeling

The little girl *blicked* the kitten on the stairs.
1. Evaluating different linking theory proposals using acquisition modeling

2. Exploring how a linking theory could be derived from children’s input

The little girl *blicked* the kitten on the stairs.
1. Evaluating different linking theory proposals using acquisition modeling

2. Exploring how a linking theory could be derived from children’s input
Goal:
Build a modeled learner who learns close enough to how real children learn to tell us something informative about these linking theory proposals.
Goal: Build a modeled learner who learns close enough to how real children learn to tell us something informative about these linking theory proposals.
Evaluating different linking theory proposals using acquisition modeling

Close enough to this process
Evaluating different linking theory proposals using acquisition modeling

Close enough to this process

…which has a lot going on. It can be helpful when acquisition modeling to think about five main parts.
Evaluating different linking theory proposals using acquisition modeling

five main parts

initial state
What does the child start with? What knowledge, abilities, and learning biases does the child already have?

N, V, Adj, P, …
Agent, Patient, Goal, …

h1
h2
x

five main parts

What does the child start with? What knowledge, abilities, and learning biases does the child already have?

N, V, Adj, P, …
Agent, Patient, Goal, …

h1
h2
x
Evaluating different linking theory proposals using acquisition modeling

**five main parts**

**initial state**
What does the child **start with?**
What knowledge, abilities, and learning biases does the child already have?

N, V, Adj, P, …
Agent, Patient, Goal, …

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Evaluating different linking theory proposals using acquisition modeling
Evaluating different linking theory proposals using acquisition modeling

five main parts

initial state

data intake

How does the modeled child perceive the input (= perceptual intake)? What part of the perceived data is used for acquisition (= acquisitional intake)?
Evaluating different linking theory proposals using acquisition modeling

five main parts

initial state

data intake
How does the modeled child perceive the input (= perceptual intake)? What part of the perceived data is used for acquisition (= acquisitional intake)?

The kitten was blicked by the little girl.
Evaluating different linking theory proposals using acquisition modeling

five main parts

initial state

data intake

How does the modeled child perceive the input (= perceptual intake)? What part of the perceived data is used for acquisition (= acquisitional intake)?

The kitten was blicked by the little girl.

blick: movement 2
Evaluating different linking theory proposals using acquisition modeling

five main parts

initial state

data intake

How does the modeled child perceive the input (= perceptual intake)? What part of the perceived data is used for acquisition (= acquisitional intake)?

The kitten was blicked by the little girl.

blick: Subject = proto-Patient
Oblique = proto-Agent

Pearl in press
Evaluating different linking theory proposals using acquisition modeling

five main parts

initial state

data intake

inference

How are \textit{updates} made to the modeled child's internal representations?

Pearl \textit{in press}
Evaluating different linking theory proposals using acquisition modeling

five main parts

initial state
data intake
inference

learning period

How long does the child have to learn?

ex: 3 years, ~1,000,000 data points
ex: 4 months, ~36,500 data points

Pearl in press
What does successful acquisition look like? What knowledge is the child trying to attain (often assessed in terms of observable behavior)?
What does successful acquisition look like? What knowledge is the child trying to attain (often assessed in terms of observable behavior)?

The little girl kissed the kitten on the stairs.
Evaluating different linking theory proposals using acquisition modeling

**five main parts**
- initial state
- data intake
- inference
- learning period
- target state

What does **successful acquisition** look like? What **knowledge** is the child trying to attain (often assessed in terms of observable behavior)?
Evaluating different linking theory proposals using acquisition modeling

five main parts

initial state
data intake
inference

learning period

target state
What does successful acquisition look like? What knowledge is the child trying to attain (often assessed in terms of observable behavior)?

pet
touch
hug

interpretations or productions in context

Pearl in press
If we can define those pieces, we can make sure we’ve captured the relevant parts of this acquisition process in our modeled learner.
So let’s do this for modeled learners who implement different linking theory proposals.
Evaluating different linking theory proposals using acquisition modeling

five main parts
initial state
data intake
inference
learning period

target state

Goal: Model the developmental trajectory of verb class knowledge from 3 to 4 to 5 years old in English

Source, Goal, Location

relative

fixed

Pearl & Sprouse 2019a
Evaluating different linking theory proposals using acquisition modeling

initial state

data intake inference target state
learning period

relative fixed

Agent > Experiencer > Theme > Patient > (Source, Goal, Location)

Pearl & Sprouse 2019a
Evaluating different linking theory proposals using acquisition modeling

Thematic roles that indicate event participant roles are salient to very young children. (<10 months: Gordon 2003; 6 months: Hamlin, Wynn, & Bloom 2007, Hamlin, Wynn, Bloom, & Mahajan 2011)
Evaluating different linking theory proposals using acquisition modeling.

Initial state:

- Agent > Experiencer
- Theme > Patient
- Source, Goal, Location

Target state:

- Data intake
- Inference
- Learning period

Thematic roles that indicate event participant roles are salient to very young children. (<10 months: Gordon 2003; 6 months: Hamlin, Wynn, & Bloom 2007, Hamlin, Wynn, Bloom, & Mahajan 2011)

Cognitively plausible.

Pearl & Sprouse 2019a
Children are also sensitive to the animacy of verb arguments.

The little girl *blicked* the kitten on the stairs.
Children pay attention to the linguistic context of a verb (its *syntactic frame*) to figure out how it behaves (e.g., Fisher et al. 2010, Gutman et al. 2015, Harrigan et al. 2016).

The little girl *blicked* the kitten on the stairs.
Children pay attention to the linguistic context of a verb (its syntactic frame) to figure out how it behaves (e.g., Fisher et al. 2010, Gutman et al. 2015, Harrigan et al. 2016).

The little girl *blicked* the kitten on the stairs.
Evaluating different linking theory proposals using acquisition modeling

Initial state

Agent > Experiencer > Theme > Patient > (Source, Goal, Location)

Relative

Fixed

Daemon intake inference target state

Learning period

\[ \text{data intake} \quad \text{inference} \quad \text{target state} \]

\[ \text{learning period} \]

\[ + \text{ whatever statistical learning abilities are required to do inference (Saffran et al. 1996, Gerken 2006, Mintz 2006, Xu & Tenenbaum 2007, Smith & Yu 2008) } \]

\[ \text{NP} \quad \_\_\_ \quad \text{NP} \quad \text{PP} \]

\[ \text{source, goal, location} \]

\[ \text{animate}, \text{non-animate} \]

\[ \text{fixed, relative} \]

\[ \text{rUTAH, UTAH} \]

\[ \text{Pearl & Sprouse 2019a} \]
Evaluating different linking theory proposals using acquisition modeling

**initial state**    **inference**    **target state**
learning period

input that yields data intake

Samples of child-directed speech

**CHILDES Treebank**

*Pearl & Sprouse 2013*

<3yrs
18 and 32 months
~40,000 utterances
239 verbs

<4yrs
18 and 48 months
~51,000 utterances
267 verbs

<5yrs
18 and 58 months
~56,500 utterances
284 verbs

The little girl *blicked* the kitten on the stairs.
<table>
<thead>
<tr>
<th>initial state</th>
<th>inference</th>
<th>target state</th>
</tr>
</thead>
<tbody>
<tr>
<td>learning period</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

data intake

The little girl *blicked* the kitten *on* the *stairs*.

NP ___ NP PP

syntactic frame

Pearl & Sprouse 2019a
Evaluating different linking theory proposals using acquisition modeling

initial state   inference   target state
learning period

data intake

The little girl *blicked* the kitten on the stairs.

NP ___   NP PP
NP ___   NP PP   -surface morphology
NP ___+past NP PP   +surface morphology

*syntactic frame*

Children may either ignore verb *surface morphology* (like the past tense marker -ed) or pay attention to it when encoding the syntactic frame information.
Evaluating different linking theory proposals using acquisition modeling

initial state  inference  target state
learning period

data intake

+animate  +animate  -animate
The little girl *blicked* the kitten on the stairs.

NP ___ NP PP  -surface morphology
NP ___+past NP PP  +surface morphology

Pearl & Sprouse 2019a
Evaluating different linking theory proposals using acquisition modeling

**initial state**    **inference**    **target state**
learning period

data intake

The little girl blicked the kitten on the stairs.

NP ___  NP PP  -surface morphology
NP ___+past NP PP  +surface morphology

blick:
3 no-movement

+expect-mapping

rUTAH

relative
fixed

Pearl & Sprouse 2019a
The little girl blicked the kitten on the stairs.

- animate
- animate
- animate

\[
\begin{align*}
\text{NP} & \quad \text{NP PP} \\
\text{NP} & \quad \text{+past NP PP} \\
\end{align*}
\]

- surface morphology

- expect-mapping

Subject = proto-Agent
Object = proto-Patient
Oblique = Other

+ surface morphology

rUTAH

UTAH

relative

fixed

Evaluating different linking theory proposals using acquisition modeling
The little girl blicked the kitten on the stairs.

**NP** ___ NP PP  
- surface morphology

**NP** ___ +past NP PP  
+ surface morphology

**blick:**

Highest-syn = Highest
2nd-Highest-syn = 2nd-Highest
3rd-Highest-syn = 3rd-Highest

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Pearl & Sprouse 2019a
Basic question: Is it possible for the child to use the **acquisitional intake** to achieve the **target knowledge/behavior**?
Basic question: Is it possible for the child to use the acquisitional intake to achieve the target knowledge/behavior?

Ideal learner model: not concerned with the cognitive limitations and incremental learning restrictions children have.

Concerned with what assumptions are useful for children to have.
Evaluating different linking theory proposals using acquisition modeling

**initial state**  **data intake**  **target state**

Inference

**learning period**

Basic question: Is it possible for the child to use the acquisitional intake to achieve the target knowledge/behavior?

Ideal learner model: not concerned with the cognitive limitations and incremental learning restrictions children have.

Concerned with what assumptions are useful for children to have.

It’s good to do this before we start worrying if the assumptions are usable by children.
Basic question: Is it possible for the child to use the *acquisitional intake* to achieve the *target knowledge/behavior*?

Learners use a **generative model** of how the observable data for each verb are created.
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*This represents how the different information is integrated into the process of determining a verb’s class.*

**Basic question:** Is it possible for the child to use the *acquisitional intake* to achieve the *target knowledge/behavior*?
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Learners use a generative model of how the observable data for each verb are created.

This represents how the different information is integrated into the process of determining a verb’s class.
Evaluating different linking theory proposals using acquisition modeling

Initial state | Data intake | Target state

Inference

Basic question: Is it possible for the child to use the acquisitional intake to achieve the target knowledge/behavior?

Learners use a generative model of how the observable data for each verb are created.

Each verb appears in a certain number of instances in the input.

“it’s falling off”
“she fell down”
“don’t fall!”
“is London Bridge falling down?”

Pearl & Sprouse 2019a
Evaluating different linking theory proposals using acquisition modeling

initial state  data intake  target state

inference

Basic question: Is it possible for the child to use the acquisitional intake to achieve the target knowledge/behavior?

Learners use a generative model of how the observable data for each verb are created.

Each instance is observed some number of times.

(3x) “it’s falling off”
“she fell down”  “don’t fall!”
“is London Bridge falling down?”

Pearl & Sprouse 2019a
Evaluating different linking theory proposals using acquisition modeling

Initial state  Data intake  Target state

Inference

Basic question: Is it possible for the child to use the acquisitional intake to achieve the target knowledge/behavior?

Each verb belongs to some class which determines its linguistic behavior. $\text{class}_7$
Evaluating different linking theory proposals using acquisition modeling

initial state  data intake  target state

inference

Basic question: Is it possible for the child to use the acquisitional intake to achieve the target knowledge/behavior?

Each verb belongs to some class which determines its linguistic behavior.

Objective: Infer verb class

(3x)

“it’s falling off”
“she fell down”  “don’t fall!”
“is London Bridge falling down?”

Pearl & Sprouse 2019a
Evaluating different linking theory proposals using acquisition modeling

Initial state  Data intake  Target state

Inference

Basic question: Is it possible for the child to use the acquisitional intake to achieve the target knowledge/behavior?

Each verb belongs to some class which determines its linguistic behavior. Objective: Infer verb class

The learner doesn’t know beforehand how many classes there are or which verbs belong to which. There’s a bias for classes in a power law distribution.

“(3x) “it’s falling off”
“she fell down” “don’t fall!”
“is London Bridge falling down?”

Pearl & Sprouse 2019a
Evaluating different linking theory proposals using acquisition modeling

**Initial state**  **Data intake**  **Target state**

**Inference**

**Basic question:** Is it possible for the child to use the acquisitional intake to achieve the target knowledge/behavior?

The learner doesn't know beforehand how many classes there are or which verbs belong to which. There's a bias for classes in a power law distribution.

A few classes with many members, and most classes with few members.

Each verb belongs to some class which determines its linguistic behavior. **Class**

Objective: Infer verb **class**

(3x)

"it's falling off"

"she fell down"  "don't fall!"

"is London Bridge falling down?"
Evaluating different linking theory proposals using acquisition modeling

**Initial state**  **Data Intake**  **Target State**

**Inference**

Basic question: Is it possible for the child to use the **acquisitional intake** to achieve the **target knowledge/behavior**?

Depending on the verb **class**, the **observed usage** will have certain characteristics.

<table>
<thead>
<tr>
<th>FALL</th>
</tr>
</thead>
<tbody>
<tr>
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</tr>
<tr>
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<tr>
<td>“don’t fall!”</td>
</tr>
<tr>
<td>“is London Bridge falling down?”</td>
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</table>

**class**

(3x)
Evaluating different linking theory proposals using acquisition modeling

- **Initial state**
- **Data intake**
- **Target state**

**Basic question:** Is it possible for the child to use the acquisitional intake to achieve the target knowledge/behavior?

These characteristics include binary choices such as whether the subject is animate or not.

- **FALL**
  - “it’s falling off”
  - “she fell down”
  - “don’t fall!”
  - “is London Bridge falling down?”

*Pearl & Sprouse 2019a*
Evaluating different linking theory proposals using acquisition modeling

initial state  data intake  target state

Basic question: Is it possible for the child to use the acquisitional intake to achieve the target knowledge/behavior?

Each class has a probability of preferring each option.

These characteristics include binary choices such as whether the subject is animate or not.

class 7

\[ \begin{align*}
+\text{anim} & \quad 0.3 \\
-\text{anim} & \quad 0.7 \\
\end{align*} \]

"it's falling off"
"she fell down"
"don't fall!"
"is London Bridge falling down?"

Pearl & Sprouse 2019a
Evaluating different linking theory proposals using acquisition modeling

**Initial state** | **Data Intake** | **Target State**

**Basic question:** Is it possible for the child to use the acquisitional intake to achieve the target knowledge/behavior?

Each class has a probability of preferring each option.

Binary choices:
- +/-animate subject
- +/-animate object
- +/-animate oblique object
- +/-movement (when +exp-mapping)

**Example utterances:**
- "it's falling off"
- "she fell down"
- "don't fall!"
- "is London Bridge falling down?"

**Class 7**
- `+anim` Subject
- `-anim`

**Probability:**
- Subject: 0.3
- Object: 0.7

*Pearl & Sprouse 2019a*
Evaluating different linking theory proposals using acquisition modeling

Basic question: Is it possible for the child to use the acquisitional intake to achieve the target knowledge/behavior?

Each class has a probability of preferring each option.

These characteristics include multinomial choices such as which syntactic frame a verb appears in.

-class7

-anim (3x)
“it’s falling off”
“she fell down” “don’t fall!”
“is London Bridge falling down?”

Pearl & Sprouse 2019a
Evaluating different linking theory proposals using acquisition modeling

initial state  data intake  target state

inference

Basic question: Is it possible for the child to use the acquisitional intake to achieve the target knowledge/behavior?

These characteristics include multinomial choices such as which syntactic frame a verb appears in.

\[ NP \ V \ PRT \]
\[ NP \ V \]
\[ \ldots \]
\[ NP \ V \ S \]

Each class has a probability of preferring each option.

- \textit{anim} (3x)
  
  "it's falling off"
  
  "she fell down"  "don't fall!"
  
  "is London Bridge falling down?"

Pearl & Sprouse 2019a
Evaluating different linking theory proposals using acquisition modeling

**Basic question**: Is it possible for the child to use the acquisitional intake to achieve the target knowledge/behavior?

Each class has a probability of preferring each option.

<table>
<thead>
<tr>
<th>Class</th>
<th>NP V</th>
<th>PRT</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.3</td>
<td>NP V</td>
<td>0.25</td>
<td>0</td>
</tr>
</tbody>
</table>

- **NP V PRT 0.3**
- **NP V 0.25**
- **NP V S 0**
Evaluating different linking theory proposals using acquisition modeling

**Initial state**

**Data intake**

**Target state**

**Inference**

Basic question: Is it possible for the child to use the acquisitional intake to achieve the target knowledge/behavior?

Each class has a probability of preferring each option.

Multinomial choices:

- Syntactic frame: **NP V PRT**
  - (when -exp-mapping)
  - Position of proto-Agent/Highest
  - Position of proto-Patient/2nd-Highest
  - Position of Other/3rd-Highest

```
Subject  Highest-syn
Object   2nd-Highest-syn
Oblique  Object  3rd-Highest-syn
```

FALL

-**anim**

```
“it’s falling off”
“she fell down”  “don’t fall!”
“is London Bridge falling down?”
```

Pearl & Sprouse 2019a
Evaluating different linking theory proposals using acquisition modeling

- **initial state**
- **data intake**
- **target state**

**Basic question:** Is it possible for the child to use the acquisitional intake to achieve the target knowledge/behavior?

Using the observed instances of verb usage, Bayesian inference can be used to determine …

- **-anim**
  - “it’s falling off”
  - “she fell down”
  - “don’t fall!!”
  - “is London Bridge falling down?”

Pearl & Sprouse 2019a
Evaluating different linking theory proposals using acquisition modeling

Basic question: Is it possible for the child to use the *acquisitional intake* to achieve the *target knowledge/behavior*?

Using the observed instances of *verb usage*, Bayesian inference can be used to determine
- how many classes there are

Using the observed instances of *verb usage*, Bayesian inference can be used to determine
- how many classes there are

*-anim (3x)
“it’s falling off”
“she fell down” “don’t fall!”
“is London Bridge falling down?”

Pearl & Sprouse 2019a
Evaluating different linking theory proposals using acquisition modeling

**Basic question**: Is it possible for the child to use the acquisitional intake to achieve the target knowledge/behavior?

Using the observed instances of verb usage, Bayesian inference can be used to determine
- how many classes there are
- which class each verb belongs to

- **class**
- **FALL (3x)**
  - “it’s falling off”
  - “she fell down”
  - “don’t fall!”
  - “is London Bridge falling down?”

**Pearl & Sprouse 2019a**
Basic question: Is it possible for the child to use the acquisitional intake to achieve the target knowledge/behavior?

Using the observed instances of verb usage, Bayesian inference can be used to determine

- how many classes there are
- which class each verb belongs to
- what the characteristics are of each class
Evaluating different linking theory proposals using acquisition modeling

initial state  data intake  target state

inference

Basic question: Is it possible for the child to use the acquisitional intake to achieve the target knowledge/behavior?

Best answer: maximizes the probability of the observed data.

Using the observed instances of verb usage, Bayesian inference can be used to determine
- how many classes there are
- which class each verb belongs to
- what the characteristics are of each class

\[ F_{ji} \]

-anim

(3x)

“it’s falling off”

“she fell down”  “don’t fall!”

“is London Bridge falling down?”
Evaluating different linking theory proposals using acquisition modeling

**initial state**  **data intake**  **target state**

**Basic question:** Is it possible for the child to use the acquisitional intake to achieve the target knowledge/behavior?

\[ p_{c_j} = P(c_j | c_{-j}, \gamma, F_{-j}, \lambda) = P_{\text{cat}_j} \times P_{\text{binary}_{c_j}} \times P_{\text{multinomial}_{c_j}} \]

+ Gibbs sampling

Using the observed instances of verb usage, Bayesian inference can be used to determine
- how many classes there are
- which class each verb belongs to
- what the characteristics are of each class

- **-anim** (3x)
  - “it’s falling off”
  - “she fell down”  “don’t fall!”
  - “is London Bridge falling down?”
Evaluating different linking theory proposals using acquisition modeling

initial state  data intake  target state

Basic question: Is it possible for the child to use the acquisitional intake to achieve the target knowledge/behavior?

\[ p_{c_j} = P(c_j|c_{-j}, \gamma_c, F_{-j}, \lambda) = P_{cat_j} * P_{binary_{c_j}} * P_{multinomial_{c_j}} \]

+ Gibbs sampling

This is what makes this an ideal learner model — the inference computation is accomplished using something that’s not incremental or constrained, and is guaranteed to converge on the optimal answer, given enough time to run.

Using the observed instances of verb usage, Bayesian inference can be used to determine
- how many classes there are
- which class each verb belongs to
- what the characteristics are of each class

Using the observed instances of verb usage, Bayesian inference can be used to determine:
- how many classes there are
- which class each verb belongs to
- what the characteristics are of each class

\[ F_{ji} \]

- **anim** (3x)
  - “it's falling off”
  - “she fell down”
  - “don’t fall!”
  - “is London Bridge falling down?”

Pearl & Sprouse 2019a
Evaluating different linking theory proposals using acquisition modeling

**initial state**  **data intake**  **target state**

**inference**

\[ p_{c_j} = P(c_j|c_{-j}, \gamma_c, F_{-j}, \lambda) = p_{cat_j} \cdot p_{binary_{cj}} \cdot p_{multinomial_{cj}} \]

+ Gibbs sampling

**Goal:** Determine what the best answer we can get is, given this characterization of the learning problem.

Using the observed instances of verb usage, **Bayesian inference** can be used to determine
• how many classes there are
• which class each verb belongs to
• what the characteristics are of each class

**Basic question:** Is it possible for the child to use the **acquisitional intake** to achieve the **target knowledge/behavior**?

Using the *falling* instances of verb usage, Bayesian inference can be used to determine
• how many classes there are
• which class each verb belongs to
• what the characteristics are of each class

- **-anim** (3x)
  • “it’s falling off”
  • “she fell down”  “don’t fall!”
  • “is London Bridge falling down?”

*Pearl & Sprouse 2019a*
Evaluating different linking theory proposals using acquisition modeling

**Basic question:** Is it possible for the child to use the acquisitional intake to achieve the target knowledge/behavior?

- *-anim (3x)*
  - "it's falling off"
  - "she fell down"  "don't fall!"
  - "is London Bridge falling down?"
Evaluating different linking theory proposals using acquisition modeling

**Basic question:** Is it possible for the child to use the acquisitional intake to achieve the target knowledge/behavior?

**Goal:** Determine if the information provided in the modeled learner’s acquisitional intake is sufficient to identify verb classes the way children do.

- **-anim** (3x)
  - “it’s falling off”
  - “she fell down”
  - “don’t fall!!”
  - “is London Bridge falling down?”

*Pearl & Sprouse 2019a*
Evaluating different linking theory proposals using acquisition modeling

- initial state
- data intake
- inference

target state

So what does the target knowledge/behavior look like?
Goal: Model the developmental trajectory of verb class knowledge from 3 to 4 to 5 years old in English.
Evaluating different linking theory proposals using acquisition modeling

initial state    data intake    inference

target state    verb class knowledge

Survey of 38 experimental studies on children’s production and comprehension of specific verbs

Pearl & Sprouse 2019a
Survey of 38 experimental studies on children’s production and comprehension of specific verbs...yields 12 verb behaviors

+/-passive +unaccusative
+ditransitive +control-object
+raising-object
+raising-subject +control-subject
+that-comp
+whether/if-comp +subject-experiencer
+non-finite to-comp +object-experiencer
These *verb behaviors* yield a number of *verb classes* at each age

*Verbs only belong to one class*
These verb behaviors yield a number of verb classes at each age

Example classes  *Verbs only belong to one class*

[+passive]: carry, chase, crash, drop, eat, hit, hold, hurt, jump, kick, kiss, knock, lick, punch, push, scratch, shake, turn, wash, watch

[-passive]: believe, remember

[+non-finite to]: ask, have, need, start, suppose, teach, try, use, want

[+that-comp]: bet, hope, think, wish

[+passive, +non-finite to]: like

[+passive, +that-comp]: see
These verb behaviors yield a number of verb classes at each age

**Example classes**  *Verbs only belong to one class*

[+passive]: bite, bump, carry, chase, crash, drop, find, hit, hold, hurt, jump, kick, kill, kiss, knock, lick, pull, punch, push, ride, scratch, shake, shoot, turn, wash, watch

[-passive]: believe, remember

[+that-comp]: bet, hope, think, wish

<4yrs

[+non-finite to, +raising-obj]: need

[+non-finite to, +raising-obj, +control-subj]: want

[+passive, +non-finite to, +psych-subj]: like

[+passive, +that-comp]: see
These verb behaviors yield a number of verb classes at each age

Example classes *Verbs only belong to one class*

[+passive]: bite, bump, carry, chase, crash, drop, find, hit, hold, hurt, jump, kick, kill, kiss, knock, lick, pull, push, ride, scratch, shake, shoot, turn, wash, watch

[-passive]: believe, remember

[+that-comp]: bet, dream, guess, hope, lie, pretend, think, wish

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[+non-finite to, +raising-obj, +control-subj]: want

[+passive, +non-finite to, +psych-subj]: like

[+passive, +that-comp, +whether/if-comp]: see

Pearl & Sprouse 2019a
These verb behaviors yield a number of verb classes at each age:

- **<3yrs**
  - 15 classes of 60 verbs total

- **<4yrs**
  - 23 classes of 76 verbs total

- **<5yrs**
  - 25 classes of 84 verbs total
Evaluating different linking theory proposals using acquisition modeling

**Evaluation:**
How well did the modeled learner do at finding these verb classes?

Pearl & Sprouse 2019a
Evaluating different linking theory proposals using acquisition modeling

**Evaluation:**
How well did the modeled learner do at finding these verb classes?

**Implementation:**
Rand Index

0.0 ≤ RI ≤ 1.0
Evaluating different linking theory proposals using acquisition modeling

**Evaluation:**
How well did the modeled learner do at finding these verb classes?

**Implementation:**
Rand Index

\[ 0.0 \leq RI \leq 1.0 \]

**Intuition:** Get credit for putting things together that belong together and keeping things apart that should be apart.
Evaluation:
How well did the modeled learner do at finding these verb classes?

For each pair of verbs in the inferred classes: \( \text{verb}_i \quad \text{verb}_j \)

**Inferred Class**

- Same class
- Different class

**Child Class**

- Same class
- Different class

Intuition: Get credit for putting things together that belong together and keeping things apart that should be apart.

Rand Index

\[ 0.0 \leq RI \leq 1.0 \]

Evaluating different linking theory proposals using acquisition modeling
Evaluating different linking theory proposals using acquisition modeling

**Evaluation:**
How well did the modeled learner do at finding these verb classes?

<table>
<thead>
<tr>
<th>Child Class</th>
<th>Inferred Class</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Same class</em></td>
<td><em>Same class</em></td>
</tr>
<tr>
<td><em>Different class</em></td>
<td><em>Different class</em></td>
</tr>
</tbody>
</table>

For each pair of verbs in the inferred classes: $\text{verb}_i, \text{verb}_j$

**Inferred Class**

- **Same class**
- **Different class**

Intuition: Get credit for putting things together that belong together and keeping things apart that should be apart.

 Rand Index: $0.0 \leq RI \leq 1.0$

Pearl & Sprouse 2019a
Evaluating different linking theory proposals using acquisition modeling

**Evaluation:**
How well did the modeled learner do at finding these verb classes?

For each pair of verbs in the inferred classes: \( \text{verb}_i, \text{verb}_j \)

<table>
<thead>
<tr>
<th>Child Class</th>
<th>Inferred Class</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Same class</em></td>
<td><em>Same class</em></td>
</tr>
<tr>
<td><em>Different class</em></td>
<td><em>Different class</em></td>
</tr>
</tbody>
</table>

Intuition: Get credit for putting things together that belong together and keeping things apart that should be apart.

Pearl & Sprouse 2019a

<5yrs

<3yrs

<4yrs

<5yrs

23 classes

15 classes

25 classes

0.0 \( \leq \) RI \( \leq \) 1.0

Rand Index

Pearl & Sprouse 2019a
Evaluating different linking theory proposals using acquisition modeling

Evaluation:
How well did the modeled learner do at finding these verb classes?

For each pair of verbs in the inferred classes: \( \text{verb}_i, \text{verb}_j \)

**Inferred Class**

- **Same class**
  - True Positive
  - False Negative

- **Different class**
  - False Positive
  - True Negative

Intuition: Get credit for putting things together that belong together and keeping things apart that should be apart.

Rand Index
0.0 \( \leq \) RI \( \leq \) 1.0

Pearl & Sprouse 2019a
Evaluating different linking theory proposals using acquisition modeling

**Evaluation:**
How well did the modeled learner do at finding these verb classes?

For each pair of verbs in the inferred classes: $\text{verb}_i \quad \text{verb}_j$

<table>
<thead>
<tr>
<th>Child Class</th>
<th>Inferred Class</th>
<th>True Positives</th>
<th>True Negatives</th>
<th>False Positives</th>
<th>False Negatives</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Same class</em></td>
<td><em>Same class</em></td>
<td>True Positive</td>
<td>True Negative</td>
<td>False Positive</td>
<td>True Negative</td>
</tr>
<tr>
<td><em>Different class</em></td>
<td><em>Different class</em></td>
<td>True Positive</td>
<td>True Negative</td>
<td>False Positive</td>
<td>True Negative</td>
</tr>
</tbody>
</table>

**Rand Index**

$$\frac{\text{True Positives} + \text{True Negatives}}{\text{True Positives} + \text{True Negatives} + \text{False Positives} + \text{False Negatives}}$$

Intuition: Get credit for putting things together that belong together and keeping things apart that should be apart.

Pearl & Sprouse 2019a
Evaluating different linking theory proposals using acquisition modeling

**Evaluation:**
How well did the modeled learner do at finding these verb classes?

But how do we know we’re doing better than chance?

**Rand Index**

True Positives + True Negatives

True Positives + True Negatives + False Positives + False Negatives

Pearl & Sprouse 2019a
Evaluating different linking theory proposals using acquisition modeling

Evaluation:
How well did the modeled learner do at finding these verb classes?

Bootstrapped confidence intervals for RI, with randomly generated classes of random size and random verb assignment

- RI > 99% = better than chance
- RI < 1% = worse than chance

Rand Index

True Positives + True Negatives
True Positives + True Negatives + False Positives + False Negatives

Pearl & Sprouse 2019a
Evaluating different linking theory proposals using acquisition modeling

<3yrs

<4yrs

<5yrs

Thematic systems
Evaluating different linking theory proposals using acquisition modeling

<3yrs

<4yrs

<5yrs

Thematic systems

relative

Agent > Experiencer >
Theme > Patient >
(Source, Goal, Location)
Evaluating different linking theory proposals using acquisition modeling
Evaluating different linking theory proposals using acquisition modeling

Thematic systems

<table>
<thead>
<tr>
<th>Relative</th>
<th>Fixed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agent &gt; Experiencer &gt; Theme &gt; Patient &gt; (Source, Goal, Location)</td>
<td></td>
</tr>
</tbody>
</table>

Expected mapping

<table>
<thead>
<tr>
<th>Subject</th>
<th>Highest-syn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Object</td>
<td>2nd-Highest-syn</td>
</tr>
<tr>
<td>Oblique Object</td>
<td>3rd-Highest-Syn</td>
</tr>
</tbody>
</table>

Pearl & Sprouse 2019a
### Thematic systems

<table>
<thead>
<tr>
<th>Age</th>
<th>Relative</th>
<th>Expected mapping</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;3yrs</td>
<td>fixed</td>
<td>yes</td>
</tr>
<tr>
<td>&lt;4yrs</td>
<td>fixed</td>
<td>yes</td>
</tr>
<tr>
<td>&lt;5yrs</td>
<td>fixed</td>
<td>yes</td>
</tr>
</tbody>
</table>

#### Expected mapping

- **Subject**: Highest-syn
- **Object**: 2nd-Highest-syn
- **Oblique Object**: 3rd-Highest-Syn

#### Surface morphology

- **<3yrs**: NP V<sub>past</sub> PRT
- **<4yrs**: NP V PRT
- **<5yrs**: NP V PRT
Evaluating different linking theory proposals using acquisition modeling

A modeled learner implements one of each (thematic system, expected mapping, and surface morphology)

Pearl & Sprouse 2019a
Evaluating different linking theory proposals using acquisition modeling

Good news! There were some for each age that performed better than chance (RI > 99%).
Evaluating different linking theory proposals using acquisition modeling

RI > 99% = better than chance

<3yrs

Agent > Experiencer > Theme > Patient > (Source, Goal, Location)

relative  yes  no

NP V PRT

<4yrs

<5yrs

Pearl & Sprouse 2019a
Evaluating different linking theory proposals using acquisition modeling

<3yrs

Agent > Experiencer > Theme > Patient > NP V PRT
(Source, Goal, Location)

<4yrs

fixed

no

NP V PRT

yes

no

<5yrs

Pearl & Sprouse 2019a
Evaluating different linking theory proposals using acquisition modeling

<3yrs

Agent > Experiencer > Theme > Patient > NP V PRT
(Source, Goal, Location)

<4yrs

Agent > Experiencer > Theme > Patient > NP V PRT

<5yrs

Agent > Experiencer > Theme > Patient > NP V PRT

 который превосходит случай

Pearl & Sprouse 2019a
Evaluating different linking theory proposals using acquisition modeling

<3yrs

Agent > Experiencer > Theme > Patient > NP V PRT
(Source, Goal, Location)

<4yrs

NP V PRT

Agent > Experiencer > Theme > Patient > NP V PRT
(Source, Goal, Location)

<5yrs

NP V PRT

Agent > Experiencer > Theme > Patient > NP Vpast PRT
(Source, Goal, Location)

RI > 99% = better than chance

Pearl & Sprouse 2019a
Evaluating different linking theory proposals using acquisition modeling

<3yrs

<4yrs

<5yrs

RI > 99% = better than chance

Pearl & Sprouse 2019a
How do we interpret this with respect to our linking theory proposals?
How do we interpret this with respect to our linking theory proposals?

These are innately specified. Early maturation would assume they’re present at all ages.

<3yrs

<4yrs

<5yrs

Pearl & Sprouse 2019a
How do we interpret this with respect to our linking theory proposals?

But the thematic representation isn’t present at three, even though the link could be.

Pearl & Sprouse 2019a
How do we interpret this with respect to our linking theory proposals?

<3yrs

Agent > Experiencer > Theme > Patient > NP V PRT
(Source, Goal, Location)

<4yrs

NP V PRT

<5yrs

NP V past PRT

Both are present at four and five, though.

Pearl & Sprouse 2019a
How do we interpret this with respect to our linking theory proposals?

So UTAH is compatible with late maturation (at four or later).
How do we interpret this with respect to our linking theory proposals?

These are innately specified. Early maturation would assume they’re present at all ages.

<3yrs

<4yrs

<5yrs

Agent > Experiencer > Theme > Patient > (Source, Goal, Location)

NP V PRT

NP V PRT

NP V PAST PRT

NP V PRT

NP V PAST PRT

NP V PRT

Agent > Experiencer > Theme > Patient > (Source, Goal, Location)

Agent > Experiencer > Theme > Patient > (Source, Goal, Location)

Agent > Experiencer > Theme > Patient > (Source, Goal, Location)
How do we interpret this with respect to our linking theory proposals?

Both are present at three and five, but absent together at four.

How do we interpret this with respect to our linking theory proposals?

Both are present at three and five, but absent together at four.
How do we interpret this with respect to our linking theory proposals?

This means development is complicated for early maturation — the knowledge has to be inaccessible at four for some reason.

Pearl & Sprouse 2019a
How do we interpret this with respect to our linking theory proposals?

Late maturation is compatible, and would predict that the linking knowledge doesn’t emerge till five. Pearl & Sprouse 2019a
How do we interpret this with respect to our linking theory proposals?

The derived-mapping variant using the fixed system would look for this knowledge to be present after the child has had sufficient language experience.

Pearl & Sprouse 2019a
How do we interpret this with respect to our linking theory proposals?

The child would need to derive the fixed system knowledge as well as the linking knowledge, since it's not present at age three.

Pearl & Sprouse 2019a
How do we interpret this with respect to our linking theory proposals?

The child would need to derive the fixed system knowledge as well as the linking knowledge, since it’s not present at age three.
How do we interpret this with respect to our linking theory proposals?

The derived-mapping variant using the relative system would look for this knowledge to be present after the child has had sufficient language experience.
How do we interpret this with respect to our linking theory proposals?

This seems compatible: for example, the linking knowledge could be absent at three and four, but derived by five.

Pearl & Sprouse 2019a
Our linking theory proposals can now be coupled with the developmental theories that have to accompany them in order to match empirical data from children.
Our linking theory proposals can now be coupled with the developmental theories that have to accompany them in order to match empirical data from children.

Takeaway 1: **Innate-mapping** approaches must involve **late maturation**.
Our linking theory proposals can now be coupled with the developmental theories that have to accompany them in order to match empirical data from children.

Takeaway 2: Approaches with fixed thematic systems must involve late maturation or derivation from the input.

Pearl & Sprouse 2019a
Our linking theory proposals can now be coupled with the developmental theories that have to accompany them in order to match empirical data from children.

Question: If knowledge matures late, how does that work? We need evidence from developmental neurobiology.
Our linking theory proposals can now be coupled with the developmental theories that have to accompany them in order to match empirical data from children.

Question: If knowledge is derived from the input, how does that work? We need a concrete proposal for how children could do this.
1. Evaluating different linking theory proposals using acquisition modeling

2. Exploring how a linking theory could be derived from children’s input
Let's remind ourselves what children are learning about links.

Pearl & Sprouse 2019b
Exploring how a linking theory could be derived from children’s input

**Syntax**

The little girl *blicked* the kitten on the stairs.

If children have a particular intermediate representation for thematic roles, then they need to link those representations to syntactic positions.

Event participant roles = Thematic roles

*Agent > Experiencer > Theme > Patient > (Source, Goal, Location)*

Pearl & Sprouse 2019b
Exploring how a linking theory could be derived from children’s input

The little girl *blicked* the kitten on the stairs.

Agent > Experiencer >
Theme > Patient >
(Source, Goal, Location)

Pearl & Sprouse 2019b
Exploring how a linking theory could be derived from children’s input

The little girl *blicked* the kitten on the stairs.

Agent > Experiencer > Theme > Patient > (Source, Goal, Location)

Pearl & Sprouse 2019b
Exploring how a linking theory could be derived from children’s input

The little girl *blicked* the kitten on the stairs.

Pearl & Sprouse 2019b
Exploring how a linking theory could be derived from children’s input

The little girl *blicked* the kitten on the stairs.

Agent > Experiencer > Theme > Patient > (Source, Goal, Location)
Exploring how a linking theory could be derived from children’s input

The little girl *blicked* the kitten on the stairs.

*Agent* > *Experiencer* > *Theme* > *Patient* > *(Source, Goal, Location)*

*Subject* *Object* *Oblique Object* *fixed* *relative* *Highest*
Exploring how a linking theory could be derived from children’s input

The little girl *blicked* the kitten on the stairs.

The linking theories we looked at before (UTAH and rUTAH, and their derived-mapping equivalents) treat these as atomic units (3-link theories).

*Pearl & Sprouse 2019b*
Exploring how a linking theory could be derived from children’s input

The little girl *blicked* the kitten on the stairs.

Acquisition task for one 3-link theory:
(1) Derive all three links from the input.
(2) Derive the 3-link linking theory from the input.

*Pearl & Sprouse 2019b*
Exploring how a linking theory could be derived from children’s input.

The little girl *blicked* the kitten on the stairs.

**Acquisition task for one 3-link theory:**
(1) Derive all three links from the input.
(2) Derive the 3-link linking theory from the input.

How would this work?

---

**Pearl & Sprouse 2019b**
Exploring how a linking theory could be derived from children’s input.

The little girl *blicked* the kitten on the stairs.

**Acquisition task for one 3-link theory:**

1. Derive all three links from the input.
2. Derive the 3-link linking theory from the input.

One way: Consider all possible links and see which ones are reliable enough in the input.

---

Pearl & Sprouse 2019b
Exploring how a linking theory could be derived from children’s input

The little girl *blicked* the kitten on the stairs.

**Acquisition task for one 3-link theory:**
(1) Derive all three links from the input.
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One way: Consider all possible links and see which ones are reliable enough in the input.

---

**First-syn**

**Subject**

**Second-syn**

**Object**

**Third-syn**

**Oblique Object**

**fixed**

**relative**

**First**

**Second**

**Third**

*Pearl & Sprouse 2019b*
Exploring how a linking theory could be derived from children’s input

The little girl *blicked* the kitten on the stairs.

**Acquisition task for one 3-link theory:**

1. Derive all three links from the input.
2. Derive the 3-link linking theory from the input.

One way: Then construct the 3-link linking theory from the reliable links and see if the 3-link theory is reliable enough as a unit.

Pearl & Sprouse 2019b
The little girl *blicked* the kitten on the stairs.

**Acquisition task for one 3-link theory:**
(1) Derive all three links from the input.
(2) Derive the 3-link linking theory from the input.

But why even bother with this second step?
Exploring how a linking theory could be derived from children’s input

The little girl *blicked* the kitten on the stairs.

**Acquisition task for one 3-link theory:**
(1) Derive all three links from the input.
(2) Derive the 3-link linking theory from the input.

What if we just had three 1-link theories?

---

Pearl & Sprouse 2019b
Exploring how a linking theory could be derived from children’s input

The little girl *blicked* the kitten on the stairs.

**An alternative acquisition task for three 1-link theories:**
Derive all three links from the input (and don’t worry about binding them together — just have three 1-link theories)

![Diagram showing links and alignment]

First-syn
Subject

Second-syn
Object

Third-syn
Oblique Object

**fixed**
First

Second

Third

**relative**

Pearl & Sprouse 2019b
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</tr>
</thead>
<tbody>
<tr>
<td>Subject</td>
<td>Object</td>
<td>Oblique Object</td>
</tr>
</tbody>
</table>

- First: fixed
- Second: relative
- Third: relative

Pearl & Sprouse 2019b
Exploring how a linking theory could be derived from children’s input

The little girl *blicked* the kitten on the stairs.

**one 3-link theory**

<table>
<thead>
<tr>
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<th>Third-syn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subject</td>
<td>Oblique</td>
<td>Object</td>
</tr>
</tbody>
</table>

**three 1-link theories**

<table>
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<td>Oblique</td>
<td>Object</td>
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</tbody>
</table>
Exploring how a linking theory could be derived from children’s input

The little girl *blicked* the kitten on the stairs.

Is either of these possible, given the kind of input children get?

---

**One 3-link theory**

- First-syn
- Second-syn
- Third-syn

**Three 1-link theories**

- First-syn
- Second-syn
- Third-syn

Pearl & Sprouse 2019b
five main parts to defining an acquisition task concretely

initial state

data intake

inference

learning period

target state
Defining the acquisition task

Data intake inference
learning period target state

One 3-link theory

First-syn Subject
Second-syn Object
Third-syn Oblique Object

Three 1-link theories

First-syn Subject
Second-syn Object
Third-syn Oblique Object

Initial state

Fixed
Relative

Pearl & Sprouse 2019b
Defining the acquisition task

data intake inference

learning period target state

Pearl & Sprouse 2019b
Defining the acquisition task

- Data intake
- Inference
- Learning period
- Target state

Constraints on possible links

Initial state

- One 3-link theory
- Three 1-link theories

Fixed
- Subject
- Object

Relative
- First
- Second
- Third

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Defining the acquisition task

- Data intake
- Inference
- Learning period
- Target state

Constraints on possible links:

- Knowing which syntactic positions are relevant

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Defining the acquisition task

- data intake
- inference
- learning period
- target state

Constraints on possible links:
- Knowing which syntactic positions are relevant
- A link can go from role to position...

Pearl & Sprouse 2019b
Defining the acquisition task

- data intake
- inference
- learning period
- target state

Constraints on possible links:

- Knowing which syntactic positions are relevant
- A link can go from role to position...

Pearl & Sprouse 2019b
Defining the acquisition task

data intake     inference
learning period target state

Constraints on possible links:
- Knowing which syntactic positions are relevant
- A link can go from role to position or from position to role

Related concepts:
- initial state
- fixed
- relative

Pearl & Sprouse 2019b
Defining the acquisition task

First

Subject

Oblique

Object

Second

Third

Data intake inference

Learning period target state

One 3-link theory

Three 1-link theories

Constraints on possible links:

- Knowing which syntactic positions are relevant
- A link can go from role to position or from position to role

Initial state
Defining the acquisition task

Data intake inference
learning period target state

Constraints on possible links:
- Knowing which syntactic positions are relevant
- A link can go from role to position or from position to role
- A thematic role can only participate in one link at a time
Defining the acquisition task

Data intake inference
Learning period target state

Constraints on possible links:
- Knowing which syntactic positions are relevant
- A link can go from role to position or from position to role
- A thematic role can only participate in one link at a time
- A syntactic position can only participate in one link at a time
Defining the acquisition task

Data intake  Inference
Learning period  Target state

First  Second  Third
Subject  Object  Oblique  Object

Fixed

Relative

Initial state

One 3-link theory

Three 1-link theories

+ Whatever abilities are required to do inference

Pearl & Sprouse 2019b
Defining the acquisition task

- Initial state
- Inference
- Learning period
- Target state

Samples of child-directed speech

### CHILDES Treebank

#### <3yrs
- 18 and 32 months
- ~40,000 utterances
- 239 verbs

#### <4yrs
- 18 and 48 months
- ~51,000 utterances
- 267 verbs

#### <5yrs
- 18 and 58 months
- ~56,500 utterances
- 284 verbs

The little girl *blicked* the kitten on the stairs.

---

Pearl & Sprouse 2013

Pearl & Sprouse 2019b
The little girl *blicked* the kitten *on* the stairs.
Remember that the acquisition process we imagined hinges on a child perceiving individual links and multi-link theories as “reliable enough”, given the input.
Defining the acquisition task

initial state | data intake | target state

learning period | inference

How can “reliable enough” be implemented?

Pearl & Sprouse 2019b
One answer: **The Tolerance Principle** (Yang 2005, 2016)

This principle is derived from considerations of knowledge storage and retrieval in real time, incorporating how frequently individual items occur, the absolute ranking of items by frequency, and serial memory access.
Defining the acquisition task

initial state  data intake  learning period  target state

inference

The Tolerance Principle (Yang 2005, 2016)

Designed for situations where there are exceptions to a potential rule — provides a precise threshold for how many exceptions a potential rule can tolerate before it’s no longer worthwhile to have the rule in terms of average retrieval time.

\[
\frac{e}{N} Time(e,e) + (1 - \frac{e}{N})e < \sum_{r=1}^{N} r \frac{1}{rH_n} \\
\frac{e}{N} \sum_{k=1}^{e} \frac{1}{k} + (1 - \frac{e}{N})e < \sum_{r=1}^{N} \sum_{k=1}^{N} \frac{1}{k}
\]

Pearl & Sprouse 2019b
The Tolerance Principle (Yang 2005, 2016)

Designed for situations where there are exceptions to a potential rule — provides a **precise threshold** for how many exceptions a potential rule can tolerate before it’s no longer worthwhile to have the rule in terms of average retrieval time.

\[ N \approx \frac{N}{\ln(N)} \]

= # of items that the rule could apply to

Pearl & Sprouse 2019b
Defining the acquisition task

initial state  data intake
learning period  target state

inference

\[ \frac{N}{\ln(N)} \]

The Tolerance Principle (Yang 2005, 2016)

Here we can use it to evaluate both individual links and multi-link theories.
Defining the acquisition task

initial state  data intake  target state

inference

\[ N \quad \text{ln}(N) \]

The Tolerance Principle (Yang 2005, 2016)

Here we can use it to evaluate both individual links and multi-link theories.

As before, we'll be using an ideal learner model, where the learner applies the Tolerance Principle to all the data available, rather than deploying it with the cognitive limitations and incremental learning restrictions real children have.

Goal: Is it possible to derive the linking theories from realistic child input?
Defining the acquisition task

initial state  data intake

target state

inference

\[ \frac{N}{\ln(N)} \]

How do we evaluate an individual link?

First-syn
Subject

Pearl & Sprouse 2019b
Defining the acquisition task

initial state  data intake

target state

inference

\[
\frac{N}{\ln(N)}
\]

How do we evaluate an individual link?

If it goes from role to position, we compare this link to the others that link from this role.
Defining the acquisition task

Initial state | Data intake | Target state

Inference

\[ \frac{N}{\ln(N)} \]

How do we evaluate an individual link?

If it goes from role to position, we compare this link to the others that link from this role.

Pearl & Sprouse 2019b
Defining the acquisition task

initial state  data intake

target state

inference

How do we evaluate an individual link?

If it goes from role to position, we compare this link to the others that link from this role (the exceptions to this link).

\[ \frac{N}{\ln(N)} \]

Does it have few enough exceptions according to the child's intake?
Defining the acquisition task

How do we evaluate an individual link?

If it goes from position to role, we compare this link to the others that link from this position.
Defining the acquisition task

initial state | data intake | target state

inference

How do we evaluate an individual link?

If it goes from position to role, we compare this link to the others that link from this position.

Pearl & Sprouse 2019b
Defining the acquisition task

initial state    data intake

target state

inference

How do we evaluate an individual link?

If it goes from position to role, we compare this link to the others that link from this position (the exceptions to this link).

\[ N < \frac{\ln(N)}{\ln(N)} \]

Does it have few enough exceptions according to the child's intake?

Pearl & Sprouse 2019b
Defining the acquisition task

initial state  data intake  target state

inference

How do we evaluate multi-link theories?

Pearl & Sprouse 2019b
Defining the acquisition task

Initial state data intake

Target state

Inference

How do we evaluate multi-link theories?

We compare the link instances that follow the multi-link theory against the link instances that don’t (the exceptions to this multi-link theory).

\[
N < \frac{1}{\ln(N)}
\]

Does the 3-link theory have few enough exceptions according to the child’s intake?

Note: This is a simple binary distinction between links that follow the multi-link theory and links that don’t.
Defining the acquisition task

initial state  data intake

target state

inference

How do we evaluate theories (1-link or 3-link)?

A linking theory should hold for the verb \textit{lexical items} (types).

fall  kick  love  think
hug  belong  hear

Pearl & Sprouse 2019b
Defining the acquisition task

initial state  data intake  target state

inference

How do we evaluate theories (1-link or 3-link)?

So, a linking theory is evaluated over the verb types — how many obey the linking theory and how many are exceptions?

Pearl & Sprouse 2019b
Defining the acquisition task

How do we evaluate theories (1-link or 3-link)?

So, a linking theory is evaluated over the verb types — how many obey the linking theory and how many are exceptions?

\[ N < \frac{N}{ln(N)} \]

We want the number of verb types that disobey this linking theory to be less than the Tolerance Principle threshold.

Pearl & Sprouse 2019b
Defining the acquisition task

initial state  data intake

target state

inference

How do we evaluate theories (1-link or 3-link)?

How do we tell if a verb type obeys the linking theory or is an exception?
Defining the acquisition task

initial state  data intake

target state

inference

How do we evaluate theories (1-link or 3-link)?

We evaluate that verb type's instances according to whether they follow the linking theory or not.

Pearl & Sprouse 2019b
How do we evaluate theories (1-link or 3-link)?

So, a linking theory is evaluated over the verb type instances — how many obey the linking theory and how many are exceptions?
Defining the acquisition task

initial state  data intake  target state

inference

How do we evaluate theories (1-link or 3-link)?

So, a linking theory is evaluated over the verb type instances — how many obey the linking theory and how many are exceptions?

\[ \frac{N}{ln(N)} \]

= verb type instances this theory could apply to

We want the number of verb type instances that disobey this linking theory to be less than the Tolerance Principle threshold.
Defining the acquisition task

initial state  data intake

target state

inference

How do we evaluate theories (1-link or 3-link)?

We do this for each verb type, and then we know how many obey the linking theory and how many are exceptions.
Defining the acquisition task

Initial state  Data intake  Target state

Inference

How do we evaluate theories (1-link or 3-link)?

We do this for each verb type, and then we know how many obey the linking theory and how many are exceptions.

If the exceptions are less than the Tolerance Principle threshold, the linking theory is reliable enough for the verb types.

\[
N < \frac{N}{\ln(N)}
\]
So which linking theories are derivable from children’s input?
Which linking theories are derivable from children's input?

One 3-link theory

First-syn  Second-syn  Third-syn

Subject  Object  Oblique  Object

First  Second  Third

Three 1-link theories

First-syn  Second-syn  Third-syn

Subject  Object  Oblique  Object

First  Second  Third

Subject  Object  Oblique  Object

Same results for all three ages.

Pearl & Sprouse 2019b
Which linking theories are derivable from children’s input?

Let’s look at individual links first.
Which linking theories are derivable from children’s input?

Let’s look at individual links first.

Individual links are the 1-link theories and the building blocks for the 3-link theories.

three 1-link theories

<table>
<thead>
<tr>
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<tbody>
<tr>
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<td>Oblique</td>
</tr>
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one 3-link theory

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Pearl & Sprouse 2019b
Which linking theories are derivable from children's input?

one 3-link theory

- First-syn
- Second-syn
- Third-syn
- Object
- Oblique

three 1-link theories

- First-syn
- Second-syn
- Third-syn
- Object
- Oblique

Are the individual links reliable enough?

- First-syn
- Second-syn
- Third-syn
- Subject
- Object

Pearl & Sprouse 2019b
Which linking theories are derivable from children’s input?

Here are the ones that are.

Good: At least one in one direction (role to position or position to role) for each of the three posited links.
Which linking theories are derivable from children’s input?

Here are the ones that are.

Good: At least one in one direction (role to position or position to role) for each of the three posited links.

Good: No extraneous links are reliable enough.

Pearl & Sprouse 2019b
Which linking theories are derivable from children’s input?

Here are the ones that are.

...but none have a reliable link in both directions, and it’s not clear if both directions are needed to posit a link for the linking theory.
Which linking theories are derivable from children's input?

![Diagram of linking theories]

**one 3-link theory**
- First-syn
- Second-syn
- Third-syn

**three 1-link theories**
- First-syn
- Second-syn
- Third-syn

Subject
Object
Oblique
Object

Here are the ones that are.

Only the most liberal approach to positing theories from links (one link in either direction is sufficient) would allow a child to posit the appropriate 1-link theories or the appropriate building blocks for the 3-link theory.

---

Pearl & Sprouse 2019b
Which linking theories are derivable from children's input?

<table>
<thead>
<tr>
<th>Age</th>
<th>Subject</th>
<th>Object</th>
<th>Oblique</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;3yrs</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>&lt;4yrs</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>&lt;5yrs</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

Here are the ones that are.

- **fixed**
- **relative**

This contrasts with the relative thematic system, where links in both directions are reliable enough (and there are also no extraneous links).

Pearl & Sprouse 2019b
Which linking theories are derivable from children's input?

<table>
<thead>
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<th>&lt;3yrs</th>
<th>&lt;4yrs</th>
<th>&lt;5yrs</th>
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one 3-link theory

- First-syn
- Second-syn
- Third-syn

three 1-link theories

- First-syn
- Second-syn
- Third-syn

Subject Object Oblique Object

First Second Third

Here are the ones that are.

fixed

relative

So more conservative strategies for positing theories from links (e.g., needing a link in both directions) would also posit the appropriate theories or building blocks.
Which linking theories are derivable from children’s input?

**one 3-link theory**

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**three 1-link theories**

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Here are the ones that are.

**fixed**

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**relative**

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This means relying on relative thematic representations is more robust to different learning scenarios.
Which linking theories are derivable from children's input?

But what about the 3-link theories?
If in fact the appropriate building blocks are composed into the appropriate 3-link theories, are those theories reliable enough?
Which linking theories are derivable from children's input?

It turns out that the 3-link theory relying on a fixed thematic representation isn't reliable enough — not enough verb types obey it.
Which linking theories are derivable from children's input?

Meanwhile, the 3-link theory using the relative thematic representation is reliable enough as a unit.

Pearl & Sprouse 2019b
Which linking theories are derivable from children's input?

Takeaway 1: Relying on a relative thematic representation makes it easier to derive three 1-link theories of the kind compatible with those that linguists have theorized (rUTAH).

Pearl & Sprouse 2019b
Which linking theories are derivable from children’s input?

Takeaway 2: Relying on a relative thematic representation is the <span class="highlight" style="background-color: green;">only</span> way to derive a 3-link theory of the kind linguists have theorized (rUTAH).
Which linking theories are derivable from children's input?

Bigger takeaway:
Acquisition support for relative over fixed.

Whether we think the linking theories that humans use are multi-link theories or multiple 1-link theories, it seems that English children would need to rely on a relative thematic representation if they're going to derive these linking theories from their input.
What we learned about linking theories using the lens of acquisition

The little girl *blicked* the kitten on the stairs.
What we learned about linking theories using the lens of acquisition

The little girl *blicked* the kitten on the stairs.

Linking theory proposals relying on innate knowledge require late maturation if they’re going to be compatible with what we know about English children’s developing verb knowledge.
What we learned about linking theories using the lens of acquisition

The little girl *blicked* the kitten on the stairs.

Linking theory proposals relying on innate knowledge require late maturation if they’re going to be compatible with what we know about English children’s developing verb knowledge.
What we learned about linking theories using the lens of acquisition

The little girl *blicked* the kitten on the stairs.

Linking theory proposals relying on *derived* knowledge are also compatible with what we know about English children's developing verb knowledge.

*Pearl & Sprouse 2019a*
Linking theory proposals relying on derived knowledge are also compatible with what we know about English children's developing verb knowledge.
What we learned about linking theories using the lens of acquisition

The little girl blicked the kitten on the stairs.

We provided an existence proof for how linking knowledge could be derived from realistic English child input. It only works for learners relying on relative thematic representations.

Pearl & Sprouse 2019b
What we learned about linking theories using the lens of acquisition

The little girl *blicked* the kitten on the stairs.

We provided an existence proof for how linking knowledge could be derived from realistic English child input. It only works for learners relying on relative thematic representations.

This can be interpreted as an argument from acquisition for theories of relative thematic representations over theories of fixed thematic representations.
Open questions

The little girl *blicked* the kitten on the stairs.

So now what?
Open questions

The little girl *blicked* the kitten on the stairs.

(1) A broader assessment of children’s verb class knowledge
Open questions

The little girl *blicked* the kitten on the stairs.

(1) A broader assessment of children’s verb class knowledge

This will allow us to further validate our acquisition modeling results for these theoretical proposals.
Open questions

The little girl *blicked* the kitten on the stairs.

(1) A broader assessment of children’s verb class knowledge

<table>
<thead>
<tr>
<th></th>
<th>&lt;3yrs</th>
<th>&lt;4yrs</th>
<th>&lt;5yrs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Children’s input</td>
<td>239 verbs</td>
<td>267 verbs</td>
<td>284 verbs</td>
</tr>
<tr>
<td>Children’s known behavior</td>
<td>15 classes of 60 verbs</td>
<td>23 classes of 76 verbs</td>
<td>24 classes of 82 verbs</td>
</tr>
</tbody>
</table>
Open questions

The little girl *blicked* the kitten on the stairs.

(1) A broader assessment of children’s verb class knowledge

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<td>classes</td>
<td>15 of 60 verbs</td>
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There are nearly 200 verbs in each age that we have acquisition model predictions for based on children’s input but no behavioral data for.
Open questions

The little girl *blicked* the kitten on the stairs.

(2) Models incorporating more cognitively plausible assumptions

\[
\frac{N}{\ln(N)}
\]
Open questions

The little girl *blicked* the kitten on the stairs.

(2) Models incorporating more cognitively plausible assumptions

\[
\frac{N}{\ln(N)}
\]

This will allow us to further validate our acquisition modeling results for these theoretical proposals.
Open questions

The little girl *blicked* the kitten on the stairs.

(2) Models incorporating more cognitively plausible assumptions

about intake & inference: +memory & processing limitations

Is what’s useful actually useable by children?
Open questions

The little girl *blicked* the kitten on the stairs.

(2) Models incorporating more cognitively plausible assumptions about developing grammar:

+ incorporating additional age-appropriate information

"It seemed to be right"

\[ NP \_ \_ IP_{finite} \rightarrow NP_{\text{raised}} \_ \_ [IP_{finite} \_ \_ NP] \]
Open questions

The little girl *blicked* the kitten on the stairs.

(2) Models incorporating more cognitively plausible assumptions

about target state: +predicting *behavioral* data available from experiments
Open questions

The little girl *blicked* the kitten on the stairs.

(3) Are there other theoretical options for linking thematic role information to syntactic structure that are compatible with what we know about development?
Open questions

The little girl *blicked* the kitten on the stairs.

(3) Are there other theoretical options for linking thematic role information to syntactic structure that are compatible with what we know about development?

We can use these acquisition modeling approaches to investigate them.
The little girl *blicked* the kitten on the stairs.

These acquisition modeling approaches allow us to connect theories of *linguistic representation* with theories of *language development* and so understand more about both.
This work was supported in part by NSF grant BCS-1347028.

Special thanks to Abbie Thornton, Alandi Bates, Emily Yang, and BreAnna Silva for CHILDES Treebank corpus annotation.