Quantitative approaches to learning linking theories in language

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

Event participants
Linking theories

What is this likely to mean?

Subject  Object  Oblique Object

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

Event participants
Linking theories

This event is much more likely...

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

**Event participants**
- Subject: The little girl
- Object: the kitten
- Oblique Object: on the stairs

**Syntactic positions**
- Subject
- Object
- Oblique Object
The little girl *blicked* the kitten on the stairs. …compared to these.
The little girl *blicked* the kitten on the stairs.

**Syntactic positions**
- Subject
- Object
- Oblique Object

**Event participants**

**Linking theories**

*Why?*
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.

**Syntactic positions**

- Subject
- Object
- Oblique Object

**Event participants**
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.
What does a linking theory look like?

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

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…

Current proposals involve prior (innate) knowledge
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…
What does a linking theory look like?

**Syntax**

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

**The Uniformity of Theta Assignment Hypothesis**


**Event participant roles**

= Thematic roles

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

Syntax

Event participant roles

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

What does a linking theory look like?

Subject  Object  Oblique Object
The little girl *blicked* the kitten on the stairs.

Syntax

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

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…
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.

These map to syntactic positions.

UTAH

fixed

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

The (relativized) *UTAH*

Larson 1988, Larson 1990
What does a linking theory look like?

Syntax

Intermediate representations

Event participant roles = Thematic roles

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

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

Syntax

Event participant roles = Thematic roles

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

Thematic roles are ordered relative to each other.

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

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

Intermediate representations

Mapping to syntax

UTAH

fixed

rUTAH

Thematic roles are *ordered relative* to each other.
Linking theories

What does a linking theory look like?

Syntax

Event participant roles = Thematic roles

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

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

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

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

Intermediate representations

Mapping to syntax
Linking theories

What does a linking theory look like?

Syntax

Intermediate representations

Mapping to syntax

Event participant roles = Thematic roles

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

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

**UTAH**
- Agent
- Experiencer
- Patient
- Theme
- Goal
- Source
- Location

**rUTAH**
- Agent > Experiencer > Theme > Patient > (Source, Goal, Location)
What does a linking theory look like?

Syntax

Mapping to syntax

Intermediate representations

Event participant roles = Thematic roles

Linking theories

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

UTAH & rUTAH assume the mapping to syntax is *innate*.

UTAH

fixed

rUTAH

relative

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

Thematic roles

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

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.
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**...

**Linking theories**

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

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

**Fixed**

**Relative**

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

UTAH

fixed
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)

**relative**

---

**UTAH**

**fixed**
Linking theories

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

Good news: These proposals make developmental predictions.
The little girl *blicked* the kitten on the stairs.

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.

Implication: A learner who has knowledge of the mapping to syntax should always match real children's behavior best.
Linking theories

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

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

![Diagram of the sentence structure](chart)

**rUTAH**

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

**UTAH**

fixed

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

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

The little girl blicked the kitten on the stairs.

So what behavior should we look at that would leverage linking theory knowledge?

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

relative

fixed
Linking theories

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.

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

UTAH  
relative

fixed
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.

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**rUTAH**

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

**relative**

---

**UTAH**

**fixed**
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.
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.
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.
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.
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:
2nd-Highest = Subject
Highest = Oblique

**relative**

Agent > Experiencer >
Theme > Patient >
(Source, Goal, Location)
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 learning) and corpus studies of their input.
The little girl *blicked* the kitten on the stairs.

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

1. Evaluating different linking theory proposals using developmental modeling

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

1. Evaluating different linking theory proposals using developmental modeling

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

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.
Evaluating different linking theory proposals using developmental modeling

Goal:
Build a modeled learner who learns close enough to how real children learn to tell us something informative about these linking theory proposals.

What's close enough?
Evaluating different linking theory proposals using developmental modeling

Close enough to this process

Pearl in press
Evaluating different linking theory proposals using developmental modeling

Close enough to this process

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

Pearl in press
Evaluating different linking theory proposals using developmental modeling

five main parts

initial state

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

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**Agent**, **Patient**, **Goal**, …

---

N, V, Adj, P, …

---

**h1**

---

**h2**

---

```
UTAH
```

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**rUTAH**

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**Theme > Patient >**

(Source, Goal, Location)

---

**relative**

---

**fixed**

---

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Pearl *in press*
Evaluating different linking theory proposals using developmental 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 developmental 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 developmental 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: 2 movement
Evaluating different linking theory proposals using developmental 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: proto-Patient = Subject
proto-Agent = Oblique

rUTAH relative

Pearl in press
Evaluating different linking theory proposals using developmental 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)?

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The kitten was *blicked* by the little girl.

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

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Pearl in press
Evaluating different linking theory proposals using developmental modeling

five main parts

initial state

data intake

inference

How are updates made to the modeled child’s internal representations?

Pearl *in press*
Evaluating different linking theory proposals using developmental 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
Evaluating different linking theory proposals using developmental 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 developmental 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)?

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

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Pearl *in press*
Evaluating different linking theory proposals using developmental 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)?

blick kiss pet touch hug
Evaluating different linking theory proposals using developmental 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 developmental modeling

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

If we can define those pieces, we can make sure we’ve captured the relevant parts of this acquisition process in our modeled learner.

Pearl in press
Evaluating different linking theory proposals using developmental modeling

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

So let’s do this for modeled learners who implement different linking theory proposals.
Evaluating different linking theory proposals using developmental 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

Pearl & Sprouse 2018a
Evaluating different linking theory proposals using developmental modeling

data intake inference target state
learning period

initial state

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

rUTAH relative
fixed

UTAH

Pearl & Sprouse 2018a
Evaluating different linking theory proposals using developmental modeling

data intake  inference  target state
learning period

initial state

Cognitive plausibility check?

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

relative
fixed

Pearl & Sprouse 2018a
Evaluating different linking theory proposals using developmental modeling

- data intake
- inference
- target state
- learning period

Thematic roles that indicate event participant roles are salient to very young children.

Pearl & Sprouse 2018a
Evaluating different linking theory proposals using developmental modeling

Children are also sensitive to the \textit{animacy} of verb arguments.


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

\texttt{+animate} \hspace{1cm} \texttt{+animate} \hspace{1cm} \texttt{-animate}

Pearl & Sprouse 2018a
Evaluating different linking theory proposals using developmental modeling

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 developmental modeling

Data intake ♦ Inference ♦ Target state
Learning period

Initial state

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

Relative ♦ Fixed

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

NP ___ NP PP

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).

NP ___ NP PP

*Pearl & Sprouse 2018a*
Evaluating different linking theory proposals using developmental modeling

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

data intake  inference  target state
learning period

initial state

rUTAH

relative

fixed

NP ___  NP  PP

UTAH

+animate  -animate

Pearl & Sprouse 2018a
Evaluating different linking theory proposals using developmental modeling

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

input that yields data intake

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

Samples of child-directed speech

**CHILDES Treebank**

Pearl & Sprouse 2013

<table>
<thead>
<tr>
<th>Age Group</th>
<th>Utterances</th>
<th>Verbs</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;3yrs</td>
<td>~40,000</td>
<td>239</td>
</tr>
<tr>
<td>&lt;4yrs</td>
<td>~51,000</td>
<td>267</td>
</tr>
<tr>
<td>&lt;5yrs</td>
<td>~56,500</td>
<td>284</td>
</tr>
</tbody>
</table>

Pearl & Sprouse 2018a
Evaluating different linking theory proposals using developmental 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

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 developmental 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

*Pearl & Sprouse 2018a*
Evaluating different linking theory proposals using developmental modeling

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

*blick*:
3 no-movement

*blick*:
*relative*
*fixed*

*UTAH*

*Pearl & Sprouse 2018a*
Evaluating different linking theory proposals using developmental modeling

**Initial state**

- Surface morphology

**Inference**

Learning period

**Target state**

- Surface morphology

**Data intake**

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

*blick*: Subject = proto-Agent, Object = proto-Patient, Oblique = Other

-rUTAH

-Expect-mapping

-Relative

Fixed

NP ___ NP PP

NP ___+past NP PP

NP ++++past NP PP
Evaluating different linking theory proposals using developmental modeling

initial state  inference  target state
learning period

data intake

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

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

blick:
Subject = Highest
Object = 2nd-Highest
Oblique = 3rd-Highest

-expect-mapping

Pearl & Sprouse 2018a
Evaluating different linking theory proposals using developmental 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?

Pearl & Sprouse 2018a
Evaluating different linking theory proposals using developmental 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*?

**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.

*Pearl & Sprouse 2018a*
Evaluating different linking theory proposals using developmental modeling

**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.

---

Pearl & Sprouse 2018a
Evaluating different linking theory proposals using developmental 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?

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

---

Pearl & Sprouse 2018a
Evaluating different linking theory proposals using developmental modeling

**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 2018a
Evaluating different linking theory proposals using developmental 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?

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 2018a
Evaluating different linking theory proposals using developmental 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.

*class* \^7

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"it's falling off"

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

"is London Bridge falling down?"

---

*Pearl & Sprouse 2018a*
Evaluating different linking theory proposals using developmental 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

Pearl & Sprouse 2018a

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

"it's falling off"  "don't fall!"

"is London Bridge falling down?"

Pearl & Sprouse 2018a
Evaluating different linking theory proposals using developmental 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?

Depending on the verb class, the observed usage will have certain characteristics.
Evaluating different linking theory proposals using developmental 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.

Pearl & Sprouse 2018a
Evaluating different linking theory proposals using developmental 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.

Each class has a probability of preferring each option.

Pearl & Sprouse 2018a
Evaluating different linking theory proposals using developmental 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)

Pearl & Sprouse 2018a

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

FALL
Evaluating different linking theory proposals using developmental modeling

**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.

Pearl & Sprouse 2018a
Evaluating different linking theory proposals using developmental 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 multinomial choices such as which syntactic frame a verb appears in.

NP V  PRT
NP V
...
NP V S

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

Pearl & Sprouse 2018a
Evaluating different linking theory proposals using developmental 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.

NP V PRT 0.3
NP V 0.25

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

-anim (3x)

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

Pearl & Sprouse 2018a
Evaluating different linking theory proposals using developmental 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 …
Evaluating different linking theory proposals using developmental 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?

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 2018a
Evaluating different linking theory proposals using developmental 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?

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- which class each verb belongs to

-**anim** (3x)
  
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Pearl & Sprouse 2018a
Evaluating different linking theory proposals using developmental 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:
- how many classes there are
- which class each verb belongs to
- what the characteristics are of each class

NP V PRT 0.3
NP V 0.25
NP V S 0

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Evaluating different linking theory proposals using developmental modeling

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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

**Best answer:** maximizes the probability of the observed data.

---

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Evaluating different linking theory proposals using developmental 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
- what the characteristics are of each class

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

+ Gibbs sampling

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

Pearl & Sprouse 2018a
Evaluating different linking theory proposals using developmental 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?

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 2018a*
Evaluating different linking theory proposals using developmental modeling

initial state  data intake  inference

target state

So what does the target knowledge/behavior look like?
Evaluating different linking theory proposals using developmental modeling

initial state  data intake  inference

target state

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

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Evaluating different linking theory proposals using developmental modeling

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

Pearl & Sprouse 2018a
Evaluating different linking theory proposals using developmental modeling

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

...yields 12 verb behaviors

initial state  data intake  inference

target state

verb class knowledge

+/−passive  +control-subject
+unaccusative  +control-object
+ditransitive  +raising-object
+raising-subject  +raising-object
+that-comp
+whether/if-comp  +subject-experiencer
+non-finite to-comp  +object-experiencer

Pearl & Sprouse 2018a
Evaluating different linking theory proposals using developmental modeling

initial state  data intake  inference

target state

These verb behaviors yield a number of verb classes at each age
Evaluating different linking theory proposals using developmental modeling

**target state**

These **verb behaviors** yield a number of **verb classes** at each age

**Example classes**

* [+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

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Evaluating different linking theory proposals using developmental modeling

initial state  data intake  inference

target state

These verb behaviors yield a number of verb classes at each age

Example classes

[+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

Pearl & Sprouse 2018a
Evaluating different linking theory proposals using developmental modeling

**target state**

These verb behaviors yield a number of verb classes at each age

**Example classes**

[+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

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

Pearl & Sprouse 2018a
Evaluating different linking theory proposals using developmental modeling

**initial state**  **data intake**  **inference**

**target state**

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

*Pearl & Sprouse 2018a*
Evaluating different linking theory proposals using developmental modeling

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

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Evaluating different linking theory proposals using developmental modeling

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

Implementation:
Rand Index

0.0 \leq RI \leq 1.0
Evaluating different linking theory proposals using developmental 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.
Evaluating different linking theory proposals using developmental modeling

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

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

<table>
<thead>
<tr>
<th>Verb Class</th>
<th>Rand Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;3yrs</td>
<td>15 classes</td>
</tr>
<tr>
<td>&lt;4yrs</td>
<td>23 classes</td>
</tr>
<tr>
<td>&lt;5yrs</td>
<td>25 classes</td>
</tr>
</tbody>
</table>

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

Pearl & Sprouse 2018a
Evaluating different linking theory proposals using developmental modeling

**Evaluation:**

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<tr>
<td>Different class</td>
<td>Different class</td>
</tr>
</tbody>
</table>

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

**Inferred Class**

<table>
<thead>
<tr>
<th>Same class</th>
<th>Different class</th>
</tr>
</thead>
<tbody>
<tr>
<td>True Positive</td>
<td>True Negative</td>
</tr>
</tbody>
</table>

Rand Index: $0.0 \leq \text{RI} \leq 1.0$

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

Pearl & Sprouse 2018a
Evaluating different linking theory proposals using developmental modeling

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

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<tbody>
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<td>True Positive</td>
</tr>
<tr>
<td>Different class</td>
<td>False Positive</td>
</tr>
</tbody>
</table>

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

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

\[
0.0 \leq RI \leq 1.0
\]

Rand Index

Pearl & Sprouse 2018a
Evaluating different linking theory proposals using developmental modeling

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

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</tr>
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<tbody>
<tr>
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<td>False Negative</td>
</tr>
<tr>
<td>Different class</td>
<td>False Positive</td>
<td>True Negative</td>
</tr>
</tbody>
</table>

True Positives + True Negatives

Intuition: Get credit for putting things together that belong together and keeping things apart that should be apart.
Evaluating different linking theory proposals using developmental modeling

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

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

Rand Index

But how do we know we’re doing better than chance?
Evaluating different linking theory proposals using developmental modeling

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

<table>
<thead>
<tr>
<th>Age Group</th>
<th>Classes</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;3yrs</td>
<td>15</td>
</tr>
<tr>
<td>&lt;4yrs</td>
<td>23</td>
</tr>
<tr>
<td>&lt;5yrs</td>
<td>25</td>
</tr>
</tbody>
</table>

Rand Index

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

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Thematic systems

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<3yrs

<4yrs

<5yrs

Thematic systems

relative

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

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Thematic systems

relative

fixed

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

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<table>
<thead>
<tr>
<th>Thematic systems</th>
<th>Expected mapping</th>
</tr>
</thead>
<tbody>
<tr>
<td>relative</td>
<td>yes</td>
</tr>
<tr>
<td>fixed</td>
<td>no</td>
</tr>
</tbody>
</table>

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Thematic systems

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

- **fixed**
  - Subject
  - Object
  - Oblique Object

Expected mapping

- **<3yrs**
  - yes

- **<4yrs**
  - no

- **<5yrs**

Surface morphology

- **<3yrs**
  - yes NP V\text{\scriptsize past} PRT

- **<4yrs**
  - no NP V PRT

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

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

relative yes no

NP V PRT

<3yrs

<4yrs

<5yrs

RI > 99% = better than chance

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<3yrs

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

<4yrs

NP V PRT
fixed

no

yes

no

<5yrs

RI > 99% = better than chance

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<3yrs

Agent > Experiencer > Theme > Patient > \( NP \ V \ PRT \)

(Source, Goal, Location)

<4yrs

Agent > Experiencer > Theme > Patient > \( NP \ V \ PRT \)

<5yrs

Agent > Experiencer > Theme > Patient > \( NP \ V_{past} \ PRT \)

(Source, Goal, Location)

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<3yrs

<4yrs

<5yrs

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

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

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

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

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

RI > 99% = better than chance

Pearl & Sprouse 2018a
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

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.
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.

<3yrs

<4yrs

<5yrs

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

(rUTAH) relative fixed

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

Both are present at four and five, though.

<3yrs

<4yrs

<5yrs

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

So UTAH is compatible with late maturation (at four or later).

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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 2018a
How do we interpret this with respect to our linking theory proposals?

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

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

<3yrs <4yrs <5yrs

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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.

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

<3yrs

<4yrs

<5yrs

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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.

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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.
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 2018a
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 2018a
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.

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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 2018a
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.
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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 2018a
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.

rUTAH

late maturation

UTAH

+fixed matures late

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

derive by five

fixed

+derive fixed

Pearl & Sprouse 2018a
1. Evaluating different linking theory proposals using developmental modeling

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

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

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

Let's remind ourselves what children are learning about links.
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.

**Intermediate representations**

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

**Fixed**

**Relative**

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

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

Pearl & Sprouse 2018b
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 2018b
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 2018b*
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)*
The linking theories we looked at before (UTAH and rUTAH, and their derived-mapping equivalents) treat these as atomic units (3-link theories).

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

*Pearl & Sprouse 2018b*
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.

**How would this work?**

*fixed*

*relative*
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.

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

Pearl & Sprouse 2018b
Exploring how a linking theory could be derived from children’s input

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

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Pearl & Sprouse 2018b
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 this 3-link linking theory.

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

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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)

Subject
Object
Oblique Object

fixed
relative

First
Second
Third

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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 3 1-link theories)

**How would this work?**

The same way: Consider all possible links and see which ones are reliable enough in the input
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 3 1-link theories)

How would this work?

And then you’re finished.

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

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

One 3-link theory

Three 1-link theories

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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?

*Pearl & Sprouse 2018b*
Defining the acquisition task

one 3-link theory  three 1-link theories

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

- Subject
- Object
- Oblique Object

Three 1-link theories

- Subject
- Object
- Oblique Object

Initial state

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Defining the acquisition task

data intake   inference
learning period target state

one 3-link theory

✓

three 1-link theories

initial state

Knowledge of intermediate thematic representation

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Defining the acquisition task

- Data intake
- Inference
- Learning period
- Target state

One 3-link theory

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

Three 1-link theories

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

Initial state

Constraints on possible links

Fixed

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

Relative

Pearl & Sprouse 2018b
Defining the acquisition task

- data intake
- inference
- learning period
- target state

One 3-link theory

Three 1-link theories

Subject
First

Object
Second

Oblique Object
Third

Initial state

Constraints on possible links:

- Knowing which syntactic positions are relevant
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 2018b
Defining the acquisition task

- 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...

Pearl & Sprouse 2018b
Defining the acquisition task

one 3-link theory

✓

three 1-link theories

• Knowing which syntactic positions are relevant

• A link can go from role to position or from position to role

Constraints on possible links:

initial state

Subject

Object

Oblique Object

fixed

relative

First

Second

Third

Pearl & Sprouse 2018b
Defining the acquisition task

- 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

Pearl & Sprouse 2018b
Defining the acquisition task

- 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
- A thematic role can only participate in one link at a time

Pearl & Sprouse 2018b
Defining the acquisition task

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

initial state

fixed relative

Pearl & Sprouse 2018b
Defining the acquisition task

- Data intake
- Inference
- Learning period
- Target state

One 3-link theory

- Subject
- Object
- Oblique

Three 1-link theories

- Subject
- Object
- Oblique

Initial state

- Subject
- Object
- Oblique

Fixed
- First
- Second
- Third

Relative
- First
- Second
- Third

+ Whatever abilities are required to do inference

Pearl & Sprouse 2018b
Defining the acquisition task

- Initial state
- Inference
- Learning period
- Target state

One 3-link theory

Three 1-link theories

Samples of child-directed speech

CHILDES Treebank

Input that yields data intake

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

- **<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

Pearl & Sprouse 2018b
Defining the acquisition task

- initial state
- inference
- learning period
- target state

One 3-link theory

- Subject
- Object
- Oblique

Three 1-link theories

- Subject
- Object
- Oblique

Input that yields data intake

The little girl blicked the kitten on the stairs.

blick:
Subject = proto-Agent/First
Object = proto-Patient/Second
Oblique = Other/Third

Pearl & Sprouse 2018b
Defining the acquisition task

initial state  data intake
learning period  target state

inference

Remember that the acquisition process we imagined hinges on a child perceiving individual links and multi-link theories as “reliable enough”, given the input.
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
learning period  target state

inference

How can “reliable enough” be implemented?
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

One 3-link theory

Three 1-link theories

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.

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

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

Pearl & Sprouse 2018b
Defining the acquisition task

First

Subject

Object

Oblique

Object

one 3-link theory

✓

×

✓

X

three 1-link theories

First

Second

Third

Subject

Object

Oblique

Object

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.

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

\( N \) = # of items that the rule could apply to

Pearl & Sprouse 2018b
Defining the acquisition task

Initial state data intake learning period target state

Subject

Object Oblique Object

First Second Third

One 3-link theory

Three 1-link theories

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

**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**

### The Tolerance Principle (Yang 2005, 2016)

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

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

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

How do we evaluate an individual link?

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

Pearl & Sprouse 2018b
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

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.

\[
\frac{N}{\ln(N)}
\]
Defining the acquisition task

one 3-link theory

three 1-link theories

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).

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

Which has few enough exceptions (if any) according to the child's intake?
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 2018b
Defining the acquisition task

initial state  data intake

target state

inference

one 3-link theory
three 1-link theories

Subject  Object  Oblique Object
First  Second  Third
Subject  Object  Oblique Object
First  Second  Third

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

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).

Which has few enough exceptions (if any) according to the child’s intake?

Pearl & Sprouse 2018b
Defining the acquisition task

How do we evaluate multi-link theories?

Pearl & Sprouse 2018b
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).

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

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

The rest of the inference process depends on the target knowledge for the modeled learner.
Defining the acquisition task

initial state  data intake

inference

target state

Pearl & Sprouse 2018b
Defining the acquisition task

initial state  data intake  target state

one 3-link theory

three 1-link theories

Subject  Object  Oblique Object
First  Second  Third

<3yrs  <4yrs  <5yrs

Subject  Object  Oblique Object
First  Second  Third

inference

…requires a few steps

Pearl & Sprouse 2018b
Defining the acquisition task

initial state  data intake

target state

inference

one 3-link theory

three 1-link theories

subject  object  oblique object

First  Second  Third

Step 1: Are the individual links reliable enough?

Look at all the instances from all the verbs collectively — which links surface as reliable?

He kicked the ball to his friend.
She fell on the ice.  I like penguins.
I love kittens.  I think so.
She’s hugging the kitten.
I hear you talking.
This belongs to me.

Pearl & Sprouse 2018b
Defining the acquisition task

Step 2: If the right links are reliable, the child posits this as one 3-link theory.
Defining the acquisition task

initial state  data intake

target state

inference

three 1-link theories

one 3-link theory

Subject  Object  Oblique Object

First  Second  Third

<3yrs  <4yrs  <5yrs

Step 3: …and evaluates it against the verbs of the language.

Subject  Object  Oblique Object

First  Second  Third

fall  kick  like

hug  belong  think

love  hear

Pearl & Sprouse 2018b
Defining the acquisition task

initial state    data intake

target state

inference

three 1-link theories

Subject    Object    Oblique Object
First      Second     Third

Step 3: ...and evaluates it against the verbs of the language.

This means this linking theory should hold for the verb *lexical items* (types).

Pearl & Sprouse 2018b
Defining the acquisition task

initial state  data intake

target state

inference

<3yrs  <4yrs  <5yrs

one 3-link theory

Step 3: …and evaluates it against the verbs of the language.

Subjects  Objects  Oblique Objects

So we want the number of verb types that disobey this 3-link theory to be less than the Tolerance Principle threshold.

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

Pearl & Sprouse 2018b
Defining the acquisition task

initial state  data intake  target state

inference

one 3-link theory

Step 3: ...and evaluates it against the verbs of the language.

one 3-link theory

Subject  Object  Oblique Object

First  Second  Third

<3yrs  <4yrs  <5yrs

target state

inference

Step 3: ...and evaluates it against the verbs of the language.

How do we tell if a verb type obeys the 3-link theory?

\[ \frac{N}{\ln(N)} = \text{verb types this theory could apply to} \]

Pearl & Sprouse 2018b
Defining the acquisition task

initial state  data intake

target state

Inference

<3yrs  <4yrs  <5yrs

one 3-link theory

three 1-link theories

Subject  Object  Oblique Object
First  Second  Third

Step 3: …and evaluates it against the verbs of the language.

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

\[
\frac{N}{\ln(N)} = \text{verb types this theory could apply to}
\]

Pearl & Sprouse 2018b
Defining the acquisition task

initial state  data intake

target state

inference

three 1-link theories

First

Second

Third

Subject

Object

Oblique Object

Subject

Object

Oblique Object

Subject

Object

Oblique Object

Inference

Step 3: …and evaluates it against the verbs of the language.

She’s hugging the kitten on the stairs.

I hugged him.

Penguins should be hugged.

Please hug me.

She was hugged.

She’ll hug the penguin.

Hug the kitten.

We want the number of verb instances that disobey this 3-link theory to be less than the Tolerance Principle threshold.

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

= verb instances this theory could apply to

= verb types this theory could apply to

Pearl & Sprouse 2018b
Defining the acquisition task

initial state  data intake

target state

inference

three 1-link theories

Subject  Object  Oblique Object

First  Second  Third

one 3-link theory

Step 3: …and evaluates it against the verbs of the language.

If it is, then this linking theory is reliable enough for this verb type.

\[
\frac{N}{\ln(N)} \quad = \quad \text{verb types this theory could apply to}
\]

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

= verb instances this theory could apply to

Pearl & Sprouse 2018b
Defining the acquisition task

one 3-link theory

initial state  data intake

Subject  Object  Oblique Object
First  Second  Third

<3yrs  <4yrs  <5yrs

Step 3: …and evaluates it against the verbs of the language.

If enough verb types are reliable enough, then this linking theory is reliable enough for the verbs of the language.

\[
\frac{N}{\ln(N)} < \text{verb types}
\]

this theory could apply to

fall  kick  like
hug  love  think
belong  hear

Pearl & Sprouse 2018b
Defining the acquisition task

initial state  data intake

inference

Pearl & Sprouse 2018b

But what if the target state is three 1-link theories?
Defining the acquisition task

initial state  data intake  target state

Subject  Object  Oblique Object
First  Second  Third

inference

<3yrs  <4yrs  <5yrs

three 1-link theories

Step 1: Are the 1-link theories reliable enough?

This means each link should individually hold for the verb `lexical items` (types).

Pearl & Sprouse 2018b
Defining the acquisition task

initial state  data intake  target state  

inference

one 3-link theory

Subject  Object  Oblique Object

<3yrs  <4yrs  <5yrs

three 1-link theories

Step 1: Are the 1-link theories reliable enough?

So we want the number of verb types that disobey each 1-link theory to be less than the Tolerance Principle threshold.

\[ N = \text{verb types this theory could apply to} \]

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

Pearl & Sprouse 2018b
Defining the acquisition task

initial state  data intake  target state

inference

one 3-link theory

✓  

three 1-link theories

Step 1: Are the 1-link theories reliable enough?

How do we tell if a verb type obeys a 1-link theory?

\[ \frac{N}{\ln(N)} = \text{verb types this theory could apply to} \]
Defining the acquisition task

Initial state: data intake

Target state

Inference

One 3-link theory

Three 1-link theories

Step 1: Are the 1-link theories reliable enough?

We evaluate that verb type's instances according to whether they follow the 1-link theory or not.

\( N \) = verb types this theory could apply to

\( \ln(N) \)
Defining the acquisition task

initial state  
data intake

target state

inference

one 3-link theory

three 1-link theories

Step 1: Are the 1-link theories reliable enough?

We want the number of verb instances that disobey the 1-link theory to be less than the Tolerance Principle threshold.

\[ \frac{N}{\ln(N)} = \text{verb types this theory could apply to} \]

\[ \frac{N}{\ln(N)} = \text{verb instances this theory could apply to} \]

Pearl & Sprouse 2018b
Defining the acquisition task

initial state  data intake  target state

inference

one 3-link theory

Subject  Object  Oblique Object

First  Second  Third

< 3yrs  < 4yrs  < 5yrs

three 1-link theories

Step 1: Are the 1-link theories reliable enough?

If it is, then this 1-link linking theory is reliable enough for this verb type.

\[ \frac{N}{\ln(N)} = \text{verb types this theory could apply to} \]

\[ \frac{N}{\ln(N)} < \text{verb instances this theory could apply to} \]

Pearl & Sprouse 2018b
Defining the acquisition task

initial state  data intake  target state

inference

one 3-link theory

Subject  Object  Oblique Object
First  Second  Third

<3yrs  <4yrs  <5yrs

three 1-link theories

Step 1: Are the 1-link theories reliable enough?

If enough verb types are reliable enough, then this linking theory is reliable enough for the verbs of the language.

\[ N < \frac{\ln(N)}{\text{verb types}} \]

for the verbs of the language.

Pearl & Sprouse 2018b
Defining the acquisition task

initial state  data intake  target state

Inference

<3yrs  <4yrs  <5yrs

three 1-link theories

…and that’s it.

If enough verb types are reliable enough, then this linking theory is reliable enough for the verbs of the language.

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

= verb types this theory could apply to

Pearl & Sprouse 2018b
Which linking theories are derivable from children's input?

- **One 3-link theory**
  - Subject
  - Object
  - Oblique

- **Three 1-link theories**
  - First
  - Second
  - Third

<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>X</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>

Same results for all three ages.

(Pearl & Sprouse 2018b)
Which linking theories are derivable from children's input?

- three 1-link theories
  - Subject
  - Object
  - Oblique Object

- one 3-link theory

Step 1: Are the individual links reliable enough?

- fixed
- relative

Pearl & Sprouse 2018b
Which linking theories are derivable from children's input?

three 1-link theories

- Subject
- Object
- Oblique Object

First Second Third

Subject  Object  Oblique Object

one 3-link theory

Step 1: 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?

<3yrs  <4yrs  <5yrs

three 1-link theories

Subject  Object  Oblique Object
First  Second  Third

one 3-link theory

Step 1: 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 2018b
Which linking theories are derivable from children’s input?

three 1-link theories

Subject

First

Object

Second

Oblique Object

Third

<3yrs

<4yrs

<5yrs

one 3-link theory

Step 1: 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.

Pearl & Sprouse 2018b
Which linking theories are derivable from children's input?

- **<3yrs**
- **<4yrs**
- **<5yrs**

### 1-link theories

- Subject
- Object
- Oblique Object

### 3-link theory

- First
- Second
- Third

**Step 1:** Here are the ones that are.

- **Fixed**

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

Pearl & Sprouse 2018b
Which linking theories are derivable from children's input?

Three 1-link theories:
- Subject
- Object
- Oblique Object

One 3-link theory:
- Subject
- Object
- Oblique Object

Step 2 & 3: Compose the links into a 3-link theory & evaluate it.

But let's suppose that one unidirectional link is enough to form a link between thematic representation and syntactic position.

Pearl & Sprouse 2018b
Which linking theories are derivable from children's input?

three 1-link theories

Subject  
First  
Object  
Second  
Oblique  
Object  
Third

<3yrs  <4yrs  <5yrs

one 3-link theory

Step 2 & 3: Compose the links into a 3-link theory & evaluate it.

Subject  Object  Oblique Object

fixed

relative

It turns out that this 3-link theory isn’t reliable enough — not enough verb types obey it.
Which linking theories are derivable from children's input?

three 1-link theories

Subject
First

Object
Second

Oblique Object
Third

one 3-link theory

Step 2 & 3: Compose the links into a 3-link theory & evaluate it.

Meanwhile, the 3-link theory using the relative thematic representation is easy to form from reliable links and is reliable enough as a unit.

Pearl & Sprouse 2018b
Which linking theories are derivable from children's input?

three 1-link theories

Subject  Object  Oblique Object
First  Second  Third

<3yrs  ✓  ✓
<4yrs  ✓
<5yrs  ✓

one 3-link theory

Takeaway: Relying on a relative thematic representation is the only way to derive a 3-link theory of the kind linguists have theorized (UTAH, rUTAH).

fixed

relative

Subject  Object  Oblique Object
First  Second  Third
Which linking theories are derivable from children’s input?

Three 1-link theories

Subject  Object  Oblique Object
First  Second  Third

<3yrs  <4yrs  <5yrs

One 3-link theory

Takeaway: Relying on a relative thematic representation is the only way to derive a 3-link theory of the kind linguists have theorized (UTAH, rUTAH).

Pearl & Sprouse 2018b
Which linking theories are derivable from children's input?

What about if children only have to derive three 1-link theories?
Which linking theories are derivable from children's input?

- <3yrs
- <4yrs
- <5yrs

**one 3-link theory**

Subject: ✓  Subject
Object: X  Object
Oblique Object:  Oblique Object

**Relative**  Fixed

---

**three 1-link theories**

**Step 1: Are the individual links reliable enough?**

Subject:  Subject
Object:  Object
Oblique Object:  Oblique Object

**Fixed**  Relative
Which linking theories are derivable from children's input?

![Diagram showing linking theories]

**three 1-link theories**

**Step 1:** Here are the ones that are.

The same 3 unidirectional links as before are reliable enough when the learner relies on a fixed thematic representation.
Which linking theories are derivable from children's input?

three 1-link theories

Step 1: Here are the ones that are.

This means it may be harder to form 1-link theories.
Which linking theories are derivable from children's input?

Pearl & Sprouse 2018b

<3yrs  <4yrs  <5yrs

three 1-link theories

Step 1: Here are the ones that are.

This again contrasts with the relative thematic system, where links in both directions are reliable enough (and there are also no extraneous links).
Which linking theories are derivable from children's input?

Takeaway: Relying on a relative thematic representation is the only way to easily derive three 1-link theories of the kind compatible with those that linguists have theorized (UTAH, rUTAH).

Pearl & Sprouse 2018b
Which linking theories are derivable from children's input?

one 3-link theory

three 1-link theories

Bigger takeaway:
Developmental support for rUTAH over UTAH.

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 quantitative approaches

The little girl *blicked* the kitten on the stairs.
What we learned about linking theories using quantitative approaches

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 quantitative approaches

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 quantitative approaches

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.
What we learned about linking theories using quantitative approaches

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.
What we learned about linking theories using quantitative approaches

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.
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.

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

This can be interpreted as developmental support 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

This will allow us to further validate our developmental 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>

There are nearly 200 verbs in each age that we have developmental model predictions for based on children’s input but no behavioral data for.

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

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

(2) Models incorporating more cognitively plausible assumptions

This will allow us to further validate our developmental 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

This will allow us to further validate our developmental 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 developing grammar: +incorporating additional age-appropriate information

This will allow us to further validate our developmental 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 target state:
+predicting behavioral data available from experiments

This will allow us to further validate our developmental modeling results for these theoretical proposals.
(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 quantitative approaches to investigate them.
The little girl *blicked* the kitten *on* the stairs.

These quantitative approaches allow us to connect theories of *linguistic representation* with theories of *language development* and so understand more about both.
Thank you!

Jon Sprouse

MathPsych 2017
UCI Linguistics 2017
SynLinks workshop 2016
McGill Linguistics 2016

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