Integrating conceptual and syntactic cues to understand the development of English verb classes

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The penguin climbed.

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

The ice melted.

Subject
Object
Indirect Object

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Today's plan

Verb classes

done-to
The ice melted.
The penguin climbed.
doer

Computational modeling

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

Object

Subject

Indirect Object

Results & implications
Verb classes

Verbs allow a variety of options for where their arguments appear ...

**try**

She **tried** to **melt** the ice.

*It **tried** that she **melted** the ice.*

**seem**

The penguin **seemed** to **climb** the hill.

It **seemed** that the penguin **climbed** the hill.
Verb classes

Verbs allow a variety of options for where their arguments appear and how they’re interpreted.

\[ \text{doer}_{\text{melt}} \quad \text{try} \quad \text{doer}_{\text{try}} \]

She tried to melt the ice.

\[ * \text{It tried that she melted the ice.} \]

\[ \text{doer}_{\text{melt}} \quad \text{seem} \quad \text{doer}_{\text{climb}} \]

The penguin seemed to climb the hill.

\[ \text{doer}_{\text{melted}} \quad \text{seem} \quad \text{doer}_{\text{climb}} \]

It seemed that the penguin climbed the hill.
**Verb classes**

*Verbs* allow a variety of options for where their arguments appear and how they’re interpreted.

- **doer<sub>melt</sub>**  
  *She tried to melt the ice.*

- **doer<sub>try</sub>**  
  *It tried that she melted the ice.*

- **doer<sub>tried</sub>**  
  *She tried to melt the ice.*

- **doer<sub>climb</sub>**  
  *It seemed that the penguin climbed the hill.*

- **seem**  
  *The penguin seemed to climb the hill.*

- **melt**  
  *The ice melted.*

- **done-to<sub>melted</sub>**  
  *The penguin climbed.*

- **climb**
Verb classes

Each verb has *certain linguistic patterns of behavior*, which are shared with other verbs in the same *verb class*.

- **subject-control**
  - *doer*<sub>melt</sub>*
  - *doer*<sub>tried</sub>
  - She tried to melt the ice.
  - *It tried that she melted the ice.*

- **unaccusative**
  - *doer*<sub>melted</sub>
  - The ice melted.

- **done-to**
  - *doer*<sub>melted</sub>
  - The ice melted.

- **subject-raising**
  - *doer*<sub>climb</sub>*
  - The penguin seemed to climb the hill.
  - It seemed that the penguin climbed the hill.

- **unergative**
  - *doer*<sub>climbed</sub>*
  - The penguin climbed.

- **appear**
  - *doer*<sub>tried</sub>*
  - She tried to melt the ice.
  - *It tried that she melted the ice.*

- **want** **need**

- **try** **seem**

- **break** **fall**
Verb classes

How do we tell how a new verb will behave?

The water seemed to **blick**.

want  need

**subject-control**

---

doer\textsubscript{melt}
She tried to melt the ice.

*It tried that she melted the ice.

---

doer\textsubscript{try}

---

done-to\textsubscript{melt}
The ice melted.

---

melt

---

**unaccusative**

break  fall

---

appear

**subject-raising**

---

doer\textsubscript{climb}
The penguin seemed to climb the hill.

It seemed that the penguin climbed the hill.

---

**unergative**

---

doer\textsubscript{climbed}
The penguin climbed.

---

climb

---

laugh  dance
Verb classes

We can recognize that it belongs to a specific verb class, and use that knowledge to predict its behavior.

*It tried that she melted the ice.

She tried to melt the ice.

The water seemed to blick.

The penguin seemed to climb the hill.

It seemed that the penguin climbed the hill.
Verb classes

This is what we think kids are doing, too.

**The water seemed to blick.**

want need

**subject-control**

try

doer\(_{\text{melt}}\)  
She tried to melt the ice.

*It tried that she melted the ice.*

appear

**subject-raising**

seem

doer\(_{\text{climb}}\)  
The penguin seemed to climb the hill.

It seemed that the penguin climbed the hill.

done-to\(_{\text{melted}}\)  
The ice melted.

blick melt

**unaccusative**

break fall

**unergative**

climb

The penguin climbed.

The water blicked.
Verb classes

Important developmental step: Grouping verbs into useful **classes** based on their **behavior**.

- **unaccusative**
  - melt
  - unaccusative
  - break
  - fall

- **subject-control**
  - want
  - need
  - try

- **subject-raising**
  - appear
  - seem

- **unergative**
  - climb
  - laugh
  - dance

So how might children do this?

And how can we test different proposals about how they might do this?
Today’s plan

Computational modeling of language acquisition

A brief overview
Language acquisition = Information processing task
A framework that makes components of the acquisition task more explicit.
A framework that makes components of the acquisition task more explicit.

Distinguishes between things external to the child that we can observe (input signal, child’s behavior) vs. things internal to the child (everything else).
**Perceptual encoding:**

Turning the input signal into an internal linguistic representation = perceptual intake.
Perceptual encoding:
Involves current grammar
Perceptual encoding:
Involves current grammar being deployed in real time to parse the input
Perceptual encoding:
Involves current grammar being deployed in real time to parse the input, often drawing on extralinguistic systems.
Generating observable **behavior**
Involves current linguistic representations being used by **production systems**.
Doing inference
Generalization happens
Generalization happens by using existing learning biases, (some of which may be innate and language-specific)
Doing inference

Generalization happens by using existing learning biases, (some of which may be innate and language-specific) operating over the acquisitional intake — what’s perceived as relevant for acquisition.
Doing inference

Generalization happens by using existing learning biases, (some of which may be innate and language-specific) operating over the acquisitional intake — what’s perceived as relevant for acquisition to produce the most up-to-date hypotheses about linguistic knowledge.
The current linguistic hypotheses are used in subsequent perceptual encoding.
This whole process happens over and over again throughout the learning period.
This is language acquisition

An informative computational model of language acquisition captures these important pieces in an empirically-grounded way.
This is language acquisition

Informative computational models = informative about the learning strategies children use
Learning strategies children use

A successful learning strategy is an existence proof that linguistic knowledge is attainable using the knowledge, learning biases, and capabilities comprising that strategy.
Learning strategies children use

This is what we want to evaluate with computational modeling.

The penguin tried to climb.

The ice seemed to melt.
Today’s plan

Computational modeling

Information available and how to use it
The penguin tried to climb.
The ice seemed to melt.

Children are very adept at using **syntactic bootstrapping** to learn useful generalizations about how verbs behave (e.g., Fisher et al. 2010, Gutman et al. 2015, Harrigan et al. 2016).
The penguin **tried** to climb.

**Syntactic cues**

**Syntactic frame**

The ice seemed to melt.

Information available

- subject-control
- unergative

Want
- try
- need
- melt
- appear

Subject-raising
- seem
- break
- fall

Climb
- unaccusative
- laugh
- dance

NP ___ S

NP ___ +past S

- surface morphology

+ surface morphology
The penguin tried to climb.

The ice seemed to melt.
Information available

The ice seemed to melt.

Conceptual cues
Animacy


It’s useful:
It can distinguish verb behaviors like raising vs. control verbs, and psych object-experiencer verbs.
The penguin tried to climb.
The ice seemed to melt.

**Conceptual cues**

**Animacy**

**Syntactic frame**

NP ___ S_{nonfinite} -surf morph
NP ___+past S_{nonfinite} +surf morph

**Children use it:**
Young children have been shown to use this cue in experimental studies.

The penguin tried to climb.
The ice seemed to melt.

**Syntactic frame**

NP ___ $S_{nonfinite}$ -surfmorph
NP ___+past $S_{nonfinite}$ +surfmorph

**Conceptual cues**

**Thematic roles**

Children could use them:

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

Information available

Conceptual cues + Syntactic-semantic knowledge
Thematic roles and how to use them

Syntax

She melted the ice with a blow dryer.
Subject Object Indirect Object

Syntactic frame
NP ___ $s_{nonfinite}$ -surfmorph
NP ___+past $s_{nonfinite}$ +surfmorph

Animacy
+animate
The penguin tried to climb.

-animate
The ice seemed to melt.

How do we get from here to here?

Thematic roles Agent, Experiencer, Patient, Theme, Goal, Source, Instrument...
Information available

Conceptual cues + Syntactic-semantic knowledge
Thematic roles and how to use them

Syntax

She melted the ice with a blow dryer.

Subject Object Indirect Object

Syntactic frame
NP ___ $S_{\text{nonfinite}}$ -surfmorph
NP ___+$\text{past} S_{\text{nonfinite}}$ +surfmorph

Animacy

+animate
The penguin tried to climb.

-animate
The ice seemed to melt.

Thematic roles map to one of three categories.

The Uniformity of Theta Assignment Hypothesis

Theories of prior knowledge

Intermediate representations

Thematic roles Agent, Experiencer, Patient, Theme, Goal, Source, Instrument...
Information available

Conceptual cues + Syntactic-semantic knowledge
Thematic roles and how to use them

Syntax

She melted the ice with a blow dryer.

Subject | Object | Indirect Object

Syntactic frame

NP ___ $S_{nonfinite}$ | nonfinite -surfmorph
NP ___+past $S_{nonfinite}$ +surfmorph

Animacy

+animate
The penguin tried to climb.

-animate
The ice seemed to melt.

Mapping to Syntax

These categories map to syntactic positions.

Thematic roles map to one of three categories.

UTAH

Thematic roles

Agent, Experiencer, Patient, Theme, Goal, Source, Instrument...
Information available

Conceptual cues + Syntactic-semantic knowledge
Thematic roles and how to use them

Syntax

She melted the ice with a blow dryer.

She: Subject
Ice: Object
Blow dryer: Indirect Object

Syntactic frame
NP ___ S_{nonfinite} -surf
NP ___+past S_{nonfinite} +surf

Animacy
+animate
The penguin tried to climb.

-animate
The ice seemed to melt.

Mapping to Syntax

Intermediate representations

Thematic roles
Agent, Experiencer, Patient, Theme, Goal, Source, Instrument...

The (relativized) UTAH
Larson 1988, Larson 1990

Agent > Experiencer >
Theme > Patient >
(Source, Goal, Instrument)
Information available

Conceptual cues + Syntactic-semantic knowledge
Thematic roles and how to use them

Syntax
She melted the ice with a blow dryer.

Syntactic frame
NP ___ $S_{\text{nonfinite}}$ -surfmorph
NP ___+past $S_{\text{nonfinite}}$ +surfmorph

Animacy
+animate
The penguin tried to climb.

-animate
The ice seemed to melt.

Mapping to Syntax

Intermediate representations
UTAH

Whichever ones are present map in order to syntactic positions.

Theories of prior knowledge

Thematic roles
Agent, Experiencer, Patient, Theme, Goal, Source, Instrument…
Information available

Conceptual cues + Syntactic-semantic knowledge
Thematic roles and how to use them

Syntax

She melted the ice with a blow dryer.

Subject
Object
Indirect Object

Standard UTAH and rUTAH implementations typically assume the mapping is also known a priori

Animacy

+animate
The penguin tried to climb.

-animate
The ice seemed to melt.

Syntactic frame
NP ___ S_{nonfinite} -surfmorph
NP ___+past S_{nonfinite} +surfmorph

Mapping to Syntax

Intermediate representations

Theories of prior knowledge

Thematic roles
Agent, Experiencer, Patient, Theme, Goal, Source, Instrument...
Information available

Conceptual cues + Syntactic-semantic knowledge
Thematic roles and how to use them

Syntactic frame
NP ____ S\text{nonfinite} -\text{surfmorph}
NP ____ +past S\text{nonfinite} +\text{surfmorph}

Animacy
+animate
The penguin tried to climb.

-animate
The ice seemed to melt.

Syntax
She melted the ice with a blow dryer.

But these are separate components

Mapping to Syntax

Theories of prior knowledge

Intermediate representations

UTAH

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

Thematic roles
Agent, Experiencer, Patient, Theme, Goal, Source, Instrument...
Information available

Conceptual cues + Syntactic-semantic knowledge
Thematic roles and how to use them

Syntax
She melted the ice with a blow dryer.

\[
\text{Subject} \rightarrow \text{Object} \rightarrow \text{Indirect Object}
\]

Whether children expect a mapping a priori impacts how they perceive the intake for acquisition

Syntactic frame
NP ___ S_{\text{nonfinite}} -surfmorph
NP ___+past S_{\text{nonfinite}} +surfmorph

Animacy
+animate
The penguin tried to climb.

-animate
The ice seemed to melt.

Theories of prior knowledge

Intermediate representations

UTAH

rUTAH

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

Thematic roles
Agent, Experiencer, Patient, Theme, Goal, Source, Instrument...
Information available

+ expect a mapping

Salient when mapping doesn’t hold:
Interpreted as movement

Syntax

The ice was *melted* by the girl.

Subject

Indirect Object

done-to

doer

melt: + movement

Mapping to Syntax

Theories of prior knowledge

Intermediate representations

Thematic roles

Agent, Experiencer, Patient, Theme, Goal, Source, Instrument...

Unexpected by UTAH

rUTAH

Agent > Experiencer >
Theme > Patient >
(Source, Goal, Instrument)
Information available

+expect a mapping

Salient when mapping doesn’t hold: Interpreted as movement

Syntax

The ice was melted by the girl.

melt: +movement

Mapping to Syntax

Theories of prior knowledge

Intermediate representations

UTAH

rUTAH

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

Thematic roles Agent, Experiencer, Patient, Theme, Goal, Source, Instrument...
Information available

- expect a mapping

Children track grammatical positions of intermediate representations

Syntax

The ice was **melted** by the girl.

**Subject**

**Indirect Object**

**done-to**

**doer**

The thematic roles...
Information available

Syntax

The ice was **melted** by the girl.

*Subject*  **Indirect Object**

2nd highest

Highest

- expect a mapping

Children track grammatical positions of intermediate representations

Thematic roles: **Agent, Experiencer, Patient, Theme, Goal, Source, Instrument**...

Mapping to Syntax

Theories of prior knowledge

Intermediate representations

UTAH

rUTAH

Agent > Experiencer > Theme > Patient > (Source, Goal, Instrument)
Information available

Conceptual cues + Syntactic-sematic knowledge
Thematic roles and how to use them

Syntax

The ice was melted by the girl.

Mapping to Syntax

Thematic roles Agent, Experiencer, Patient, Theme, Goal, Source, Instrument...

Intermediate representations

UTAH

rUTAH

Agent > Experiencer > Theme > Patient > (Source, Goal, Instrument)
Information available

Syntactic frame
NP ___ S_{nonfinite} -surfmorph
NP ___+past S_{nonfinite} +surfmorph

Animacy
+animate
The penguin tried to climb.

-animate
The ice seemed to melt.

Thematic roles and how to use them
Agent > Experiencer > rUTAH +expmap
Theme > Patient > (Source, Goal, Instrument)
Potential learning strategies

Syntactic frame
NP ___ S_{nonfinite} -surfmorph
NP ___+past S_{nonfinite} +surfmorph

Thematic roles and how to use them
Agent > Experiencer > rUTAH +expmap
Theme > Patient > (Source, Goal, Instrument)

Animacy
+animate
The penguin tried to climb.

-animate
The ice seemed to melt.
Potential learning strategies

Thematic roles and how to use them

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

UTAH - expmap
rUTAH + expmap

Subject Object Indirect Object

Animacy
+animate
The penguin tried to climb.

-animate
The ice seemed to melt.

Syntactic frame
NP ___ S_{nonfinite} -surf morph
NP ___+past S_{nonfinite} +surf morph

Choice 1

The ice seemed to melt.
The penguin tried to climb.
Potential learning strategies

**Thematic roles and how to use them**

Choice 1

- animate
  - The penguin tried to climb.

- animate
  - The ice seemed to melt.

**Syntactic frame**

NP ____ S\_nonfinite -surfmorph
NP ____+past S\_nonfinite +surfmorph

**Animacy**

+animate
-animate

**Choice 2**

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

- expmap
+ expmap

**Subject** **Object** **Indirect Object**

**Subject** **Object** **Indirect Object**

movement?
Potential learning strategies

Animacy
+animate
The penguin tried to climb.

-sanimate
The ice seemed to melt.

Syntactic frame
Choice 1
NP ____ S\text{nonfinite} -\text{surf morph}
NP ____ +past S\text{nonfinite} +\text{surf morph}

Thematic roles and how to use them

Choice 2
Agent > Experiencer > r\text{UTAH}
Theme > Patient > (Source, Goal, Instrument)

Choice 3
Subject Object Indirect Object -expmap
Subject Object Indirect Object +expmap

movement?

3 binary choices = 8 strategies
Today’s plan

Computational modeling

How do we model this?
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

“it’s falling off”
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

"it's falling off"

**Input:**
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
Basic question: Is it possible for the child to use the acquisitional intake to achieve the target knowledge/behavior?
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

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.
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

<3yrs  <4yrs  <5yrs

Learners use a generative model of how the observable data for each verb are created.
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

<3yrs  <4yrs  <5yrs

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

FALL
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

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?”
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

<3yrs  <4yrs  <5yrs

Each instance is observed some number of times.

“it’s falling off” (3x)  “it’s falling off”  “it’s falling off”
Each verb belongs to some class which determines its linguistic behavior.

Objective: Infer verb class

Goal: Model the developmental trajectory from 3 to 4 to 5 years old

<3yrs <4yrs <5yrs

“it’s falling off”
(3x) “it’s falling off”
“it’s falling off”

The learner doesn’t know beforehand how many classes there are or which verbs belong to which.
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

<3yrs <4yrs <5yrs

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

“it’s falling off”
(3x) “it’s falling off”
“it’s falling off”
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

<3yrs  <4yrs  <5yrs

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

Each class has a probability of preferring each option.

\[ \text{class}_7 \]

-anim  Subject  -anim

0.3  0.7

“it’s falling off”

(3x)  “it’s falling off”

“it’s falling off”
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

<3yrs  <4yrs  <5yrs

**FALL**

"it's falling off"

(3x)  "it's falling off"  "it's falling off"

---

**Binary choices:**

+/−animate subject
+/−animate object
+/−animate indirect object
+/−movement (when +exp-mapping)

---

**movement?**

---

**Subject  Object  Indirect Object**

---

**+animate  -animate**
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

<3yrs  <4yrs  <5yrs

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

Each class has a probability of preferring each option.

- **NP V PRT**  0.3
- **NP V**  0.25
- ...  
- **NP V S**  0

-anim  “it’s falling off”  
NP V  PRT  “it’s falling off”  
(3x)
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

<3yrs  <4yrs  <5yrs

"it's falling off" (3x) NP V PRT "it's falling off"

Multinomial choices:
which syntactic frame is used \textit{NP V PRT}

(if -exp-mapping)

position of doer/Highest role
position of done-to/next-highest role
position of done-by/third-highest role

Agent > Experiencer >
Theme > Patient >
(Source, Goal, Instrument)
Subject  Object  Indirect Object

0.3  0.7

\begin{align*}
\gamma_c & \rightarrow \theta_c \\
\theta_{c_j} & \rightarrow \pi_{\phi_{c_j}} \\
\pi_{\phi_{c_j}} & \rightarrow F_{j_i} \\
F_{j_i} & \rightarrow F_j \\
F_j & \rightarrow V
\end{align*}

\begin{align*}
\alpha\psi & = \beta\phi_0 \\
\beta\phi_1 & = 0.3 \\
\beta\phi_0 & = 0.7
\end{align*}

\begin{align*}
\text{class}_7 & \rightarrow +\text{anim}  \quad \text{Subject}  \quad -\text{anim} \\
& \rightarrow NP V  \quad PRT  \quad 0.25  \quad \ldots  \quad NP V  \quad S  \quad 0
\end{align*}
Using the observed instances of verb usage, Bayesian inference can be used to determine ...
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

<3yrs  <4yrs  <5yrs

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

"it’s falling off"  NP V PRT
(3x)  "it’s falling off"  "it’s falling off"
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
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
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

<3yrs <4yrs <5yrs

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.
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

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

+ Gibbs sampling

Goal: Model the developmental trajectory from 3 to 4 to 5 years old

\[<3\text{yrs} \quad <4\text{yrs} \quad <5\text{yrs}\]

-anim "it’s falling off"

NP V PRT 0.25

NP V S 0

NP V 0.3...
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

<3yrs  <4yrs  <5yrs

FALL

“it’s falling off”

NP V PRT

0.25

NP V S

0

Goal: Determine if the information provided in the modeled learner’s acquisitional intake is sufficient to identify verb classes this way.
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

verb classes
Verb classes

Survey of 32 experimental studies on children’s production and comprehension of specific verbs

Goal: Model the developmental trajectory from 3 to 4 to 5 years old

<3yrs  <4yrs  <5yrs
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

<3yrs  <4yrs  <5yrs

verb classes

Survey of 32 experimental studies on children’s production and comprehension of specific verbs

Yields 12 verb behaviors

+/-passive  +unaccusative
+ditransitive  +control-object
+raising-object  +raising-subject
+that-comp  +control-subject
+whether/if-comp  +subject-experiencer
+object-experiencer
+non-finite to-comp
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

These verb behaviors yield a number of verb classes at each age
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

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

Example classes

<3yrs

[+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
Goal: Model the developmental trajectory from 3 to 4 to 5 years old.

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

**Example classes**

- **<4yrs**
  - [+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
  - [+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
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

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

[-passive]: believe, remember

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

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

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

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

[+passive, +that-comp, +whether/if-comp]: see
Goal: Model the developmental trajectory from 3 to 4 to 5 years old.

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
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

Evaluation:
How well did the modeled learner do at finding these verb classes?
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

<3yrs  15 classes
<4yrs  23 classes
<5yrs  25 classes

Implementation:
Random Index
0.0 <= RI <= 1.0

Intuition: Get credit for putting things together that belong together and keeping things apart that don’t belong together.
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

Implementation: Random Index

\[ 0.0 \leq RI \leq 1.0 \]

For each pair of verbs in the inferred classes:

**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 don’t belong together.
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

15 classes
<3yrs

23 classes
<4yrs

25 classes
<5yrs

Implementation: Random Index

0.0 <= RI <= 1.0

For each pair of verbs in the inferred classes:

Inferred Class

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

Intuition: Get credit for putting things together that belong together and keeping things apart that don’t belong together.
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

Implementation: Random Index

Intuition: Get credit for putting things together that belong together and keeping things apart that don’t belong together.

But how do we know we’re doing better than chance?
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

Implementation 1: Bootstrapped confidence intervals for RI, based on class distribution

- 😊 RI > 99% = better than chance
- 😞 RI in between = chance performance
- ☹️ RI < 1% = worse than chance
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

15 classes
23 classes
25 classes

Implementation 2: Adjusted Random Index

-1.0 <= ARI <= 1.0

Compared against the expected value of the Random Index:

1.0 = perfect classification
>0 = better than chance
0 = chance performance
<0 = worse than chance
-1.0 = perfectly awful classification
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

Implementation 1:
Bootstrapped confidence intervals for RI, based on class distribution

RI > 99% = better than chance
RI in between = chance performance
RI < 1% = worse than chance

Implementation 2:
Adjusted Random Index (ARI)

1.0 = perfect classification
>0 = better than chance
0 = chance performance
<0 = worse than chance
-1.0 = perfectly awful classification

Look for agreement between these two measures as signal of significant difference
Today’s plan

Results & implications
This is the first articulation of the trajectory of learning assumptions children may have that causes them to group verbs into useful classes the way we observe.
The ice seemed to melt.

It suggests there are different timelines for
- ignoring vs. heeding surface morphology on verbs ...
It suggests there are different timelines for:
- ignoring vs. heeding surface morphology on verbs
- a more fixed vs. more relative intermediate thematic representation...
It suggests there are different timelines for
- ignoring vs. heeding surface morphology on verbs
- a more fixed vs. more relative intermediate thematic representation...
- not expecting vs. expecting a mapping between that intermediate thematic representation and syntactic positions
What does this mean for linguistic theory?
What doesn’t need to be built in

An expectation for how to map between intermediate thematic representations and grammatical positions.
What we saw today

Verb classes

done-to
The ice melted.
The penguin climbed.
doer

Computational modeling

Results & implications
What we saw today

Verb classes: An example of complex linguistic knowledge that children develop, involving several theoretical options for the representations they may be using and how they’re integrating conceptual and syntactic information.

Computational modeling

Results & implications
What we saw today

Verb classes: complex linguistic knowledge involving several theoretical options for representations

Computational modeling: A way to explicitly test these theories by implementing them concretely in an empirically grounded model of the acquisition process.

Results & implications
What we saw today

**Verb classes:** complex linguistic knowledge involving several theoretical options for representations

**Computational modeling:** explicitly test these theories

**Results & implications:** Articulating the trajectory of representations and learning assumptions children have at different stages of development
What we saw today

Verb classes: complex linguistic knowledge involving several theoretical options for representations

Computational modeling: explicitly test these theories

Results & implications: Articulating the representational trajectory over development

This approach allows us to connect theories of linguistic representation and theories of language acquisition to understand more about both.
Thank you!

Jon Sprouse

UCI Linguistics 2017
SynLinks workshop 2016
McGill Linguistics 2016

The ice melted.
The penguin climbed.
doe

Special thanks to Abbie Thornton, Alandi Bates, Emily Yang, and BreAnna Silva for CHILDES Treebank corpus annotation.
Language acquisition = Information processing task

Given the available input ...

The penguin tried to climb.

The ice seemed to melt.
Language acquisition = Information processing task

Given the available input, information processing done by human minds...

The penguin tried to climb.

The ice seemed to melt.
Language acquisition = Information processing task

Given the available input, information processing done by human minds to build a system of linguistic knowledge ...

Processing &

generalization

The penguin tried to climb.

The ice seemed to melt.

appear

subject-raising

want

subject-control

try

need

climb

unaccusative

melt

unergative

break

fall

laugh

dance
Language acquisition = Information processing task

Given the available input, information processing done by human minds to build a system of linguistic knowledge whose output we observe.

The penguin tried to climb.
The ice seemed to melt.

The penguin wanted to dance.
It appeared that the ice broke.
Language acquisition = Information processing task

To understand how children solve the acquisition task, we need to make explicit the relevant components of the task.

The penguin tried to climb.

The ice seemed to melt.

The penguin wanted to dance.

It appeared that the ice broke.
Thematic roles & how to use them

One idea about how children could use thematic role information: (r)UTAH.

The (relativized) UUniformity of Theta Assignment Hypothesis


Each thematic role maps to a specific syntactic position (grammatical role).
Thematic roles & how to use them

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Each thematic role maps to a specific syntactic position (grammatical role).

Agent-like = grammatical subject

Agent
Causer
Experiencer
Possessor

("internal cause“ = Rappaport-Hovav 1995)
Thematic roles & how to use them

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Each thematic role maps to a specific syntactic position (grammatical role).

Agent-like = grammatical subject

- Agent
- Causer
- Experiencer (*Baker: only when subject)
- Possessor

("internal cause“ = Rappaport-Hovav 1995)

**She fears spiders.**
**Spiders frighten her.**

**The penguin seemed to climb the hill.**
It seemed that the penguin climbed the hill.

**She tried to melt the ice.**
*It tried that she melted the ice.*
Thematic roles & how to use them

One idea about how children could use thematic role information: (r)UTAH.

The (relativized) Uniformity of Theta Assignment Hypothesis


Each thematic role maps to a specific syntactic position (grammatical role).

Agent-like = grammatical subject
Patient-like = grammatical object

Patient
Theme
Experiencer
Subject Matter

("external cause")

She tried to melt the ice.

*It tried that she melted the ice.

The penguin seemed to climb the hill.

It seemed that the penguin climbed the hill.
Thematic roles & how to use them

One idea about how children could use thematic role information: \((r)\)UTAH.

The relativized \textbf{U}niformity of \textbf{T}heta \textbf{A}ssignment \textbf{H}ypothesis


Each thematic role maps to a specific syntactic position (grammatical role).

Agent-like = grammatical subject
Patient-like = grammatical object

Patient
Theme
Experiencer (*Baker: only when not subject)
Subject Matter

(“external cause”)

She fears spiders.
Experiencer

Spiders frighten her.
Experiencer

\begin{itemize}
  \item \textbf{She} tried to melt the ice.
  \item *\textbf{It} tried that she melted the ice.
  \item \textbf{The penguin} seemed to climb the hill.
  \item \textbf{It} seemed that the penguin climbed the hill.
\end{itemize}
Thematic roles & how to use them

One idea about how children could use thematic role information: (r)UTAH.

The (relativized) Uniformity of Theta Assignment Hypothesis


Each thematic role maps to a specific syntactic position (grammatical role).

Agent-like = grammatical subject
Patient-like = grammatical object
Goal-like = grammatical indirect object

Location
Source
Goal
Benefactor
Instrument

She tried to melt the ice with a blow dryer.

*It tried that she melted the ice with a blow dryer.

The penguin seemed to climb the hill.

It seemed that the penguin climbed the hill.
Thematic roles & how to use them

She melted the ice with a blow dryer.

Syntax

Mapping to Syntax

The Uniformity of Theta Assignment Hypothesis:

Intermediate representations

UTAH

Thematic roles map to one of three categories.

(likely derived from lower level conceptual info) = Agent, Experiencer, Patient, Theme, Goal, Source, Instrument...
Thematic roles & how to use them

One idea about how children could use thematic role information: (r)UTAH.

The (relativized) Uniformity of Theta Assignment Hypothesis

rUTAH: Larson 1988, Larson 1990

Thematic roles are ordered relative to each other, with the highest thematic role mapping to the highest grammatical role (subject > object > indirect object).

She tried to melt the ice with a blow dryer.

*It tried that she melted the ice with a blow dryer.

The penguin seemed to climb the hill.

It seemed that the penguin climbed the hill.
Thematic roles & how to use them

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Thematic roles are ordered relative to each other, with the highest thematic role mapping to the highest grammatical role (subject > object > indirect object).

Basic intuition:
doer (Agent-like) >
done-to (Patient-like) >
done-for/with (Goal-like)

She tried to melt the ice with a blow dryer.

*It tried that she melted the ice with a blow dryer.

The penguin seemed to climb the hill.

It seemed that the penguin climbed the hill.
Thematic roles & how to use them

One idea about how children could use thematic role information: (r)UTAH.

The (relativized) Uniformity of Theta Assignment Hypothesis

**rUTAH**: Larson 1988, Larson 1990

Thematic roles are ordered relative to each other, with the highest thematic role mapping to the highest grammatical role (subject > object > indirect object).

**Basic intuition:**

**doer** (Agent-like) >
  **done-to** (Patient-like) >
  **done-for/with** (Goal-like)

**An example implementation:**

Agent > Causer > Experiencer > Possessor >
  Subject Matter > Causee > Theme > Patient >
  (Location, Source, Goal, Benefactor, Instrument)

---

**Control**

*She tried to melt the ice with a blow dryer.*

```
*It tried that she melted the ice with a blow dryer.
```

**The penguin seemed to climb the hill.**

```
It seemed that the penguin climbed the hill.
```

---

*Pearl & Sprouse in progress*
Thematic roles & how to use them

One idea about how children could use thematic role information: (r)UTAH.

The (relativized) Uniformity of Theta Assignment Hypothesis

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Thematic roles are ordered relative to each other, with the highest thematic role mapping to the highest grammatical role (subject > object > indirect object).

Basic intuition:
doer (Agent-like) >
done-to (Patient-like) >
done-for/with (Goal-like)

An example implementation:
Agent > Causer > Experiencer > Possessor >
Subject Matter > Causee > Theme > Patient >
(Location, Source, Goal, Benefactor, Instrument)

Note: You don’t need to have every role relatively ranked. If some are unranked with respect to each other, the order in which they get mapped to grammatical positions doesn’t matter.
Thematic roles & how to use them

One idea about how children could use thematic role information: (r)UTAH.

The (relativized) Uniformity of Theta Assignment Hypothesis

rUTAH: Larson 1988, Larson 1990

Thematic roles are ordered relative to each other, with the highest thematic role mapping to the highest grammatical role (subject > object > indirect object).

Basic intuition:

*doer (Agent-like) >
  *done-to (Patient-like) >
  *done-for/with (Goal-like)*

An example implementation:

*Agent > Causer > Experiencer > Possessor >
  *Subject Matter > Causee > Theme > Patient >
  *Location, Source, Goal, Benefactor, Instrument*#

This relative ranking can help deal with certain situations, like those involving Experiencers.

She fears spiders.

*Experiencer Subject Matter*

*Experiencer Subject Matter*

*Subject Object*

Spiders frighten her.

*Causer Experiencer*

*Causer Experiencer*

*Subject Object*
Potential learning strategies

**Choice 1**

- Animacy
  - +animate
  - -animate

- Syntactic frame
  - NP ___ S
  - NP ___ +past S

- Thematic roles and how to use them
  - UTAH
  - rUTAH

**Choice 2**

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

**Choice 3**

- Subject    Object    Indirect Object
- Subject    Object
- movement?

3 binary choices = 8 strategies

All strategies require learner’s initial state to be sufficient to extract this information from the input.
Potential acquisitional intakes

3 binary choices = 8 strategies
Each strategy has a different impact on the acquisitional intake

Animacy

Syntactic frame
- surfmorph    + surfmorph

Thematic roles and how to use them

UTAH
Agent > Experiencer > Theme > Patient >
(Source, Goal, Instrument)

rUTAH

-expmap
+ expmap

Subject  Object  Indirect Object
Subject  Object  Indirect Object

movement?

"it’s falling off"

(from Brown-Eve corpus in CHILDES Treebank)
Potential acquisitional intakes

3 binary choices = 8 strategies
Each strategy has a different impact on the acquisitional intake

Animacy
Syntactic frame
- surfmorph + surfmorph

Thematic roles and how to use them

- expmap + expmap

Animacy

Input

“it’s falling off”

“it’s falling off”

Possible perceptual intake

Inferring engine

Acquisitional intake

Universal grammar

Subject Object Indirect Object

Source, Goal, Instrument

Subject Object Indirect Object

movement?
Potential acquisitional intakes

3 binary choices = 8 strategies
Each strategy has a different impact on the acquisitional intake

Animacy
Syntactic frame
- surfmorph + surfmorph

Thematic roles and how to use them

UTAH
rUTAH

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

-expmap + expmap
Subject Object Indirect Object
Subject Object Indirect Object

movement?

FALL

- animate subject: 1
Potential acquisitional intakes

3 binary choices = 8 strategies
Each strategy has a different impact on the acquisitional intake

Animacy
Syntactic frame
+surfsmorph
Thematic roles and how to use them

rUTAH
Agent > Experiencer >
Theme > Patient >
(Source, Goal, Instrument)
+expmap

Subject Object Indirect Object
Subject Object Indirect Object

movement?

FALL
animate subject: 1
Done-to as subject: 1

UTAH
-expmap
-surfsmorph
Potential acquisitional intakes

3 binary choices = 8 strategies
Each strategy has a different impact on the acquisitional intake

Animacy

Syntactic frame
+surfmorph
Thematic roles and how to use them
rUTAH
Agent > Experiencer >
Theme > Patient >
(Source, Goal, Instrument)
+expmap

Subject Object Indirect Object
Subject Object Indirect Object
movement?

FALL
-animate subject: 1
Done-to as subject: 1

NP V PRT

UTAH
- expmap
-surfmorph
Potential acquisitional intakes

3 binary choices = 8 strategies
Each strategy has a different impact on the acquisitional intake

Animacy
Syntactic frame
-surfmorph
Thematic roles and how to use them

rUTAH
Agent > Experiencer >
Theme > Patient >
(Source, Goal, Instrument)
+expmap

Possible perceptual intake

“it’s falling off”

Input

Inference engine
Acquisitional intake
Universal grammar

FALL
-animate subject: 1
Done-to as subject: 1

NP V_{prog} PRT

UTAH
-expmap
+surfmorph
Potential acquisitional intakes

3 binary choices = 8 strategies
Each strategy has a different impact on the acquisitional intake

Animacy

Syntactic frame
-surfmorph

Thematic roles and how to use them

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

-expmap

-animate subject: 1
+movement: 1

Input
“it’s falling off”

Possible perceptual intake

Possible perceptual intake

Theme is expected to map to object, not subject.
Indicator of movement.

FALL

UTAH

NP V_{prog} PRT

+expmap
+surfmorph
Potential acquisitional intakes

3 binary choices = 8 strategies
Each strategy has a different impact on the acquisitional intake

Animacy

Syntactic frame
-surfmorph
Thematic roles and how to use them

UTAH

-expmap

Subject Object Indirect Object

movement?

-rUTAH

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

+expmap
+surfmorph

NP V_{prog} PRT

“it’s falling off”

“it’s falling off”

Possible perceptual intake

Theme is only role so is default highest. Expected mapping is to highest syntactic position (subject).
Potential acquisitional intakes

3 binary choices = 8 strategies
Each strategy has a different impact on the acquisitional intake

Animacy

Syntactic frame
- surfmorph

Thematic roles and how to use them

UTAH

Possible perceptual intake

“it’s falling off”

Input

Possible perceptual intake

Inference engine

Acquisitional intake

Universal grammar

Subject Object Indirect Object

Subject Object Indirect Object

movement?

FALL

- animate subject: 1

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

Highest role as subject: 1

NP V_{+prog} PRT

rUTAH

+ expmap

- expmap

+ surfmorph

Each strategy has a different impact on the acquisitional intake
8 modeled learners and their acquisitional intakes
“it’s falling off”

Input

Possible perceptual intake

Animacy -animate subject: 1  All 8 learners

8 modeled learners and their acquisitional intakes
"it's falling off"

8 modeled learners and their acquisitional intakes

Input

Possible perceptual intake

FALL

Animacy -animate subject: 1

All 8 learners

Syntactic frame -surfmorph +surfmorph

4 learners 4 learners

NP V PRT NP V\_prog PRT

4 learners
"it’s falling off"

8 modeled learners and their acquisitional intakes

Input

Possible perceptual intake

Animacy

-animate subject: 1

All 8 learners

Syntactic frame

-surfmorph

4 learners

NP V PRT

Intermediate representation

- animate

rUTAH

 Done-to as subject

2 learners

rUTAH

 Highest as subject

2 learners

UTAH

 Done-to as subject

2 learners

UTAH

 Highest as subject

2 learners
8 modeled learners and their acquisitional intakes

“it’s falling off”

Possible perceptual intake

Animacy

Animate subject: 1

All 8 learners

Syntactic frame

-surfmorph

+surfmorph

4 learners

NP V PRT

4 learners

NP V prog PRT

Intermediate representation

UTAH
Done-to as subject
2 learners

rUTAH
Highest as subject
2 learners

Mapping to syntax

+expmap

- expmap

+ mvmt: 1

1 learner

1 learner

1 learner

1 learner

UTAH
Highest as subject
2 learners

+expmap

- expmap

+ mvmt: 0

1 learner

1 learner

rUTAH
Done-to as subject
2 learners

+expmap

- expmap

+ mvmt: 1

1 learner

1 learner

rUTAH
Highest as subject
2 learners
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

"it’s falling off"

<3 years old

Brown-Eve corpus (Brown 1973) and the Valian corpus (Valian 1991), with syntactic & thematic annotations provided by the CHILDES Treebank (Pearl & Sprouse 2013).

Speech directed at 22 children between 18 and 32 months.

~40,000 utterances (~197,000 word tokens, 555 verbs)

Focus on the 239 verbs occurring 5 or more times.
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

“it’s falling off”

CHILDES Treebank

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

<4 years old

<3yrs + Brown-Adam subsection (Brown 1973), with syntactic & thematic annotations provided by the CHILDES Treebank (Pearl & Sprouse 2013).

Speech directed at 23 children between 18 and 48 months.

~51,000 utterances (~254,000 word tokens, 617 verbs)
Focus on the 267 verbs occurring 5 or more times.
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

“it’s falling off”

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

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

<5 years old

<4yrs + Brown-Adam subsection (Brown 1973), with syntactic & thematic annotations provided by the CHILDES Treebank (Pearl & Sprouse 2013).

Speech directed at 23 children between 18 and 58 months.
~56,500 utterances (~285,000 word tokens, 651 verbs)
Focus on the 284 verbs occurring 5 or more times.
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

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

This is the goal of learnability approaches (computational-level of analysis: Marr 1982)

Goal: Model the developmental trajectory from 3 to 4 to 5 years old.

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

Ideal learner model: Also an excellent first step to see if this is the right conceptualization of the acquisition task.
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

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

Objective: Infer verb class

"it's falling off" (3x) "it's falling off" "it's falling off"
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

<3yrs  <4yrs  <5yrs

The learner infers these probabilities, and begins with no bias towards either option per class.

Binary choices:

+animate  -animate

Subject  Object  Indirect Object

movement?

"it’s falling off"

(3x)  "it’s falling off"

"it’s falling off"
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

The learner infers these probabilities, and begins with no bias towards any option per class.

Multinomial choices:

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

Subject Object Indirect Object

“it’s falling off” NP V PRT (3x) “it’s falling off”

These are some examples of the types of sentences that the learner might encounter and analyze.
Inference: The learner forms different classes because the characteristics are sufficiently different for each class.
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

<3yrs  <4yrs  <5yrs

verb classes

Survey of 32 experimental studies on children’s production and comprehension of specific verbs


“It was ___-en.”
done-to
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

verb classes

Survey of 32 experimental studies on children’s production and comprehension of specific verbs


“It was ___-en.”

done-to

3yrs

+= hit, see, ...
-= know, remember, ...

<4yrs <5yrs
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

verb classes

Survey of 32 experimental studies on children’s production and comprehension of specific verbs


“It was ___-en.”
done-to

4yrs
+= hit, scare, see, ...
-= know, love, remember, ...
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

verb classes

Survey of 32 experimental studies on children’s production and comprehension of specific verbs


“It was ___-en.”

done-to

5yrs

+= hit, love, scare, see, ...
-= know, remember, ...
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

Verb classes

Survey of 32 experimental studies on children’s production and comprehension of specific verbs


“Jack ___ Lily the thing.”
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

Survey of 32 experimental studies on children’s production and comprehension of specific verbs


“Jack ___ Lily the thing.”

3yrs

+= give, read, *say, ...
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

**Verb classes**

Survey of 32 experimental studies on children’s production and comprehension of specific verbs


“Jack ___ Lily the thing.”

4yrs

+= give, read, *say, teach, ...
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

Survey of 32 experimental studies on children’s production and comprehension of specific verbs


“Jack ___ Lily the thing.”

5yrs

+= ask, give, read, *say, teach, ...
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

Survey of 32 experimental studies on children’s production and comprehension of specific verbs


“It ___.”
done-to
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

Survey of 32 experimental studies on children’s production and comprehension of specific verbs


“**It ____.”**

done-to

3yrs

+= break, fall, ...
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

verb classes

Survey of 32 experimental studies on children’s production and comprehension of specific verbs

Control object & Raising object: Kirby 2009a, Kirby 2009b, Kirby 2010, Becker 2014

Control object
“I ___ him to leave.”
done-recipient (main)
doer (embedded)
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

verb classes

Survey of 32 experimental studies on children’s production and comprehension of specific verbs

Control object & Raising object: Kirby 2009a, Kirby 2009b, Kirby 2010, Becker 2014
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

verb classes

Survey of 32 experimental studies on children’s production and comprehension of specific verbs

Control object & Raising object: Kirby 2009a, Kirby 2009b, Kirby 2010, Becker 2014

Raising object
“I ___him to leave.”

doer (embedded)

4yrs 5yrs
+= need, want
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

verb classes

Survey of 32 experimental studies on children’s production and comprehension of specific verbs


Control subject
“I ___ to leave.”
deer (main)
deer (embedded)
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

verb classes

Survey of 32 experimental studies on children’s production and comprehension of specific verbs


Control subject
“I ___ to leave.”
doer (main)
doer (embedded)

4yrs
5yrs
+= try, want
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

verb classes

Survey of 32 experimental studies on children’s production and comprehension of specific verbs


Raising subject
“I ___ to leave.”
doer (embedded)

4yrs 5yrs
+= seem
Goal: Model the developmental trajectory from 3 to 4 to 5 years old.

Survey of 32 experimental studies on children’s production and comprehension of specific verbs.

Subject-experiencer and Object-experiencer psych verbs: Hartshorne et al. 2015

"Jack ____ Lily."
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

**Verb classes**

Survey of 32 experimental studies on children’s production and comprehension of specific verbs

Subject-experiencer and Object-experiencer psych verbs: Hartshorne et al. 2015

Subject-experiencer

“Jack ___ Lily.”

Experiencer

4yrs

5yrs

+= like, love
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

verb classes

Survey of 32 experimental studies on children’s production and comprehension of specific verbs

Subject-experiencer and Object-experiencer psych verbs: Hartshorne et al. 2015

Object-experiencer
“Jack ___ Lily.”

Experiencer

4yrs 5yrs

+= frighten, scare, surprise
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

Survey of 32 experimental studies on children’s production and comprehension of specific verbs


Non-finite to
“Jack ___ to go.”
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

Survey of 32 experimental studies on children’s production and comprehension of specific verbs


Non-finite to
“Jack ___ to go.”

3yrs
+= get, start, suppose, ...

verb classes
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

<3yrs  <4yrs  <5yrs

Survey of 32 experimental studies on children’s production and comprehension of specific verbs


“Jack ___ that he can go.”
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

Survey of 32 experimental studies on children’s production and comprehension of specific verbs


that
“Jack ___ that he can go.”

3yrs
+= hope, know, say, ...
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

verb classes

Survey of 32 experimental studies on children’s production and comprehension of specific verbs


that

“Jack ___ that he can go.”

5yrs

+= guess, hope, know, pretend, say, …
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

Survey of 32 experimental studies on children’s production and comprehension of specific verbs


“Jack ___ whether/if he can go.”
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

verb classes

Survey of 32 experimental studies on children’s production and comprehension of specific verbs


<3yrs

<4yrs

“Jack ___ whether/if he can go.”

<5yrs

+= ask, care, know, see, ...
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

1% <= RI <= 99% CI

-1.0 <= ARI <= 1.0

15 classes  <3yrs
23 classes  <4yrs
24 classes  <5yrs
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

1% ≤ RI ≤ 99% CI

-1.0 ≤ ARI ≤ 1.0

Animacy

+animate
The penguin tried to climb.

-animate
The ice seemed to melt.
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

- <3yrs: 15 classes
- <4yrs: 23 classes
- <5yrs: 24 classes

$1\% \leq RI \leq 99\%$ CI

$-1.0 \leq ARI \leq 1.0$

**Animacy**

**Syntactic frame**

The ice seemed to melt.

NP ____ $S_{nonfinite}$ -surf morph

NP ____ +past $S_{nonfinite}$ +surf morph
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

<3yrs  15 classes
<4yrs  23 classes
<5yrs  24 classes

Animacy
- +surfmorph

Syntactic frame
- -surfmorph

Thematic roles and how to use them

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

UTAH
-expmap

rUTAH
+expmap

Subject  Object  Indirect Object

movement?
Thematic roles and how to use them

Animacy
Syntactic frame

-1.0 <= ARI <= 1.0
1% <= RI <= 99% CI

<4yrs 24 classes
<5yrs 23 classes

3yrs 15 classes

<4yrs 24 classes
<5yrs 23 classes
Two learning strategies are doing significantly better than chance based on both metrics.
Animacy
Syntactic frame
Thematic roles and how to use them

-1.0 <= ARI <= 1.0
1% <= RI <= 99% CI

<5yrs
24 classes

<4yrs
23 classes

<4yrs
24 classes

<5yrs
15 classes

rUTAH
UTAH
+surfmorph
-surfmorph

+expmap
-expmap

Animacy

### Animacy

**Syntactic frame**

- +surfmorph
- -surfmorph

### Thematic roles and how to use them

<table>
<thead>
<tr>
<th></th>
<th>UTAH +expmap</th>
<th>UTAH -expmap</th>
<th>rUTAH +expmap</th>
<th>rUTAH -expmap</th>
</tr>
</thead>
<tbody>
<tr>
<td>RI</td>
<td>0.639</td>
<td>0.758</td>
<td>0.670</td>
<td>0.504</td>
</tr>
<tr>
<td>ARI</td>
<td>0.143</td>
<td><strong>0.261</strong></td>
<td>0.080</td>
<td>0.103</td>
</tr>
</tbody>
</table>

### One strategy (a different one) is doing significantly better than chance.

- 1% \( \leq \) RI \( \leq \) 99% CI
- -1.0 \( \leq \) ARI \( \leq \) 1.0

**<5yrs**

- 24 classes

**3yrs**

- 15 classes

**4yrs**

- 23 classes
Thematic roles and how to use them

Animacy

Syntactic frame

1% \leq RI \leq 99% CI
-1.0 \leq ARI \leq 1.0

+surfmorph

-surfmorph

<5yrs

24 classes

<5yrs

3yrs

15 classes

4yrs

23 classes

<5yrs

24 classes
### Animacy

**Syntactic frame**

- +surfmorph
- -surfmorph

### Thematic roles and how to use them

<table>
<thead>
<tr>
<th></th>
<th>UTAH (+expmap)</th>
<th>UTAH (-expmap)</th>
<th>rUTAH (+expmap)</th>
<th>rUTAH (-expmap)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>RI</strong></td>
<td>0.751</td>
<td>0.703</td>
<td>0.754</td>
<td>0.682</td>
</tr>
<tr>
<td><strong>ARI</strong></td>
<td>0.256</td>
<td>0.087</td>
<td>0.279</td>
<td>0.096</td>
</tr>
</tbody>
</table>

#### Measures

- 1% ≤ RI ≤ 99% CI
- -1.0 ≤ ARI ≤ 1.0

#### Learning strategies

- Several learning strategies are doing better than chance...

#### Ages and Classes

- **3yrs** (15 classes)
- **4yrs** (23 classes)
- **5yrs** (24 classes)
Thematic roles and how to use them

<table>
<thead>
<tr>
<th></th>
<th>UTAH</th>
<th>rUTAH</th>
<th>UTAH</th>
<th>rUTAH</th>
</tr>
</thead>
<tbody>
<tr>
<td>RI</td>
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<td>0.256</td>
<td>0.087</td>
<td>0.279</td>
<td>0.113</td>
</tr>
</tbody>
</table>

1% ≤ RI ≤ 99% CI
-1.0 ≤ ARI ≤ 1.0

...but two have ARIs that seem much higher than the rest, and on par with the ARIs of previous strategies with significantly higher performance (ARI > 0.20).

- expmap
- surfmorph
+ surfmorph

Animacy
Syntactic frame

3yrs
15 classes

4yrs
23 classes

5yrs
24 classes
Goal: Model the developmental trajectory from 3 to 4 to 5 years old

- <3yrs: 15 classes
- <4yrs: 23 classes
- <5yrs: 24 classes

1% \leq RI \leq 99% CI
-1.0 \leq ARI \leq 1.0

Thematic roles and how to use them

- Animacy
  - +surf morph
  - -surf morph

- Syntactic frame
  - +expmap
  - -expmap
Thematic roles and how to use them

Animacy
Syntactic frame

+surfmorph
-surfmorph

Focus on strategies with performance significantly above chance

What does this mean?
Before 3, children ignore verb morphology and seem to be using relative information about thematic roles.

The ice seemed to melt.

NP ___  S\textsubscript{nonfinite} -surfmorph

Agent > Experiencer > Theme > Patient > (Source, Goal, Instrument)
By 4, children heed verb morphology, are using the UTAH intermediate representation, and don’t expect a mapping a priori.
By 5, children still heed verb morphology, but now may be using either the UTAH or rUTAH representation and expect a mapping.
Using animacy, syntactic frame, and thematic role information can be a pretty good match for what children seem to be doing when creating verb classes.
The ice seemed to melt.

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

Subject   Object   Indirect Object

\[ -\text{animate} \]
\[ \text{NP} \quad S_{\text{nonfinite}} \]

3yrs

-\text{surfmorph}

rUTAH

4yrs

+\text{surfmorph}

UTAH -expmap

5yrs

+\text{surfmorph}

UTAH rUTAH +expmap
The ice seemed to melt.

Subject

NP ___+past S nonfinite

Object

Animate

Subject

Indirect Object

-animate

Subject

NP

past

S

nonfinite
The ice seemed to melt.

Subject +movement

Highest +movement

Theme

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

3yrs
-surfmorph rUTAH

4yrs
+surfmorph UTAH

5yrs
+surfmorph UTAH rUTAH
What seems to develop earlier (perhaps because it’s easy to derive from existing biases):

-surfmorph: Preference to ignore surface morphology (perhaps due to processing limitations)
What seems to be available earlier (perhaps because it doesn’t involve abstracting over conceptual information):

**rUTAH: More detailed thematic representation**

Agent > Experiencer >
Theme > Patient >
(Source, Goal, Instrument)
What seems to develop somewhat earlier (perhaps because it’s easy to derive from existing biases):

UTAH: More abstract, categorical thematic representation
What seems to develop somewhat earlier (perhaps because it’s easy to derive from existing biases):

-expmap: No prior expectation about how to map — learn this from the intake
What seems to develop later (perhaps building on prior knowledge and the intake): rUTAH, +expmap: more detailed thematic representation coupled with expectation of mapping
Bigger theoretical takeaway:

Everyone’s right about the representation at some stage of development.
3yrs -surfmorph
   rUTAH

4yrs +surfmorph
    UTAH
   -expmap

5yrs +surfmorph
    UTAH    rUTAH
    +expmap

So now what?
So now what?

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

We need more observable behavior for more verbs in children’s input to match modeling results against.

**Input**

<table>
<thead>
<tr>
<th>Age (yrs)</th>
<th>Verbs</th>
<th>Classes</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;3 yrs</td>
<td>239</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>verbs</td>
<td>classes of 60 verbs</td>
</tr>
<tr>
<td>&lt;4 yrs</td>
<td>267</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>verbs</td>
<td>classes of 76 verbs</td>
</tr>
<tr>
<td>&lt;5 yrs</td>
<td>284</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>verbs</td>
<td>classes of 82 verbs</td>
</tr>
</tbody>
</table>
(1) A broader assessment of children’s verb class knowledge
This will further test these theoretical proposals, and validate (or not) the current findings.

So now what?

3yrs
-surfmorph
rUTAH

4yrs
+surfmorph
UTAH
-expmap

5yrs
+surf morph
UTAH rUTAH
+expmap

Input
Children’s behavior

<3yrs
239 verbs
15 classes
of 60 verbs

<4yrs
267 verbs
23 classes
of 76 verbs

<5yrs
284 verbs
24 classes
of 82 verbs
So now what?

3yrs
- surfmorph
  rUTAH

4yrs
+ surfmorph
  UTAH
- expmap

5yrs
+ surfmorph
  UTAH
  rUTAH
+ expmap

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

(a) More verbs

<3yrs

239 verbs
15 classes of 60 verbs

<4yrs

267 verbs
23 classes of 76 verbs

<5yrs

284 verbs
24 classes of 82 verbs

Input
Children’s behavior
So now what?

3yrs
- surfmorph
 rUTAH

4yrs
+ surfmorph
 UTAH
- expmap

5yrs
+ surfmorph
 UTAH rUTAH
+ expmap

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

(a) More verbs

<3yrs
239 verbs
15 classes of 60 verbs

<4yrs
267 verbs
23 classes of 76 verbs

<5yrs
284 verbs
24 classes of 82 verbs

(b) More behaviors

Input
Children’s behavior

transitive
unergative
intransitive
non-finite -ing
small clause
wager-class
So now what?

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

(2) Models incorporating more cognitively plausible assumptions

+memory & processing limitations
+predicting experimental behavior
+incorporating additional age-appropriate information
So now what?

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

What happens when we embed these theories in a learning model that learns incrementally and has age-appropriate memory & processing limitations?

(2) Models incorporating more cognitively plausible assumptions
So now what?

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

(2) Models incorporating more cognitively plausible assumptions

What kinds of child behavior does the model predict in the experimental scenarios already available, based on its internal representations?
So now what?

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

(2) Models incorporating more cognitively plausible assumptions

What other types of information may be available, especially throughout development as children learn from their intake?
So now what?

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

(2) Models incorporating more cognitively plausible assumptions

(3) Other theories of representation

Are there other options for linking thematic role information to syntactic structure that we can explore in this framework?
So now what?

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

(2) Models incorporating more cognitively plausible assumptions

(3) Other theories of representation

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