

Chapter 1

How statistical learning can play well with Universal Grammar

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Abstract: One motivation for Universal Grammar (UG) is that it's what allows children to acquire the linguistic knowledge that they do as quickly as they do from the data that's available to them. One key legacy of Chomsky's work in language acquisition is highlighting the separation between children's hypothesis space of possible representations (typically defined by UG) and how children might navigate that hypothesis space (sometimes defined by UG). While statistical learning is sometimes thought to be at odds with UG, I review how statistical learning can both complement UG and help us refine our ideas about the contents of UG. I first review some cognitively-plausible statistical learning mechanisms that can operate over a predefined hypothesis space, like those UG creates. I then review two sets of examples: (i) those where statistical learning allows more efficient navigation through a UG-defined hypothesis space, and (ii) those where statistical learning can replace prior UG proposals for navigating a hypoth-

esis space, and in turn lead to new ideas about how UG might construct the hypothesis space in the first place. I conclude with a brief discussion of how we might make progress on understanding language acquisition by incorporating statistical learning into our UG-based acquisition theories.

Keywords: Universal Grammar, statistical learning, linguistic parameters, parameter setting, linking theories, Subset Principle, syntactic islands

1.1. Introduction

A key motivation for Universal Grammar (**UG**) is developmental: UG can help children acquire the linguistic knowledge that they do as quickly as they do from the data that's available to them [Chomsky, 1981, Jackendoff, 1994, Laurence and Margolis, 2001, Crain and Pietroski, 2002]. That is, UG allows children to solve what Chomsky [Chomsky, 1965, 1975, 1980a,b] and many subsequent others (see Pearl [2019] for a recent review) have called the *Poverty of the Stimulus*, where the available data often seem woefully inadequate for pinpointing the right linguistic knowledge as efficiently as children seem to. So, without some internal bias, children would be lost when it comes to language acquisition. Enter UG: a concrete proposal for what that internal bias could be that enables language acquisition to succeed.

Among other things, UG provides a way to structure a child's hypothesis space about the linguistic system – what explicit hypotheses are considered, and (perhaps more importantly) what building blocks allow children to construct those explicit hypotheses for consideration. For example, traditional linguistic macro-parameters [Chomsky, 1981, 1986] are building blocks that children can construct language grammars from – that is, a language's grammar would be a specific collection of parameter values for these linguistic pa-

rameters. Having these building blocks then allows a child to construct and consider explicit hypotheses about a language’s grammar as language data are encountered. But, setting these parameters from the available language data is a *hard* problem, which is why a lot of energy has been devoted to figuring out how that process could work (e.g., see the more detailed discussion of this body of work in Pearl [in press]). In particular, parameter setting is hard even if UG allows the child to already know which parameters there are and which parameter values are possible for each parameter. The problem is simply that the hypothesis space is vast (e.g., n binary parameters yield 2^n possible grammars – this number gets very big very quickly); also, the child’s input data are often ambiguous between different grammars.

Yang & Legate leveraged the crucial idea that language grammars were made up of individual parameter building blocks and demonstrated one concrete way for identifying a language’s grammar from realistic child input data [Yang, 2002, 2004, Legate and Yang, 2007, Yang, 2012, Legate and Yang, 2013]; they called their approach *variational learning*. Importantly, variational learning relies on reinforcement learning – a domain-general statistical learning mechanism – applied to linguistic parameter values (see Pearl [in press] for more discussion on variational learning). That is, this language acquisition approach involves a statistical learning mechanism (i.e., reinforcement learning) applied to the hypothesis space defined by UG (i.e., linguistic parameters). Pearl and Lidz [2013] review similar approaches for learning parameter values that involve deploying domain-general statistical learning mechanisms over a hypothesis space defined by linguistic parameters. Relatedly, some of the most fruitful recent work in language acquisition has combined ideas about different hypothesis space building blocks with domain-general statistical learning (e.g.,

Piantadosi et al. [2012], Orita et al. [2013], Pearl and Sprouse [2013a], Abend et al. [2017], Pearl and Sprouse [in press]).

What all these approaches to language acquisition demonstrate is that statistical learning can only work in tandem with a predefined hypothesis space. To me, this is one key legacy of Chomsky’s work in the area of language acquisition: statistical learning by itself can’t be an answer to how children learn the linguistic representations they do. More specifically, Chomsky highlighted that children’s hypothesis space of representations is a crucial component in the language acquisition process – and therefore, understanding the nature of that hypothesis space is a concrete way to make progress in understanding how language acquisition proceeds. Statistical learning can then provide a way to help navigate the hypothesis space (e.g., of possible grammars) in order to converge on the correct hypothesis (e.g., a specific language’s grammar). In this way, statistical learning can complement the prior knowledge that defines the hypothesis space – but statistical learning does *not* itself define the hypothesis space and so could never replace prior knowledge that does in fact define the hypothesis space. So, any components of UG that define the child’s linguistic hypothesis space are not replaceable by statistical learning. However, any components of UG that involve navigating the hypothesis space *may* be replaceable by statistical learning. And, perhaps by considering other ways of navigating a predefined hypothesis space, we may be able to refine our ideas about the UG knowledge that constructs that hypothesis space in the first place.

In the rest of this chapter, I explore these ideas more concretely – cognitively-plausible statistical learning mechanisms, how statistical learning can complement UG, and how statistical learning can help us refine our ideas about what’s

in UG. To this end, I'll first give a brief overview of statistical learning mechanisms we have evidence for in small humans, along with some illustrative examples. This evidence is the foundation for talking about statistical learning at all for language acquisition – if these mechanisms aren't there in small humans, there's no need to spend energy thinking about how they might be used by small humans learning language. But, if statistical learning mechanisms are in fact there and useable by small humans, we have motivation for thinking about how children might leverage them during language acquisition.

I'll then discuss some examples where statistical learning complements UG, which happens when statistical learning offers a way to efficiently navigate the hypothesis space defined by UG. I'll then turn to some examples where statistical learning can replace prior UG proposals for navigating a hypothesis space; this in turn can lead to new ideas for how the hypothesis space might therefore be constructed in the first place. I'll conclude briefly with what I think is a concrete way to make progress on understanding the process of language acquisition, integrating what we know about statistical learning.

1.2. Statistical learning mechanisms in small humans

At its core, statistical learning is about counting things (this is the “statistical” part), and updating hypotheses on the basis of those counts (this is the “learning” part, sometimes also called *inference* [Pearl, in press]). Counting things is a domain-general ability, because we can count lots of different things (both linguistic and non-linguistic). So, to effectively use statistical learning,

a child has to know what to count. These counts can then be converted into probabilities (for example, seeing something 3 times out of 10 yields a probability of $\frac{3}{10}=0.30$); then, things with higher probabilities can be interpreted as more likely than things with lower probabilities.

For language acquisition, counting things often means counting linguistic things (though sometimes non-linguistic things might be relevant to count too, depending on what the child's trying to learn). Importantly, what the child might be counting often depends on the representational and learning theories we currently have for the linguistic knowledge to be acquired [Pearl, in press]. For instance, depending on the theories involved, a child acquiring syntactic knowledge might be doing inference over counts of of lexical items [Yang, 2005, Freudenthal et al., 2007, 2009, 2010, 2015, Yang, 2016, 2017], syntactic category sequences [Perfors et al., 2010, 2011a, Pearl and Sprouse, 2013a], syntactic signals realized in certain overt structures [Sakas and Fodor, 2001, Yang, 2004, Legate and Yang, 2007, Mitchener and Becker, 2010, Pearl and Sprouse, 2013a, Becker, 2014, Sakas, 2016, Pearl and Sprouse, 2019], or something else entirely. Importantly, the statistical learning mechanism itself doesn't seem to change – once the child knows the units over which inference is operating, counts of the relevant units are collected and inference can operate.

Also importantly, we have good reason to think that small humans are good at both counting things and doing inference over those counts. There's a lot of evidence that infants under a year old (and often quite a bit under a year old) are capable of exactly this (9-month-olds: Fiser and Aslin [2002], Wu et al. [2011]; 8-month-olds: Saffran et al. [1996], Aslin et al. [1998], Saffran et al. [1999], Stahl et al. [2014], Aslin [2017]; 2-month-olds: Kirkham et al. [2002]; newborns: Ferry et al. [2016], Fló et al. [2019]; among many other

studies). So, statistical learning isn't unreasonable to think about as something children could use during language acquisition. Happily, we have several current proposals for useful ways children could harness statistical learning for language acquisition, which I'll briefly review below.¹

1.2.1. Some ways of doing statistical learning

1.2.1.1. Reinforcement learning

Reinforcement learning (see Sutton and Barto [2018] for a recent overview) is a principled way to update the probability of a categorical option which is in competition with other categorical options. So, if we're thinking in terms of linguistic parameters, perhaps a child might consider a parameter that controls whether *wh*-movement is required as the default in questions (such as in English, with the *wh*-word *what* in *What's Jack climbing ____{what}?* = +*wh*-movement), or whether the *wh*-word can remain in-situ (such as in Japanese = -*wh*-movement). As mentioned above, Yang & Legate's variational learning relies on reinforcement learning, and uses an implementation by Bush and Mosteller [1951] called the linear reward-penalty scheme. As the name suggests, there are two choices when a data point is processed – either the categorical option under consideration is rewarded or it's punished. This translates to the option's current probability being increased (rewarded) or decreased (punished). For instance, if the +*wh*-movement option is under consideration, and it's compatible with the current data point (like *What's Jack climbing ____{what}?*), the

¹In the interest of space, I'll only provide abbreviated descriptions of each statistical learning mechanism below, but see Pearl [in press] for a more comprehensive overview of each one.

+wh-movement option is rewarded and its probability is increased. In contrast, if that same option is under consideration, but it's not compatible with the current data point (such as an echo question like *Jack's climbing what?!*), the +wh-movement option is punished and its probability is decreased.

While applying reinforcement learning to linguistic parameters is a fairly recent innovation, reinforcement learning itself is well-supported in the child development literature more generally (sometimes under the name “operant conditioning”). In particular, we have evidence that very young children are capable of it (under 18 months: Hulsebus [1974]; 12 months: Lipsitt et al. [1966]; 10 months: de Sousa et al. [2015]; 3 months: Rovee-Collier and Capatides [1979]; 10 weeks: Rovee and Rovee [1969], Watson [1969]; among many others). So, it seems plausible that young children could use reinforcement learning for language acquisition.

1.2.1.2. The Tolerance and Sufficiency Principles

The Tolerance and Sufficiency Principles [Yang, 2005, 2016] together describe a particular inference mechanism, and this mechanism operates over specific kinds of counts that have already been collected. More specifically, these principles together provide a formal approach for when a child would choose to adopt a “rule”, generalization, or default pattern to account for a set of items. For example, is there a general rule for forming the past tense in English from a verb's root form (e.g., *kiss* → *kissed*), a generalization about how thematic roles connect to their syntactic positions (e.g., is the AGENT often linked to the *subject* syntactic position), or a default stress pattern for three-syllable English words (e.g., is the stress pattern in *óctopus* typical)?

Both principles are based on cognitive 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. The learning innovation of these principles is that they're designed for situations where there are exceptions to a potential rule. In the examples above, there are certainly exceptions in the child's input: past tense forms like *drank* (rather than *drinked*), non-AGENTS appearing in the *subject* position (*Jack_{PATIENT} got kissed*), and three-syllable words with different stress patterns like *horizon*.

So, these two principles help the child infer whether the rule is robust enough to bother with, despite the exceptions. In particular, a rule should be bothered with if it speeds up average retrieval time for any item. So, for instance, it's faster on average to have (i) a past tense rule to retrieve a regular past tense form, (ii) a linking rule to retrieve a thematic role reliably associated with a syntactic position, or a syntactic position reliably associated with a thematic role, and (iii) a metrical stress rule to retrieve a predictable metrical stress pattern. However, if the past tense is too irregular, the link too unreliable, or the metrical stress too unpredictable, it's not useful to have the rule: retrieving the target information takes too long on average.

The Tolerance Principle determines how many exceptions a rule can “tolerate” in the data before it's not worthwhile for the child to have that rule at all; the Sufficiency Principle uses that tolerance threshold to determine how many rule-abiding items are “sufficient” in the data to justify having the rule. This means, of course, that the child needs to have previously counted how many items obey the potential rule and how many don't. With these counts in hand, the child can then apply the Tolerance and Sufficiency Principles to infer whether the data justify the adoption of the rule under consideration (or not).

Together, these two principles have been used for investigating a rule, generalization, or default pattern for a variety of linguistic knowledge types, including English past tense morphology [Yang, 2005, 2016], English noun pluralization [Yang, 2016], German noun pluralization [Yang, 2005], English nominalization [Yang, 2016], English metrical stress [Legate and Yang, 2013, Yang, 2015, Pearl et al., 2017], English *a*-adjective morphosyntax [Yang, 2015, 2016], English dative alternations [Yang, 2016, 2017], noun morphology in an artificial language [Schuler et al., 2016], linking theories in English [Pearl and Sprouse, 2019], and the development of causative use in English [Irani, 2019]. However, there isn't yet much evidence that children are capable of using the Tolerance and Sufficiency Principles – the main support comes from the study by Schuler et al. [2016], which demonstrates that 5- to 8-year-old behavior is consistent with children using these principles. Still, these principles seem like a promising statistical learning mechanism.

1.2.1.3. Bayesian inference

Bayesian inference operates over probabilities, and involves both prior assumptions about the probability of different options (typically referred to as hypotheses) and an estimation of how well a given hypothesis fits the data. A Bayesian model assumes the learner (for our purposes, the modeled child) has some space of hypotheses H , each of which represents a possible explanation for how the data D in the relevant part of the child's input were generated. For example, a child might consider both a +wh-movement option and a -wh-movement option as two hypotheses ($\{+wh\text{-movement}, -wh\text{-movement}\} \in H$), while the data might be the collection of questions in the child's input involving *wh*-words ($\{What\ did\ Jack\ climb?,\ Jack\ climbed\ what?!,\ \dots\} \in D$).

Given D , the modeled child’s goal is to determine the probability of each possible hypothesis $h \in H$, written as $P(h|D)$, which is called the *posterior* for that hypothesis. This is calculated via Bayes’ Theorem as shown in (1), and we’ll walk through each of the relevant terms.

$$(1) \quad P(h|D) = \frac{P(D|h)*P(h)}{P(D)} = \frac{P(D|h)*P(h)}{\sum_{h' \in H} P(D|h')*P(h')} \propto P(D|h) * P(h)$$

In the numerator, $P(D|h)$ represents the *likelihood* of the data D given hypothesis h , and describes how compatible that hypothesis is with the data. Hypotheses with a poor fit to the data (e.g., the -wh-movement hypothesis for a dataset with 30% of the data compatible only with +wh-movement) have a lower likelihood; hypotheses with a good fit to the data have a higher likelihood.

$P(h)$ represents the *prior* probability of the hypothesis. Intuitively, this corresponds to how plausible the hypothesis is, irrespective of any data. This is often where considerations about the complexity of the hypothesis will be implemented (e.g., considerations of simplicity or economy, such as those included in the grammar evaluation metrics of Chomsky [1965], and those explicitly implemented in Perfors et al. [2011b] and Piantadosi et al. [2012]). So, for example, more complex hypotheses will typically have lower prior probabilities.

The likelihood and prior make up the numerator of the posterior calculation, while the denominator consists of the normalizing factor $P(D)$, which is the probability of the data under any hypothesis. Mathematically, this is the summation of the likelihood * prior for all possible hypotheses in H , and ensures that all the hypothesis posteriors sum to 1. Notably, because we often only care about how one hypothesis compares to another (e.g., is +wh-movement or -wh-movement more probable after seeing the data D ?), calculating $P(D)$ can be skipped over and the numerator alone used (hence, the \propto in (1)).

Importantly from a developmental perspective, there's a considerable body of evidence suggesting that young children are capable of Bayesian inference (3 years: Xu and Tenenbaum [2007]; 9 months: Gerken [2006], Dewar and Xu [2010], Gerken [2010]; 6 months: Denison et al. [2011], among many others). Given this, Bayesian inference seems a plausible statistical learning mechanism for language acquisition.

1.2.2. Why statistical learning in small humans shouldn't alarm people who like UG

What all these statistical learning approaches demonstrate is that there are in fact several cognitively-plausible statistical learning mechanisms that children could harness for language acquisition. Perhaps more importantly, there are linguistically-savvy ways to harness those mechanisms. That is, being able to count things and do inference over those counts doesn't negate the need to figure out what to count. This key point about what to count is echoed outside the UG-supporting community as well – for example, see the discussion on this point in Scholz and Pullum [2006].

Within the generative linguistics community, there are several examples of researchers who take both statistical learning and theories of linguistic representation very seriously; their studies demonstrate how linguistically-savvy statistical learning can yield informative results about both language acquisition and the linguistic representations being acquired (e.g., parameter setting in syntax [Yang, 2002, 2004, 2012], parameter setting in metrical phonology [Legate and Yang, 2013, Pearl et al., 2017], phonetic category acquisition [Feldman et al., 2013], morphosyntactic acquisition [Yang, 2005, 2015, 2016], pro-

noun acquisition [Orita et al., 2013, Pearl and Mis, 2016], syntactic island acquisition [Pearl and Sprouse, 2013a], linking theory acquisition [Pearl and Sprouse, in press, 2019], as well as many other examples of syntactic acquisition discussed in Pearl [in press]).

So, these studies allow us to see how statistical learning can complement the innate language-specific structure that UG can provide. In the next section (section 1.3), I'll give the highlights of an example set of recent studies on linking theory acquisition [Pearl and Sprouse, 2019, in press], where Bayesian inference and both the Tolerance Sufficiency Principles complement hypothesis spaces constrained by UG; this combination of statistical learning and UG then yields insights about both the language acquisition process children undergo and the linguistic representations they develop over time.

Before doing that, I want to first highlight a strong connection between Bayesian inference and the intuition of linguistic macro-parameters [Chomsky, 1981]. I think this connection underscores the potential that statistical learning has to aid theories of language acquisition that rely on UG – and this connection is a ripe avenue for future investigation.

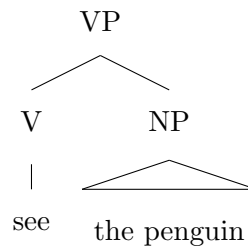
The key idea is that Bayesian inference can be implemented over a hierarchical hypothesis space, such that there are different levels of abstraction for the hypothesis space [Goodman, 1955, Kemp et al., 2007, Kemp and Tenenbaum, 2008]. In particular, there may be narrower hypotheses about certain observable properties, and more abstract hypotheses (called *overhypotheses*) about the nature of those narrower hypotheses. A concrete example taken from Pearl and Lidz [2013] can help demonstrate the intuition of this, specifically linking it to the concept of linguistic macro-parameters.

Suppose an English-learning child has a collection of utterances in her data

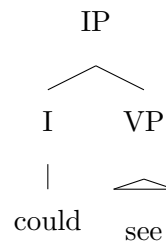
D. Some utterances contain verbs and objects, and whenever there's an object, suppose it appears after the verb, e.g., *see the penguin* rather than *the penguin see*. Other utterances contain modal verbs and nonfinite main verbs, and whenever both occur, the modal verb precedes the main verb, e.g., *could see* rather than *see could*. A child could be aware of the shared structure of these data – specifically that these observable forms can be characterized as the head of a phrase appearing before its complements, as shown in (2).

(2) Shared structure in observable forms: Phrasal heads before complements

a. *see the penguin*



b. *could see*

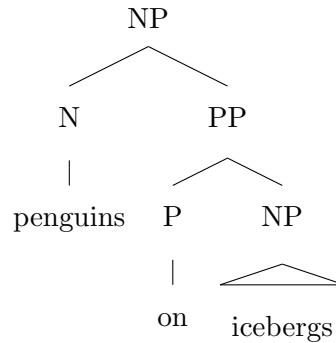


This “head-first” idea can be encoded at a level that describes utterances in general, and would represent an overhypothesis about structure which is similar to the classical headedness linguistic macro-parameter: namely, phrases have their heads before their complements. Each example from (2) instantiates this overhypothesis for particular phrases, VPs and IPs, and so predicts the narrower hypotheses these data support: both VPs and IPs have their heads before their complements. Each narrower hypothesis strengthens the more abstract head-first overhypothesis, and allows the child to make predictions about

phrases not yet encountered. For example, if this child encountered an utterance with a preposition surrounded by NPs, such as *penguins on icebergs*, there are (at least) two structural hypotheses possible, shown in (3).

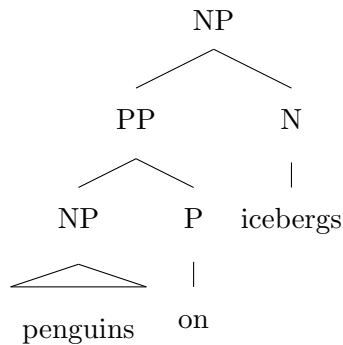
(3) Possible structures for *penguins on icebergs*

a. head-first:



Meaning: penguins who are on icebergs

b. head-last:



Meaning: icebergs that are on penguins

Using the head-first overhypothesis for both the NP and the PP, the child would prefer the structure in (3a), whose meaning indicates this phrase is about penguins who are on icebergs (rather than icebergs that are on penguins). Importantly, the child could have this head-first preference about NP and PP structure, even *without* having encountered a single NP or PP data point. This is the power of overhypotheses, and is the same powerful intuition that made the classical notion of linguistic macro-parameters attractive to developmental

linguists. Children can learn how to make generalizations for data they've never seen before on the basis of the data they do see precisely because of the abstract system underlying the generation of the observable data.

In short, the classical notion of a linguistic macro-parameter is an abstract structural property that constrains the hypothesis space of the child, and is defined by UG. So, this type of parameter is an overhypothesis about the narrower structural hypotheses available. Bayesian inference can easily operate over hypothesis spaces that involve overhypotheses (and even more abstract levels like over-over-hypotheses, which are overhypotheses of overhypotheses – see Perfors et al. [2011b] for a concrete example in the syntactic domain). Because of this, there may be a very intuitive connection between hierarchical Bayesian inference and acquisition with linguistic macro-parameters.

This connection in turn highlights the main strength of statistical learning that I mentioned in the introduction: statistical learning can help a child efficiently search a large hypothesis space. For instance, Bayesian inference can help a child efficiently search vast hypothesis spaces defined by overhypotheses and related narrower hypotheses; I discussed this above for linguistic macro-parameters, and it's also the approach taken by Pearl and Sprouse [in press] for linking theory acquisition, which is reviewed in the next section. As another example, variational learning can help a child efficiently search vast hypothesis spaces of grammars defined by combinations of individual linguistic parameters [Yang, 2002, 2004, 2012].

What this then means is that children may not need their hypothesis spaces as constrained as we thought. That is, because children can harness statistical learning to more efficiently navigate a predefined hypothesis space, that hypothesis space could be larger or messier than we thought; this in turn may

mean that we don't need as much specific innate knowledge to define children's hypothesis spaces as we thought. In other words, statistical learning could allow children to get away with hypothesis spaces that are more loosely defined – and yet children could still manage to successfully acquire their target linguistic knowledge.

So, statistical learning may either (i) replace language-specific knowledge that's meant to help a child navigate a predefined hypothesis space, or (ii) obviate the need for language-specific knowledge that constrains the child's hypothesis space so tightly. Both of these results help us refine our ideas about what's in UG, and I'll discuss a concrete example of each below in section 1.4.

An upshot of refining our ideas about what's in UG (in particular, reducing the amount of innate knowledge required – a goal at the heart of the Minimalist Program [Chomsky, 2014]) is that we save ourselves some neurobiological explanatory work. In particular, everything that's part of UG must be present in a human's neurobiological endowment somehow. So, the more we build into UG, the more we have to explain about how that neurobiological endowment works. This generally involves explanations from both developmental neurobiology and evolutionary biology. So, it seems like a good idea to be very careful about what we propose to be in UG; if we consider the contributions of statistical learning in order to refine what's in UG, we may save ourselves some difficult explanatory work on the biological front.

1.3. When statistical learning complements UG

I'll now briefly review the highlights of two recent studies [Pearl and Sprouse, 2019, in press] that use statistical learning to investigate the acquisition of linking theories. (See Pearl [in press] for a more extensive review of both studies.) In each case, children's hypothesis space for linking theory knowledge is constrained by UG, and so statistical learning is operating over a linguistically-predefined hypothesis space.

To get an idea about what linking theories are for, consider the following sentence: *The little girl blicked the kitten on the stairs*. Even if we don't know what *blick* means, we still have preferences about how to interpret this sentence. In particular, out of all the logically possible interpretations involving the little girl, the kitten, and the stairs, we prefer an interpretation where the little girl is doing something (blicking) to the kitten, and that event is happening on the stairs. The reason we as adults have this preferred interpretation is because we've solved the *linking problem*. That is, we have *linking theories* that link the thematic roles specified by a verb's lexical semantics to the syntactic argument positions specified by that verb's syntactic frame. Moreover, our linking theories are so well-developed that they can impose these links even when we don't know a verb's specific lexical semantics (as we see here with *blick*). Solving the linking problem – that is, developing linking theories – is a fundamental component of verb learning for children.

There are two prominent options for linking theory theoretical representations: the Uniformity of Theta Assignment Hypothesis (**UTAH**) and the relativized form of that theory, relativized UTAH (**rUTAH**). The key difference

between these two approaches has to do with how they deal with individual thematic roles. UTAH [Fillmore, 1968, Perlmutter and Postal, 1984, Jackendoff, 1987, Baker, 1988, Grimshaw, 1990, Speas, 1990, Dowty, 1991, Baker, 1997] groups these roles into larger thematic categories (like AGENT-ish, PATIENT-ish, or OTHER-ish) that then always map to a specific syntactic position (e.g., AGENT-ish \leftrightarrow *subject*). In contrast, rUTAH assumes there's a relative ordering of thematic roles (e.g., AGENT>PATIENT), and whichever thematic roles are present are sorted according to this ordering. Then, the highest role available maps to the highest syntactic position (e.g., *subject*). This gives rUTAH more flexibility than UTAH, for example allowing it to easily handle unaccusative constructions like *The ice_{PATIENT} broke*. In this case, UTAH would expect the *subject* to have an AGENT-ish role, which PATIENT certainly isn't. In contrast, rUTAH would note there was only one role available (PATIENT) and expect that role to appear in the highest syntactic position available (*subject*), which it does. Notably, both UTAH and rUTAH seem to be compatible with current cross-linguistic data, and so cross-linguistic coverage can't easily decide which one is likely to be the correct one.

There are also two main approaches to how children develop linking theory knowledge: (i) it's innate knowledge of the specific links between thematic roles and syntactic positions that comes fully-formed in the child's mind [Fillmore, 1968, Perlmutter and Postal, 1984, Baker, 1988, Larson, 1990, Speas, 1990, Grimshaw, 1990], or (ii) the specific linking knowledge develops over time via an interplay between the input that children receive and the mechanisms (both statistical and otherwise) that underlie verb learning [Bowerman, 1988, Goldberg, 1995, 2006, Boyd and Goldberg, 2011, Goldberg, 2013]. As with the theoretical representations, both developmental options seem viable

at face value.

This is where models using linguistically-savvy statistical learning may help. In particular, Pearl and Sprouse [in press] offers insight into the development of linking theory knowledge, suggesting that derivation of specific linking theory knowledge may occur over time from children’s input. More specifically, their results argue against early maturation of innate linking theory knowledge. So, deriving that linking theory knowledge from the input becomes a plausible option to explore. An important takeaway from Pearl and Sprouse [in press] is that these results come from combining the statistical learning mechanism of hierarchical Bayesian inference with linguistic representations that define a child’s hypothesis space (here, UTAH and rUTAH); by doing so, we gain insight about the process of acquisition that needs to accompany either linking theory representation.

Pearl and Sprouse [2019] offers insight into which theoretical option is more compatible with deriving linking theory knowledge from children’s input. In particular, their results suggested two significant advantages for rUTAH over UTAH, if children derive their linking theories from their input using the Tolerance and Sufficiency Principles. First, a rUTAH-learning child will have a much easier time generating the complex linking patterns that comprise the rUTAH linking theory from the available input. Second, only rUTAH – and not UTAH – can be successfully generalized from English children’s input using the Tolerance and Sufficiency Principles. So, by combining statistical learning with a linguistically-defined hypothesis space, Pearl and Sprouse [2019] found support for a relativized linking theory like rUTAH over a fixed linking theory like UTAH, when coupled with a derivational theory of acquisition.

1.4. When statistical learning refines what's in UG

We'll now turn to some examples where statistical learning can help refine our ideas of what's in UG. The first example demonstrates how statistical learning can replace a language-specific way to navigate a certain type of linguistic hypothesis space, where one hypothesis is a subset of another. The second example demonstrates how statistical learning can allow us to replace very specific UG syntactic knowledge with more general-purpose UG syntactic knowledge.

1.4.1. A bias for the subset hypothesis

One potential issue, known as the *Subset Problem* [Berwick, 1985, Manzini and Wexler, 1987], can arise when a child is navigating her hypothesis space. This problem occurs when the correct hypothesis for the language is a subset of a competing hypothesis for the language and the observed data are ambiguous between these hypotheses, as shown in Figure 1.1. Here we see a two-dimensional space, where some data points are observed (each indicated with a d). All the observed data are compatible with both correct hypothesis C and incorrect hypothesis N.

The problem is that there are no data that can unambiguously indicate C is correct – every d in Figure 1.1 that can be accounted for by C can also be accounted for by N. Importantly, this isn't just an issue with the observed data in this particular scenario – it's a problem for C in general. There are no data a child could possibly encounter that would be compatible with C but not with N – this is what it means for C to be a subset of N (and for N to be

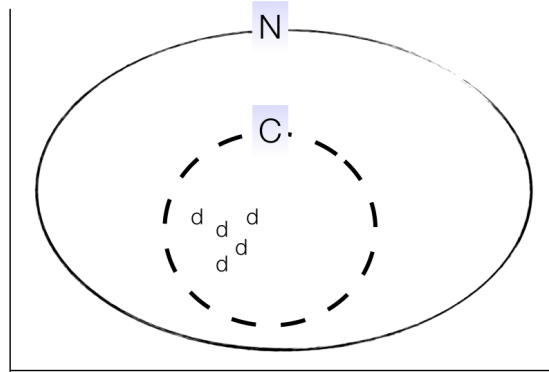


Figure 1.1: A visual demonstration of the Subset Problem: a two-dimensional hypothesis space where one hypothesis (the correct one, C , in dashed lines) is a subset of a competing hypothesis (one that’s not correct, N). Each d corresponds to an observed data point, and both hypotheses are compatible with the observed data.

a superset of C). So, because every data point in C is also in N , all “ C ” data points have unresolvable ambiguity between C and N (i.e., there’s a Subset Problem caused by N if the child needs to learn C).

Importantly, this is a problem for the type of learning mechanisms that learning theorists previously assumed children used: in particular, (i) mechanisms relying on unambiguous data to trigger the correct hypothesis [Lightfoot, 1989, Fodor, 1998, Dresher, 1999, Sakas and Fodor, 2001, 2012], or (ii) mechanisms involving error-driven learning that relied on some data being incompatible with the incorrect hypotheses [Gibson and Wexler, 1994, Niyogi and Berwick, 1996, Sakas and Fodor, 2001]. In our example, a child looking for data that unambiguously signal C won’t find any – all data compatible with C are also compatible with N ; a child looking for data that signal N is incorrect also won’t find any – again, all the data she’ll encounter (which come from speakers using C) will be compatible with N , too.

To tackle this problem, the Subset Principle [Berwick, 1985, Manzini and

Wexler, 1987] was proposed; this principle causes the child to prefer the subset hypothesis, even if the data are ambiguous (e.g., preferring C over N, despite all the ds being compatible with both hypotheses). This principle was language-specific (and so part of UG), and intended to help children successfully navigate the linguistic hypothesis spaces that had these subset problems.

However, this same preference can be derived from the mechanics of Bayesian inference, which is a domain-general mechanism (and therefore doesn't have to be built into UG). Let's see how, by recalling the two components from the equation in (1) that are used to calculate the posterior probabilities of different hypotheses: the prior of a hypothesis, $P(h)$, and the likelihood of the data, given a hypothesis, $P(D|h)$. The prior captures how much the child favors the hypothesis before any data have been encountered yet. Let's suppose that the priors for both C and N are the same (say, $P(C) = P(N) = 0.5$), so there's no reason to prefer one over the other a priori (and certainly no reason to prefer subset C over superset N).

The likelihood can be calculated by considering the probability of a particular hypothesis generating the observed data. This is where a child's expectations about the data each hypothesis could generate are really important. In particular, because C is a subset of N, C is by definition capable of generating fewer data than N is. Just to be concrete, let's suppose C is capable of generating 10 data points (including the 5 we saw in Figure 1.1) while N is capable of generating 20 data points (including the 10 that C can generate, which include the 5 we saw in Figure 1.1). This is shown in Figure 1.2.

Let's now consider the probability of each hypothesis generating a data point like d_1 , which is compatible with both C and N. Because C can generate 10 data points, the probability of C generating d_1 is $\frac{1}{10}$ ($P(d_1|C) = 0.10$).

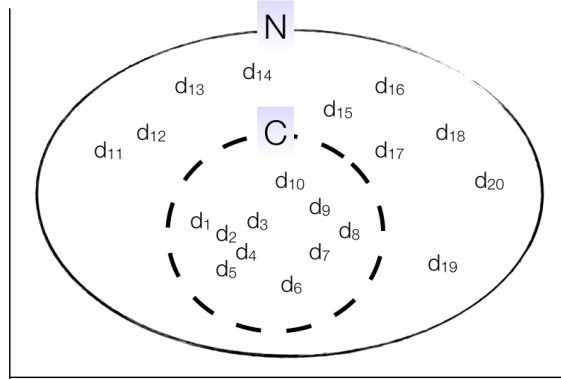


Figure 1.2: A visual demonstration of the data each hypothesis (correct subset hypothesis C and incorrect superset hypothesis N) can generate.

Because N can generate 20 data points, the probability of N generating d_1 is $\frac{1}{20}$ ($P(d_1|N) = 0.05$).

Now, because the posterior probabilities of C and N, given the data, are proportional to their prior * likelihood, this means that a child seeing only ambiguous data point d_1 would assess the posterior probabilities of C and N as in (4):

$$(4) \quad \begin{aligned} \text{a.} \quad & P(C|d_1) \propto P(C) * P(d_1|C) = 0.5 * 0.1 = 0.05 \\ \text{b.} \quad & P(N|d_1) \propto P(N) * P(d_1|N) = 0.5 * 0.05 = 0.025 \end{aligned}$$

So, just from seeing d_1 , a child would believe correct subset hypothesis C is twice as likely as incorrect superset hypothesis N ($\frac{P(C|d_1)}{P(N|d_1)} = \frac{0.05}{0.025} = 2$). That is, the child has a preference for the subset hypothesis C, even without having encountered either unambiguous data for C or error data indicating N is incorrect. This is exactly what the Subset Principle was meant to instill.

Moreover, the more data the child sees like d_1 (i.e., compatible with both the subset and superset hypotheses), the stronger this preference becomes.

For instance, if the child saw 5 data points compatible with both C and N (i.e., $\{d_1, d_2, d_3, d_4, d_5\} = Data$, as in Figure 1.1), the likelihood for C would be $(\frac{1}{10})^5 = 0.00001$, while the likelihood for N would be $(\frac{1}{20})^5 = 0.0000003125$. This would lead to the posteriors in (5).

$$\begin{aligned}
 (5) \quad a. \quad & P(C|Data) \propto P(C) * P(Data|C) = 0.5 * 0.00001 \\
 & = 0.000005 \\
 b. \quad & P(N|Data) \propto P(N) * P(Data|N) = 0.5 * 0.0000003125 \\
 & = 0.00000015625
 \end{aligned}$$

So, on the basis of these ambiguous data, the child would believe correct subset hypothesis C is 32 times more likely than incorrect superset hypothesis N ($\frac{P(C|Data)}{P(N|Data)} = \frac{0.000005}{0.00000015625} = 32$). This is an even stronger bias for the subset. Notably, Bayesian inference allows us to quantify how much the child ought to prefer the subset hypothesis, given the data encountered; this is in contrast to the Subset Principle, which specifies that the child ought to prefer the subset hypothesis, but not how *how much* she ought to prefer it.

More generally, this example is meant to highlight how statistical learning (in this case, Bayesian inference) can offer an alternative solution for navigating a tricky language learning scenario (i.e., when the linguistic hypotheses overlap in a particular way and all the available data are ambiguous). So, a child could successfully navigate this linguistic hypothesis space without relying on a language-specific mechanism to do so; instead, Bayesian inference would allow her the same navigation ability and also not require us to build that navigation mechanism into UG.

1.4.2. Linguistic knowledge for syntactic islands

One hallmark of the syntax of human languages is the ability to have long-distance dependencies: relationships between two words in a sentence that aren't adjacent to each other. Long-distance dependencies, such as the dependency between *what* and *stole* in (6a), can be potentially infinite in length. However, there are specific syntactic structures that long-distance dependencies can't cross. These structures are known as *syntactic islands*. Four examples of syntactic islands are shown in (6b)-(6e) [Chomsky, 1965, Ross, 1967, Chomsky, 1973]. During acquisition, children must infer the constraints on long-distance dependencies (i.e., the syntactic islands) that allow them to recognize that the *wh*-dependencies in (6b)-(6e) aren't allowed, while the *wh*-dependency in (6a) is fine.

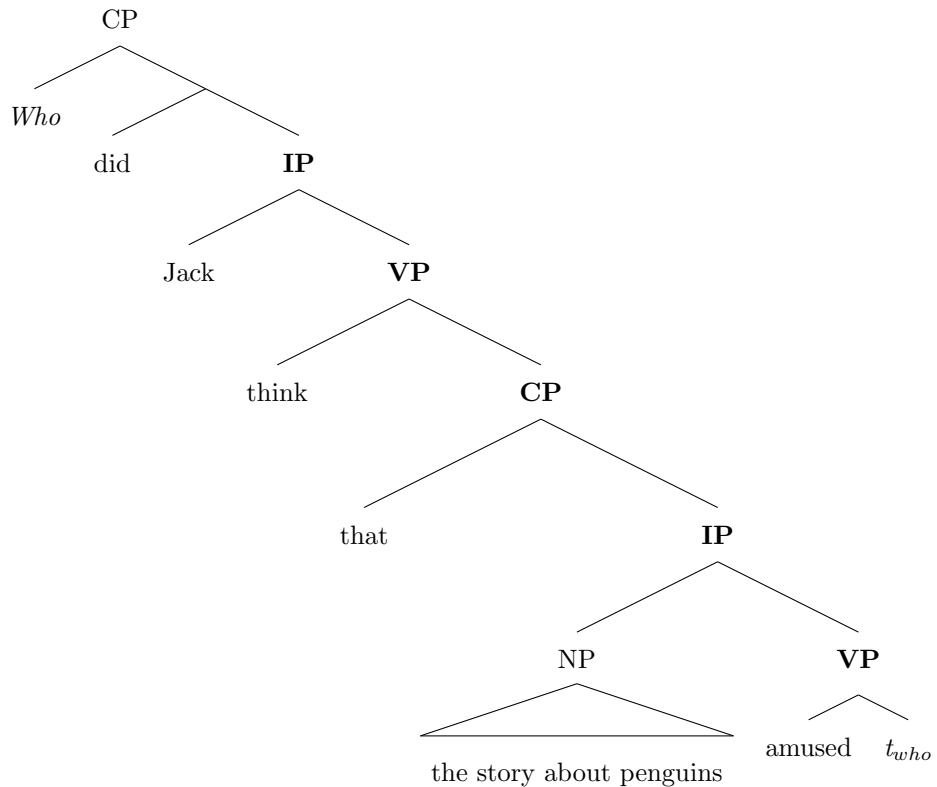
- (6) a. What does Jack think that Lily said that the goblins stole *t_{what}*?
- b. *whether* island
*What do you wonder [whether Jack bought *t_{what}*]?
- c. complex NP island
*What did you make [the claim that Jack bought *t_{what}*]?
- d. subject island
*What do you think [the joke about *t_{what}*] was hilarious?
- e. adjunct island
*What do you worry [if Jack buys *t_{what}*]?

Pearl and Sprouse [2013b,a, 2015] investigated a statistical learning strategy for learning about syntactic islands that probabilistically leveraged linguistic knowledge; more specifically, this strategy relied on children characterizing a long-distance dependency as a path from the head of the dependency (e.g.,

Who in (7)) through the phrasal nodes that contain the tail of the dependency, as shown in (7a)-(7b). Under this view, children simply need to learn which long-distance dependencies have licit syntactic paths and which don't. The probabilistic learning strategy of Pearl & Sprouse tracks local pieces of these syntactic paths, which we can think of as the building blocks of the syntactic paths. In the interest of space, I'll briefly review here the highlights of how we can interpret the results of this linguistically-savvy statistical learning strategy, but see Pearl [in press] for a more detailed overview of both the strategy itself and how to interpret it.

(7) Who did Jack think that the story about penguins amused t_{who} ?

a. Phrasal node structure containing the *wh*-dependency:



Who did [*IP* Jack [*VP* think [*CP* that [*IP* the story about penguins

[_{VP} amused *t_{who}*]]]]]])?

- b. Syntactic path of *wh*-dependency:

start-IP-VP-CP_{that}-IP-VP-end

Pearl & Sprouse’s results suggested that their proposed learning strategy was a reasonable way for English children to acquire knowledge of the four islands in (6b)-(6e). Importantly, this strategy offers an alternative to a previous acquisition theory for syntactic islands from the Government and Binding framework of the 1980s, which involved a constraint called the *Subjacency Condition*. This constraint basically says that dependencies can’t cross two or more *bounding nodes* (Chomsky 1973, Huang 1982, Lasnik and Saito 1984, among others); if a dependency crosses two or more bounding nodes, a syntactic island occurs. What counts as a bounding node varies cross-linguistically, though bounding nodes are always drawn from the set {NP, IP, CP}. So, when using this representation, children needed to learn which of these are bounding nodes in their language, though they already know (via UG) about the restriction the Subjacency Condition imposes and the set of possible bounding nodes. This was fairly specific innate linguistic knowledge, in that it was only relevant for learning about syntactic islands.

The learning strategy of Pearl and Sprouse [2013b,a, 2015] shares the intuition with Subjacency that there’s a local structural anomaly when syntactic islands occur. However, instead of characterizing this anomaly with bounding nodes, Pearl & Sprouse suggested that it could be described as a low probability region with respect to the phrase structure nodes that characterize the syntactic path of the *wh*-dependency. There’s no need for the child to know about a hard constraint prohibiting the crossing of two bounding nodes, and in fact no need for the child to identify bounding nodes at all. Instead, children would

need to identify the phrase structure nodes containing the *wh*-dependency and break that syntactic path into smaller building blocks based on phrase structure nodes – certainly no trivial matter, but one that involves building blocks that are more general-purpose than bounding nodes.

And this is the point: the knowledge of building blocks based on phrase structure nodes and how to use them doesn't seem to be as specific to learning islands as the knowledge about bounding nodes and how to use them. That is, the syntactic path building blocks, because they're comprised of phrase structure nodes, may be useful for other syntactic phenomena. So, Pearl & Sprouse's investigation of a learning strategy that incorporates statistical learning allows us to refine our ideas about the contents of UG that are necessary for learning syntactic islands. More specifically, because children can use statistical learning to navigate a hypothesis space comprised of syntactic path building blocks, their linguistic hypothesis space doesn't have to be as constrained as the original Subjacency approach assumed it was.

1.5. Concluding thoughts

I hope to have shown here how statistical learning can play well with UG, by both complementing and refining our ideas about UG. This is in fact why I believe researchers who like the idea of UG should be interested in incorporating statistical learning into their theories of language acquisition. Of course, there's much work to be done if we continue down this avenue: we need to provide concrete, testable theories of how acquisition could proceed using both statistical learning and whatever innate linguistic knowledge we think may be appropriate (e.g., see Pearl [2014, in press] for specific examples of how to do

this with mathematical and computational developmental modeling). By doing so, we can see how statistical learning can allow children to get far more mileage out of the innate, language-specific knowledge we believe is in UG.

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