Language learners privilege structured meaning over surface frequency

Jennifer Culbertson[a,1] and David Adger[b]

[a]Linguistics Program, English Department, George Mason University, Fairfax, VA 22030; and [b]Department of Linguistics, Queen Mary University of London, London E1 4NS, England

Edited by Barbara H. Partee, South College, Amherst, MA, and approved February 28, 2014 (received for review October 31, 2013)

Although it is widely agreed that learning the syntax of natural languages involves acquiring structure-dependent rules, recent work on acquisition has nevertheless attempted to characterize the outcome of learning primarily in terms of statistical generalizations about surface distributional information. In this paper we investigate whether surface statistical knowledge or structural knowledge of English is used to infer properties of a novel language under conditions of impoverished input. We expose learners to artificial-language patterns that are equally consistent with two possible underlying grammars—one more similar to English in terms of the linear ordering of words, the other more similar on abstract structural grounds. We show that learners' grammatical inferences overwhelmingly favor structural similarity over preservation of superficial order. Importantly, the relevant shared structure can be characterized in terms of a universal preference for isomorphism in the mapping from meanings to utterances. Whereas previous empirical support for this universal has been based entirely on data from cross-linguistic language samples, our results suggest it may reflect a deep property of the human cognitive system—a property that, together with other structure-sensitive principles, constrains the acquisition of linguistic knowledge.

learning biases | typology | artificial grammar learning | semantic scope | transitional probabilities

A central goal of linguistics is to provide a formal characterization of human knowledge of language. It has long been argued that this knowledge crucially involves rules that refer to abstract structure rather than surface word order (1–3). One classic example is the relationship between English declarative and interrogative sentences. Although in many cases a rule forming the interrogative from the declarative could simply change the surface position of the auxiliary verb, the full range of English facts can only be captured by a rule making reference to the structural position of the auxiliary. For example, to generate the correct interrogative for complex declaratives such as "The man who is a fool is amusing" and "The man is a fool who is amusing," a rule referring to the superficial surface position of the auxiliary—for instance, leftmost or rightmost—will not do. Rather, the rule must pick out the auxiliary in the main clause. Because these complex cases are relatively rare, language learners could initially entertain a surface-based rule before converging on the structure-based alternative. Interestingly, though, children acquiring English do not seem to do this, suggesting that structure-based generalizations are preferred from the very start (4).

The idea that explaining the syntax of natural languages requires abstract structure—and that learners posit structure-based generalizations early in the acquisition process—has been challenged from multiple angles. For example, simple recurrent networks trained on English input can replicate correct interrogative ordering patterns, suggesting that surface-based generalizations may be sufficient to characterize linguistic knowledge (5, 6) (but see refs. 7–9 on shortcomings of these models). Recent efforts at modeling the acquisition of complex syntactic phenomena argue that learners need not prefer structure-dependent rules to acquire them (10, 11).

More generally, the claim that knowledge of language centrally involves tracking and storing surface distributional information—such as the frequencies of word sequences ("chunks")—has been made by proponents of constructivist (12, 13), use-based (14, 15), and statistical learning (16, 17) approaches. A central tenet of construction grammar, for example, is that "what you see is what you get" (18); in other words, structure-based rules and abstract representations are eschewed wherever possible in favor of surface-based generalizations. This is consistent with recent claims that language acquisition, production, and comprehension rely primarily on sequential information rather than hierarchical structure (19, 20). This perspective also offers an explanation for cross-linguistic variation; aside from general constraints on the cognitive mechanisms involved (18, 21), language-specific patterns in the input should be the major determinant of what is learned. Indeed, the surface diversity exhibited by the world's languages has been used to support a closely related claim, namely, that there are no (nondefinitional) universal characteristics of language (22, 23). This is in contrast to a view that proposes a set of universal design features of language—such as structure-dependence—that delimit the set of generalizations that learners entertain (24, 25).

In sum, these alternative approaches emphasize either that:

(*i*) the outcome of learning is structure-based and reflects inherent properties of the human linguistic system, or

(*ii*) the outcome of learning is surface-based and reflects the inherent ability of learners to track distributional information in the input.

These approaches are not mutually exclusive—learners may well represent both abstract structural and distributional information.

Significance

How humans represent aspects of the grammar of the languages they speak is a fundamental question in psychology and linguistics. Two kinds of proposals have been made: One posits abstract structural representations, while the other takes the relevant generalizations to be stated over surface statistical regularities from data learners are exposed to. Our results, based on artificial language learning experiments, show that language learners, when confronted with a new linguistic system, systematically privilege structural similarity to their native language over surface statistical similarity. We propose that the relevant structural bias is one that prefers word order and meaning to line up in a particular way.

Author contributions: J.C. and D.A. designed research; J.C. performed research; J.C. analyzed data; and J.C. and D.A. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

[1]To whom correspondence should be addressed. E-mail: jculber4@gmu.edu.

This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1320525111/-/DCSupplemental.

Furthermore, the issue of whether language acquisition involves statistical learning is distinct from the nature of the representations acquired (10, 26, 27). Nevertheless, the two approaches have distinct null hypotheses, and here we directly pit their predictions against one another experimentally. In particular, we provide evidence that, when given ambiguous input data from a miniature artificial language, learners' grammatical inferences make use of structure- rather than surface-based knowledge (see ref. 28 for converging evidence in a different domain). In particular, they show a strong preference for word orders consistent with an abstract structural property found in English, even though these orders have much lower probability according to the sequential statistics of English. Moreover, this preference comports with a generalization from language typology [Greenberg's Universal 20 (29)] that has been the focus of important work in syntactic theory but has not previously received experimental support. We argue that our results can be explained by an underlying cognitive constraint enforcing an isomorphism in the mapping between semantics and surface word order via hierarchical syntax.

Surface Order, Semantic Scope, and Universal 20

The classic case of interrogative inversion concerns structure dependence of displacement rules, but the same issues about how grammatical knowledge is represented arise in the phenomenon of basic word order: Is knowledge of word order represented in terms of surface frequencies computed over linear strings of words (or their categories), or is it derivative of the abstract structural relations that the words enter into?

To investigate this, we first describe a core relevant concept from linguistics: scope. In a number of linguistic domains, semantic composition and surface word order are linked through the notion of scope. For example, derivational morphemes (which change the meaning of a word) are typically placed closer to the root noun than inflectional morphemes (which provide grammatical information). This reflects scope: In a complex word like *neighbor–hood–s*, the inflectional affix *–s* semantically combines with (pluralizes) not the root *neighbor* alone, but the root and derivational morpheme *–hood* together. Inflectional morphemes scope over, and are hence ordered more peripherally than derivational affixes. More generally, fixed orderings of morphemes (e.g., tense markers), nominal modifiers (e.g., adjectives), and verbs (in verbal complexes such as "might have been") in a given language have been argued to reflect semantic scope (30–34).

Here we focus on a cross-linguistic generalization about the ordering of nominal modifiers, Universal 20 (U20), first postulated in ref. 29 on the basis of 30 languages and subsequently supported by larger controlled samples (341 languages[†]). According to U20, the order of demonstratives (words such as *this* and *that*), numerals (e.g., *three* or *six*) and adjectives (e.g., *red* or *big*) is constrained as follows.

> U20 (as restated in Cinque, ref. 33)
>
> In prenominal position the order of demonstrative, numeral, and adjective (or any subset thereof) conforms to the order Dem-Num-Adj.
>
> In postnominal position the order of the same elements (or any subset thereof) conforms to either the order Dem-Num-Adj or to the order Adj-Num-Dem.

For example, in English all three categories are prenominal (precede the noun) and conform to U20: *these two red cars* (Dem-Num-Adj-N) but not **red two these cars*. Indeed, this pattern is the only cross-linguistically attested order of all three modifiers before the noun[†]. When all modifiers are postnominal, two types of languages are attested: those using the mirror order of the prenominal pattern *cars red two these* (N-Adj-Num-Dem) [e.g., Thai (35)] and those maintaining the surface order found prenominally but placing the noun first, *cars these two red* (N-Dem-Num-Adj) [e.g., Kikuyu (29)]. However, there is a further striking asymmetry in the distribution of postnominal patterns. Languages with N-Adj-Num-Dem are much more frequent than languages with N-Dem-Num-Adj [~25:1[†]]. (Other orders are possible, where the N is medial, but we focus here on only the cases where N is to the left or the right of the entire sequence, the N-peripheral orders.)

Why do languages order nominal modifiers in these proscribed ways? We know independently that orders where the noun is peripheral (on the right or left edge of the phrase) are most common typologically (29) and strongly preferred by learners (36). However, this would not distinguish N-Adj-Num-Dem (typologically common) from N-Dem-Num-Adj (rare). One intriguing possibility is that Dem-Num-Adj-N and N-Adj-Num-Dem are most common precisely because these orders maintain an isomorphism between scope and surface order.

There are three converging sources of evidence, from three distinct approaches to investigating noun phrases, that the scope is universally Dem > Num > Adj—as shown in Fig. 1*A*: (*i*) Research on formal semantics motivates an analysis of adjectives as predicates that combine with the nominal predicate, numerals as functions from nominal predicates to countable units, and demonstratives as functions that map nominal predicates to individuals (37, 38), so that semantic type constraints enforce the scope relations; (*ii*) syntactic constituency tests show that adjectives are in a structural unit with the noun that they modify ([Adj N]), to the exclusion of the numeral, which in turn belongs to a hierarchically superior unit ([Num [Adj N]]) that excludes the demonstrative, giving a syntactic hierarchy isomorphic to semantic scope (39, 40); and (*iii*) typological and functionally oriented work proposes a metric of semantic closeness (iconicity) that places adjectives closest to the noun because they modify dimensions inherent to noun meaning, numerals further away because they do not modify such dimensions, and demonstratives yet further away because they serve to connect the internal material to the surrounding discourse ([†], 41, 42). These three distinct traditions agree on the core scope relations.

These scope relations are typically represented as hierarchical structures ("trees") as in Fig. 1*B*. Trees have applications in broader cognition (43), can capture the constituency tests just mentioned, and can be given a well-defined semantics (44). They do not, however, specify linear word order—this is derived from the hierarchical structure by a mapping principle collapsing a 2D tree to a unidimensional string: Each binary branching of a node $[_X \text{ Y Z}]$ can be linearized in one of two ways, Y–Z or Z–Y, giving eight orders for the four hierarchically ordered categories Dem, Num, Adj, and N (as shown in Fig. 2). Only two orders conform to this transparent scope-order mapping and are N-peripheral

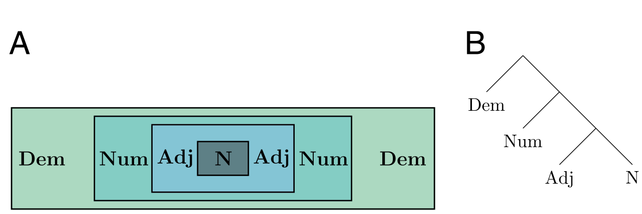

Fig. 1. (*A*) Scope relations within the nominal domain. (*B*) Hierarchical representation of scope. Dem(onstrative) takes outermost scope, over inner modifiers Num(eral) and Adj(ective).

[†]Dryer M, On the order of demonstrative, numeral, adjective and noun: An alternative to Cinque. Talk presented at Theoretical Approaches to Disharmonic Word Orders, May–June 2009, Newcastle University, Newcastle Upon Tyne, United Kingdom.

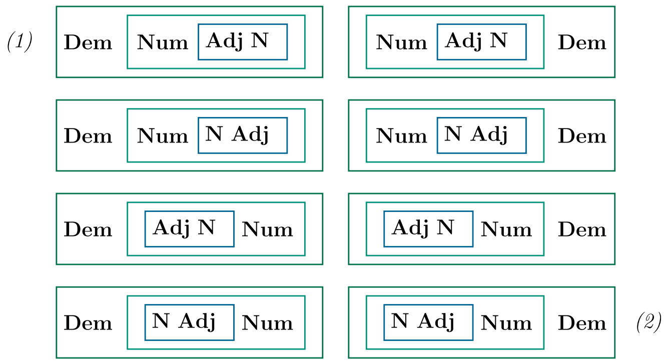

Fig. 2. The eight scope-isomorphic linearizations, or surface orders, in which the constituency determined by the semantics is preserved (as shown by the colored squares). The first and last two orders are N-peripheral and typologically most common.

(Dem-Num-A-N and N-A-Num-Dem). These are the two most common orders.

Additional N-peripheral orders cannot be derived directly from the scope—they are nonisomorphic to the scope. These orders do not violate the mapping principle, but instead reflect language-specific displacement rules modifying isomorphic linearizations. For example, the alternative N-peripheral order for postnominal modifiers is N-Dem-Num-Adj. This can be derived from Dem-Num-Adj-N by a rule that moves N to the left edge. An analogous rule for moving N to the right edge would derive Adj-Num-Dem-N from Adj-Num-Dem-N. [Some theories posit a leftward but not rightward analog of this kind of operation (45); this restriction has been used to rule out the unattested order Adj-Num-Dem-N (33).]

To summarize, the claim is that N-Adj-Num-Dem and Dem-Num-Adj-N are typologically common because they are isomorphic to the underlying scopal structure. By contrast, orders such as N-Dem-Num-Adj and Adj-Num-Dem-N are nonisomorphic and hence rare (or unattested). A preference for isomorphism during language learning could account for the strong typological asymmetries and makes the following novel prediction: It should be possible to infer the relative order of modifiers given only evidence of their individual placement relative to the noun. In other words, if a learner is exposed to N-Adj and N-Dem phrases, she should implicitly assume that the relative order among modifiers is isomorphic to scope, yielding N-Adj-Dem. This is precisely what we test here, by training English-speaking learners on a subset of phrases in a new language and testing their inferences. However, an equally plausible alternative is that a learner under these conditions will transfer her knowledge of the sequential statistics of English to the new language. In this case, upon hearing N-Adj and N-Dem, knowledge that Dem precedes Adj in English will lead to an inference of N-Dem-Adj—an order that is nonisomorphic to the scope.

Experiment 1

Design, Procedure, and Hypotheses. A growing body of research uses laboratory language learning studies to investigate adult learners' knowledge of language, with results that converge with typology and natural language acquisition (see refs. 46 and 47 for reviews of this literature). To test whether learners' inferences are guided more strongly by structural or distributional knowledge, we conducted an artificial language learning experiment requiring learners to generalize from ambiguous evidence (48–50). In this paradigm, learners are presented with examples from a new language in a way that withholds critical evidence about its structure—concretely instantiating in an artificial language the notion of poverty of the stimulus that is hypothesized but controversial for natural language. At test, learners must generalize to held-out data that will disambiguate the alternative hypotheses. In experiment 1, participants were randomly assigned to one of four conditions (Table 1). Each condition featured a subset of noun modifiers, and training provided deterministic evidence that these modifiers were postnominal in the language (unlike English). Learners were told that the language was similar to English—English lexical items were used (following ref. 51; *Materials and Methods*)—but they would notice some differences. During training, English phrases were presented orthographically, and learners heard an informant produce a translation. For example, in condition 1 the English phrases *purple vase* or *those shoes* might be displayed on-screen, and the translations "vase purple" (N-Adj) or "shoes those" (N-Dem) would be heard. Crucially, however, no phrase contained more than a single modifier, and therefore no evidence for the relative ordering of modifiers was provided. At test, participants were required to infer, based on the impoverished evidence received during training, the relative ordering of the modifiers.

If learners have an implicit preference for modifier orders that can be derived directly from the semantic scope relations, then they should infer N-Adj-Dem (condition 1), N-Num-Dem (condition 2), and N-Adj-Num (condition 3). By contrast, if learners privilege surface distributional information—for example, operationalized in terms of transitional probabilities (TPs)—the opposite predictions hold. English-speaking learners should infer N-Dem-Adj (condition 1), N-Dem-Num (condition 2), and N-Num-Adj (condition 3). This is because, for example, the probability that an Adj such as *green* is preceded by a Dem such as *this* is much higher than the probability that *this* is preceded by *green* (and, more generally, $P(\text{Adj}|\text{Dem}) > P(\text{Dem}|\text{Adj})$). This can be verified using data from the Corpus of Contemporary American English (52), which show that, for each combination of modifiers, the probability of the canonical English ordering (e.g., Dem-Adj) is higher than the reverse (e.g., Adj-Dem) (see Figs. S1–S3 and Tables S1 and S2 for TP estimates and raw frequencies). Another way to think about the sequential similarity of phrases such as *vase this green* to English *this green vase* is in terms of chunks (word sequences); there is a chunk present in the former that is also present in latter (i.e., *two green*). By comparison, there is no such chunk in common between *vase green this* and English *this green vase*.

To summarize, the data learners are exposed to—phrases with a single modifier—are ambiguous between two hypotheses:

Hypothesis 1: The generating grammar is one that can be derived from English by placing the noun at the beginning of the phrase—that is, the order is surface-identical to English except the noun comes first.

Hypothesis 2: The generating grammar is one whose order is isomorphic to the semantic scope but has left-branching direction as opposed to right-branching—that is, the order can be derived directly from the scope, but in the reverse order from English (Fig. 2).

To determine which hypothesis learners have inferred, disambiguating choices are presented at test. In condition 1, for example, N-Dem-Adj is generated by hypothesis 1, whereas N-Adj-Dem is generated by hypothesis 2. Two distractor choices are also presented, featuring prenominal modifiers not consistent

Table 1. Summary of conditions (experiment 1)

Training combination	Training order	Testing (held-out combination)
{Adj, Dem}	N-Adj, N-Dem	{N, Adj, Dem}
{Num, Dem}	N-Num, N-Dem	{N, Num, Dem}
{Adj, Num}	N-Adj, N-Num	{N, Adj, Num}

with training. (An example testing trial in condition 1 can be seen in Fig. S4.)

Results. The average proportion of trials on which participants chose the scope-isomorphic order in each condition is shown in Fig. 3 (see Fig. S5 for individual subject results). In all three conditions, participants reliably chose this order over the alternative that is more surface-similar to English, suggesting that they systematically infer hypothesis 2. The effect is most dramatic in the {Adj, Dem} condition, in which the scope-isomorphic order was chosen over 90% of the time ($M=0.94, \hat{\beta}=8.39, P<0.01$).[‡] This preference was reliable, although weaker, for {Num, Dem} ($M=0.70, \hat{\beta}=3.43, P<0.01$) and N-Adj-Num ($M=0.75, \hat{\beta}=5.33, P<0.01$). These results suggest a scope-order preference that is strong but potentially dependent on the structural (i.e., scopal) distance of the modifiers in question (the preference for {Adj, Dem} was clearly strongest; $\hat{\beta}=1.8, P=0.02$). If the underlying structure of the noun phrase is as shown in Fig. 1, Dem and Adj are relatively far apart (the former taking widest scope, the latter most narrow scope), whereas Num and Dem, and Adj and Num, are respectively closer together. The notion of structural distance has been independently used to explain differences in acceptability of adjective orders [e.g., switching the order of two adjectives that are hypothesized to be structurally distant, as in *the green fascinating truck*, is worse than reversing two that are relatively close, as in *the green small truck* (55)].

Experiment 2

Design, Procedure, and Hypotheses. A preference for surface order that is isomorphic to underlying scope should function as a high-level macroparameter (24) or overhypothesis (56) about the noun phrase as a whole. If this is the case, then any strong preference relevant to a subset of modifier types might lead learners to immediately infer hypothesis 2, and therefore postulate a scope-conforming mapping from structure to linear order for all modifiers. Experiments 2a and 2b test this hypothesis by training participants on all three modifier types of interest (Dem, Num, and Adj) and observing whether under these conditions a strong preference for scope-isomorphic ordering of Adj and Dem leads to conformity for other modifier orderings (i.e., those that showed only a weaker scope preference in experiment 1). As in experiment 1, training provided deterministic evidence that modifiers were postnominal in the language (e.g., *leaves three*, *ribbon blue*, *bowl this*), but no evidence for the relative ordering among modifier types was provided. At test, participants were required to infer, based on the impoverished evidence they received during training, both the ordering of phrases with all subcombinations of two modifiers (experiment 2a) and phrases with all three modifiers (experiment 2b).

Results. The results of these experiments, shown in Fig. 4, again reveal a clear preference for the scope-isomorphic order, both for phrases with each combination of two modifiers and for phrases with all three modifiers. In experiment 2a, learners choose the scope-conforming order on average more than 85% of the time for two-modifier phrase types ($\hat{\beta}=5.84, P<0.01$, with no significant differences among phrase types). In experiment 2b, this result is replicated (collapsed across all two modifier phrase types, $\hat{\beta}=5.94, P<0.01$) and extended to phrases in which all three modifier types are simultaneously present ($\hat{\beta}=9.47, P<0.01$).

‡All statistical models of the data used Bayesian mixed-effects logistic regression, with random intercept terms for participants and items. Fixed effects were sum-coded. Models were fit using the R package MCMCglmm (53), with a weak informative prior on the fixed effects similar to that suggested by ref. 54, and *P* values estimated by Markov chain Monte Carlo sampling.

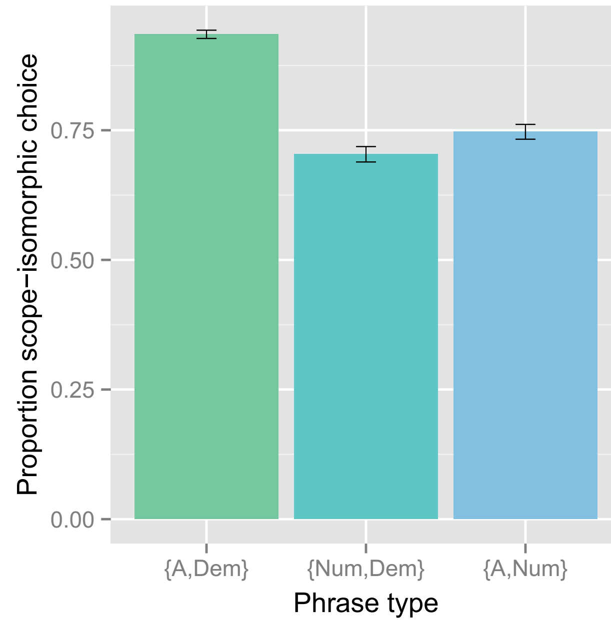

Fig. 3. Experiment 1 results. Choice of scope-isomorphic order in critical phrase types across conditions.

These results suggest the following picture across experiments. In experiment 1, learners generally favor hypothesis 2; they are more likely to infer a relative order of modifiers that is isomorphic to scope compared with an alternative that is more probable according to the sequential statistics of English noun phrases. However, this preference is stronger for Adj and Dem—more distant in terms of the semantic structure—than for other phrase types. In experiments 2a and 2b, all modifiers, including Adj and Dem, are present in training. This leads to a strong preference for hypothesis 2, which is extended from N-Adj-Dem to all phrase types.

Discussion

The relative contribution of abstract structural versus surface-based knowledge was investigated using a series of experiments on word order learning in an artificial language. Learners were trained on noun phrases with a single postnominal modifier (N-Dem, N-Num, or N-Adj) and had to infer, based on that evidence alone, the relative order among modifiers. The orders they chose between were crucially different in terms of similarity to English. One order—N-Dem-Num-Adj—was very similar to English in terms of surface sequential properties; although the modifiers were postnominal, the order among them was identical to English. The alternative order—N-Adj-Num-Dem—had a much lower surface similarity to English but preserved the semantic scope relations among modifiers. Learners consistently preferred the latter order, suggesting that structural knowledge trumps distributional knowledge of English when learners make inferences about a new language system.

Could the preference for N-Adj-Num-Dem be explained by a (conscious) strategy by learners to simply "reverse" the English order? The idea that such strategizing may occur applies quite generally to artificial language learning experiments and deserves further study. However, there are two reasons why this is not a likely explanation for our results. First, if this were a general strategy, we would not expect to see results depend on the set of modifiers in the phrase—as in experiment 1. By contrast, structural distance between modifiers does predict this possibility. Second, it is not at all obvious why a reversal strategy would actually be preferred over one that maintains surface identity to

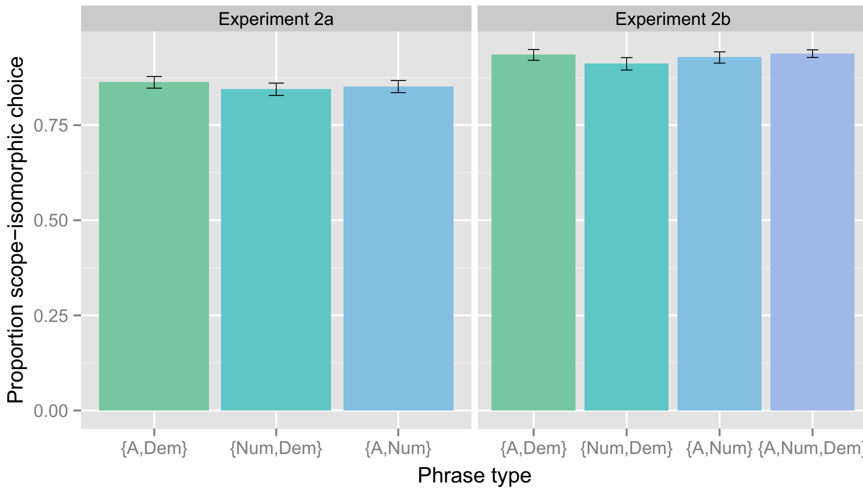

Fig. 4. Experiment 2 results. Choice of scope-isomorphic order in phrases with a subset of two modifiers (experiments 2a and 2b), and all three modifiers (experiment 2b).

English but simply places the noun first. The theory we have provided here offers an explanation for why N-Adj-Num-Dem should be preferred, but only under the hypothesis that underlying structural representations are driving performance, not conscious strategizing. Another possibility is that learners choose the order that is most surface-dissimilar to English because they know they are learning a non-English language (57). However, previous studies of laboratory language learning (36, 58), as well as the rich body of literature on native-language transfer effects in second-language acquisition (59–61), suggest that learners acquire rules (e.g., of word order) more easily when they are similar to English and make errors reflecting extension of English patterns to a new language. The main motivation for the experiments conducted here was to determine what notion of similarity—surface-based or structural—is more likely to influence learning.

The results of these experiments show that, when they are pitted against one another, structural rather than distributional knowledge is brought to bear most strongly in learning the syntax of a new language. This sheds light on the representations encoded in the adult grammar and how these affect learning; noun phrase structure is likely represented not primarily in terms of linear order, but rather in terms of hierarchical relations encoding semantic scope. The particular notion of structural knowledge we have suggested involves the mapping between a hierarchy of semantic relations among elements in the noun phrase, and how that hierarchy is linearized by the syntax to derive a surface word order. Our results leave open how such knowledge is learned and whether it is encoded probabilistically or categorically. For learners in our experiment, this knowledge could have been derived from English or could reflect a more general cognitive bias leading learners to prefer isomorphic mappings from scope to surface order. If the structural preference learners apparently bring to our task reflects not (only) knowledge of English, but a general bias favoring isomorphic mapping between semantics and surface order, then this would provide, to our knowledge, the first evidence that the statistical aspect of Greenberg's U20 (that N-Dem-Num-Adj orders are rarer than N-Adj-Num-Dem orders) is unlikely to be explained by historical or other cultural factors alone (22, 23) but rather is emergent from a property of the linguistic system.

Materials and Methods

The experiments were implemented as a web-based translation task and were completed by 160 native English-speaking adults (32 in each condition of experiment 1 and 32 in each of experiments 2a and 2b) through Amazon Mechanical Turk, a crowd-sourcing service that matches interested participants with available tasks. Participants were given either \$0.50 or \$0.75 for their participation (depending on the length of the experiment). Experiment 1 lasted ∼10 min, and experiment 2 lasted ∼15 min.

Participants were told that they would be learning a language similar to English but that they would notice some differences. The lexicon of the language was composed of English words: 30 nouns, 10 adjectives (including color, texture, and composition), 10 numerals (1–10), and 4 demonstratives ("this," "that," "these," and "those") (see Table S3 for full lexicon). During training participants heard only a subset of the possible items in the larger lexical categories (noun, adjective, numeral). Thus, generalization to novel lexical items was required. In all conditions and across both experiments modifiers followed the noun rather than preceding it, as in English. For experiment 1, participants heard only those modifier types relevant for their condition; in experiment 2, participants heard all modifier types. During training, participants saw phrases composed of a single modifier and a noun (15 of each type, totaling 30 trials in experiment 1 and 45 in experiments 2a and 2b) and heard an informant translate them aloud. They were then required to choose which among two options corresponded to what they had heard by clicking on a button containing one of two "translated" phrases. The two phrase options were always N-Mod and Mod-N but the position in which they appeared (left or right) was randomized.

At test, participants were told that they would be given phrases to translate that might be like the ones they heard during training or might be longer. Participants heard both old (heard during training) and new (never heard during training) lexical items. For experiment 1, the test was composed of 20 trials with single modifiers (10 of each type) and 30 trials with two modifiers (10 of each combination). For experiment 2a testing trials were composed of 30 single-modifier (10 of each type) and 48 two-modifier (16 of each combination) trials. For experiment 2b, testing trials were composed of 30 single-modifier, 30 two-modifier, and 20 three-modifier trials. On each trial, participants saw one of the phrases and had to choose its translation from among a set of options. The position of the options was randomized. For single-modifier trials, the options were identical to those provided during training (N-Mod and Mod-N). For two- and three-modifier trials, four options were given: two prenominal orders and two postnominal orders. The prenominal orders, which served as distractors because they were not consistent with the training, were Dem-Num-Adj-N and Adj-Num-Dem-N, or a subset with two of the modifiers. The two postnominal orders were the criticial options—the scope-isomorphic order (N-Adj-Num-Dem or a subset) and the typologically rare (but more English-like) alternative (e.g., N-Dem-Num-Adj or a subset). The relative proportions of these two orders chosen is analyzed here. Subjects who consistently chose orders not consistent with their training were removed (eight total).

ACKNOWLEDGMENTS. The authors thank Klaus Abels, Matt Goldrick, Andy Martinez, Paul Smolensky, Colin Wilson, and two anonymous PNAS reviewers for comments on previous versions of the paper.

1. Chomsky N (1957) *Syntactic Structures* (Mouton de Gruyter, Berlin).
2. Chomsky N (1965) *Aspects of the Theory of Syntax* (MIT Press, Cambridge, MA).
3. Gleitman LR, Newport EL (1995) *An Invitation to Cognitive Science*, eds Osherson DN, Gleitman LR (MIT Press, Cambridge, MA), pp 1–24.
4. Crain S, Nakayama M (1987) Structure dependence in grammar formation. *Language* 63(3):522–543.
5. Reali F, Christiansen MH (2005) Uncovering the richness of the stimulus: structure dependence and indirect statistical evidence. *Cogn Sci* 29(6):1007–1028.
6. Lewis JD, Elman J (2001) Learnability and the statistical structure of language: Poverty of stimulus arguments revisited. *Proceedings of the 26th Annual Boston University Conference on Language Development*, eds Skarabela B, Fish S, Do AH-J (Cascadilla, Somerville, MA), pp 359–370.
7. Kam XNC, Stoyneshka I, Tornyova L, Fodor JD, Sakas WG (2008) Bigrams and the richness of the stimulus. *Cogn Sci* 32(4):771–787.
8. Berwick RC, Pietroski P, Yankama B, Chomsky N (2011) Poverty of the stimulus revisited. *Cogn Sci* 35(7):1207–1242.
9. Frank R, Mathis D, Badecker W (2013) The acquisition of anaphora by simple recurrent networks. *Lang Acquis* 20(3):181–227.
10. Perfors A, Tenenbaum JB, Regier T (2011) The learnability of abstract syntactic principles. *Cognition* 118(3):306–338.
11. Pearl L, Sprouse J (2013) Syntactic islands and learning biases: Combining experimental syntax and computational modeling to investigate the language acquisition problem. *Lang Acquis* 20(1):23–68.
12. Goldberg A (1995) *Constructions: A Construction Grammar Approach to Argument Structure* (Univ of Chicago Press, Chicago).
13. Croft W (2001) *Radical Construction Grammar* (Oxford Univ Press, Oxford).
14. Lieven EV, Pine JM, Baldwin G (1997) Lexically-based learning and early grammatical development. *J Child Lang* 24(1):187–219.
15. Tomasello M (2009) *Constructing a Language*: *A Usage-Based Theory of Language Acquisition* (Harvard Univ Press, Cambridge, MA).
16. Saffran JR, Newport EL, Aslin RN (1996) Word segmentation: The role of distributional cues. *J Mem Lang* 35(4):606–621.
17. Mintz TH, Newport EL, Bever TG (2002) The distributional structure of grammatical categories in speech to young children. *Cogn Sci* 26(4):393–424.
18. Goldberg AE (2003) Constructions: A new theoretical approach to language. *Trends Cogn Sci* 7(5):219–224.
19. Frank SL, Bod R (2011) Insensitivity of the human sentence-processing system to hierarchical structure. *Psychol Sci* 22(6):829–834.
20. Frank SL, Bod R, Christiansen MH (2012) How hierarchical is language use? *Proc Biol Sci* 279(1747):4522–4531.
21. Saffran JR (2003) Statistical language learning mechanisms and constraints. *Curr Dir Psychol Sci* 12(4):110–114.
22. Evans N, Levinson SC (2009) The myth of language universals: Language diversity and its importance for cognitive science. *Behav Brain Sci* 32(5):429–448, discussion 448–494.
23. Dunn M, Greenhill SJ, Levinson SC, Gray RD (2011) Evolved structure of language shows lineage-specific trends in word-order universals. *Nature* 473(7345):79–82.
24. Baker M, McCloskey J (2007) On the relationship of typology to theoretical syntax. *Linguistic Typology* 11(1):273–284.
25. Prince A, Smolensky P (2004) *Optimality Theory*: *Constraint Interaction in Generative Grammar* (Blackwell, New York).
26. Chomsky N (1975) *The Logical Structure of Linguistic Theory* (Plenum, New York).
27. Yang CD (2004) Universal grammar, statistics or both? *Trends Cogn Sci* 8(10):451–456.
28. Lidz J, Musolino J (2002) Children's command of quantification. *Cognition* 84(2): 113–154.
29. Greenberg J (1963) *Universals of Language*, ed Greenberg J (MIT Press, Cambridge, MA), pp 73–113.
30. Baker M (1985) The mirror principle and morphosyntactic explanation. *Linguist Inq* 16(3):373–415.
31. Rijkhoff J (1990) Explaining word order in the Noun Phrase. *Linguistics* 28(1):5–42.
32. Rice K (2000) *Morpheme Order and Semantic Scope*: *Word Formation in the Athapaskan Verb* (Cambridge Univ Press, Cambridge, UK).
33. Cinque G (2005) Deriving Greenberg's Universal 20 and its exceptions. *Linguist Inq* 36(3):315–332.
34. Koopman HJ, Szabolcsi A (2000) *Verbal Complexes* (MIT Press, Cambridge, MA).
35. Jenks P (2011) The hidden structure of Thai noun phrases. PhD thesis (Harvard Univ, Cambridge, MA).
36. Culbertson J, Smolensky P, Legendre G (2012) Learning biases predict a word order universal. *Cognition* 122(3):306–329.
37. Partee BH (1987) *Studies in Discourse Representation Theory and the Theory of Generalized Quantifiers*, eds Groenendijk J, de Jongh D, Stokhof M (Foris, Dordrecht), pp 115–143.
38. Elbourne P (2008) Demonstratives as individual concepts. *Linguist Philos* 31(4):409–466.
39. Adger D (2003) *Core Syntax* (Oxford Univ Press, Oxford).
40. Alexiadou A, Haegeman L, Stavrou M (2007) *Noun Phrase in the Generative Perspective* (Mouton de Gruyter, Berlin).
41. Rijkhoff J (2004) *The Noun Phrase* (Oxford Univ Press, Oxford, UK).
42. Aikhenvald AY (2000) *Classifiers*: *A Typology of Noun Categorization Devices* (Oxford Univ Press, Oxford, UK).
43. Tenenbaum JB, Kemp C, Griffiths TL, Goodman ND (2011) How to grow a mind: Statistics, structure, and abstraction. *Science* 331(6022):1279–1285.
44. Adger D (2013) *A Syntax of Substance* (MIT Press, Cambridge, MA).
45. Kayne R (1994) *The Antisymmetry of Syntax* (MIT Press, Cambridge, MA).
46. Culbertson J (2012) Typological universals as reflections of biased learning: Evidence from artificial language learning. *Language Linguistics Compass* 6(5):310–329.
47. Moreton E, Pater J (2012) Structure and substance in artificial-phonology learning, part I: Structure. *Language Linguistics Compass* 6(11):686–701.
48. Gerken L (2004) Nine-month-olds extract structural principles required for natural language. *Cognition* 93(3):B89–B96.
49. Wilson C (2006) Learning phonology with substantive bias: An experimental and computational study of velar palatalization. *Cogn Sci* 30(5):945–982.
50. Takahashi E (2009) Beyond statistical learning in the acquisition of phrase structure. PhD dissertation (Univ of Maryland, College Park, MD).
51. Smith K, Wonnacott E (2010) Eliminating unpredictable variation through iterated learning. *Cognition* 116(3):444–449.
52. Davies M (2011) N-grams data from the Corpus of Contemporary American English (COCA). Available at www.ngrams.info. Accessed January 6, 2014.
53. Hadfield JD (2010) MCMC methods for multi-response generalized linear mixed models: The MCMCglmm R package. *J Stat Softw* 33(2):1–22.
54. Gelman A, Jakulin A, Grazia Pittau M, Su YS (2008) A weakly informative default prior distribution for logistic and other regression models. *The Annals of Applied Statistics* 2(4):1360–1383.
55. Hetzron R (1978) *Language Universals*, ed Seiler H (Narr, Tübingen, Germany), pp 165–184.
56. Kemp C, Perfors A, Tenenbaum JB (2007) Learning overhypotheses with hierarchical Bayesian models. *Dev Sci* 10(3):307–321.
57. Richtsmeier PT (2011) Word-types, not word-tokens, facilitate extraction of phonotactic sequences by adults. *Lab Phonol* 2(1):157–183.
58. Tily H, Frank M, Jaeger T (2011) The learnability of constructed languages reflects typological patterns. *Proceedings of the 33rd Annual Conference of the Cognitive Science Society*, eds Carlson L, Hoelscher C, Shipley TF (Cognitive Sci Soc, Austin, TX), pp 1364–1369.
59. Gass SM, Selinker L (1992) *Language Transfer in Language Learning* (John Benjamins Publishing, Amsterdam).
60. Schwartz B, Sprouse R (1996) L2 cognitive states and the Full Transfer/Full Access model. *Second Lang Res* 12(1):40–72.
61. Odlin T (2003) *The Handbook of Second Language Acquisition*, ed Doughty CJ (Blackwell, Oxford, UK), pp 436–486.