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A simulation study on word order bias

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The majority of the extant languages have one of three dominant basic word orders: SVO, SOV or VSO. Various hypotheses have been proposed to explain this word order bias, including the existence of a universal grammar, the learnability imposed by cognitive constraints, the descent of modern languages from an ancestral protolanguage, and the constraints from functional principles. We run simulations using a multi-agent computational model to study this bias. Following a local order approach, the model simulates individual language processing mechanisms in production and comprehension. The simulation results demonstrate that the semantic structures that a language encodes can constrain the global syntax, and that local syntax can help trigger bias towards the global order SOV/SVO (or VOS/OVS).

Key words: word order bias, computational simulation, local order, global order, semantics

1. Introduction

Declarative sentences involving the basic constituents, verb (V), subject (S) and object (O), have one of the six logically possible word orders: SVO, SOV, OSV, VSO, VOS, and OVS. Greenberg (1963), based on 30 languages, observed that only three of these orders (SOV, SVO and VSO) are common among the world's extant languages. This word order bias has been confirmed by more recent, larger language samples. Tomlin (1986), based on 1,063 languages, has calculated the following distribution: SOV (e.g., Japanese, 45.8%) > SVO (e.g., Chinese, 41.5%) > VSO (e.g., Tagalog, 11.0%) > VOS (e.g., Malagasy, 1.5%) > OVS (e.g., Coos, 0.3%) > OSV (e.g., Mamvu, 0.0%). A similar distribution, based on the raw data from 1,228 languages, is shown in The World Atlas of Language Structures (WALS) (Dryer 2008a): SOV (40.5%) > SVO (35.5%) > No dominant order (13.9%) > VSO (7%) > VOS (2.1%) > OVS (0.7%) > OSV (0.3%). The distribution value of SVO

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may become bigger than that of SOV if the distribution is calculated based on language families.

A number of hypotheses have been put forward to explain this bias. Some ascribe it to genetic, cognitive, or historical reasons. For instance, Briscoe (2000) has argued that the acquisition of word order is affected by a built-in universal grammar. Lupyan and Christiansen (2002) have emphasized that non-language-specific cognitive constraints can help acquire the word order. Gell-Mann and Ruhlen (2005) have concluded that if there was a language from which all modern languages derived, then that language had the word order SOV.

Other hypotheses are functionally grounded. They claim that syntactic alternations serve to signal specific semantic or pragmatic functions that reflect the language specific instantiation of general constraints on information processing in the human mind (Hawkins, 1994; Tomlin, 1986). For instance, Tomlin (1986) has put forward three functional principles: a) *theme-first principle*, "old" information that is shared or thematic should precede "new" information; b) *VO-binding*, a transitive verb and its object form a more cohesive syntactic and semantic whole than do a transitive verb and its subject; and c) *animate-first*, the most animate entity tends to occur first in sentences. Apart from these principles at the global order level, there are other functional paraphrases that concern the local orders among constituents. For instance, Steele (1978) has detected several general patterns of word order variation in languages, many of which involve local order changes, e.g., the reordering from SO to OS and vice versa, which is common among V-initial (VSO or VOS) and V-final (SOV or OSV) languages. Dryer (1997) has proposed a typology involving the local order pairs VO/OV and SV/VS. This typology allows an easier classification of word order, especially for languages having flexible word orders, and takes account of the position of intransitive S, which has been largely ignored by previous studies. Moreover, Tomlin's principles also imply some local order relations, e.g., by the theme-first and animate-first principles, S should tend to precede O; by the VO-binding principle, S should tend to appear either sentence initial or sentence final.

These functional explanations describe the nature and extent of grammatical variation among the languages of the world, but they do not address in detail how these principles take effect in discourse production and comprehension or how word order evolves. In this paper, we adopt a computational model that simulates the evolution of individual language processing behaviors to study word order bias. Syntax is modeled as a set of local, binary rules (e.g., S before V) that specify the relative orders of words belonging to distinct, emergent syntactic categories. A simulation consists of a population of individuals, each with its own language. Individuals can express both intransitive predicates involving one argument and transitive predicates involving two arguments. Intransitive sentences are ordered by local, binary rules comprising subject and verb categories (e.g., SV); transitive sentences are ordered by local, binary rules comprising subject, verb, and object categories (e.g., SV and VO). The competition of these local orders results in the evolution of global orders (e.g., SVO). By evaluating the relative frequencies of transitions among different sets of local orders, we investigate whether the lower-level constraints that take effect in production and comprehension can trigger functional principles that operate at the sentence level, and whether the bias in global orders can be explained by the semantic structures cognized by language users and self-organization of local orders among constituents. Instead of replicating the word order distribution in the extant natural languages, we aim to provide some insights on the general characteristics of this distribution, such as what factors lead to the bias towards certain word orders and how such bias emerges through language communications.

The paper is organized as follows: Section 2 reviews the model; Section 3 explains two simulations based on this model that we have conducted to study word order bias; Section 4 discusses the simulation results; and finally, Section 5 presents our conclusions.

2. The computational model

The computational model that we use was originally designed to study the phylogenetic emergence of language (Gong et al. 2005; Gong, 2008). It shows that a population of interacting, language-capable agents can acquire a common set of lexical items and word orders as a result of general learning mechanisms, such as ordering and detecting recurrent patterns. In this section, we present a conceptual description of this model (see Figure 1). In a nutshell, through iterated communications, individuals can gradually detect the recurrent patterns in exchanged utterances and acquire them as lexical items. By considering the semantic information and ordering relations of lexical items in exchanged utterances, individuals can categorize lexical rules into syntactic categories. Then, based on local, binary syntactic rules between syntactic categories, individuals can regulate the global word order of multiple lexical items in exchanged utterances. The empirical bases of the mechanisms adopted in this model can be found in Gong (2007, in press).

Language in this model is treated as a set of bi-directional mappings between meanings and utterances (*M-U mappings*). Each utterance comprises a string of *syllables*; each integrated meaning comprises a *predicate* and its *arguments*. The predicates represent the actions that individuals can conceptualize (e.g., "run" or "chase"); their arguments represent the types of entity by which and on which those actions can be performed (e.g., "fox" or "tiger"). The predicates are of two types:

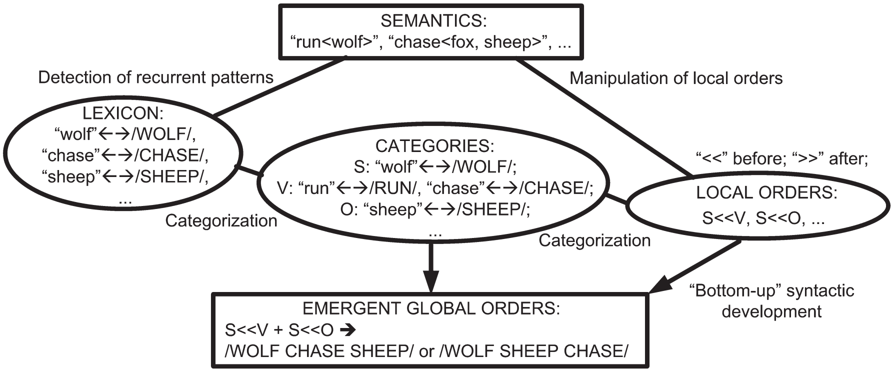
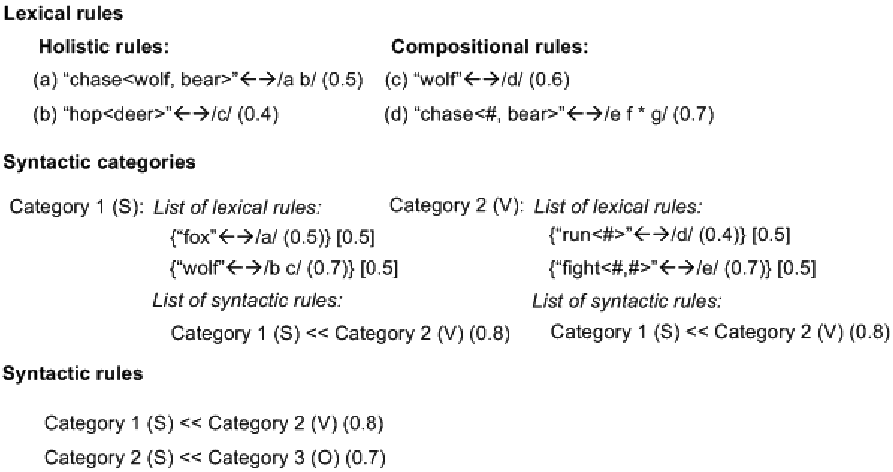


Figure 1. The conceptual framework of the computational model. The SEMANTICS rectangle represents the predefined semantic space, and the ovals represent the three aspects of linguistic knowledge acquired by individuals using different domain-general abilities, such as pattern extraction, sequential learning, and categorization. The EMERGENT GLOBAL ORDERS rectangle represents the emergent syntactic patterns triggered by these domain-general abilities and the correlated linguistic knowledge (indicated by arrows). The items within "" are semantic items, syllables within // are utterances.

intransitive predicates take a single argument, e.g., "run<tiger>" ("a tiger is running"); *transitive predicates* take two arguments, e.g., "chase<tiger, fox>" ("a tiger is chasing a fox"). For transitive predicates, the order of the arguments within "< >" distinguishes their thematic relations: the first argument, "tiger", denotes the *agent* (the entity instigating the action) of the predicate, "chase"; the second argument, "fox", denotes the *patient* (the entity undergoing the action) of the predicate.

Individuals' linguistic knowledge is represented by different types of linguistic rules (see Figure 2). *A lexical rule* specifies the mapping between a particular meaning and a particular utterance. Lexical rules that map whole integrated meanings are termed *holistic rules* (e.g., rules (a) and (b) in Figure 2); those that map smaller semantic structures are termed *compositional rules* (e.g., rules (c) and (d) in Figure 2, "#" indicates an unspecified argument). *A syntactic category* specifies a list of lexical items, each having the same semantic relation (agent, patient, or predicate), that follow the same local order with respect to lexical items belonging to other syntactic categories. Those local orders appear as a list of syntactic rules in this category. *A syntactic rule* specifies a relative local order (e.g., before or after, but not necessarily immediately before or after) of particular pairs of utterances (e.g., Category 1 (S) << Category 2 (V) in Figure 2, "<<" means "before", this rule can be simplified as "SV"). Both lexical and syntactic rules have *strengths*, which denote the likelihood (within the interval [0.0, 1.0]) that these rules are successfully applied. In Figure 2, the rule strengths are denoted by numbers within parentheses. Each lexical member of a syntactic category has an *association weight*,



Lexical rules

Holistic rules:
(a) "chase<wolf, bear>"←→/a b/ (0.5)
(b) "hop<deer>"←→/c/ (0.4)

Compositional rules:
(c) "wolf"←→/d/ (0.6)
(d) "chase<#, bear>"←→/e f * g/ (0.7)

Syntactic categories

Category 1 (S): *List of lexical rules:*
{"fox"←→/a/ (0.5)} [0.5]
{"wolf"←→/b c/ (0.7)} [0.5]
List of syntactic rules:
Category 1 (S) << Category 2 (V) (0.8)

Category 2 (V): *List of lexical rules:*
{"run<#>"←→/d/ (0.4)} [0.5]
{"fight<#,#>"←→/e/ (0.7)} [0.5]
List of syntactic rules:
Category 1 (S) << Category 2 (V) (0.8)

Syntactic rules

Category 1 (S) << Category 2 (V) (0.8)
Category 2 (S) << Category 3 (O) (0.7)

Figure 2. The examples of lexical rules, syntactic categories and syntactic rules. "#" represents unspecified semantic item, and "*" unspecified syllables. Lexical rules are itemized by letters. "Category 1", "Category 2" and "Category 3" are syntactic categories; "S", "V", and "O" denote their respective syntactic roles. Numbers enclosed by ( ) denote rule strengths, and those by [ ] denote association weights. "<<" indicates the relative local order "before".

the value of its membership in that category (in Figure 2, the association weight is shown by numbers within square brackets). For convenience, we label syntactic categories with the corresponding syntactic roles in simple declarative sentences in English: S, V, and O (e.g., Category 1 (S) in Figure 2 is a syntactic category having the syntactic role of S). Note that, in our model, both intransitive and transitive predicates may be associated with the same V category, and that the agents of both types of predicate may be associated with the same S category. Thus, we simulate a nominative-accusative language, not an ergative-absolutive language (Song, 2001) — we discuss this issue further in Section 4.

Individuals acquire linguistic knowledge by applying general learning mechanisms during communications. This acquisition process comprises the following three stages:

1. *Acquisition of lexical rules* (see Figure 3). Lexical rules are acquired by detecting recurrent patterns in M-U mappings. Each individual has a buffer that stores *previous experience* (a fixed number of M-U mappings obtained from previous communications in which this individual was the listener). New mappings are compared with those in the buffer before they too are inserted into the buffer. A recurrent pattern is one or more meanings and one or more syllables that appear recurrently in at least two M-U mappings. For example, by comparing the M-U mappings "hop<fox>"↔/a b/ and "run<fox>"↔/a c

Available M-U mappings	**Newly acquired lexical rules**
(1) "hop<***fox***>"←→/***a*** b/	"fox"←→/a/ (0.5)
(2) "run<***fox***>"←→/***a*** c d/	

Figure 3. The example of acquisition of lexical rules from available M-U mappings.

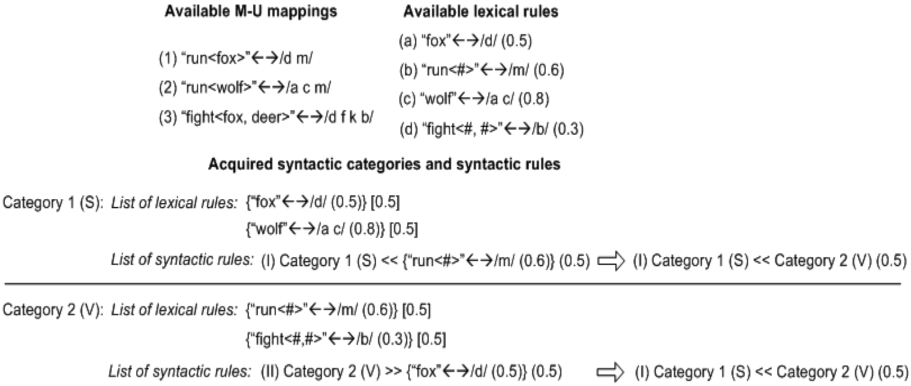
d/, shown in Figure 3, an individual can detect the recurrent pattern "fox" and /a/, and map it as the lexical rule "fox"↔/a/ with initial strength 0.5.

2. *Acquisition of syntactic categories* (see Figure 4). After some lexical rules have been acquired, individuals can develop syntactic categories based on the semantic roles of lexical rules and the local orders among their utterances in M-U mappings. For example, evident in the M-U mappings (2) and (3) in Figure 4, the syllables /d/ of rule (a) and /a c/ of rule (c) precede /m/ of rule (b). Since the items "wolf" and "fox" both represent agents, rules (a) and (c) are associated, with initial association weights 0.5, into a new S category (Category 1). Similarly, checking M-U mappings (1) and (3) in Figure 4, the syllables /m/ of rule (b) and /b/ of rule (d) follow /d/ of rule (a), which leads to a V category (Category 2) that associates rules (b) and (d).
3. *Acquisition of syntactic rules* (see Figure 4). During the acquisition of syntactic categories, the detected local orders are simultaneously acquired as syntactic rules. For example, during the acquisition of Category 1 (S), the detected local order "before" between rule (b) and rules (a) and (c) is acquired as syntactic rule (I) with initial strength 0.5. Similarly, syntactic rule (II) is acquired during the acquisition of Category 2 (V). Now, since Category 1 and Category 2 respectively associate rules (a) and (c) and rules (b) and (d), those two syntactic rules can be updated as "Category 1 (S) << Category 2 (V)" in both categories. This new rule indicates that the syllables of lexical rules in the S category should precede those of lexical rules in the V category.

These item-based learning mechanisms for forming categories, also traced in empirical studies (e.g., Mellow, 2008), are similar to what is described in *the "Verb-island" hypothesis* (Tomasello, 2003). Based on these mechanisms, individuals can gradually build up categories to regulate available lexical items and to associate novel ones that encode constituents having the same semantic roles and commonly used in sentences.

Individuals use local orders to regulate the syllables of compositional rules to form sentences. For example, referring to Figure 5, to encode "fight<fox, sheep>", lexical rules (a), (d), (e) and syntactic rules (I) and (II) are activated. The local orders in these syntactic rules (SV and SO) lead to two global word orders (SVO and SOV), and the created utterance can be either /a e f/ or /a f e/.

Communication in this model involves two randomly chosen individuals: a speaker (referred to as 'she') and a listener (referred to as 'he'). The speaker first



Available M-U mappings

(1) "run<fox>"←→/d m/
(2) "run<wolf>"←→/a c m/
(3) "fight<fox, deer>"←→/d f k b/

Available lexical rules

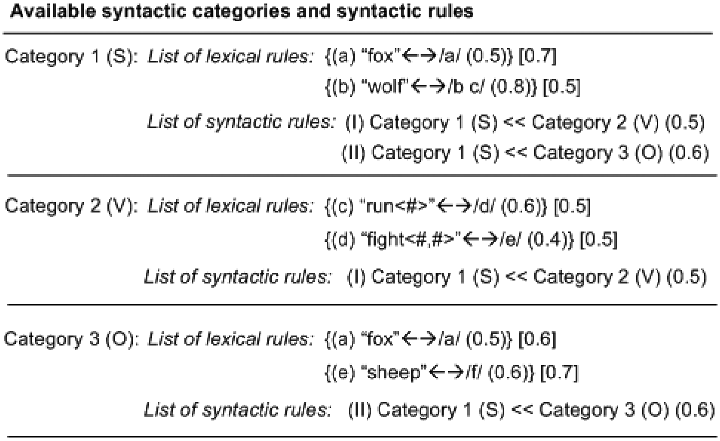
(a) "fox"←→/d/ (0.5)
(b) "run<#>"←→/m/ (0.6)
(c) "wolf"←→/a c/ (0.8)
(d) "fight<#, #>"←→/b/ (0.3)

Acquired syntactic categories and syntactic rules

Category 1 (S): *List of lexical rules:* {"fox"←→/d/ (0.5)} [0.5]
{"wolf"←→/a c/ (0.8)} [0.5]
List of syntactic rules: (I) Category 1 (S) << {"run<#>"←→/m/ (0.6)} (0.5) ⇨ (I) Category 1 (S) << Category 2 (V) (0.5)

Category 2 (V): *List of lexical rules:* {"run<#>"←→/m/ (0.6)} [0.5]
{"fight<#,#>"←→/b/ (0.3)} [0.5]
List of syntactic rules: (II) Category 2 (V) >> {"fox"←→/d/ (0.5)} (0.5) ⇨ (I) Category 1 (S) << Category 2 (V) (0.5)

Figure 4. The examples of acquisition of syntactic categories and syntactic rules from M-U mappings and lexical rules. M-U mappings are itemized by numbers, lexical rules by letters.



Available syntactic categories and syntactic rules

Category 1 (S): *List of lexical rules:* {(a) "fox"←→/a/ (0.5)} [0.7]
{(b) "wolf"←→/b c/ (0.8)} [0.5]
List of syntactic rules: (I) Category 1 (S) << Category 2 (V) (0.5)
(II) Category 1 (S) << Category 3 (O) (0.6)

Category 2 (V): *List of lexical rules:* {(c) "run<#>"←→/d/ (0.6)} [0.5]
{(d) "fight<#,#>"←→/e/ (0.4)} [0.5]
List of syntactic rules: (I) Category 1 (S) << Category 2 (V) (0.5)

Category 3 (O): *List of lexical rules:* {(a) "fox"←→/a/ (0.5)} [0.6]
{(e) "sheep"←→/f/ (0.6)} [0.7]
List of syntactic rules: (II) Category 1 (S) << Category 3 (O) (0.6)

Figure 5. An example of production based on lexical rules, syntactic rules, and syntactic categories. Numbers enclosed by ( ) denote rule strengths, and those by [ ] denote association weights. "<<" indicates the relative local order "before". Note that the lexical rule (a) is associated into both Category 1 (S) and Category 3 (O) with different association weights.

chooses an integrated meaning to express. She then activates the lexical rules that can encode some or all semantic constituents in the intended meaning, as well as the syntactic rules and related categories by which the lexical rules can be combined and ordered to form a sentence. The activated linguistic rules form candidate sets for production, each of which allows her to produce an utterance to encode the intended meaning. Then, following Equation 1 (in which "Avg" means taking average, "aso" taking association weights, and "str" taking rule strengths), the speaker calculates the combined strength ($CS_{production}$) of each set. In production, the combined strength of a set of linguistic rules is the sum of two parts. The first part is the contribution of lexical information, which is determined by the average strength of the lexical rules in the set. The second part is the contribution of syntactic information, which is the average product of two elements: the first element is the strengths of the syntactic rules that are used to regulate the syllables of the lexical rules in this set, and the second element is the association weights of those lexical rules to the categories in this set. The speaker identifies the set of *winning rules* with the greatest combined strength, builds up the sentence accordingly, and transmits the sentence to the listener. If she is unable to construct a complete sentence to encode the intended meaning, she may occasionally (based on a random creation rate) create a holistic rule to express the entire integrated meaning.

$$CS_{production} = Avg(str(LexRule(s))) + Avg(aso(Cats) \times str(SynRule(s))) \tag{1}$$

For example, referring to Figure 5, the lexical rules (a), (d), and (e), the syntactic rules (I) and (II), and the three syntactic categories form a candidate set to encode "fight<fox, sheep>". The combined strength of this set is: 0.5 [the contribution of the lexical information: (0.5+0.4+0.6)/3] + 0.36 [the contribution of the syntactic information: (0.6×(0.7+0.7)/2+0.5×(0.7+0.5)/2)/2] = 0.86.

The listener receives the sentence from the speaker and a cue from the environment. This cue consists of an integrated meaning and an associated strength. The cue can assist the listener's comprehension, but is unreliable: the probability that the cue is identical to the speaker's intended meaning is represented by the *Reliability of Cues* (*RC*). For instance, if *RC* is 0.4, there is a 40% chance that the listener's cue matches the speaker's intended meaning; otherwise, a randomly selected meaning that differs from the speaker's intended meaning becomes the cue. All cues have the same strength, and are treated equally by the listener.

After receiving the speaker's sentence and the cue, the listener activates the lexical rules whose syllables fully or partially match the heard sentence, the categories that associate those lexical rules, and the syntactic rules of these categories that are consistent with the heard sentence. These activated linguistic rules can form candidate sets, each providing an integrated meaning for comprehension. If the meaning in the cue exactly matches the one provided by a particular candidate set, the cue is combined with that set of linguistic rules. Also, if some linguistic rules fail to provide an integrated meaning, but the meaning in the cue matches those meaning constituent(s) that are specified by these rules, the cue is combined with those linguistic rules to form a candidate set and its meaning becomes the meaning of this set. Moreover, if the listener has no linguistic rules, or the available ones fail to form an integrated meaning and the meaning of the cue does not match any constituent specified by those rules, the cue itself forms a candidate set and its meaning becomes the meaning of this set. Then, following Equation 2, the listener calculates the combined strength of each candidate set. The combined strength of a set without a cue is calculated in the same way as that in production. For a set that contains a cue, the contribution of the nonlinguistic information, in the form of the cue strength, is added to the combined strength. For a set having the cue only, the cue strength becomes the combined strength. After that, the listener selects the set of winning rules that allow him to comprehend an integrated meaning with the highest combined strength.

$$CS_{comprehension} = Avg(str(LexRule(s))) + Avg(aso(Cats) \times str(SynRule(s))) + str(Cue) \qquad (2)$$

Throughout the utterance exchange, there is no direct check whether the speaker's intended meaning matches the listener's comprehended one. Neither individual has access to the other's linguistic knowledge. If the combined strength of the listener's winning rules exceeds a *Confidence Threshold* (*CT*), the listener adds the perceived M-U mapping to his buffer, and transmits a positive feedback to the speaker. Then, both individuals reward their winning rules by increasing their rule strengths and association weights, and penalize other competing ones by decreasing their rule strengths and association weights. Otherwise, the listener sends a negative feedback, and both agents penalize only their winning rules.

The rule competition described above simulates a multi-level selection (Steels et al., 2007) among lexical, syntactic, and non-linguistic information. For activated rules having initial strengths and association weights, the contribution of linguistic (lexical and syntactic) information is 0.75 (0.5+0.5×0.5). Therefore, the cue strength and *CT* are both set to 0.75 in order to treat equally linguistic and non-linguistic information.

After a number of communications (scaled to the number of agents), all individuals gradually "forget" their rules by deducting a fixed amount from their strengths and association weights. Rules having negative strengths or association weights to some syntactic categories are removed from the rule list as well as the relevant syntactic categories. Syntactic categories that have no lexical members are also removed from the rule list, together with their syntactic members.

This model simulates the development of both lexical and syntactic knowledge. In the simulations of this paper, we define a semantic space that contains 12 items (4 agents, 4 intransitive predicates, and 4 transitive predicates; each of the 4 agents may also be the patient of each transitive predicate). These items can form 64 (16 intransitive, 48 transitive) integrated meanings.[1] In order to study word order bias, we initialize a population of individuals that share a compositional language. Each of the 12 meaning items is encoded by a single compositional rule (with strength 1.0, its utterance is randomly selected). The 4 agents are all associated with a single S category (with association weight 1.0); likewise, the patients and predicates are associated respectively with an O category and a V category.

Each run of the simulation is initialized with a particular set of either two or three local syntactic rules (with strength 1.0).

3. Simulations of word order bias

3.1 Terminology to classify local orders and order changes

There are six possible global word orders of a declarative sentence that comprises a subject, an object, and a verb. In the model that we adopt, the global word order is determined by syntactic rules that record the local orders of constituents. Each of the six global word orders can be formed by two or three local orders. We define several terms to characterize local orders of different types:

1. *Precise syntax*: two or three local orders that generate a single global order, e.g., SV and VO form a precise syntax that generates the global order SVO;
2. *Imprecise syntax*: two local orders that generate two competing global orders, e.g., SV and SO form an imprecise syntax that generates the competing global orders SVO and SOV;
3. *X-dominant syntax*: two local orders that both operate on a particular constituent, *X*, e.g., SV and SO form an S-dominant syntax, both operating on S. Some *X*-dominant syntaxes are precise, e.g., SV and VO; others are imprecise, e.g., SV and SO;
4. *Complete syntax*: three local orders that generate a single global order, e.g., SV, VO and SO form a complete syntax that generates the global order SVO. All complete syntaxes are precise.

Table 1. The 19 local order states.

State	Dominant local orders	Dominant global orders	Syntax type
1	none	none	none
2	SV andSO	SVO or SOV	S-dominant syntax
3	SV and OS	OSV	
4	VS and SO	VSO	
5	VS and OS	VOS or OVS	
6	SV and VO	SVO	V-dominant syntax
7	SV and OV	SOV or OSV	
8	VS and VO	VSO or VOS	
9	VS and OV	OVS	
10	SO and VO	SVO or VSO	O-dominant syntax
11	SO and OV	SOV	
12	OS and VO	VOS	
13	OS and OV	OSV or OVS	
14	SV, VO and SO	SVO	Complete syntax
15	SV, OV and SO	SOV	
16	SV, OV and OS	OSV	
17	VS, VO and SO	VSO	
18	VS, VO and OS	VOS	
19	VS, OV and OS	OVS	

The sets of local orders that can form one or two global orders[2] are classified into 18 states (States 2–19 in Table 1; State 1 represents the situation in which the communal language has no dominant word order). These 18 states can be separated into 4 types: a) S-dominant syntax (States 2–5), b) V-dominant syntax (States 6–9), c) O-dominant syntax (States 10–13), and d) complete syntax (States 14–19).

Local orders are assumed to evolve as a result of three operations:

1. *The addition of a local order*, e.g., the addition of VO to SV leads to the emergence of SVO; the addition of VO to the set of SV and SO leads to the disappearance of SOV, SVO being the sole remaining global order;
2. *The loss of a local order*, e.g., the loss of VO from the set of SV and VO leads to the disappearance of SVO; the loss of VO from the set of SV, VO and SO leads to SOV competing with the previously dominant SVO;
3. *The mutation of a local order*,[3] e.g., the mutation of VO to OV, in combination with the local order SV, leads to SVO being replaced by competition between SOV and OSV; the mutation of SV to VS, in combination with the local syntax VO and SO, leads to SVO being replaced by VSO;

For example, the change from State 10 (SO and VO) to State 2 (SV and SO) can be caused by the addition of SV and the loss of VO.

We analyse word order bias in two ways:

1. The *stability* of each word order state, which is defined as the frequency of transition to *any other* word order state;
2. The *frequency of transition* between each pair of word order states;

We expect the simulation to converge to word order states that are stable and for which the frequency of transition to them from other word order states are high.

We design two distinct sets of simulations to examine the effect of the structure of the semantic space on word order bias. Simulation 1 adopts a semantic space containing only transitive predicates; Simulation 2 adopts a semantic space containing both transitive and intransitive predicates. In Simulation 2, the probabilities that the speaker chooses to convey a transitive or intransitive sentence are made equal by adjusting the token frequencies of integrated meanings of each type. In each set, we run 18 distinct simulations 20 times each. In each simulation, the word order state of the initial compositional language is set to one of the 18 states (States 2–19) in Table 1. The population consists of 10 individuals who perform 6,000 communications (600 rounds of communications) between a randomly selected speaker and listener. Each communication consists of 20 utterance exchanges. In an utterance exchange, the reliability of cues is set to 0.6, the random creation rate is 0.25, the amount by which the winning rules are rewarded upon success or penalized upon failure is 0.1, and the amount in rule forgetting after a round of communication is 0.01. Each individual's buffer size is 40.

After a round of communications, we calculate the *understanding rate* (*UR*), which is defined as the average percentage of integrated meanings that are understandable to each pair of individuals based on their linguistic knowledge only. Some local order changes that give rise to a change in the global order can affect the understanding rate. We also measure the *global order understanding rate*, UR_{GloOrd} (the average percentage of transitive meanings accurately comprehended using one of the six global orders) and the *local order understanding rate*, UR_{LocOrd} (the average percentage of transitive or intransitive meanings accurately comprehended using one of six local orders).

We determine the current word order state of the communal language based on the score of each of the 18 word order states. The score of a particular word order state i ($2 \le i \le 19$) is measured following the formula in Equation 3, where the 3 components $Value_{SV/VS}$, $Value_{SO/OS}$, and $Value_{VO/OV}$ evaluate the state of the local orders between S and V, S and O, and V and O, respectively.

$$\begin{aligned} & Score_i = \sqrt[3]{Value_{SV/VS} \times Value_{SO/OS} \times Value_{VO/OV}} \\ & Value_{XY/YX} \begin{cases} UR_{LocOrd}(XY/YX) & \text{if } XY/YX \text{ is in order state } i; \\ 1-\max(UR_{LorOrd}(XY), UR_{LocOrd}(YX)) & \text{otherwise;} \end{cases} \end{aligned} \tag{3}$$

$$Score_2 = \sqrt[3]{UR_{LocOrd}(SV) \times UR_{LocOrd}(SO) \times (1-\max(UR_{LocOrd}(VO), UR_{LocOrd}(OV)} \tag{4}$$

$$Score_{10} = \sqrt[3]{(1-\max(UR_{LocOrd}(SV), UR_{LocOrd}(VS))) \times UR_{LocOrd}(SO) \times UR_{LocOrd}(VO)} \tag{5}$$

The calculation proceeds as follows. At a given stage, we first calculate UR_{LocOrd} of all 6 local orders. Then, if SV/VS is included in a word order state, $Value_{SV/VS}$ of that state is calculated as UR_{LocOrd}(SV/VS); otherwise, if a word order state does not contain SV or VS, its $Value_{SV/VS}$ is calculated as 1-max(UR_{LocOrd}(SV), UR_{LocOrd}(VS)). After that, the score of a word order state is calculated as the cube root of those three components. For example, for State 2 (SV and SO), the final score is calculated as in Equation 4; for State 10 (SO and VO), it is calculated as in Equation 5. The communal language is assumed to stay in the state whose score is the highest and exceeds 0.5; otherwise, it is assumed to stay in State 1, i.e., there is no shared dominant word order. Figure 6 exemplifies this method by tracing the local order states (the above figure) in which the communal language stays and their scores (the bottom figure) in one run from Simulation 2. As shown in Figure 6, the initial State 2 (SV and SO) changes to State 6 (SV and VO) and stays there throughout the simulation.

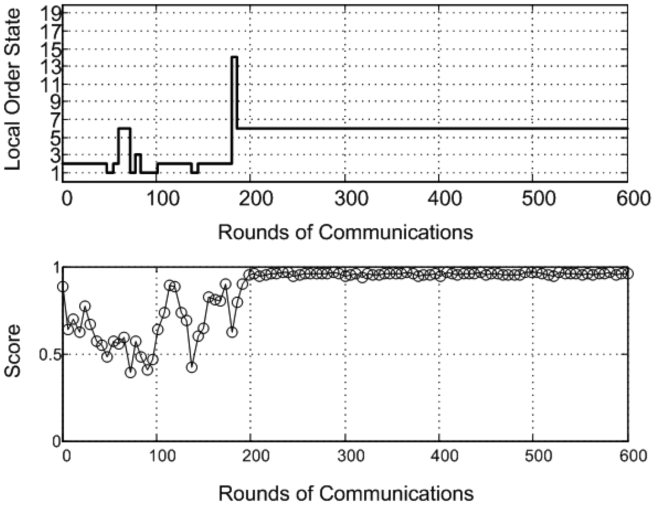


Figure 6. The results of one run for initial State 2 in Simulation 2. The upper panel records the local order states of the communal language and the lower panel records the scores of these local order states.

Throughout the simulation, we calculate both the durations of stability of each word order state and the frequencies of the transitions among them, which are recorded based on the state of the communal language at different sampling points. Only the transitions that involve at most two intermediate states are considered in this study.[4] After analyzing all simulations from the 18 sets, we construct a *stability matrix*, each element in the leading diagonal of which traces the frequency with which a particular local order state remains unchanged, and a *transition matrix*, each element of which traces the frequency with which a particular word order state changes to another.

3.2 Simulation 1: transitive sentences only

Figure 7 visualizes the stability and transition matrices obtained in Simulation 1. In the above table, each value indicates the frequency with which one of the 18 states (State 2–19) remains unchanged. In the bottom panel, the X- and Y-axes list these 18 states; those along the X-axis indicate the state of the initial communal language, and those along the Y-axis indicate the final state after the completion of the simulation. The different colors in crossing points (except the ones in the leading diagonal) indicate the frequencies with which the final states differ from the initial ones.

As shown in the stability matrix, the S-, V- and O-dominant precise syntaxes, i.e., States 3 (SV and OS), 4 (VS and SO), 6 (SV and VO), 9 (VS and OV), 11 (SO

State	Loca orders	Global orders	Stability (%)
2	SV + SO	SVO or SOV	47.63
3	SV + OS	OSV	96.7
4	VS + SO	VSO	97.36
5	VS + OS	VOS or OVS	45.3
6	SV + VO	SVO	96.54
7	SV + OV	SOV or OSV	18.29
8	VS + VO	VSO or VOS	14.75
9	VS + OV	OVS	96.03
10	SO + VO	SVO or VSO	45.08
11	SO + OV	SOV	96.82
12	OS + VO	VOS	97.17
13	OS + OV	OSV or OVS	45.56
14	SV + VO + SO	SVO	3.02
15	SV + OV + SO	SOV	0
16	SV + OV + OS	OSV	0
17	VS + VO + SO	VSO	0
18	VS + VO + OS	VOS	0
19	VS + OV + OS	OVS	3.82

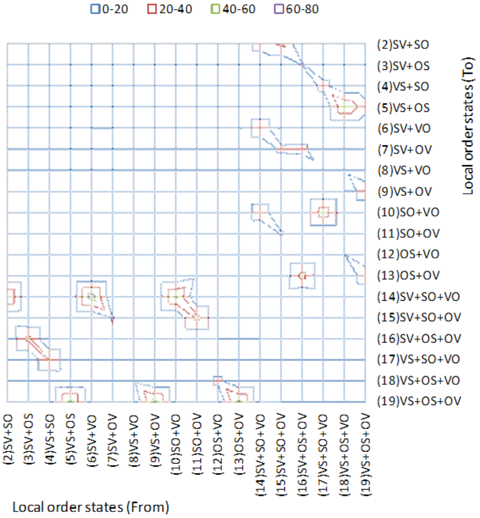


Figure 7. The stability (the above table) and transition (the bottom panel) matrices in Simulation 1.

and OV) and 12 (OS and VO), are all stable (their stabilities are over 90%) — their global orders are OSV, VSO, SVO, OVS, SOV and VOS, respectively. V-dominant imprecise syntaxes, i.e., States 7 (SV and OV) and 8 (VS and VO), for which the local order between S and O is ambiguous are unstable (their stabilities are below 20%). All complete syntaxes are unstable (their stabilities are below 5%).

As illustrated in the transition matrix, imprecise syntaxes tend to become complete by developing a local order to resolve the ambiguous local order that was unspecified in the original syntax. For instance, State 2 (SV and SO) may change to State 14 (SV, VO and SO) by adding VO to resolve the ambiguous order between V and O. Meanwhile, complete syntaxes tend to lose one of their local orders. For instance, State 14 (SV, VO and SO) can change to State 2 (SV and SO) by losing VO, to State 6 (SV and VO) by losing SO, or to State 10 (SO and VO) by losing SV.

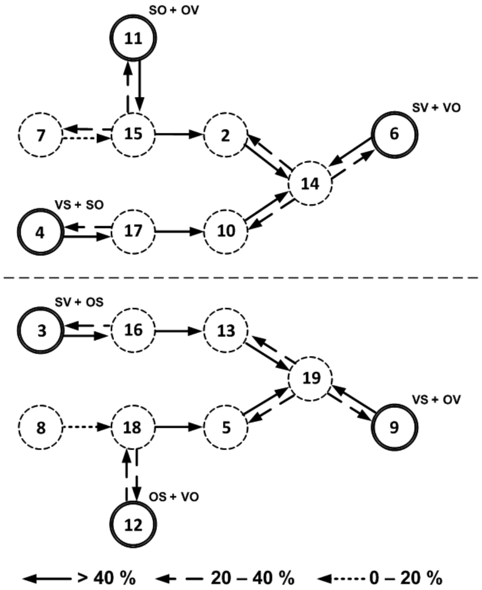
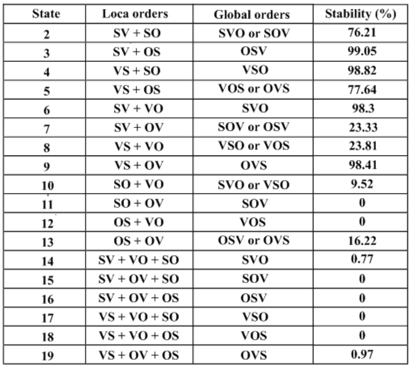


Figure 8. The evolution of local order states in Simulation 1. Solid circles indicate the stable states, and dotted circles indicate the unstable or transient states. Different types of arrows correspond to different frequencies of transitions among states. The dashed line divides the network into two isolated parts.

Based on these two matrices, we can draw a network of local order states to illustrate their evolution, as shown in Figure 8. This figure clearly shows that S-, V-, and O-dominant precise syntaxes are attractors of the network. In addition, complete syntaxes are transient states among order changes, and V-dominant imprecise syntaxes are unstable. Since the global orders of those attractors (listed outside solid circles) cover all six global orders, the results in Simulation 1 do not give rise to any word order bias. Furthermore, this network falls into two isolated parts; the states above the dashed line all have an explicit or *implicit* (inferred from the available local orders) local order SO, whereas those below the dashed line all have a local order OS. The local order between S and O determines the evolution of these local order states.

3.3 Simulation 2: both transitive and intransitive sentences

The stability and transition matrices of Simulation 2 are shown in Figure 9. As shown in the stability matrix, S- and V-dominant precise syntaxes, i.e., States 3 (SV and OS), 4 (VS and SO), 6 (SV and VO), and 9 (VS and OV), are very stable (their stabilities are over 90%) — their global orders are OSV, VSO, SVO, and OVS, respectively. Some S-dominant imprecise syntaxes, i.e., States 2 (SV and SO) and



State	Loca orders	Global orders	Stability (%)
2	SV + SO	SVO or SOV	76.21
3	SV + OS	OSV	99.05
4	VS + SO	VSO	98.82
5	VS + OS	VOS or OVS	77.64
6	SV + VO	SVO	98.3
7	SV + OV	SOV or OSV	23.33
8	VS + VO	VSO or VOS	23.81
9	VS + OV	OVS	98.41
10	SO + VO	SVO or VSO	9.52
11	SO + OV	SOV	0
12	OS + VO	VOS	0
13	OS + OV	OSV or OVS	16.22
14	SV + VO + SO	SVO	0.77
15	SV + OV + SO	SOV	0
16	SV + OV + OS	OSV	0
17	VS + VO + SO	VSO	0
18	VS + VO + OS	VOS	0
19	VS + OV + OS	OVS	0.97

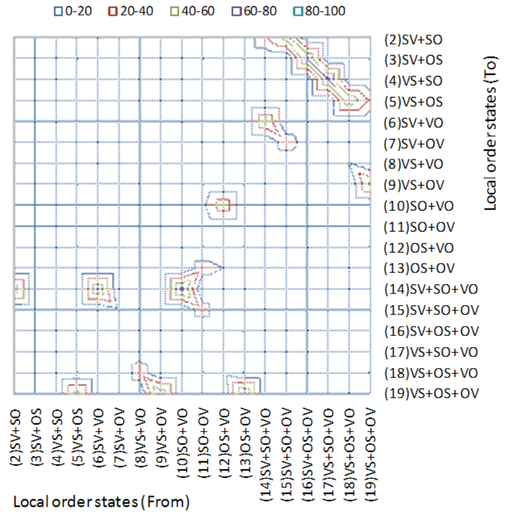


Figure 9. The stability (the above table) and transition (the bottom panel) matrices in Simulation 2.

5 (VS and OS), are also stable (their stabilities are over 70%) — their global orders are SVO/SOV and VSO/OVS, respectively. Moreover, States 7 (SV and OV) and 8 (VS and VO) are slightly stable; whose stabilities are around 20%.

As illustrated in the transition matrix, V-dominant precise syntaxes, i.e., States 6 (SV and VO) and 9 (VS and OV), may become complete syntaxes, i.e., States 14 (SV, VO and SO) and 19 (VS, OV and OS), by adding a local order to specify the implicit local order. In addition, S-dominant imprecise syntaxes, States 2 (SV and SO) and 5 (VS and OS), tend to become complete by adding a local order to resolve the ambiguity between some syntactic items. In such cases, they also tend to change to States 14 (SV, VO and SO) and 19 (VS, OV and OS), giving rise to the dominant global word order SVO or OVS. Furthermore, complete syntaxes are transient, and tend to lose either their VO/OS or SO/OS local order. For example, State 14 (SV,

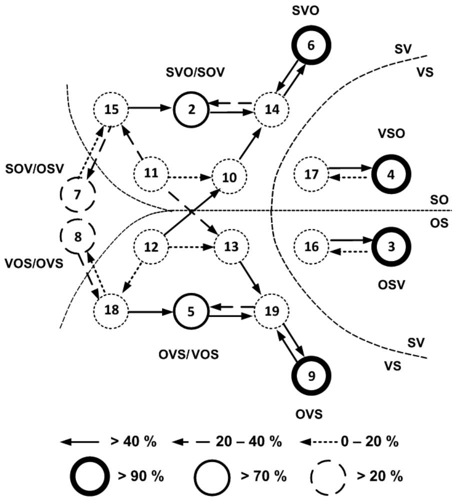


Figure 10. The evolution of local order states in Simulation 2. Different types of circles indicate different kinds of stabilities, and different types of arrows correspond to different frequencies of transitions among states. Based on the SO/OS and SV/VS local orders, the network can be divided into different parts.

VO and SO) can change to State 2 (SV and SO) by losing VO or to State 6 (SV and VO) by losing SO, but rarely to State 10 (SO and VO) by losing SV.

Based on these two matrices, we can also draw a network of local order states to illustrate their evolution, as shown in Figure 10. It is shown that VSO (and OSV) only occur when those were the initial states. SVO (and OVS) are the strongest attractors in this network, with the variants of SOV (and VOS) in States 2 (and 5). In addition, SOV (and VOS) are weaker attractors, coexisting with OSV (and OVS), and they can decay into SVO (and OVS) attractors, but not vice versa. This makes SOV and SVO (or OVS and VOS) the biased global word orders in Simulation 2. Furthermore, the network also falls into two isolated parts, divided by the local order SV/VS. Similar to Simulation 1, it can be further divided based on the local order SO/OS.

4, Discussion

In this section, we first summarize the driving forces for the simulation results, and then compare these results with the empirical findings based on the human language data, and finally discuss the impact of a simplification that we have made in this model.

There are three primary factors that lead to the simulation results.

1. *The Clarification Requirement*. Sets of local orders that form a unique global order can help individuals to clearly comprehend utterances. In particular, the sets that distinguish agent (S) from patient (O) enable individuals to accurately comprehend transitive sentences. Under the drive of this clarification requirement, there is a consistent bias towards the order of S and O being specified either explicitly by a local order or implicitly by a precise syntax. This will result in the gradual loss of syntaxes that do not distinguish S and O, i.e., SV and OV (State 7), VS and VO (State 8).
2. *Rule Competition*. When producing a transitive sentence, speakers may have the option to choose whether to invoke either two local orders, for example, SV and VO, or three local orders, for example, SV, VO and SO. Which combination of the competing local orders is invoked depends on the combined strength of the respective rules that are activated. Except in the case that all three local orders have identical contribution to the combined strength, there will be at least one pair of local orders for which the combined strength is greater than that for the three local orders, resulting in the complete syntax gradually be replaced by a syntax that comprises two local order rules. Local orders have identical strengths only rarely. As a result, the complete syntaxes (States 14–19) occur only as transient states during word order change.
3. *The structure of the semantic space*. To express an intransitive sentence, individuals must develop an explicit local order for S and V. Since both transitive and intransitive predicates can apply to the same set of agents, the SV and VS local orders, once acquired, are seldom lost or changed. As a result, O-dominant syntaxes, which do not specify the local order of S and V, i.e., SO and VO (State 10), SO and OV (State 11), OS and VO (State 12), and OS and OV (State 13), emerge only rarely.

Collectively, these three factors favor the S-dominant (States 2–5) and the precise V-dominant syntaxes (States 6 and 9). Although all stable, these six syntaxes arise with different frequencies in Simulation 2 that involves both transitive and intransitive sentences.

As shown in Figure 10, for the sake of argument, once SO is specified to distinguish agent and patient in transitive sentences, excluding complete syntaxes, which are transient, there are 5 possible sets of local orders: SV and SO (State 2), SO and VO (State 10), SO and OV (State 11), VS and SO (State 4) and SV and VO (State 6), among which SO is explicitly defined in the first four sets and implicitly defined in the last set. Among these sets, VS and SO (State 4) only become biased if they were the initial state. SO and VO (State 10) and SO and OV (State 11) have to decay, via complete syntaxes, into other states, such as SV and VO (State 6) and SV and SO (State 2), in order to specify a local order of S and V for expressing intransitive sentences. However, via complete syntaxes, SV and SO (State 2) and SV and VO (State 6) can change to each other, but SV and VO (State 6) are more stable. Other syntaxes can also change to these states, which increase the bias towards these states. Therefore, once SO is specified, explicitly or implicitly, to distinguish agent and patient constituents in sentences, SVO and SOV tend to become the biased global orders, while VSO becomes biased only if it emerges as a *frozen accident* (Crick, 1968). Similarly, if OS is specified to distinguish agent and patient, VOS and OVS tend to become biased, while OSV becomes so only as a frozen accident.

These simulation results are partially consistent with the empirical findings in the extant languages. The prevalence of SOV and SVO in the extant languages is supported by the empirical data (e.g., Tomlin, 1986; Dryer, 2008a). The coexistence of these orders is found in many natural languages. For instance, Steele (1978) has discovered that SOV exists in some sentences of many primarily SVO languages (e.g., Chinese). The changes from SOV to SVO and vice versa also occurred in some languages. For instance, Mandarin underwent a change from SOV in Middle Chinese to SVO in Modern Mandarin, and a reverse change is argued to be ongoing (Li & Thompson, 1981). In addition, our study, in line with Dryer (1997), has shown that intransitive predicates can affect the biased word orders. Furthermore, all the biased global orders in Simulation 2 follow the functional principle of VO-binding (Tomlin, 1986). Instead of being built in, this principle is an emergent property in our simulations.

Apart from these similarities, there are distinct differences between the word order bias shown in our study and that in the extant languages. For instance, although the Dryer's raw data (Dryer, 2008a) suggest that SOV and SVO occur with roughly equal frequencies, Dryer (1989) himself has noted that this is due, in part, to biased sampling of SVO languages that are related, either genetically or areally. Based on the same data, in genetic groups comparable to the subfamilies of Indo-European, languages having SOV will outnumber those having SVO. In other words, there seems to be a greater bias towards SOV than SVO. On this point, there is a mismatch between our results in Simulation 2 and the empirical findings.

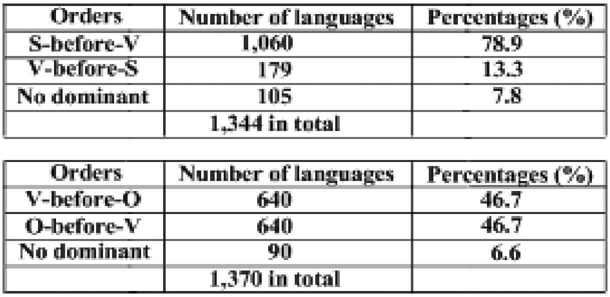
Although we are not able to resolve this discrepancy, it is noteworthy that, whereas most SVO languages (79.2%) do not mark the case of full noun phrases, most SOV languages (62.8%) do mark the case by some means (Comrie, 2008; Dryer, 2008a). It is possible that SOV languages are more numerous than SVO languages (in terms of genera) partly because case marked languages tend to evolve to SOV. As shown in Figure 10, only SV and SO (State 2), SV and OV (State 7), and SO and OV (State 11) can trigger SOV. Among them, SV and SO are stable, but they also lead to SVO. SO and OV are unstable, since they cannot express intransitive sentences. SV and OV, also supporting SOV, are slightly stable, but they cannot clearly distinguish

S and O. This set of local orders could trigger the emergence of case marking to clarify S and O, and then, increase the occurring frequency of SOV.

In our study, VOS and OVS become biased when OS is specified to distinguish agent and patent in transitive sentences, but these orders are among the least frequent word orders in the extant languages; according to the distributions of Tomlin (1986) and Dryer (2008a), fewer than 3% of all languages have these word orders. Although SO and OS are not directly formed in many languages, based on the distribution of the order of subject and verb (Dryer, 2008b) and that of object and verb (Dryer, 2008c) among the language data from WALS (see Table 2), we can see a preference for S-before-O syntaxes over O-before-S ones. As shown in Table 2, the majority of the languages have S-before-V syntaxes, while languages having V-before-O or O-before-V syntaxes are roughly the same. S-before-V and V-before-O lead to the global word order SVO, and S-before-V plus O-before-V can trigger SOV and OSV. Similarly, V-before-S and O-before-V lead to OVS, and V-before-S plus V-before-O can trigger VOS and VSO. If OSV and VSO both occur less frequently, the prevalence for S-before-V syntaxes over V-before-S ones corresponds to the preference for SO over OS. Some factors that are not addressed in this model may cause this preference. For example, the theme-first principle (Tomlin 1986) and the prominence of subject over object (Ocampo 2003) may select SO rather than OS. The dominant SOV order in nonverbal descriptions of natural events (Goldin-Meadow et al., 2008) may also affect the order selection in verbal languages.

Here, another difference between our results and the empirical data reveals itself. In our model, both VSO and OSV occur only as frozen accidents. In human languages, however, VSO occurs more frequently than OSV. This may be due to the different learnabilities of these word orders. As shown in the connectionist models (e.g., Lupyan & Christiansen, 2002), without the case system, VSO is more easily learned than OSV. In addition, the higher frequency of VSO than that of

Table 2. The numbers and frequencies of languages that have different orders of subject and verb (the above table) and those of object and verb (the bottom table). The data are from (Dryer, 2008b) and (Dryer, 2008c).



Orders	Number of languages	Percentages (%)
S-before-V	1,060	78.9
V-before-S	179	13.3
No dominant	105	7.8
	1,344 in total	

Orders	Number of languages	Percentages (%)
V-before-O	640	46.7
O-before-V	640	46.7
No dominant	90	6.6
	1,370 in total	

OSV is in line with the prevalence of SO over OS, which may also trigger their different occurring frequnecies in human languages.

The approach that we adopted in this model involves a questionable simplification: that intransitive and transitive predicates can be associated into the same V category, and that the agents of both types of predicates can be associated into the same S category. In other words, we have assumed the evolving language to be nominative–accusative. This contrasts with the ergative–absolutive languages, in which the agents of intransitive predicates and the patients of transitive predicates map to a category, referred to as *absolutive*, and the agents of transitive predicates map to a different category, referred to as *ergative* (Song, 2001). If, instead of assuming the evolving language to be nominative–accusative (or simply accusative), we had assumed it to be ergative–absolutive (or simply ergative), the results of Simulation 1 would not have changed qualitatively. But the results of Simulation 2 would have changed.

In ergative languages, the clarification between agent and patient in transitive sentences is also critical for comprehension. And since intransitive agents are mapped with transitive patients, the local order for intransitive sentences corresponds to VO or OV. Then, if SO is specified to distinguish agent and patient in transitive sentences, once VO emerges for expressing intransitive sentences, the global order tends to be SVO or VSO; whereas if OV emerges, the global word order becomes SOV. Despite of whether they are syntactically mapped to the same or different categories, both intransitive and transitive agents are semantically similar, which may cause them to be posited in a similar position with respect to verbs in utterances. This factor may cause SO to coexist with OV, since OV corresponds to a "S"V order in intransitive sentences and both transitive and intransitive agents are before verbs. Then, SOV will be biased. Based on the same factor, SO may also coexist with VO and cause VSO to be biased. In this situation, both transitive and intransitive subjects are after verbs. However, SO and VO may also trigger SVO, but SVO will cause transitive and intransitive agents to appear in different positions with respect to verbs. Considering these, if SO is specified to distinguish agent and patient in transitive sentences, SOV should be more biased than VSO, SVO is not biased. Similarly, if OS is specified to distinguish agent and patient in transitive sentences, VOS is more biased than OSV, and OVS is not biased. Considering the preference for SO over OS, in ergative languages, SOV is more biased than VOS, and VSO is more biased than OSV. However, SVO and OVS are not biased.

By examing the distribution of the order of verb and object (Dryer, 2008c) focusing on just those ergative languages, we observe that 71.9% (23) of the 32 ergative languages considered by Comrie (2008) have the order OV. In addition, according to the Drayer's data from WALS (2008a), 17 out of 20 of the ergative languages have the dominant word order SOV (Comrie, 2008), only 2 (Tukangbesi and Zoque) have VOS. Furthermore, there are only a few ergative languages having VSO, such as Tagalog, Watakassi, Tokana, Skerre, and even fewer having OSV, such as Dyirbal. This empirical evidence is consistent with our predictions about the biased word orders in ergative languages.

5. Conclusions

In this paper, we investigate word order bias using a computational model that adopts a local order approach. Compared with direct changes in global word order, gradual changes in local order involve fewer constituents and less global information. We analyze the stabilities of different local orders and the frequencies of transitions among them in two simulations having different semantic structures. Given a semantic space containing only transitive predicates, the model tends to avoid V-dominant imprecise syntax; given a semantic space containing both transitive and intransitive predicates, SVO and SOV (or OVS and VOS) may coexist as the biased global orders.

These results reflect the "*semantics driving syntax*" hypothesis (Schoenemann, 2005), which suggests that complex syntactic structure arose from the need to convey complex semantic structures. Our simulations demonstrate that grammar lies in the conceptual structure in semantics (Newmeyer, 2008), i.e., the emergent syntax reflects the pre-existing semantic structures, and that the self-organization of local orders among constituents can influence word order bias.

Our work focuses on nominative-accusative languages, but the results are also insightful for ergative-absolutive languages. The comparison between the simulation results and the empirical data indicates that, besides word order itself, other linguistic and nonlinguistic factors, such as pragmatics and case marking, also contribute to the word order bias. It remains as future work to investigate the effect of these factors on word order.

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Notes

1. Due to the item-based learning mechanisms adopted in this model, the simulation results are not restricted by the size of semantic space, except that given a semantic space with a bigger size, more communications are required to clearly study the word order bias. As shown in the results, it is the structure of integrated meanings, rather than the size, that plays a role in word order bias.

2. Since the local order approach requires at least two local orders to express a transitive sentence, the sets containing a single local order (which lead to three competing global orders) are excluded.

3. Mutation may not occur as frequently as the other two operations, since a mutation of some local order between certain syntactic items, such as S and O, may incur misunderstanding.

4. We assume that the transitions among local order states tend to proceed through fewer operations of addition, loss or mutation, and via fewer intermediate states. For instance, most transitions within the S-, V-, or O-dominant syntaxes can be directly achieved by the mutation of a local order, except for some cases, i.e., State 2 → State 5, State 3 → State 4, State 6 → State 9, State 7 → State 8, State 10 → State 13, and State 11 → State 12. Most transitions across the S-, V-, or O-dominant syntaxes can be achieved via one intermediate state, except for some cases, i.e., State 2 → States 8 and 13, State 3 → States 9 to 12, State 4 → States 6, 7, 9, and 12, State 5 → States 7 and 10, State 6 → States 3 to 5, and 11 to 13, State 7 → States 5, 10, 11, and 13, State 8 → States 2 and 13, State 9 → States 3, 4, 10 to 12, State 10 → States 5 and 7, State 11 → States 3, 6, 8, and 9, State 12 → States 2 to 4, 6, 7, and 9, State 13 → States 2 and 8. Most transitions within the complete syntax can be achieved via at most one intermediate state, except for some cases, i.e., State 14 → State 19, State 15 → State 18, and State 16 → State 17. In order to calculate the stability and transitivity through a single addition, loss or mutation, we need to replace the transitions that proceed via one or two intermediate states with those intermediate ones. For transitions via one intermediate state, e.g. State A → State B → State C, the number of direct transitions from State A to State C is added to the number of transitions both from State A to State B and from State B to State C, and then, the original direct transition from State A to State C is removed. For transitions via two intermediate states, e.g., State A → State B → State C → State D, the number of direct transition from State A to State D is added to the transitions from State A to State B, from State B to State C, and from State C to State D, and then, the direct transition from State A to State D is removed. For transitions that can be achieved by either of two sets of operations both via one or two intermediate states, e.g., State A → State B → State D or State A → State C → State D, one half of the direct transition from State A to State D is added to the transitions both from State A to State B and from State B to State D, and the other half is added to the transitions both from State A to State C and from State C to State D. And then, the direct transition is removed. After these adjustments, complex transitions are replaced by simple ones, and the stability and transitivity of different word order states can be clearly analyzed.

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