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Syntactic bootstrapping attitude verbs despite impoverished morphosyntax

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ABSTRACT

Attitude verbs like *think* and *want* describe mental states (belief and desire) that lack reliable physical correlates that could help children learn their meanings. Nevertheless, children succeed in doing so. For this reason, attitude verbs have been a parade case for syntactic bootstrapping. We assess a recent syntactic bootstrapping hypothesis, in which children assign belief semantics to verbs whose complement clauses morphosyntactically resemble the declarative main clauses of their language, while assigning desire semantics to verbs whose complement clauses do not. This hypothesis, building on the cross-linguistic generalization that belief complements have the morphosyntactic hallmarks of declarative main clauses, has been elaborated for languages with relatively rich morphosyntax. This article looks at Mandarin Chinese, whose null arguments and impoverished morphology mean that the differences necessary for syntactic bootstrapping might be much harder to detect. Our corpus analysis, however, shows that Mandarin belief complements have the profile of declarative main clauses, while desire complements do not. We also show that a computational implementation of this hypothesis can learn the right semantic contrasts between Mandarin and English belief and desire verbs, using morphosyntactic features in child-ambient speech. These results provide novel cross-linguistic support for this syntactic bootstrapping hypothesis.

1. Introduction

In all languages where they have been tested, children seem to differentiate two types of attitude verbs at an early age. For instance, children make consistent errors with *think*, interpreting it as a veridical belief verb entailing the truth of its complement clause; they do not make similar mistakes with *want*. This article is concerned with how children can distinguish between these verbs so early and learn their semantics, even though these verbs describe mental states that lack reliable physical correlates that could help children determine what the verbs mean.

An influential general solution for the problem of learning meaning from uninformative extralinguistic contexts is syntactic bootstrapping. As proposed by Gleitman et al., children might use syntactic properties associated with a lexical item, such as the syntactic frames it appears in, to draw inferences about its meaning (Gleitman 1990; Gleitman et al. 2005; Papafragou, Cassidy & Gleitman 2007; Gillette et al. 1999, etc.). However, fleshing out a linguistically robust syntactic bootstrapping account is much more challenging, since languages vary widely in their morphosyntax. In recent work, Hacquard & Lidz (2019) address this challenge in the context of learning attitude verbs, presenting a syntactic bootstrapping account that is directly intended to accommodate morphosyntactic diversity across languages.

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Specifically, Hacquard & Lidz's (2019) proposal makes use of the fact that attitude verbs converge cross-linguistically at an abstract level: Complement clauses of belief verbs have the same morphosyntactic profile as declarative main clauses. For instance, in English, declarative main clauses are finite, as are complement clauses of belief verbs like *think*, but the complement clauses of desire verbs like *want* are typically nonfinite (for a substantially different account based on similar facts, see de Villiers 2005 and de Villiers & de Villiers 2000). In Spanish (and other Romance languages), the relevant distinction is in mood. As a high-level generalization, complement clauses of belief verbs, like *creer* 'believe' and declarative main clauses tend to appear in the indicative mood, while complement clauses of desire verbs, like *querer* 'want,' do not allow the indicative but often require the subjunctive (Bolinger 1968; Anand & Hacquard 2013; Villalta 2008, among many others). With the right inference mechanisms, English and Spanish learners who observe that desire complements are morphosyntactically different from belief complements and declarative main clauses can conclude that *think* and *creer* have belief semantics but *want* and *querer* do not.

(1) English

a. John thinks [Mary will leave]. [Belief verb]

b. John wants [Mary to leave]. [Desire verb]

(2) Spanish

a. Creo [que Peter va a la casa].

I.think that Peter goes.IND to the house

'I think Peter is going to the house.'[1] [Belief verb]

b. Quiero [que Peter vaya a la casa].

I.want that Peter goes.SBJ to the house

'I want Peter to go to the house.' [Desire verb]

Evidently, this proposal assumes that there are clear differences in clausal morphosyntax within a language. Although there is little reason to challenge this assumption in the context of English or Romance, one might question its validity for languages whose morphosyntax is more impoverished. One such language is Mandarin Chinese. Mandarin—with no overt markers for finiteness, mood, tense, etc.—has much less verbal morphology than languages like English or Spanish. Mandarin also allows subjects and objects to be dropped, so in principle, it might also be difficult to rely on the distribution of overt arguments to distinguish between different types of complement clauses. The morphosyntactic properties of Mandarin therefore conspire to allow belief and desire verbs to appear with complement clauses that are string-identical (3), which in turn raises questions about the robustness of the syntactic bootstrapping account.

(3) a. Wo zhidao [chi shuiguo].

I know eat fruit

'I know {I/you/he/she/it/ . . . } eat(s) fruit.' [Belief verb]

b. Wo ai [chi shuiguo].

I love eat fruit

'I love to eat fruit.' [Desire verb]

[1]Abbreviations used in glosses: IND: indicative; PART: particle; PROG: progressive aspect; SBJ: subjunctive; 3s: third person singular pronoun.

Here, we present a case study of Mandarin Chinese to show that the "worst-case scenario" for this syntactic bootstrapping account (to borrow a term of Lee & Naigles's [2005]) is not as dire as it seems. Our analysis of child-ambient speech corpora shows that the complement clauses of Mandarin belief and desire verbs have distinct morphosyntactic profiles and that belief complements pattern like declarative main clauses, despite the language's impoverished morphosyntax. We support this conclusion with a corpus analysis of formal written and spoken Mandarin. We also show, using a computational model (White, Hacquard & Lidz 2018), that a Mandarin learner tracking declarative main clause syntax can quickly draw a semantic distinction between belief and desire verbs. Our results serve as a proof of concept that syntactic bootstrapping is cross-linguistically viable as a strategy for learning attitude verb semantics, even in languages without a clear finiteness or mood contrast.

This article is organized as follows. Section 2 reviews Hacquard & Lidz's (2019) proposal and the syntactic properties of attitude verbs in Mandarin. In Section 3, we discuss how the morphosyntactic idiosyncrasies of Mandarin pose challenges for syntactic bootstrapping. Section 4 presents the Mandarin corpus studies, and Section 5 presents the adaptation of White, Hacquard & Lidz's (2018) computational model. We show that this model succeeds in learning the appropriate semantic contrasts in both Mandarin and English. Section 6 discusses implications for theories of syntactic bootstrapping and areas for future work on the acquisition of attitude verbs.

2. Attitude verbs and syntactic bootstrapping

In the literature on attitude verbs, there is a broad consensus that there is a fundamental split within attitude verbs. Belief verbs and their kin ("representational verbs" for Bolinger 1968 and "assertives" for Hooper 1975), like *think*, express the attitude holder's commitment to the truth of the verb's clausal complement. Desire verbs like *want*, on the other hand, do not; they describe the attitude holder's preference for the situation denoted by the complement.

As many have also observed, across languages, this semantic difference is often reflected in the morphosyntax of the verb's complement clause, although languages vary substantially in exactly how this difference is realized. For instance, as discussed in the introduction, English belief verbs tend to have finite complements, while desire verbs tend to have nonfinite ones (1). In Romance, however, belief verbs tend to have complements in the indicative mood, while desire verbs often have subjunctive complements; see (2) for a representative example. A third kind of reflex is word order, as found in German: Belief verb complements can have verb-second word order, while desire verb complements are verb-final (4).

(4) German (adapted from Scheffler 2009 ex. 2)

a. Ich glaube, [Peter ist nach Hause gegangen].
   I believe Peter is to home gone
   'I believe that Peter has gone home.' [Belief verb]

b. *Ich möchte, [Peter geht nach Hause].
   I want Peter goes to home
   'I want Peter to go home.' [Desire verb]

Hacquard & Lidz (2019) point out that despite these morphosyntactic differences, belief verbs tend to have complements with the morphosyntactic profile of declarative main clauses, while desire verbs do not. For instance, declarative main clauses are finite in English, indicative in Romance, and verb-second in German. Hacquard & Lidz propose that learners use this resemblance to infer whether a verb has belief semantics. The abstractness of this bootstrapping hypothesis—stated in terms of declarative morphosyntax instead of finiteness, mood, or word order—makes it applicable to a wide range of languages, as it gives the hypothesis sufficient flexibility to accommodate cross-linguistic morphosyntactic diversity.

As an example, let us consider the case of the English verbs *think* and *want*. Observing a sentence like (1a) *John thinks Mary will leave*, children learning English observe that *think*'s complement (*Mary will leave*) resembles a declarative main clause in English. They can quickly conclude on the basis of these observations that *think* is a belief verb. In contrast, the complement of *want* (e.g., *Mary to leave* in *John wants Mary to leave*) does not have declarative morphosyntax, so learners do not draw the same conclusion about *want*'s semantics.

Of course, as presented so far, this account does not explain why there is such a link between a verb's subcategorization restrictions and its semantics. One possibility, discussed by Hacquard & Lidz, is that this link is mediated through pragmatics. Declarative main clauses are typically used for assertions. Similarly, the declarative-like complement clause of a belief verb is often indirectly asserted, serving as the main point of the utterance (Hooper 1975; Dayal & Grimshaw 2009, among others). Learners with a good understanding of speech acts can infer that the verb must have belief semantics, expressing the attitude holder's (the subject's) commitment to the truth of the complement clause (for work on very young children's knowledge of speech acts, see Begus & Southgate 2012; Evans et al. 2014; Grosse, Moll & Tomasello 2010; Grosse & Tomasello 2012; Shatz 1978; Spekman & Roth 1985).[2]

3. Mandarin Chinese attitude verbs and syntactic bootstrapping

In this article, we evaluate this bootstrapping hypothesis from the perspective of Mandarin Chinese. As mentioned in the introduction, we use Mandarin because the language in principle represents a "worst-case scenario." In this section, we elaborate on the morphosyntactic properties of Mandarin that potentially make it more difficult for a learner to observe clear syntactic differences between the complements of belief and desire verbs.

Mandarin lacks case, tense, and mood morphology, so the complements of belief and desire verbs cannot be reliably distinguished with noun or verbal morphology. In fact, within the formal syntax literature, there is an ongoing debate over whether Mandarin even makes an abstract finiteness distinction and whether its attitude verbs impose distinct subcategorization requirements (e.g., C.-T. J. Huang 1989; Y.-H. A. Li 1990; Hu, Pan & Xu 2001; Lin 2012; Grano 2015; N. N. Zhang 2016; N. Huang 2018). In addition, there is no robust word order difference between the two types of complements, as there is in German. Mandarin also allows the omission of subjects (and objects) in appropriate contexts, so it is in principle possible that the presence or absence of overt subjects might not help to differentiate belief and desire complements.

Even though there is no consensus on whether there is a formal difference between the complement clauses of belief and desire verbs, there are nonetheless useful generalizations that we can draw from this literature. First, belief complements allow either null or overt subjects, while overt subjects tend to be more marked in desire complements (5). In addition, complement clauses of belief verbs tend to allow the presence of modal auxiliaries and adverbs (6) and certain aspect markers (7), such as the progressive *zai*, perfective *-le*, experiential *-guo*, and negative perfective *mei(you)*. In contrast, desire complements usually do not.

[2]As Hacquard & Lidz note, beyond providing a principled link between subcategorization properties and semantics, this pragmatically rooted syntactic bootstrapping hypothesis can help make sense of a set of experimental results in which young children incorrectly treat *think* as being incompatible with false beliefs (for discussion of English and German, see Perner et al. 2003; but see Lewis, Hacquard & Lidz 2012, 2017 for results showing adult-like behavior in English-learning children with *think*). For illustration, consider the following scenario: Children are told that Dora is playing, but Boots mistakenly believes that she is asleep. In this context, young children usually (incorrectly) judge a statement like "Boots thinks that Dora is asleep" to be false. This fact is often linked to the development of a theory of mind in young children or children's (in)ability to encode false beliefs (e.g., de Villiers 2005; de Villiers & de Villiers 2000). However, Hacquard & Lidz argue that this un-adult-like behavior arises because children take the statement to be an indirect assertion that Dora is asleep, which is inconsistent with the fact that Dora is actually playing.

(5) Overt subjects

a. Lisi renwei [(**Zhangsan**) chi-su].

Lisi think Zhangsan eat-vegetarian

'Lisi thinks that Zhangsan is a vegetarian.' [Belief verb]

b. Lisi {yao/xiang} [chi-su].

Lisi want want eat-vegetarian

'Lisi wants to be vegetarian.' [Desire verb]

c. Lisi {yao/*xiang} [**Zhangsan** chi-su].

Lisi want want Zhangsan eat-vegetarian

'Lisi wants Zhangsan to be vegetarian.' [Desire verb]

(6) Modals

a. Lisi renwei [Zhangsan {**keneng**/**hui**} chuxi huiyi].

Lisi think Zhangsan might will attend meeting

'Lisi thinks that Zhangsan might/will attend the meeting.' [Belief verb]

b. *Lisi {xiang/yao} [{**keneng**/**hui**} chuxi huiyi].

Lisi want want might will attend meeting

Intended: 'Lisi wants it to be possible that he attends the meeting.'/'Lisi wants to attend the meeting in the future.' [Desire verb]

(7) Aspect markers

a. Lisi renwei [Zhangsan **zai** shuijiao].

Lisi think Zhangsan PROG sleep

'Lisi thinks that Zhangsan is sleeping.' [Belief verb]

b. *Lisi {xiang/yao} [**zai** shuijiao].

Lisi want want PROG sleep

Intended: 'Lisi wants to be sleeping.' [Desire verb]

Of course, exceptions exist. For instance, even though *yao* 'want' is a desire verb, its complement can contain an overt subject, just like its English counterpart. However, at the verb class level, the generalizations about subjects, modals, and aspect markers are fairly robust. Table 1 provides a summary of the distribution of these features, based on native speaker intuitions of the first and third authors, for a larger set of prototypical attitude verbs.

Turning to main clauses, we note that the availability of overt subjects, modals, and aspect markers is also a hallmark of declarative main clauses in Mandarin (8). In contrast, overt subjects tend to be omitted in imperative clauses, just as overt subjects are in imperatives in languages such as English (e.g., Zanuttini, Pak & Portner 2012). Similarly, modals and aspect markers are generally unacceptable in such clauses, although we remain agnostic on whether the restriction is syntactic in nature or reflects some semantic or conceptual incompatibility. (In other words, there are also morphosyntactic parallels between imperative clauses and desire complements, at least in Mandarin and English; we return to this fact in Section 5.)

Table 1. Selected Mandarin Chinese attitude verbs and distribution of syntactic features in their complement clauses.

Verb class	Overt subject	Modal	Aspect
Belief verbs			
danxin 'worry'; *faxian* 'discover'; *huaiyi* 'suspect'; *jiang* 'tell'; *juede* 'feel'; *mingbai* 'understand'; *renwei* 'think'; *shuo* 'say'; *xiang* 'think'; *xiangxin* 'believe'; *yiwei* 'falsely believe'; *zhidao* 'know'	Possible	Possible	Possible
Desire verbs			
taoyan 'dislike'; *xihuan* 'like'; *yao* 'want/need'	Possible	Not possible	Not possible
ai 'love'; *gan* 'dare'; *xiang* 'want'	Not possible	Not possible	Not possible
dasuan 'plan'; *zhunbei* 'get ready to'	Disputed (see N. Huang 2018; Zhang 2016; Grano 2015; Hu et al. 2001)	Only *yao* (future marker)	Not possible
Emotive doxastic verbs			
xiwang 'hope'	Possible	Possible	Possible
Declarative main clause	Possible	Possible	Possible

(8) Declarative main clauses

a. (**Zhangsan**) chi-su.

Zhangsan eat-vegetarian

'Zhangsan is vegetarian.'

b. Zhangsan {**keneng**/**hui**} chuxi huiyi.

Zhangsan might will attend meeting

'Zhangsan might/will attend the meeting.'

c. Zhangsan **zai** shuijiao.

Zhangsan PROG sleep

'Zhangsan is sleeping.'

But the mere existence of these morphosyntactic differences does not make syntactic bootstrapping a foregone conclusion. A major problem lies in the fact that the overt expression of these elements is optional (we set aside the question of whether they are syntactically present but silent). For one, Mandarin is a pro-drop language, so subjects (as well as objects) can be omitted from declarative main clauses and complement clauses under the right context. Likewise, not all utterances require modals or aspect markers. Similarly, imperatives can appear with overt subjects (as can imperatives in other languages, like English). This optionality means that complement clauses of belief and desire verbs can be string-identical (9), as can declarative and imperative clauses (10). To the extent that belief and desire verbs have complements that are superficially indistinguishable from each other and are also indistinguishable from declarative and other clause types, this presents a serious problem for the syntactic bootstrapping hypothesis.

(9) a. Wo zhidao [chi shuiguo].

I know eat fruit

'I know {I/you/he/she/it/ . . . } eat(s) fruit.' [Belief verb]

b. Wo ai [chi shuiguo].

I love eat fruit

'I love to eat fruit.' [Desire verb]

(10) a. Chi shuiguo.

eat fruit

'{I/you/he/she/it/ . . . } eat(s) fruit.' [Declarative]

'Eat fruit!' [Imperative]

b. Ni chi shuiguo.

you eat fruit

'You eat fruit.' [Declarative]

'You eat fruit!'[3] [Imperative]

Nevertheless, just because these clauses can be string-identical does not mean that they always are. It could very well be the case that they are sufficiently differentiated in naturally occurring contexts. If so, the input for Mandarin-learning children might be rich enough to make syntactic bootstrapping possible. To determine whether this is the case, we looked at Mandarin child-ambient speech corpora and the Chinese Treebank (Xue et al. 2010), which reflects more formal spoken and written registers an educated native speaker might observe.

4. Corpus analyses

To preview our corpus analysis results, we find that even though overt subjects, modals, and aspect markers are in principle optional in the complement clauses of belief verbs, these properties occur relatively frequently, so that complements of belief verbs do not resemble those of desire verb complements in both corpora. Second, these syntactic properties occur in complements of belief verbs about as frequently as they do in declarative main clauses.

4.1. *Child-ambient speech*

4.1.1. *Methods*

We manually annotated five of the larger Mandarin Chinese corpora from the CHILDES database (MacWhinney 2000): Beijing (Tardif 1993, 1996), Context (Tardif, Gelman & Xu 1999), Chang1 (Chang 1998), Zhou1 (Zhou 2001), and Zhou2 (X. Li & Zhou 2004) (see Table 2 for summary). Because attitude verbs are relatively rare in naturalistic speech, we pooled all five corpora, so that we would have a relatively large number of utterances for analysis. Prior to analysis, we removed all utterances by the

Table 2. Descriptive statistics for CHILDES corpus analysis.

Corpus	Number of children	Age of children	Number of child-ambient utterances	Type of interactions
Beijing	10	1;09–2;03 (*M* = 2;01, *SD* = 0;01 at last visit)	52,225 (*M* = 5,223, *SD* = 882)	Longitudinal study involving family and caregivers
Context	24	*M* = 1;08, *SD* = 0;01	16,144 (*M* = 673, *SD* = 150)	Toy play and book reading
Chang1	24	3;06–6;05 (*M* = 5;00, *SD* = 1;00)	2,602 (*M* = 108, *SD* = 30)	Play narratives
Zhou1	50	1;02–4;00 (*M* = 1;11, *SD* = 0;07)	8,608 (*M* = 172, *SD* = 101)	Toy play with mother
Zhou2	140	2;11–6;00 (*M* = 4;06, *SD* = 1;00)	37,439 (*M* = 267, *SD* = 116)	Toy play with mother

[3]The pronoun *ni* 'you' in (10b) is ambiguous between a subject and a vocative reading. It can be disambiguated by adding a proper name as a vocative: e.g., *Zhangsan, ni chi shuiguo!* 'You eat fruit, Zhangsan!'

target child of each corpus, so our data would contain only utterances that target children might hear around them, such as utterances by parents, other relatives, and even other children.

We extracted two sets of data from these pre-tokenized corpora to compare the distribution of syntactic features like overt versus null subjects, modals, and aspect markers in complements of attitude verbs and those of main clauses. First, we used the existing tokenizations to search for utterances with the attitude verbs in Table 1. Doing so yielded about 8,900 tokens in total. For each token, the verb's complement was manually coded for syntactic category: whether it had the form of a clause, a VP, an NP, and so on. There were about 4,200 "clause-like" complements: complements with the form of a clause or a VP (Table 3). These complements were coded for the presence of an overt subject, modal, or aspect marker.[4]

The second set of data is what we will call the main clause data set, a 5% random sample of child-ambient utterances from each file of each corpus (about 6,100 tokens in total). We chose to randomly sample main clauses for practical reasons: It was not feasible to manually annotate all main clauses, even though that would better simulate a child's linguistic experience. In this data set, each utterance was coded for its clause type: whether it was a declarative, interrogative, and so on. In cases where an utterance consists of multiple conjoined independent clauses, only the first clause was coded. When it was difficult to determine clause type from the utterance itself, the context was checked. The main clause of each utterance was coded for the presence of an overt subject, modal, or aspect marker. For our analysis, we looked at 1,576 declarative main clauses, after excluding utterances of other clause types, formulaic phrases, disfluencies, repetitions of utterances by the child, etc.

Annotations were done manually by the first author and an undergraduate research assistant, both native speakers of Mandarin Chinese; the first author then reviewed and edited the annotations by the research assistant. A smaller sample of utterances (1,309 utterances from the attitude verb data set, 1,576 utterances from the main clause data set) was first independently annotated by the third author, also a native speaker of Mandarin Chinese. Excluding irrelevant utterances (e.g., disfluencies, formulaic phrases, nondeclarative clauses), the inter-annotator agreement between the third author and the annotations jointly completed by the first author and research assistant was 97%—Cohen's kappa = 0.88, 95% CI = (0.868, 0.890), $N = 16776$.

Table 3. Attitude verbs with clause-like complements in the CHILDES data set.

	Count		Count
Belief verbs		**Desire verbs**	
shuo 'say'	760	*yao* 'want/need'	1,925
zhidao 'know'	231	*ai* 'love'	169
jiang 'tell'	135	*xihuan* 'like'	132
juede 'feel'	72	*gan* 'dare'	30
yiwei 'mistakenly believe'	26	*zhunbei* 'get ready to'	26
renwei 'think'	4	*dasuan* 'plan'	3
faxian 'discover'	3	**Other**	
xiangxin 'believe'	2	*xiang* 'think, want'	642
		xiwang 'hope'	3

[4]For the corpus analysis, the following items and their negated forms were defined as modal auxiliaries and adverbs (i) and aspect markers (ii).

(i) a. Epistemics: *keneng* "might", *yiding* "must"
b. Roots: *(bi)xu, dei, yiding* "must"; *ken* "be willing to"; *ke(yi)* "can, be allowed to"; *hui, neng(gou)* "able to"; *(ying)gai, ying* "should"
c. Future: *hui, jiang*
d. Others: *shi* (focus)

(ii) a. Experiential: *-guo*
b. Progressive: *(zheng)zai*
c. Negated perfective: *mei(you)*

Table 4. Relative frequencies (%) for syntactic features in declarative clause-like complements of selected belief and desire verbs in CHILDES data set, by verb class.

Verb class/Clause type	Overt subject	Modal	Aspect
Declarative main clauses	57.2	7.1	4.8
Belief verb complements	51.3	4.8	2.2
Desire verb complements	5.0	0.4	0.1
Complement of *xiang* 'think, want'	1.6	1.1	0.0
Complement of *xiwang* 'hope'	100.0	0.0	0.0

4.1.2. *Results*

Table 4 reports relative frequencies of overt subjects, modals, and aspect markers in our data sets at the verb class level. We report *xiang*'s and *xiwang*'s figures separately, given their distinctive semantics: *Xiang* can mean 'think' or 'want,' i.e., have either belief or desire semantics, while *xiwang* 'hope' has both belief and desire semantics. For this analysis, we only consider the 3,175 complements that resemble declarative clauses, without the imperative *bie* 'don't', *wh*-phrases, or A-not-A question morphology. The modal and aspect figures here exclude all instances of the future marker *yao* and the perfective aspect *-le*. We do so because it was often difficult to determine whether *yao* was intended as a future marker or a desire verb; we effectively assume that all instances of *yao* are desire verbs. Similarly, it was challenging to tell whether *-le* was intended as the perfective aspect or the homophonous change-of-state sentence-final particle, which is not an aspect marker. Our modal and aspect marker frequencies should be understood as a conservative estimate.

With these caveats in mind, we see from Table 4 that belief verbs have complements that resemble declarative main clauses in terms of the distribution of overt subjects, modals, and aspect markers; in contrast, desire verbs do not.

At the verb level, there is more variation in profiles, possibly because of sampling: Many of these verbs occur infrequently. However, within the most frequent verbs like *shuo* 'say' and *yao* 'want,' the complements of belief verbs still bear a stronger resemblance to declarative main clauses, while desire verbs' complements do not. Table 5 presents relative frequencies by verb for some of the more common belief and desire verbs.

The results for *yao* 'want,' *xiang* 'think, want,' and *xiwang* 'hope' deserve some comment. In principle, *yao* is a desire verb that behaves like a belief verb in allowing a complement with an overt subject. However, in the input, overt subjects are rare in *yao*'s complement, occurring 5.8% of the time. As a result, in the input, the average clause-like complement of *yao* does not resemble that of a belief verb. Similar remarks hold for *xiang*, which is polysemous and in principle can mean either 'think' or 'want.' Finally, the figures for *xiwang* are unlikely to be representative, as the verb occurs very infrequently in our data set.

Overall, the results show that the contrasts in clausal morphosyntax necessary for syntactic bootstrapping are present in the aggregate in child-ambient speech. However, one might be concerned about the representativeness of these corpus results. The counts reported were based on our own

Table 5. Relative frequencies (%) for syntactic features in declarative clause-like complements of selected belief and desire verbs in CHILDES data set.

Verb class/Clause type	Overt subject	Modal	Aspect
Declarative main clauses	57.2	7.1	4.8
Belief verb complements			
shuo 'say'	57.6	5.4	2.9
zhidao 'know'	49.3	5.6	0.0
jiang 'say'	13.3	1.7	0.8
Desire verb complements			
yao 'want'	5.8	0.4	0.1
xihuan 'like'	1.0	0.0	0.0
ai 'love'	0.7	0.0	0.0

annotation standards. In addition, the data set analyzed is relatively small, even though we pooled five CHILDES corpora, raising questions about whether the data is representative of the input encountered by a Mandarin learner.

To address these issues, we ran an analysis of the Chinese Treebank, which consists of over 51,000 syntactic trees (Xue et al. 2010). The Chinese Treebank has two very useful properties that complement the child-ambient speech data set. First, it was annotated and checked according to an independent set of standards. Second, it is in a machine-readable format, which facilitates analysis on a larger scale. Admittedly, the Mandarin in the Treebank is not representative of the input of a Mandarin learner: The Treebank reflects more formal spoken and written registers, e.g., newswires, broadcasts, blogs. However, to the extent that we observe the same contrasts in the Chinese Treebank, that would suggest that the morphosyntactic differences between belief and desire complements and declaratives are robust in Mandarin and can be attested across different registers and genres. Such results would provide independent support for our CHILDES findings.

4.2. *Chinese Treebank*

4.2.1. *Methods*

We wrote a Python script to read each tree in the Chinese Treebank to determine the presence of the attitude verbs in Table 1 and to identify the complement(s) they took. We defined clause-like complements as a sister of a verb with the labels CP, IP, or VP. In this analysis, we also included the desire verbs *xuyao* ‘need’ and *yaoqiu* ‘request,’ which were not in the set of verbs in Table 1 because they are of a more formal register. However, they occur quite frequently in the Chinese Treebank and have similar semantics to *yao* ‘want.’ The same was done for the belief verb *biaoshi* ‘say, express,’ which occurs frequently and has ‘say’-like semantics.

We counted a total of 12,644 clause-like complements, treating conjoined clauses or VPs as separate clauses. The script also extracted the subject, modals, and aspect markers for each clause-like constituent, where available. A number of desire verbs, like *yaoqiu* ‘request,’ are object control verbs, which the Treebank annotated as taking an object NP and a clausal complement with a null subject coindexed with the object NP. In this case, we followed the Treebank’s annotation standards, treating these clauses as having a null subject, although we also recorded whether an object NP was present. Because the Treebank’s annotation standards do not define a class of modals, the script checked the complement to see if it contained a lexical item matching the set of modals listed in Footnote 4. For annotating aspect markers, we followed the Treebank’s definition of aspect suffixes and supplemented it with two prefixes with aspect semantics, namely, progressive *zai* and negative *mei*(*you*).

The script also checked each sentence whose root node bears the label CP, IP, or VP and extracted the subject, modal, and aspect morphemes (if available) in the main clause (or clauses, in event of conjunction). Main clauses with imperative and interrogative force, whose root nodes are marked with -IMP and -Q respectively, were excluded from analysis. Also excluded were fragments, headlines, and unmarked sentences with imperative *bie* ‘don’t,’ *wh*-phrases, or A-not-A question morphology. We assume that all remaining unmarked sentences are declaratives. This process yielded 62,038 declarative main clauses.

4.2.2. *Results*

Table 6 presents relative frequencies of overt subjects, modals, and aspect markers, by verb class, for the Chinese Treebank data set. For this analysis, we only consider the 11,962 complements that resemble declarative clauses, without the imperative *bie* ‘don’t,’ *wh*-phrases, or A-not-A question morphology. Overall, compared to desire verb complements, belief verb complements and declarative main clauses have higher rates of overt subjects, modals, and aspect markers. This difference in profiles parallels our CHILDES findings. Of course, there are differences in the magnitudes between the Treebank and CHILDES data sets. This magnitude difference can be reasonably attributed to more

Table 6. Relative frequencies (%) for syntactic features in declarative clause-like complements of selected belief and desire verbs in the Chinese Treebank, by verb class.

Verb class/Clause type	Overt subject	Modal	Aspect
Declarative main clauses	81.7	8.5	11.8
Belief verb complements	79.7	19.5	10.0
Desire verb complements	4.7	1.3	0.7
Complement of *xiang* 'think, want'	26.9	11.6	2.4
Complement of *xiwang* 'hope'	52.6	33.9	1.0

basic differences between the two data sets: The Treebank is much larger, covers different registers of Mandarin and is annotated differently.

Likewise, Table 7 shows that at the verb level, clause-like complements of belief verbs resemble declaratives, but those of desire verbs do not: There are clear differences in the relative frequencies for each syntactic feature between the complements of belief and desire verbs.

As mentioned previously, some desire verbs can appear in object control frames, where an NP object immediately precedes the clausal complement, such that it could be mistaken as the clause's subject (the clause is analyzed as having a null subject). Because the relative frequencies of overt subjects reported in Tables 6 and 7 disregard the presence of these objects, we calculate an alternative measure of the relative frequency of overt subjects: If an overt NP object is present, we treat the clause as having an overt subject, even if the Treebank posits a null subject.

Under this alternative analysis, the relative frequency of overt subjects for desire verbs as a class increases to 14%. Although higher than the 4.7% reported in Table 6, it is still clearly much lower than the corresponding relative frequency for declarative main clauses or for belief verb complements. At the verb level, the magnitude of increase varies. For *yao* 'want' (the most common desire verb) and *xuyao* 'need,' the relative frequency for overt subjects rises to 7% and 17% respectively. However, for *yaoqiu* 'request,' the relative frequency rises to 77%, comparable to that of a belief verb. The magnitude of this increase has a very limited impact on the overall relative frequency for the class of desire verbs because *yaoqiu* is much less frequent compared to *yao* (by about a factor of 10), where the increase is much smaller.

In summary, our analysis of the Chinese Treebank reveals again a contrast between belief and desire verbs' complements and a resemblance between belief complements and declarative main clauses. In this regard, the Chinese Treebank results replicate those of child-ambient speech corpora, showing that the differences in morphosyntactic profiles are robust across registers and annotation standards. It affirms our earlier conclusion that clear morphosyntactic contrasts are likely to be present in child-ambient speech.

Table 7. Relative frequencies (%) for syntactic features in declarative clause-like complements of selected belief and desire verbs in the Chinese Treebank.

Verb class/Clause type	Overt subject	Modal	Aspect
Declarative main clauses	81.7	8.5	11.8
Belief verb complements			
shuo 'say'	81.7	15.6	11.8
biaoshi 'say'	73.5	25.3	7.3
renwei 'think'	85.8	24.7	7.1
juede 'feel'	62.3	15.5	5.1
zhidao 'know'	83.4	12.9	16.3
Desire verb complements			
yao 'want'	3.8	1.0	0.8
yaoqiu 'request'	7.4	6.5	0.3
xuyao 'need'	9.9	0.0	0.4

4.3. *Discussion*

Our corpus analyses addressed concerns about the input for syntactic bootstrapping in Mandarin. Because the relevant morphosyntactic properties are all optional in Mandarin clauses, there could have been few or no observable differences between belief and desire complements, and declarative main clauses could have morphosyntactic profiles that are quite different from belief complements. If this were the case, learners would have no way of morphosyntactically distinguishing between belief and desire complements and declarative main clauses.

Our child-ambient speech corpus analysis, backed up by our Chinese Treebank analysis, indicate that the requirements of the bootstrapping account can actually be satisfied in the input of Mandarin learners. At the verb class level, belief complements tend to pattern more like declarative main clauses, but desire complements do not. We observe the same contrast at the individual verb level as well for the most frequent verbs. If Mandarin learners have sufficient knowledge of Mandarin's morphosyntax and can track the overall distribution of these morphosyntactic features fairly accurately in the input, they should be able to distinguish between the two classes of attitude verbs morphosyntactically and semantically.

At the corpus level then, Mandarin turns out to make similar distinctions like languages such as English, even though the specifics of Mandarin and English morphosyntax are of course very different. The input is thus rich enough to make syntactic bootstrapping feasible for Mandarin learners. Our findings echo remarks and corpus analyses by Lee & Naigles (2005), who independently conclude from corpus data that syntactic bootstrapping is feasible for other verb classes in Mandarin.

5. A computational model of syntactic bootstrapping

The corpus study showed that the necessary conditions for syntactic bootstrapping attitude verbs are present in naturalistic contexts in Mandarin, just as they are in morphologically richer languages. However, the corpus results alone cannot show that the abstract distributional differences between complement clauses and declarative main clauses will yield the right semantic classification. To provide more direct support for the proposal, we extend a model by White, Hacquard & Lidz (2018), which itself builds on the models of White (2015) and White & Rawlins (2016). White, Hacquard & Lidz's model implements the bootstrapping hypothesis, without hardcoding any language-specific morphosyntactic properties. However, the model was only tested on English child-ambient speech data. Given the problems set out in the previous section, Mandarin presents an ideal test case for evaluating the cross-linguistic robustness of the model.

Following White, Hacquard & Lidz (2018), for the purposes of modeling, we will adopt a stronger version of the bootstrapping hypothesis: learners not only exploit the morphosyntactic parallels between belief complements and declaratives but also the parallels between desire complements and imperatives to the extent that such parallels exist. In the context of Mandarin, this is not an unfair assumption. Impressionistically, imperatives seem to occur more frequently without overt subjects, not unlike desire complements. The same modals and aspect markers that do not appear in desire complements also cannot appear in imperatives, as we noted in Section 3.

In what follows, we review this computational model and how we adapt it. We then present results of a set of simulations: we run the model, first on White, Hacquard & Lidz's (2018) English data as a control, to replicate their results, then on a set of semi-automatically annotated Mandarin child-ambient speech data from the CHILDES database (MacWhinney 2000). To preview our findings, we show that the model successfully assigns the correct semantics to some of the most common belief and desire verbs in Mandarin and English. The data and code for the model can be accessed at github.com/z-n-huang/SyntacticBootstrappingModel

5.1. *Model preliminaries*

The general intuition behind the model goes as follows: The semantic class of an attitude verb can be characterized with a predetermined set of semantic features, including features for belief and desire. A set of projection principles map these semantic features to morphosyntactic features of the verb's complement. These assumptions capture the fact that (i) verbs, such as *hope* or *love*, can have multiple semantic features—e.g., both belief and desire—while others, like *think* or *want*, might only have one; and that (ii) differences in verb semantics have morphosyntactic reflexes. The learner's task is to use observed morphosyntactic features and projection principles to determine what semantic features are implied by these observations.

These assumptions do not yet implement the core idea in the bootstrapping proposal: that learners exploit the morphosyntactic similarities between the complement clauses of belief verbs and declarative main clauses. To do so, we stipulate that declarative and imperative clauses are actually embedded under two abstract speech act-related attitude verbs, which we will call ASSERT and REQUEST respectively. To be sure, we are not committed to the formal existence of ASSERT and REQUEST as verbs. Rather, this is a stipulation that formally lets us capture the idea that learners have knowledge of speech acts and can tell whether a main clause is used for assertions or requests. (For various implementations of ASSERT and REQUEST in the literature, see Ross 1970; Krifka 2001; Hacquard 2010, among others.)

To that end, we further assume that learners know the semantics of ASSERT and REQUEST. Since speakers make assertions when they believe the related propositions to be true (setting aside instances of lying), we make the (not unreasonable) stipulation that learners know that ASSERT has only belief semantics. Likewise, since speakers make requests when they want something to happen, we stipulate that learners know that REQUEST has only desire semantics.

Since the semantics of ASSERT and REQUEST are known, learners can use the observed morphosyntactic features of declarative and imperative clauses to draw conclusions about what abstract projection rules their languages have for mapping belief and desire semantics to morphosyntax. With these projection principles in place, they can then use observed morphosyntactic features of a verb's complement to determine what semantic class it belongs to.

More technically, following White, Hacquard & Lidz (2018), we approximate a learner's knowledge of verb semantics with a matrix **S**. An element in **S**, call it s_{vk}, denotes the probability that a verb v has a semantic feature k. We can therefore mathematically encode the stipulation that ASSERT has only belief semantics, by setting $s_{ASSERT,belief}$ to 1, while setting $s_{ASSERT,k}$ to 0 for all other semantic features k. Likewise, $s_{REQUEST,desire}$ is always equal to 1, while $s_{REQUEST,k}$ is 0 for all other k.

The projection principles are represented by a matrix **P**. An element in **P**, call it p_{kf}, denotes the probability that a semantic feature k projects onto a language-specific morphosyntactic feature f. Finally, a third matrix **O** describes the probability that the learner will actually observe verb v with feature k (notated as o_{vk}); this lets us model idiosyncrasies associated with individual verbs.

The distribution of a given morphosyntactic feature f for a given verb v, which we notate as d_{vf}, can then be defined probabilistically, as a function of s_{vk} (the probability that verb v has a semantic feature k), o_{vk} (the probability that v actually instantiates k), and p_{kf} (the probability that k projects onto morphosyntactic feature f). To illustrate this intuition, suppose that a verb v has a 60% probability of bearing a belief semantic feature ($s_{v,belief} = 0.6$). Suppose further that in general, the belief feature projects onto the verb's complement having an overt subject 30% of the time ($p_{belief,subject} = 0.3$), but learners observe the verb with the belief semantics only 80% of the time ($o_{v,belief} = 0.8$). Given the belief semantic feature, the probability of observing an overt subject with the verb is $s_{v,belief}\, o_{v,belief}\, p_{belief,subject}$ = 60% × 80% × 30% = 14.4%.

The probability of observing a morphosyntactic feature f across all semantic features is calculated in a similar way, as given in (11). As explained by White, Hacquard & Lidz (2018), this formula is derived under a set of strong independence assumptions: $1 - s_{vk}\ o_{vk}\ p_{kf}$ is the probability that a semantic feature k does not project onto a syntactic feature f. Assuming independence, Π_k $(1 - s_{vk}\, o_{vk}\, p_{kf})$ is the probability that none of the semantic features projects onto this feature. Consequently, $1 - \Pi_k$ $(1 - s_{vk}\, o_{vk}\, p_{kf})$ is the probability that there is at least one semantic feature with this projection property.

(11) For a given verb v and morphosyntactic feature f,

$d_{vf} = 1 - \Pi_k (1 - s_{vk}\, o_{vk}\, p_{kf})$, where k ranges over semantic components.

Within an utterance i, for a morphosyntactic feature f and a verb v, there are two logically possible outcomes, which we label as x_{if}. Either the feature is observed ($x_{if} = 1$), with probability d_{vf}, or it is not ($x_{if} = 0$), with probability $1 - d_{vf}$. In other words, the observation of a morphosyntactic feature f occurring with a verb v in a given utterance i (or the failure to make such an observation) follows a Bernoulli distribution stated in terms of d_{vf} (12).

(12) $\mathrm{P}(x_{if}|\ v, i, \mathbf{S}, \mathbf{O}, \mathbf{P}) = (d_{vf})^{x_{if}} (1 - d_{vf})^{(1-x_{if})}$

We further assume that whether a morphosyntactic feature is observed for a verb in an utterance is conditionally independent of the observation of other features. The probability that we observe a particular combination of features $\mathbf{x}_i$ for a given verb in an utterance is therefore the product of the distribution of each of the component features (13). For illustration, suppose that the probability of observing an overt subject is 60% and the probability of observing an aspect marker is 50%. If both observations are independent, the probability of observing both an overt subject and an aspect marker within a single utterance is 60% × 50% = 30%.

(13) $\mathrm{P}(\mathbf{x}_i|\ v, i, \mathbf{S}, \mathbf{O}, \mathbf{P}) = \Pi_f\, (d_{vf})^{x_{if}} (1 - d_{vf})^{(1-x_{if})}$

Let us now consider how learning is implemented in this framework. We randomly initialize the matrices **S, O**, and **P** such that every element in each matrix, with the exception of ASSERT and REQUEST, begins with a probability around 0.5. What this means, for instance, is that the learner begins with the assumption that the probabilities of belief semantics and desire semantics for a given attitude verb is 50%.

The learner then observes a series of utterances, or more precisely, a series of binary syntactic feature combinations, one for each verb and its complement. A hypothetical English example featuring the verb *want* is given in (14):

(14) Utterance: "I want to play."

Feature combination: [*want*, –NP object, +complement clause, –embedded WH, –embedded subject, –embedded tense, +embedded infinitival]

For each verb and combination of syntactic features observed, the learner computes the probability of observing that feature combination, using **S, O**, and **P**. The learner then compares the observed features and his/her predictions, adjusting the values of **S, O**, and **P** to maximize the probability of the data set (specifically, the log-likelihood). Crucially, the way **S** is set up means that it is logically possible that the learner ends up concluding that some verb has high probabilities for both belief and desire semantics. Such a scenario is necessary, given existing proposals that a small subset of attitude verbs, like English *hope*, encode both belief and desire semantics (Portner 1992; Scheffler 2009; Anand & Hacquard 2013).

Our stipulations about the semantics of ASSERT and REQUEST effectively impose strong constraints on how much the model can adjust **P**. Intuitively, since ASSERT only has belief semantics ($s_{ASSERT,belief} = 1$), the probability that belief semantics projects onto a particular syntactic feature f ($p_{belief,f}$) must track the actual relative frequency of f in declaratives, if the model's predictions about ASSERT (declaratives) are not to diverge too much from actual observations. Similarly, because REQUEST only has desire semantics ($s_{REQUEST,desire} = 1$), $p_{desire,f}$ also ends up tracking the actual relative frequency of f in imperatives.

Consequently, most of the adjustment that the model can make in response to observed syntactic features for a verb is to either **S** or **O**. White, Hacquard & Lidz (2018) introduce a bias in the algorithm, obliging the model to prefer adjusting **S** rather than **O**. Specifically, there is an independent sparse Beta (0.5, 0.5) prior on s_{vk} and an independent dense Beta(2, 2) prior on o_{vk}. The bias means that the model makes strong predictions about the semantic components for a given verb. In fact, to the extent that the verb's complement clause resembles the average declarative clause, the model will adjust **S** so the verb's semantic profile more closely resembles that of ASSERT; the same can be said for imperatives and REQUEST.

5.2. *An "either-or" bias*

We supplement White, Hacquard & Lidz's (2018) model with what we call an "either-or" bias. With this bias, the model adjusts **S** so that a verb v is likely to have a high $s_{v,belief}$ ("high-belief"), or a high $s_{v,desire}$ ("high-desire") but not a high $s_{v,belief}$ and high $s_{v,desire}$ (high-belief and high-desire, like *hope*). Importantly, though, the model can still represent some verbs using multiple semantic features (in contrast to models like the one proposed by Barak, Fazly & Stevenson 2014); there is merely a bias against them.

This bias is motivated by the fact that the model requires a morphosyntactic distinction between declarative and imperative main clauses. However, the distinction might not be as clear as desired in many languages, such as varieties of Chinese and typologically similar languages. In these languages, for any actual attitude verb example that the model observes, the complement clause will have the same morphosyntactic profile as a subset of declarative clauses and a subset of imperative clauses. The model will therefore raise the probability that the verb has both belief and desire semantics. In many cases, this might mean that it will incorrectly conclude that the verb has *hope*-like semantics.

To the extent that the bias is necessary, an important question to ask is what this bias actually means for the actual language acquisition process. Two possibilities stand out, although we will not be able to provide a definitive argument in favor of one or the other. The first possibility is that it reflects an actual bias on the part of the learner. It seems not implausible that learners might have a bias for expecting that any given verb (or any lexical item, for that matter) should belong to only one semantic class and not two or more classes. Conceptually, this bears a resemblance to mutual exclusivity biases discussed in the literature on word learning, in which learners avoid positing that words have overlapping denotations (see, for instance, Markman & Wachtel 1988; Merriman & Bowman 1989; Markman, Wasow & Hansen 2003). It is crucially distinct, however, in that one word's falling into a semantic class—here, the belief or desire class—does not exclude other words from falling into that class.

Another logical possibility is that this bias is an artifact, reflecting a limitation of the input data used by the computational model. For the sake of discussion, suppose that there is some salient but hard-to-transcribe linguistic feature—perhaps relating to sentence prosody or context—that reliably distinguishes imperatives from declaratives and belief complements. Although learners find it easy to observe this feature in their input, there is no way to represent it clearly in the transcripts. Consequently, this particular feature, necessary for successful bootstrapping, is missing from the model's input. In this analysis, the bias serves as a workaround to this problem.

In the model, we implement this bias with a penalty based on Jensen-Shannon Divergence (JSD) (15). The intuition behind this penalty is as follows. For a given verb v, if $s_{v,belief}$ is high and $s_{v,desire}$ is low (high-belief and low-desire, like *think*), then $1 - s_{v,desire}$ would be a good approximation for $s_{v,belief}$

and so would $1 - s_{v,belief}$ for $s_{v,desire}$. The same applies to a low-belief, high-desire verb (like *want*). The JSD quantifies how good this approximation is: The better the approximation, the lower the JSD value. In contrast, when a verb is both high-belief and high-desire (like *hope*), $1 - s_{v,desire}$ and $s_{v,desire}$ will be poor approximations for $s_{v,belief}$ and $1 - s_{v,belief}$ respectively. The JSD value in that scenario will be high.

(15) Jensen-Shannon Divergence penalty

For a given verb *v*:

- Belief_v is a discrete probability distribution with two possible outcomes: $\text{Belief}_v(1) = s_{v,belief}$, and $\text{Belief}_v(0) = 1 - s_{v,belief}$
- Similarly, Not-Desire_v is a discrete probability distribution with two possible outcomes: $\text{Not-Desire}_v(1) = 1 - s_{v,desire}$ and $\text{Not-Desire}_v(0) = s_{v,desire}$
- The penalty $\text{JSD}_v = 0.5\ \text{D}(\text{Belief}_v||\text{M}_v) + 0.5\ \text{D}(\text{Not-Desire}_v||\text{M}_v)$, where D is the Kullback-Leibler divergence, stated in nats, and $\text{M}_v = 0.5\ (\text{Belief}_v + \text{Not-Desire}_v)$; in other words, $\text{M}_v(1) = 0.5\ (s_{v,belief} + 1 - s_{v,desire})$ and $\text{M}_v(0) = 0.5\ (1 - s_{v,belief} + s_{v,desire})$.[5]

For a given utterance, the model calculates the JSD penalty for each verb. It then subtracts the mean JSD penalty from the log-likelihood of the data, so that the higher the penalty, the lower the adjusted log-likelihood. Since the model is designed to maximize log-likelihood, it has an “incentive” to adjust the belief/desire probabilities in a way that minimizes the penalty.

5.3. *The data*

5.3.1. *English*

Since we were interested in replicating White, Hacquard, and Lidz’s (2018) results for English, we used their Gleason corpus data set (Gleason 1980). Briefly, this data set was created by combining the dinner and play session recordings for each child in the Gleason corpus on CHILDES (MacWhinney 2000) to form 22 subcorpora. Morphosyntactic features were extracted using morphological analyzers and a dependency parser. We refer readers to White, Hacquard & Lidz’s (2018) paper (also White et al., under review) for more details about this annotation process.

As White, Hacquard & Lidz (2018) point out, the Gleason corpus is appropriate for several reasons: The children represented in the corpus range from ages 2 to 5, which corresponds to the ages when children acquire their first attitude verbs. Second, the recordings were obtained under fairly naturalistic conditions, namely, play contexts and meal contexts.

5.3.2. *Mandarin*

For Mandarin, we ran the model on a semi-automatically annotated child-ambient speech data, instead of the manually annotated data reported in Section 4. A major reason behind this decision was the fact that the manually annotated data set is relatively small, with some attitude verbs appearing only a handful of times. To ensure the model would have a larger set of tokens to work with, especially for the lower-frequency verbs, we pooled 10 CHILDES corpora: Chang1, Chang2, ChangPNTrad, the Taiwan Corpus of Child Mandarin, Tong, Zhou1, Zhou2, Zhou3, ZhouAssessment, and ZhouDinner (Chang 1998, 2003; McCabe & Chang 2013; Cheung et al. 2011; Deng & Yip 2018; J. Zhou 2001; X. Li & Zhou 2004; L. Zhang & Zhou 2009; H. Li & Zhou 2015). Again, it should be noted that the data were collected under a variety of conditions, and the age range of the children also varies (although mostly within the 3 to 6 range).

[5]We also tested an alternative but mathematically related version of this penalty on the English data set. For each verb, we first calculate two Kullback-Leibler divergence measures, $\text{D}(\text{Belief}_v||\text{Not-Desire}_v)$ and $\text{D}(\text{Desire}_v||\text{Not-Belief}_v)$. The penalty is calculated as the mean of the two measures. For space reasons, we do not report results obtained with this alternative penalty, except to note that they are very similar to the English results reported below in Section 5.4.

Because of the size of this pooled data set, we automated the annotation process using the Python natural language analysis package Stanza (Qi et al. 2020). Because the Chinese language models within Stanza only work with Chinese characters, we had to exclude corpora with Romanized transcripts, such as the Beijing corpus (Tardif 1993, 1996), from this data set.

The transcripts were preprocessed to exclude speech from the target children, as well as to standardize the orthography (e.g., convert transcripts in traditional Chinese to simplified Chinese) and remove special symbols, such as paralinguistic notation. From these transcripts, we randomly generate 10 samples of 5,000 utterances. The goal here was to create a set of subcorpora to mimic the structure of the Gleason data set.

The cleaned-up transcripts were then assigned part-of-speech tags and dependency parses using the simplified Chinese model in Stanza. A script was written to read the tags and parse for each sentence to extract relevant morphosyntactic information: what verbs were present in an utterance; for each verb, whether it had a nominal or clausal complement; whether the complement contained any hallmarks of interrogatives, such as *wh*-phrases; and most importantly, whether the complement clause contained overt subjects, modals, and aspect markers. Where possible, we used Stanza's annotations to determine if a clause contained an overt subject and postverbal aspect markers. For modals, the script checked the complement to see if it contained a lexical item that matched the set of modals listed in Footnote 4. The script also checked to see whether a clause contained preverbal aspect markers, namely, progressive *zai* and negative *mei*(*you*).

An important limitation is that the Stanza parser does not always produce the correct tags or parses. Although we used the script that reads the Stanza output to try to correct more common errors, the output of this process inevitably still contained some noise.

We did not use this automated annotation process for main clauses, where we needed to also determine whether main clauses were declarative or imperative. Because imperatives and declaratives can appear in string-identical frames, we can only reliably differentiate them by referring to context. We therefore randomly extracted a set of 600 utterances and their contexts, defined as the four utterances immediately preceding the utterance of interest and the utterance immediately following it. These utterances were then manually inspected and annotated for their clause type and morphosyntactic features. The ratio of declarative to imperative main clauses (2:1) and the frequency of morphosyntactic features for declaratives and imperatives were then extrapolated from this sample to apply to all noninterrogative main clauses in the entire corpus.

In Table 8, we give a summary of the morphosyntactic profiles of declarative clause-like complements for 10 prominent verbs with attitude semantics, aggregating across all 10 samples. Once again, we sort these verbs by verb class, setting aside *xiang*. We note that *xiang*'s profile is actually a mix of both

Table 8. Relative frequencies (%) for syntactic features in declarative clause-like complements of selected belief and desire verbs in sample of 50,000 utterances.

Verb	Overt subject	Modal	Aspect
Belief verbs			
kan 'see'	55.3	9.4	5.8
shuo 'say'	57.2	5.6	3.7
jiang 'say'	52.4	0.6	2.4
zhidao 'know'	55.8	6.7	8.7
gaosu 'tell'	89.3	1.3	10.7
juede 'feel'	62.0	13.0	5.6
Desire verbs			
yao 'want'	5.0	0.4	2.8
xihuan 'like'	8.6	0.0	0.7
zhunbei 'get ready to'	9.5	0.0	2.4
Other			
xiang 'think, want'	4.2	3.7	1.1
Main clauses (600-utterance sample)			
Declarative	60.3	6.7	8.4
Imperative	26.7	1.1	0.0

'think' and 'want' *xiang*s, as the automated annotation process cannot distinguish between the two uses. We excluded the verb *xiwang* 'hope' from this summary, even though the model was explicitly designed to accommodate 'hope'-like verbs that have both desire and belief semantics. *Xiwang* occurs too infrequently in our sample of child-ambient speech (only three times across all 10 samples).

Overall, overt subjects occur more often in the complements of belief verbs than in the complements of desire verbs. Similar contrasts also seem to exist for modals and aspect markers, although the difference is not as clear, because modals and aspect markers are relatively infrequent even in belief complements. Similarly, overt subjects, modals, and aspect markers also appear more frequently in declarative main clauses than imperative main clauses. In fact, these features appear in declaratives at a rate comparable to their frequency in belief complements.

Broadly speaking, these results converge with the CHILDES corpus analysis reported in Section 4: The syntactic profiles of belief and desire complements in child-ambient speech show a similar split, and the profile of belief complements resembles that of declaratives. We take this convergence as validation of our semi-automated annotation process. One could also understand the convergence to mean that the similarities and differences in syntactic profiles are robust enough as to not be obscured by the less accurate semi-automated annotation process.

5.4. *Experiment*

Following White, Hacquard & Lidz (2018), we set the number of semantic features to eight; two of these features are explicitly reserved as belief and desire features—these determine whether the verb has belief and/or desire semantics. The remaining six semantic features can be thought of as semantic properties that also contribute to the likelihood the verb appears with overt subjects, modals, and aspect markers. Recall that for each verb (except ASSERT and REQUEST), the probability of belief and desire features is initialized to 0.5. If the model is able to learn the right semantics for a verb, we expect these probabilities to change in a way that matches our intuitions about the verb. For instance, for a verb like *think*, the probability for the belief feature should rise from 0.5 to approach 1, while the probability for the desire feature should fall from 0.5 to approach 0.

The model was run on the English and Mandarin data sets. The English data set consists of 10 Gleason subcorpora (transcripts for the children "Andy" through "Julie"). The Mandarin data set consists of the 10 samples described in Section 5.3. Each subcorpus or sample can be thought of as a sample of the input available to a child. For each subcorpus/sample, the model observes one

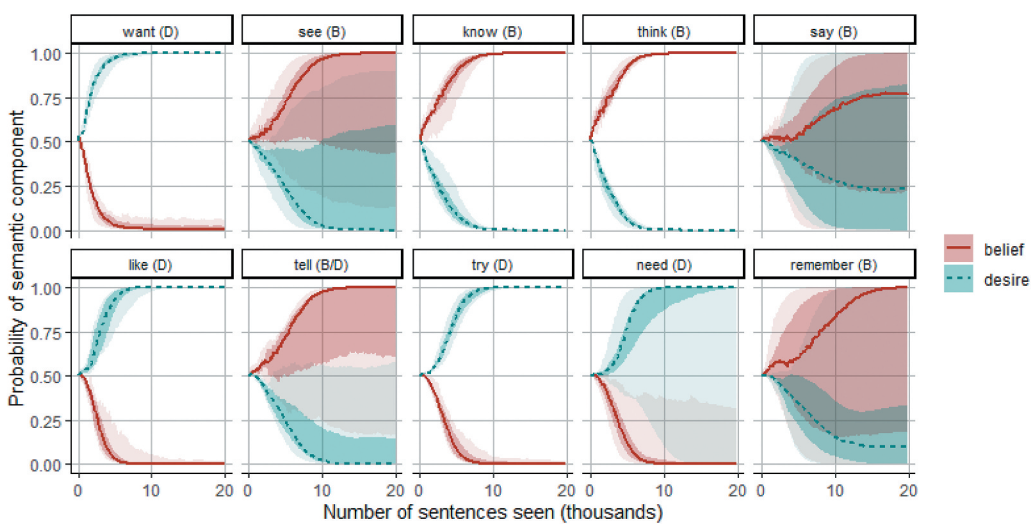

Figure 1. Belief and desire semantic features, for English model with either-or bias (B = belief verb; D = desire verb).

randomly selected utterance at a time until it has seen 20,000 utterances. As argued by White, Hacquard & Lidz (2018), 20,000 represents an estimate of the number of utterances a child might observe in a month. Following White, Hacquard & Lidz, we repeat this procedure 10 times.

To assess the empirical impact of the either-or bias, we run the algorithm on each data set two times, first with the bias, and then without the bias. To the extent the bias is necessary, we expect the first set of model results to better align with our intuitions. We report the aggregated results, first for English, as a replication of White, Hacquard & Lidz's (2018) experiment, and then for Mandarin.

5.4.1. *English*

Figure 1 shows median probabilities for the belief and desire semantic features, with the either-or bias incorporated in the model. Darker bands around the median show the interquartile range, while lighter bands show the range between maximum and minimum values; gray indicates that the bands overlap. The verbs presented here are the 10 attitude verbs modeled by White, Hacquard & Lidz (2018).

As indicated by the narrow bands, the model learns that verbs like *want* and *like* are clearly desire verbs, while verbs like *know* and *think* are clearly belief verbs. We further observe that it learns relatively quickly: The difference between belief and desire probabilities diverge by around 10,000 sentences for a number of these verbs.

However, there are a few verbs with relatively wide bands, such as *see*, suggesting that the model does not draw as clear a distinction between belief and desire. Even wider bands can be observed for *say* and *remember*. Similar observations were reported by White, Hacquard & Lidz (2018), who attribute poor performance to two reasons. In the case of *see* and *say*, White, Hacquard & Lidz show that these verbs occur with complement clauses infrequently, so the model had relatively few relevant data points to learn from. Since we use the same data set, this is also the case here; Figure 2 shows that complement clauses are less common for *see* and *say* than for *want* or *think*. For *remember* and *need*, White, Hacquard & Lidz report that the dependency parses for the verb are of a low quality, so the model was learning from flawed input representations.

Turning to the model without the either-or bias, we observe greater variability in the results (Figure 3): Bands are generally wider here compared to the previous set of results. The greater variability is visually reminiscent of the results reported by White, Hacquard & Lidz (2018), whose model does not implement such a bias. Even so, the median values still suggest that the model makes the right distinctions for the more prominent attitude verbs, like *want, like, think*, and *know*.

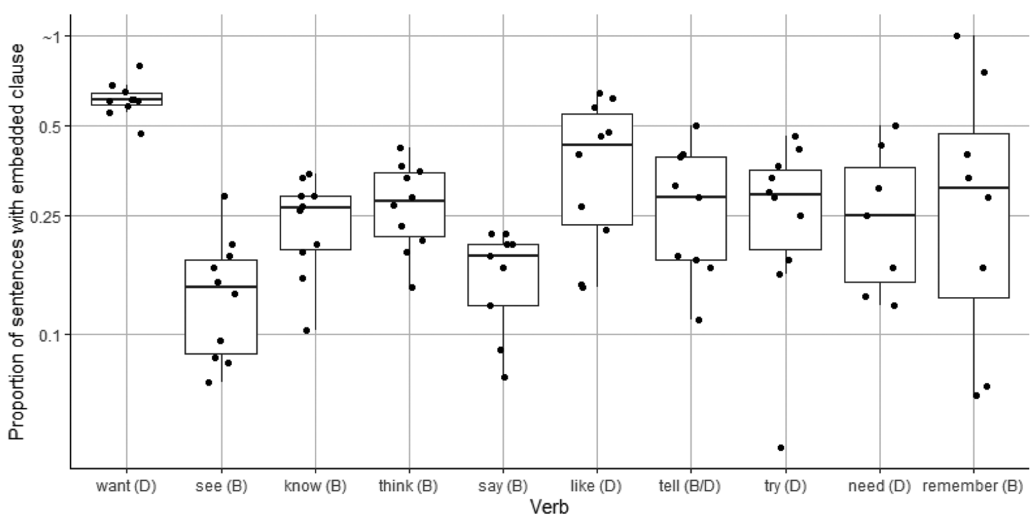

Figure 2. Proportion of English attitude verbs appearing with complement clause (each dot = sample for one learner).

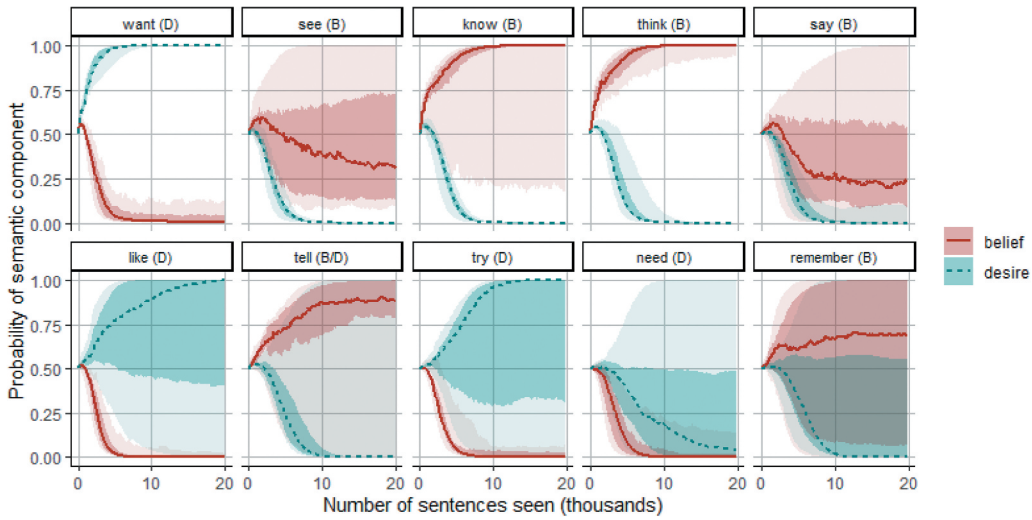

Figure 3. Belief and desire semantic features, for English model without either-or bias.

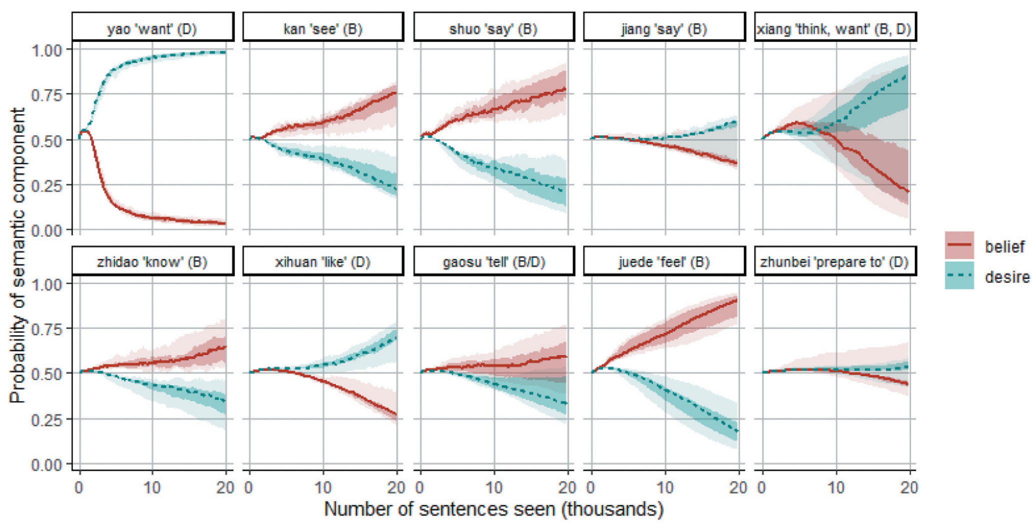

Figure 4. Belief and desire semantic features, for Mandarin model with either-or bias (B = belief verb; D = desire verb).

Overall, we successfully replicated White, Hacquard & Lidz's (2018) modeling results for English. This outcome is expected, since the model was run using essentially the same parameters and data set. However, replicating their results is important because it confirms the validity of the learning algorithm. This in turn validates our decision to apply the model to Mandarin.

5.4.2. *Mandarin*

We begin by reviewing the results for the model featuring the either-or bias (Figure 4). This model robustly learns that Mandarin verbs like *shuo* 'say,' *kan* 'see,' and *juede* 'feel' are belief verbs (and *zhidao* 'know' to a smaller extent), while *yao* 'want' and *xihuan* 'like' are desire verbs. Notably, it draws that conclusion for *yao* even though *yao*'s complement in principle can take an overt subject.

As was the case for English, the model struggles with some verbs. For example, the divergence between belief and desire for *jiang* 'say,' *gaosu* 'tell,' and *zhunbei* 'prepare to' is relatively small. Another interesting case is *xiang*, which has either 'think' or 'want' readings: On average, the model

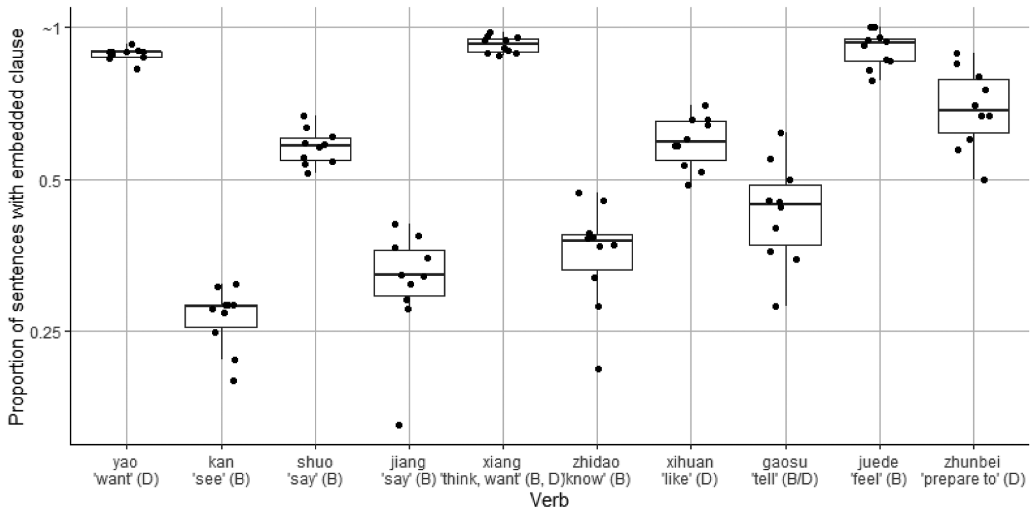

Figure 5. Proportion of Mandarin attitude verbs appearing with complement clause (each dot = sample for one learner).

concludes that *xiang* is more likely to have desire semantics, but it does so with some uncertainty, as the wide bands indicate.

The divergence problem for *jiang* and *gaosu* might be due to their profiles: They have relatively high rates of overt subjects and aspect markers, like declarative main clauses, but relatively low rates of modals, like imperatives (see Table 8). It is harder to attribute this problem to the low rate of clausal complements for these verbs; Figure 5 shows that it does not happen to verbs like *kan* 'see' or *zhidao* 'know' where complement clauses are also relatively infrequent.

In contrast, *zhunbei*'s profile is comparable to the other desire verbs. However, *zhunbei* occurs very infrequently: only 75 times in the entire data set. Considering how rare the verb is, it is unsurprising that the model struggles to draw the right conclusions about its semantics.

The model's lack of certainty with *xiang* is also unsurprising. For one, the model was not instructed that there are actually two uses of *xiang*s, one with a belief reading and another with a desire reading: the *xiang* tokens were not labeled as such. In addition, the overall profile of *xiang* complements has characteristics of both imperatives and declaratives. As shown in Table 8, on one hand, like imperatives, *xiang* complements have a low rate of overt subjects. On the other hand, like declaratives, they have a relatively high rate of modals and aspect markers.

We next discuss results for the Mandarin model without the either-or bias, presented in Figure 6. We do not observe the same kind of divergence as we did before. In fact, for many verbs, both belief and desire features tend to have much higher probabilities. For a subset of these verbs, like *yao* 'want,' *shuo* 'say,' *xiang* 'think, want,' *juede* 'feel,' the median probability of both components is above 0.5: the model seems to conclude that these verbs have *hope*-like semantics. The narrow interquartile ranges further show that this effect is robust.

This outcome bears out a prediction we made in Section 5.2—without the bias, the model will be too liberal in assigning belief and desire semantics to a Mandarin verb. As mentioned previously, for any attitude verb token presented to the model, there will be some declarative and imperative clauses that resemble its complement clause. All else being equal, the model will (incorrectly) raise the probability of belief and desire semantic features for a verb.

5.5. *Discussion*

There are three major takeaways from this set of results.

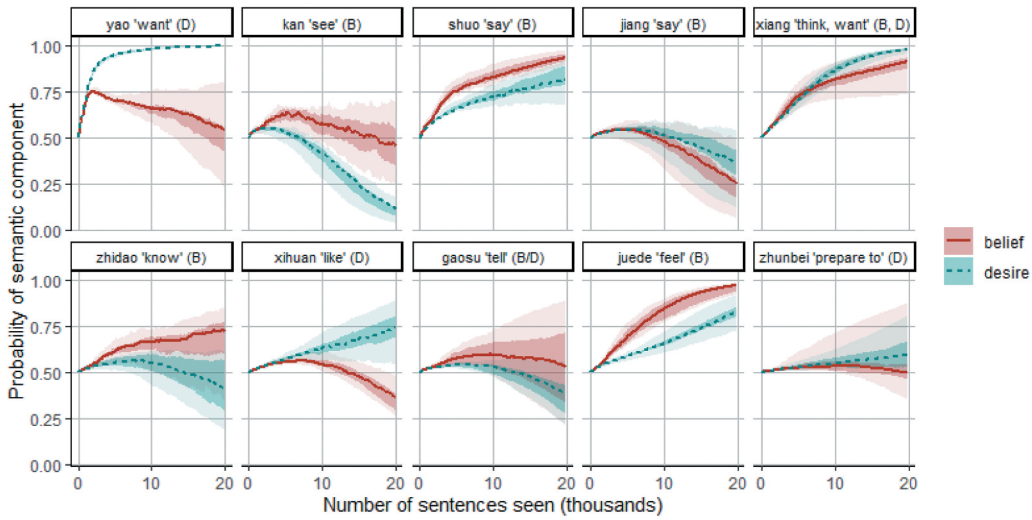

Figure 6. Belief and desire semantic features, for Mandarin model without either-or bias.

First, an either-or bias was critical to model performance in Mandarin: Without the bias, the model tended to fail to differentiate belief and desire semantics for a given verb. The model's poorer performance in the absence of the bias further underscores the importance of having the right learning algorithm. The presence of differences in the morphosyntactic profiles of verbs, reported in Section 4, is necessary, but not sufficient, for ensuring that learners will conclude that verbs fall into distinct semantic classes.

With the bias, a smaller but still noticeable improvement in model performance was also observed in English. The bias "encouraged" belief and desire features to diverge in the correct direction, reducing variability across learners in the process.

More importantly, with this bias in place, the model was able to use only morphosyntactic features to draw the right distinctions for some of the most prominent attitude verbs in both English and Mandarin, such as English *want, think, know*, and Mandarin *yao* 'want,' *shuo* 'say,' *kan* 'see,' and *zhidao* 'know.' These results thus provide novel cross-linguistic support for the syntactic bootstrapping hypothesis and this particular computational implementation.

Finally, the model was able to learn these distinctions relatively quickly, within what might be considered as a month's worth of linguistic input. This is a desirable outcome, as it is consistent with existing experimental research showing that children differentiate between the more common attitude verbs at an early age.

6. General discussion

To recap, syntactic bootstrapping can simplify the learning problem for lexical items that lack reliable physical correlates by capitalizing on correlations between semantics and syntax. However, these accounts are also potentially fragile, as there is no guarantee that the relevant correlations are present cross-linguistically. In the context of attitude verbs, Hacquard & Lidz (2019) have argued that a correlation does exist, although it has to be stated in fairly abstract terms: whether a verb has belief semantics is correlated with whether its complement clause has declarative syntax. With the right level of abstraction, syntactic bootstrapping can work independently of how the syntax-semantics link is actually realized morphosyntactically.

Even so, Hacquard & Lidz's (2019) proposal rests on the premise that there are clear morphosyntactic contrasts between the complements of belief and desire verbs. We put this proposal to a stringent test with Mandarin Chinese. Superficially, Mandarin's impoverished verbal morphology and argument-drop properties mean that there are very few morphosyntactic features that reliably distinguish the complement clauses of belief and desire verbs.

However, our findings suggest that this is not the case. Our corpus analyses (Section 4) show that Mandarin belief and desire verbs have complement clauses with distinct morphosyntactic profiles in naturalistic contexts. In addition, the profile of belief complements resembles that of declarative main clauses. Our model (Section 5) shows that the profile differences can be exploited by Mandarin learners to semantically classify verbs—if learners are sensitive to the presence of overt subjects, modals, and aspect, and can track their distribution.

The results here therefore provide novel support for Hacquard & Lidz's (2019) proposal for the acquisition of attitude verb semantics. It also suggests that their approach of stating the relevant syntactic conditions in sufficiently abstract terms is on the right track. The results also converge with evidence and arguments for syntactic bootstrapping in Mandarin independently put forward by Lee & Naigles (2005), who were concerned with the acquisition of other verb classes, such as transitive and intransitive verbs.

More importantly, our findings are not only relevant for Mandarin (or other varieties of Chinese) but have implications for other languages as well. To the extent that Mandarin is representative of other morphologically poor languages (for instance, other varieties of Chinese and many other [South]east Asian languages), the results should generalize to these languages. The results should also generalize to languages with richer morphology, where morphosyntactic cues are more reliable. Our results therefore provide a novel argument that syntactic bootstrapping is cross-linguistically viable as a learning strategy for attitude verbs.

Having said that, it is also appropriate for us to point out some limitations of our findings. First, although our corpus and modeling results provide a proof of concept that Mandarin learners can use the distribution of syntactic cues to learn the semantics of attitude verbs, it remains to be seen whether Mandarin learners actually do so in reality. This is a question that requires experimental verification, as Harrigan, Hacquard & Lidz (2016, 2019) and Lidz, Dudley & Hacquard (2016) have done for English.

A second limitation is with respect to the either-or bias. Although the results demonstrate the utility of such a bias, there is a possibility that the bias, as currently implemented, is too powerful and poses an obstacle for learning verbs with *hope* semantics, i.e., verbs that denote both belief and desire. Ideally, one would evaluate this possibility by checking how the model performs with actual tokens of *hope* and its Mandarin equivalent, *xiwang*. However, doing so is actually challenging because both verbs occur too infrequently in child-ambient speech for us to draw firm conclusions. *Hope* occurs only 10 times in the Gleason corpus, and *xiwang* occurs only three times in the 50,000-utterance Mandarin corpus.

Another limitation concerns polysemy, which we use loosely to refer to the existence of multiple readings associated with a single form (we remain neutral about the technical questions of whether the readings are actually associated with a single lexical item or multiple lexical items and whether they reflect different truth conditions or some interaction between verb semantics and pragmatic enrichment). For modeling purposes, we have assumed that a lexical item has only one reading, but of course, this assumption does not always hold in reality. Here, we briefly discuss how this issue affects two of the more common attitude verbs in Mandarin.

The first is *yao*, which we have usually referred to as 'want.' Strictly speaking, there are two other readings that *yao* could have when it appears with a complement clause without an overt subject. The first is a deontic modal reading (19a), similar to English *need* or *must*, as well as a future reading (19b), like English *will* or *be going to* (for further discussion, see, e.g., Lin 2012; Huang et al., forthcoming, and references therein). Our model does not make this kind of fine-grained distinction. In naturalistic contexts though, the distinction is not always clear to native speakers either. While manually annotating the corpora described in Section 4, we noticed that one must often refer to the situational context to determine which reading is intended, and even then, doing so does not guarantee disambiguation.

(19) a. Ni yao duo chi shuiguo.

you want more eat fruit

'You need to eat more fruit (the doctor ordered you to do so).'

b. Yao xiayu le.

want rain PART

'It's going to rain.'

The second case is *xiang*, which has 'think' and 'want' uses. There is some reason to believe that the two readings might be a case of lexical ambiguity, in that there are actually two *xiang*s with distinct syntactic and semantic properties. *Xiang* with the 'want' reading can be negated with *bu* (20a) such that negation is interpreted in the embedded clause (in other words, *xiang* here is neg-raising). In contrast, *xiang* with the 'think' reading cannot be negated by *bu* at all (20b). The model, of course, does not distinguish between these two *xiang*s.

(20) a. Wo bu xiang chi shuiguo.

I not want eat fruit

'I don't want to eat fruit.' (more accurately, 'I want to not eat fruit.')

b. *Wo bu xiang gou hui pa shu.

I not think dog can climb tree

Intended: 'I don't think dogs can climb trees.'/'I think dogs cannot climb trees.'

To be clear, the problem posed by polysemy (or lexical ambiguity) should not be seen as a weakness of the bootstrapping hypothesis because it is not the problem the hypothesis is intended to solve. The problem posed by polysemy—figuring out what readings a given form has and how these readings are represented—is an independent problem that goes well beyond attitude verbs. For this reason, it is unfair to expect the bootstrapping hypothesis to provide a solution. Instead, the hypothesis is intended to explain how learners might learn what a given lexical item means, when its meaning cannot be easily inferred from one's situational context. Our English and Mandarin modeling results show that it can handle this second problem effectively.

7. Conclusion

This article was concerned with a learning problem that appears across languages: how learners determine the meanings of attitude verbs, which are difficult to infer from the situational context alone. We considered syntactic bootstrapping as a solution to this problem: learners make use of more easily observed morphosyntactic cues to draw inferences about verb semantics.

Syntactic bootstrapping is particularly attractive as a solution because cross-linguistically, the semantic distinction between belief and desire verbs has morphosyntactic reflexes in the complement clauses of the verbs. In fact, the differences between these two types of complement clauses can be stated in an abstract way that is flexible enough to accommodate language-specific morphosyntactic differences: belief complements have a morphosyntactic profile that resembles declarative main clauses, the clause type typically used for assertions, i.e., expressions of belief. In addition, belief complements are also often indirectly asserted. Learners can then exploit this link to infer that belief verbs have a semantics that express the attitude holder's commitment to the truth of the belief complement.

Empirical evidence for this hypothesis has so far been based on languages like English, Romance, and German, where both types of complement clauses can be readily differentiated. Here, we considered a worst-case scenario for this hypothesis: Mandarin Chinese, a language in which there might be little or no differentiation between both types of complement clauses, due to the language's impoverished morphosyntax.

Our study suggests that Mandarin's impoverished morphosyntax does not pose as serious a problem as it first appears. Drawing on existing work on Chinese syntax, we show that the morphosyntactic contrasts required for this hypothesis are present in Mandarin child-ambient speech, at an aggregate level. We further showed computationally how a learner might use these morphosyntactic contrasts to distinguish between different semantic classes. On the assumption that these verbs tend to have either belief semantics or desire semantics, our model was able to assign the right semantic classes to high-frequency attitude verbs in Mandarin and English by tracking morphosyntactic features. Far from being a counterexample, Mandarin turns out to provide a strong argument in favor of this syntactic bootstrapping hypothesis.

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Declaration of interest statement

The authors have no conflicts of interest to report.

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