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**Syntactic bootstrapping as a mechanism for language learning****(To appear in *Nature Reviews Psychology*)**

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**Abstract**

How do young children solve the puzzle of mapping words to their meanings? Over decades, several mechanisms have been put forward in theories of language acquisition, and evidently such a complex problem calls for synergies between complementary mechanisms. Syntactic bootstrapping has been one of the most influential of these theories, postulating that young children learn the meaning of words (and in particular, verbs) by paying attention to the syntactic structures in which they occur. In this Review, we first look at the academic climate and pivotal experimental findings that gave rise to the syntactic bootstrapping hypothesis, how this word learning mechanism was investigated for decades, and the role it may play in the future. Drawing on insights from cognitive and developmental psychology, we discuss the prerequisites behind such a powerful inference process and connect it to contemporary learning frameworks examining how humans build and update their knowledge about the world. Syntactic bootstrapping has shaped language acquisition theory as we know it, and the theory has reshaped syntactic bootstrapping in turn - leading to ground-breaking insights into how children assign meanings to words, and more generally how they learn the complex network that is language.

## 55 Introduction

56  
 57 Children acquire hundreds of words in their second year of life, and how they learn so much in so little time  
 58 remains a central question in language development research. One of the major obstacles to word learning<sup>1</sup>  
 59 is that the evidence in a child’s environment for what a word means is both limited and noisy. It is limited,  
 60 for example, because a child cannot observe all the possible referents of a word in the world; and it is noisy,  
 61 for example, because sometimes caregivers talk about objects and events that do not unfold in front of their  
 62 eyes. Some parts of the input, however, provide highly reliable cues to meaning. Syntax is one such cue  
 63 (Box 1): How a word is used in a sentence depends on its meaning. For example, in English, nouns can be  
 64 preceded by determiners (e.g., a mouse) but not pronouns (e.g., \*they mouse<sup>2</sup>). The sentence frame can thus  
 65 serve as, what we term, a ‘meaning frame’, narrowing down the scope of possible meanings an unknown  
 66 word may have. Meaning frames are particularly valuable when evidence is limited and noisy because they  
 67 can direct learning in the right direction. For example, they could subset the possible meanings of a word  
 68 with the highest likelihood to just objects or just verbs (e.g., a *bamoule* vs. they *bamoule*). However, to use  
 69 syntax to learn words, children who themselves comprehend a limited number of words, would first need  
 70 to learn enough about the syntax of their native language and how it relates to meaning.

71  
 72 Empirical research has robustly shown that, despite the ostensible complexity of the task they face  
 73 at such an early age, toddlers use syntax to bootstrap vocabulary learning (for a metanalysis see: <sup>1</sup>). This  
 74 capacity is called ‘syntactic bootstrapping’<sup>2</sup>, and has been observed in toddlers as young as 15 months old  
 75 and for a wide variety of syntactic, as well as morphological, structures (e.g., <sup>3-5</sup>; for a review: <sup>6</sup>). Syntactic  
 76 bootstrapping is thus considered a key mechanism underlying children’s word learning. Most studies have  
 77 investigated syntactic bootstrapping as an independent word-learning mechanism, and fewer studies have  
 78 investigated the interactive role syntactic bootstrapping plays in the larger network of word learning  
 79 mechanisms (cf. <sup>7,8</sup>). To fully understand the complex cognitive process involved in word learning, it is  
 80 critical to understand the role of individual mechanisms, such as syntactic bootstrapping, in the process as  
 81 a whole (see Figure 1).

82  
 83 In this review, we will thus recontextualize syntactic bootstrapping as a mechanism within the  
 84 larger word learning literature, by investigating the reciprocal influence of syntactic bootstrapping and word  
 85 learning theory on each other. We will begin with an introduction into the emergence of the theory of

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<sup>1</sup> ‘Word learning’ throughout the manuscript refers to the acquisition of content words (words that bear meaning): nouns, verbs, adjectives, and adverbs.

<sup>2</sup> The asterisk indicates ungrammaticality.

86 syntactic bootstrapping and the subsequent, related shifts in the way researchers understood the word  
87 learning process. We will then summarize the extensive significance the syntactic bootstrapping mechanism  
88 has for learning that extends across syntactic structures, languages, and ages. We will next illustrate how  
89 contemporary learning theory has shaped how syntactic bootstrapping is understood, following the rise of  
90 computational models, novel experimental methodologies, and scaling up of empirical investigation to real-  
91 world-like learning scenarios. We will conclude with a broader vision of what syntactic bootstrapping  
92 evidences about the cognitive processes underlying word learning, and what the scientific community has  
93 yet to discover about how children learn so many words so fast.

94

### 95 **1. The origins of syntactic bootstrapping**

96 In the latter part of the 20<sup>th</sup> century, Lila Gleitman, professor at the University of Pennsylvania, proposed  
97 syntactic bootstrapping as a way children could learn, what she termed, ‘hard’ words, the kinds of words  
98 that have meanings that are hard to observe perceptually (e.g., ‘know’ or ‘probably’). This contrasts with  
99 ‘easy’ words, which refer to concrete words that can be learned through a word-to-world pairing (e.g.,  
100 ‘dog’). Word learning had traditionally been theorized from empiricist perspectives, which were centered  
101 on showing how evidence in the environment could underlie learning (e.g., connectionism: <sup>9-11</sup>), or innatist  
102 perspectives which were centered on demonstrating how an innate language capacity could underlie  
103 learning (e.g., generativism: <sup>12</sup>). Gleitman acknowledged the roles of both the environment and innate  
104 knowledge, and added a novel, rationalist perspective, centered on showing how inferences can underlie  
105 learning<sup>13</sup>: she posited that the environment likely contains more cues than we assume, innate learning bases  
106 likely accelerate acquisition, and making inferences from prior knowledge may be a key strategy for  
107 learning so much with so little.<sup>14-15</sup> The theory of syntactic bootstrapping embodied her multi-role  
108 perspective by showing that there are language learning cues in the interface between syntax and semantics,  
109 by proposing that children initially direct their attention to this interface via some learning biases, and by  
110 demonstrating that children scaffold word learning by drawing inferences about semantics from their  
111 knowledge about syntax. Syntax could be the key that enabled children growing up in vastly different  
112 environments to learn word meanings.

113

114 Historically, words were thought to be acquired primarily through perceptual cues (sensory  
115 experiences with the world).<sup>16</sup> Since children’s task was to map words onto aspects of the world, it was  
116 intuitive that it passes through the senses, our closest access to the world: a rabbit hops through a field, a  
117 child hears the word ‘rabbit’ and associates it with the animal she saw. Yet, perceptual cues, often reduced  
118 to visual cues, appeared insufficient for the learning task. The most famous thought experiment illustrating

119 insufficiency was proposed by Willard Van Orman Quine.<sup>17</sup> A learner<sup>3</sup> of a new language sees a rabbit in  
120 a field and hears a speaker of that language say ‘gavagai’. From that one scene, ‘gavagai’ could refer to any  
121 number of scene-related things (rabbit, field, hopping) or unrelated things (I’m tired, let’s go that way).  
122 Even after a number of instances of hearing ‘gavagai’ in different situations, the learner would continue to  
123 lack sufficient information about the word’s referent (rabbit, set of undetached rabbit parts, rabbit-tropes).  
124 The gap between perceptual insufficiency and children’s capacity to learn words would be bridged through  
125 two possible routes: identify other cues or sets of cues that could fix meaning, or redefine our conception  
126 of meaning. The majority of the literature focused on the former.<sup>4</sup>

127  
128         The idea that a child could use the links between syntax and semantics to learn words had been  
129 proposed decades prior to the introduction of the syntactic bootstrapping theory but had gained little  
130 traction. Roger Brown had run an empirical study investigating whether pre-school children could use  
131 linguistic classes to deduce whether a novel word was a verb, a count noun, or a mass noun.<sup>18</sup> Novel words,  
132 like ‘*sib*’ were introduced into sentence frames that corresponded to specific linguistic classes: for example,  
133 a verb in “show me another picture of *sibbing*”, a count noun in “show me another picture of a *sib*”, and a  
134 mass noun in “show me another picture of some *sib*”. Preschool children successfully interpreted ‘*sibbing*’  
135 as an action, ‘a *sib*’ as an object, and ‘some *sib*’ as a substance. Gleitman proposed syntactic bootstrapping  
136 as a mechanism that is already available when children are still building up their vocabularies in early  
137 toddlerhood.

138  
139         She first showed that children know more about syntax than is reflected in the language they  
140 produce. Shipley, Smith, & Gleitman presented one- and two-year-olds with commands using telegraphic  
141 speech, short simple sentences that are often composed just of content words (e.g., “Throw ball”) or using  
142 well-formed speech (e.g., “Throw me the ball”).<sup>19</sup> They found that toddlers best performed the correct  
143 action when it was in well-formed speech, even though they were yet to produce well-formed sentences  
144 themselves. They concluded that toddlers’ syntax comprehension may greatly outpace their syntax  
145 production.

146  
147         She then demonstrated that syntax could be a valuable cue to word meaning when perceptual cues  
148 were insufficient. Landau and Gleitman studied the speech and input of children who are blind (<sup>15</sup>; see  
149 Figure 2). Their hypothesis was that vision-related words, like the distinction between ‘see’ and ‘look’, may

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<sup>3</sup> An adult, linguist learner.

<sup>4</sup> Quine chose the latter, ceding that meaning is vague to some degree.

150 be harder to learn. They found, however, that the children used words like ‘see’ and ‘look’ appropriately.  
 151 When they investigated the perceptual input, they found that it appeared insufficient: ‘look’ was used for  
 152 items that were generally closer to the child but not consistently so. However, when they analysed the  
 153 linguistic cues, they discovered that the two words were used in different sets of sentence frames (e.g., “See  
 154 the apple?” vs. “Look at the apple”). They concluded that syntax may be a necessary cue for word learning,  
 155 especially when perceptual cues are insufficient (e.g., for certain verbs). They named the concept ‘syntactic  
 156 bootstrapping’: syntax could be used to bootstrap word learning.

157  
 158 Gleitman showed that even the youngest toddlers have knowledge about syntax, and that harnessing  
 159 that knowledge for word learning was essential. In the couple of years that followed, the theory was tested  
 160 empirically with two-year-olds.<sup>20,21</sup> Toddlers were presented with a novel verb in either a transitive sentence  
 161 (i.e., containing an agent and a patient: “The duck is gorging the bunny”) or an intransitive sentence (i.e.,  
 162 containing two agents: “The duck and the bunny are gorging”). At the same time, they saw two videos, one  
 163 of a duck performing a novel action on a bunny (transitive action) and one of a duck and bunny performing  
 164 the same novel action (intransitive action).<sup>21</sup> Toddlers’ looking time to the videos when they heard a  
 165 transitive or intransitive verb was measured. If toddlers could infer the transitivity of the verb from the  
 166 syntax (e.g., the sentence has an agent and patient, so the verb is transitive), their total looking time to each  
 167 video should differ depending on the sentence frame they heard (e.g., longer looks to the transitive action).  
 168 The results revealed that toddlers as young as 25 months looked longer to the transitive action video when  
 169 the novel verb was in a transitive sentence frame and to the intransitive action video when the verb was in  
 170 an intransitive frame. Toddlers were making inferences from their knowledge of syntax, in real time, to  
 171 deduce the meaning of new words.<sup>15</sup> These studies set the foundations for the idea of a syntactic  
 172 bootstrapping capacity. They had an influential impact on language learning theory and were subsequently  
 173 built upon with a rich body of empirical research to establish syntactic bootstrapping as a plausible and  
 174 powerful language learning mechanism.

175

## 176 **2. The premises of syntactic bootstrapping and contemporary word learning theory**

177

178 The initial evidence in favour of syntactic bootstrapping demonstrates that language learning theory should  
 179 account for three broader phenomena: (1) children’s observable behaviour is not always a direct expression  
 180 of their knowledge (Shipley, Smith, & Gleitman study);<sup>19</sup> (2) there are more learning cues in the  
 181 environment than it appears (Landau & Gleitman study)<sup>15</sup>; and (3) children are capable of making ostensibly  
 182 complex computations, like inferences from syntactic cues to semantic properties (Hirsh-Pasek, Naigles,  
 183 Golinkoff, Gleitman, & Gleitman and Naigles study).<sup>20,2</sup>

184 <sup>1</sup>The way researchers investigated word learning and language learning processes, and interpreted  
185 experimental results, shifted over the following decades, aligning with these three phenomena. This  
186 alignment was likely the result of multiple converging discoveries, of which syntactic bootstrapping was  
187 just one. This first shift was a change in focus from production to comprehension. Studies of children's  
188 lexical comprehension revealed that infants actively build their vocabulary in their first year of life, before  
189 they produce any words (e.g., <sup>22,23</sup>). Furthermore, they revealed that production is subject to additional non-  
190 linguistic cognitive constraints (e.g., speech motor control, executive functions: <sup>24</sup>), and may thus be a less  
191 reliable measure of knowledge than comprehension. These studies demonstrate that children know many  
192 more words than they produce, and they suggest that our theories may underestimate what young children  
193 know (e.g., <sup>25,26</sup>).

194  
195         The second shift in word learning research was an expansion in the range of cues studied for word  
196 learning. Word learning experiments started including other linguistic cues such as prosody (i.e., the rhythm  
197 of language) <sup>27,28</sup> and thematic relations (e.g., the relationship between the meaning of the verb and the noun  
198 in a sentence: for instance the verb 'eat' takes edible nouns as direct objects) <sup>29,30</sup>. Researchers also began  
199 to examine the benefit of extra-linguistic cues, like social ones, such as gaze-following (i.e., the capacity to  
200 track the gaze direction of another person), social contingency (i.e., the contingent reactions of one person  
201 to another), and communicative intent (i.e., that language is used for communication between people). <sup>31-</sup>  
202 <sup>33</sup>. When words or a subset of them were considered difficult to acquire from the cues present in the  
203 environment, research was oriented toward identifying hitherto unknown cues that could underlie learning  
204 (e.g., joint-attention: <sup>34</sup>; touch: <sup>35</sup>). Together, these studies show that children use an extensive array of cues  
205 to learn words, and they suggest that the ability to use many different cues underlies children's capacity to  
206 learn any human language, across a wide range of environments (e.g., <sup>36-38</sup>).

207  
208         The third shift was increased investigation of cross-domain inferences, beyond those from syntax  
209 to semantics required for syntactic bootstrapping, as a necessary strategy for language learning. Recent  
210 studies suggest that pragmatics (or communicative contexts) can inform meaning.<sup>39</sup> For example, it is  
211 difficult to observe the meaning of attitude verbs like 'want' and 'think' through the senses, but a child  
212 could use pragmatic knowledge to infer that they can communicate additional speaker intention (e.g., an  
213 indirect request vs. an indirect assertion). Furthermore, computational studies suggest that prior knowledge  
214 of words can facilitate the acquisition of other aspects of language, like phonemes (or sounds of a  
215 language).<sup>40,41</sup> The acoustic features of phonemes vary greatly depending on the context, such as  
216 neighbouring sounds, stress, and speaker.<sup>40</sup> This variation makes distinguishing one phoneme and another  
217 difficult. Computational simulations show that if learners use their knowledge of a handful of frequent



218 words to help them deduce phonetic categories, the perceived acoustic variability is attenuated.<sup>40,41</sup> Studies  
 219 on cross-domain linguistic bootstraps illustrate that children can use knowledge of different aspects of  
 220 language to guide word learning, and vice versa, and thus suggest a highly fluid word learning theory that  
 221 interfaces with learning of other aspects of language.

222  
 223         The premises underlying syntactic bootstrapping —behaviour-knowledge dissociation, hidden  
 224 environmental cues, and inference as a route to knowledge— have gained traction in recent decades, and  
 225 are now an integral part of contemporary word learning theory. They have enabled researchers to begin to  
 226 explain how children might acquire words from so little, so quickly. Syntactic bootstrapping itself had  
 227 further direct influences on word learning theory: it cemented the importance of syntax for word learning  
 228 and revealed just how much the youngest children know about syntax.

229

### 230 **3. From the conclusions of syntactic bootstrapping to a robust word learning mechanism**

231  
 232 Syntactic bootstrapping truly gained acceptance as a word-learning mechanism when the first initial  
 233 evidence in its favour began being replicated and extended (e.g.,<sup>42</sup>). As of now, a large body of work has  
 234 experimentally tested and validated its premise showing that young children can indeed learn the meaning  
 235 of novel words by paying attention to the syntactic contexts in which they appear, with verbs appearing in  
 236 intransitive (e.g., ‘She is blicking!’) and/or transitive frames (e.g., ‘She is blicking the baby’) being the  
 237 most common case study (e.g., in English: <sup>4,21,43-49</sup>; in French: <sup>50,51</sup>; in Japanese: <sup>52</sup>; in Korean:<sup>53</sup>; in  
 238 Mandarin: <sup>54,55</sup>; in Turkish:<sup>56</sup>). These types of verbs offer the advantage of labeling observable actions that  
 239 can easily be depicted while having distinct syntactic and semantic properties that can be manipulated by  
 240 an experimenter. That is, part of the meaning of a verb is a semantic predicate-argument structure specifying  
 241 how many and what type of participant-roles the verb involves. This semantic structure will constrain the  
 242 type of syntactic contexts the verb can appear with. For instance, the presence of one or two noun phrases  
 243 can commonly distinguish intransitive verbs from transitive ones in English, since intransitive verbs  
 244 describe actions requiring only one agent (one noun phrase: ‘The boy snored’ and not \*the boy snored the  
 245 girl) whereas transitive verbs tend to describe an agent’s action on a patient (two noun phrases: ‘The boy  
 246 pushed the girl’).

247  
 248         In the classical syntactic bootstrapping paradigm, participants hear sentences containing a new verb  
 249 and are tested with two side-by-side visual displays (the looking-while-listening paradigm: e.g., <sup>57,58</sup>), with  
 250 only one conforming to the restrictions linked to the syntactic cues (e.g., number of agents and/or number  
 251 of actions). Participants are first provided with essential cues to the syntactic category of the new verb and

252 some restrictions on its meaning, helping them point and/or look at the most probable candidate event when  
253 later prompted to do so. In the seminal paper by Naigles (1990)<sup>21</sup>, toddlers heard these cues while observing  
254 events, but in subsequent work (e.g., <sup>49,59</sup>), researchers showed that learners' remarkable inference process  
255 can even be active in the absence of event observation. Indeed, in Yuan & Fisher (2009)<sup>49</sup>, no informative  
256 visual information was being provided before the test phase and participants were simply introduced to the  
257 new verb's semantic restrictions via a dialogue between two actors (see Figure 3). From this short exposure,  
258 two-year-old toddlers were shown to successfully use the distributional information of the novel verb to  
259 draw inferences about its potential meanings and show a looking preference for the intended candidate  
260 event at test. These effects were even found when the dialogue and event phases were separated by a delay  
261 (from 2 min to 2 days), which shows that young children have the ability to not only form new word  
262 representations after witnessing a dialogue, but also to retain such incomplete representations in their  
263 memory (see also <sup>60</sup>).

264  
265         Acquiring the meaning of novel action verbs via a syntactic bootstrapping approach is more than  
266 meets the eye. To succeed, children need to extract meaningful information from what they hear and what  
267 they observe and find a match for their representations (out of two visual displays). They sometimes fail at  
268 mapping the novel action verb to the intended event, either showing no clear interpretation or showing an  
269 erroneous one. Based on a recent meta-analysis<sup>1</sup>, children tend to map the correct novel action in conditions  
270 using transitive sentences more systematically than in conditions using intransitive sentences. Some have  
271 explained children's difficulty at mapping a new intransitive verb with the ambiguity conveyed by some  
272 intransitive sentences, which can be interpreted as referring to both causative and non-causative actions.  
273 This may prevent learners from showing a clear preference for the target visual display. On the contrary,  
274 transitive verbs can only refer to causative actions, so the syntactic context narrows the hypothesis space to  
275 a greater extent and learners can more easily show a clear interpretation. Note that toddlers can more easily  
276 succeed at mapping a new intransitive verb to the right event when it appears in multiple frames and  
277 additional linguistic cues are provided (e.g., <sup>42,51</sup>). For instance, whereas English-learning 21-month-olds  
278 mistakenly interpret sentences such as 'The boy and the girl are gorp' as referring to a causative action  
279 between two participants, Arunachalam and colleagues (2013)<sup>42</sup> demonstrated that toddlers perform better  
280 and do not construct this wrong inference if just after hearing this sentence, they hear another intransitive  
281 frame with a pronoun in the place of the conjoined subject (e.g., 'The boy and the girl are gorp. Really?  
282 They are going to gorp?'). Hence, children might not always gather enough evidence about the intended  
283 meaning of a new word embedded in a single meaning frame, but they can reach the right interpretation  
284 given more cues. In fact, syntactic bootstrapping should be thought of as an incremental process, because

285 in learners' everyday lives, a new word can be encountered in various frames and across situations before  
286 it is mapped to its meaning (see for e.g. <sup>61</sup>).

287  
288         Years of research have uncovered the presence of several learning heuristics and biases affecting  
289 word learning (for example, mutual exclusivity: e.g. <sup>62</sup>; the whole-object assumption: e.g. <sup>63</sup>). In the  
290 syntactic bootstrapping literature, toddlers have been found to be biased by the number of nouns they hear  
291 when attempting to map a novel co-occurring verb to an event/action, mapping nouns in sentences one-to-  
292 one onto the participant roles in events (e.g., <sup>2,6,21,64,65</sup>). This structure-mapping strategy is not foolproof, as  
293 it can sometimes lead to fast-mapping errors because the number of noun phrases in a sentence is not always  
294 informative about verb transitivity (e.g., <sup>50,51,66</sup>). For instance, as mentioned above, 21-month-old toddlers  
295 can mistakenly map a sentence such as 'The boy and the girl are gorp' to a causal action between two  
296 participants, with the boy acting on the girl, because it contains two nouns (for an explanation of the  
297 phenomenon see: <sup>67,68</sup>). Interestingly, similar effects have been found in young children learning non-Indo-  
298 European languages in which the number of nouns is not even a strong cue to causal meaning (Mandarin:  
299 <sup>54</sup>; Kannada:<sup>65</sup>). As Fisher and colleagues<sup>6</sup> pointed out, these results seem to suggest that young learners do  
300 not develop this noun-number strategy based on their linguistic experiences. This line of work shows how  
301 syntactic bootstrapping is a learning mechanism that naturally emerges early in development, at a time  
302 when young children possess a simplistic analysis of linguistic structures (e.g., when they can simply spot  
303 noun phrases in the running speech).

304  
305         Beyond the number of noun phrases, syntactic bootstrapping regards many syntactic elements as  
306 relevant cues to word meaning (e.g., <sup>2,69</sup>). For instance, sentence complements can narrow the scope of  
307 semantic possibilities to a greater extent than information regarding the structure of noun arguments.  
308 Indeed, many verbs can appear in the context of two noun phrases (e.g., "Alex X the bunny"), while fewer  
309 verbs can appear with sentential complements (e.g., "Alex X that it's delicious"). When hearing a novel  
310 verb, learners can thus distinguish contexts in which the verb refers to what someone is doing to someone  
311 (e.g., petting) or what someone is feeling about something (e.g., think) by taking into account the presence  
312 of a clausal complement. Since this latter type of syntactic structure implies a thematic relation between an  
313 animate entity and a proposition, the hypothesis space is mainly restricted to verbs of communication (e.g.,  
314 "say"), perception (e.g., "hear") and mental act or state (e.g., "think"). Research investigating syntactic  
315 bootstrapping for mental verbs has shown how effective clausal complements are at restricting the semantic  
316 meaning of a new verb. In Papafragou, Cassidy and Gleitman (2007)<sup>70</sup>, four-year-old children and adults  
317 interpreted the meaning of the new verb "gorp" as a mental verb when it appeared with a complement (e.g.,  
318 "Matt gorps that his grandmother is under the covers") but not when it appeared in a transitive frame (e.g.,

319 “Matt gorps a basket of food”). The effect was even stronger when participants were dealing with false  
320 belief scenarios, which triggered more guesses involving belief verbs (e.g., thinking, believing). Recent  
321 work using natural corpora has found syntactic signatures distinguishing different sub-categories of mental  
322 verbs (e.g., “think” vs “know” in <sup>71</sup>; see also <sup>7,39,72,73</sup>), which might be highly useful to steer the learner  
323 towards the right type of semantic meaning. Overall, these findings demonstrate that syntactic bootstrapping  
324 is a feasible mechanism not only for action verbs that can be mapped to observable events, but also for  
325 mental-state predicates.

326  
327         Other syntactic elements relevant to word meanings are function words and morphemes (e.g., ‘the,’  
328 ‘a,’ ‘she,’ ‘they,’ ‘-ing’), which infants come to process, store, and recognize during their first year of life  
329 (e.g., <sup>74-77</sup>; for a review: <sup>78</sup>). In many languages such as English and French, learners can expect a novel  
330 word following a determiner to be a noun (i.e. mapping it to an object), and a novel word following a  
331 pronoun to be a verb (i.e. mapping it to an action; see e.g. <sup>79</sup>). Undoubtedly, these simple syntactic cues are  
332 imperfect and narrow the scope of potential meanings to a lesser extent than more complex ones (e.g.,  
333 clausal complement). For example, many types of nouns can follow a determiner (e.g., ‘ball’, ‘cat’, ‘wind’),  
334 even ones that refer to an action/event (e.g., ‘a dance’). But even though such syntax-semantic correlations  
335 are not perfect, the evidence is often compelling enough for learners eager to map new words to syntactic  
336 and semantic categories. Hence, functional elements have been shown to enable children to not only build  
337 syntactic expectations about new nouns and verbs (e.g., 14-month-olds expect a new word appearing in  
338 noun contexts to co-occur later with a determiner, not a pronoun; <sup>45-47</sup>), but also semantic expectations (e.g.,  
339 <sup>5,79,83-88</sup>). Moreover, studies using a single visual display have demonstrated infants’ ability to rely on simple  
340 functional elements to interpret the meaning of new words (e.g., <sup>51,54,56</sup>). For instance, in de Carvalho et al.  
341 (2019a)<sup>88</sup>, French-learning 18-month-olds interpreted a single video presenting an event (e.g., a penguin  
342 spinning) differently based on the sentence they heard: infants who heard *C’est une bamoule* ‘It is a  
343 bamoule’ interpreted the novel word ‘bamoule’ as referring to the animal performing the action (i.e., the  
344 penguin) while infants who heard *Elle bamoule* “She is bamouling” interpreted it as the action being  
345 performed by the animal (i.e., spinning). When a child sees a single object such as an animal, the syntactic  
346 cues that she hears can also help her to know if the speaker refers to the object itself or to its properties  
347 (e.g., color, shape). In Waxman (1999)<sup>89</sup>, English-learning 14-month-olds learned that a novel word  
348 presented as a count noun (e.g., ‘this one is a blicket’) referred to individual objects and categories of objects  
349 (e.g., a horse), but when presented as an adjective with an added suffix (e.g., ‘this one is blickish’), infants  
350 did not make such interpretation. In sum, shortly after their first birthday, infants can use functional  
351 elements as a “zoom lens” (see e.g., <sup>90</sup>), allowing them to figure out which part of a complex scene is being  
352 talked about (e.g., the object or agent, its properties or the action that is being performed; Box 2).

353  
354 As shown above, syntactic bootstrapping has become more than a mechanism used by English-  
355 learning children for learning hard words such as verbs. A vast body of work has attested its success with  
356 different types of words in a variety of languages. Some of the challenges and biases linked to the usage of  
357 the interface between syntax and meaning have been uncovered, but researchers still have a lot to learn  
358 about many aspects of the task and the abilities deployed by the learner during the process. As of now, most  
359 studies have found evidence of syntactic bootstraps in toddlers, between the age of one and two, when  
360 discovering the meaning of ‘easy’ words (e.g., concrete nouns) and some types of ‘hard’ words (e.g., action  
361 verbs), while successful results have only been found for learning some of the ‘hardest’ words (e.g., mental  
362 verbs) in older children (e.g., four-year-olds). Simple syntactic bootstraps (e.g., functional elements) seem  
363 to be learned early in development. More complex ones are learned as children gain more language  
364 experience, and as their representations of linguistic structures move from being rudimentary to more  
365 sophisticated<sup>68</sup>.

366

#### 367 **4. How children discover syntactic-semantic links**

368

369 The success of a syntactic bootstrapping approach depends on learners’ familiarity of and attention to  
370 systematic relationships between syntax and meaning (e.g.<sup>91</sup>). Analyses of naturalistic corpora of child-  
371 directed speech and unsupervised computational models using these corpora have demonstrated the  
372 presence of reliable correlates between the syntactic structure in which a word occurs and the word’s  
373 category or meaning (e.g.,<sup>92–98</sup>). As meaning similarity has been shown to be highly predictive of  
374 distributional similarity, this line of work strongly supports Gleitman’s idea that cues for word learning are  
375 hidden in the structure of sentences. These cues have been found to be local, which complement in an  
376 adaptive way infants’ limited working memory. As young learners process the speech stream in small  
377 chunks, they are extracting and storing simple yet powerful cues<sup>99</sup>. Even before their first birthday, infants  
378 have stored natural co-occurrence patterns between simple syntactic elements (function words) and  
379 common words, allowing them to distinguish grammatical/predictable from ungrammatical/unpredictable  
380 contexts for nouns and verbs (<sup>100</sup>; see also <sup>101,102</sup>). As Lidz (2020)<sup>103</sup> pointed out, learners’ ability to encode  
381 in their long-term memory an extensive amount of linguistic distributional information and later exploit it  
382 to guide word learning is quite remarkable, as they do not show these abilities to the same extent with  
383 nonlinguistic information (e.g., other candidate referents present during word learning;<sup>104–106</sup>; but see:<sup>107–</sup>  
384 <sup>109</sup>). The acquisition of syntax-semantic links might hence be supported by a fundamental bias to favorably  
385 retain linguistic information in small chunks, which over an extended period of time enables the discovery  
386 of syntactic patterns that can be useful for generalization.

387  
388           According to the semantic seed hypothesis (<sup>110-112</sup>, see similar proposals: <sup>68,94,113</sup>), infants’  
389 burgeoning lexicon (their semantic seed) and their notorious ability to track distributional regularities (e.g.,  
390 <sup>114-119</sup>) support their syntactic development and the creation of the first syntactic bootstraps. Although meant  
391 to outline the precursors to syntactic bootstrapping, this hypothesis shares a core assumption with a  
392 somewhat competing learning mechanism, Pinker’s semantic bootstrapping<sup>120</sup>, stressing the importance of  
393 children’s knowledge of word semantics to learn syntax. One key difference is their view of the usefulness  
394 of the meaning frames and the distributional cues present in the child’s input (e.g., see <sup>121</sup>), which are  
395 essential to the syntactic bootstrapping mechanism, but are not considered as informative in semantic  
396 bootstrapping. Another key difference is that semantic bootstrapping requires the child to possess advanced  
397 semantic knowledge to be able to learn syntax, such as understanding the meanings of sentences that are  
398 sometimes unobservable (‘I think it will snow later’), and thus hard to learn. But according to the semantic  
399 seed hypothesis, infants equipped with limited semantic knowledge could already start learning about  
400 syntax-semantics links by tracking the syntactic contexts of their first known words (e.g., ‘ball’ and ‘book’  
401 appear in meaning frames such as ‘Take the ball’, ‘Take the book’, while ‘eat’ and ‘walk’ appear in frames  
402 such as ‘You’re eating’, ‘You’re walking’). Note that most of these words would be considered “easy”  
403 according to Gleitman and her colleagues (e.g., <sup>122</sup>), as they would have been learned through rich social  
404 and multimodal experiences enabling simple word-to-world mappings (e.g., <sup>22,23,123-127</sup>). Subsequently,  
405 around their first birthday, infants would start organizing their lexicon by grouping familiar words into  
406 basic semantic categories (e.g., object, action, or agent; <sup>128</sup>). This achievement would enable them to treat  
407 semantically varying words as belonging to discrete categories (e.g., “ball” and “book” being objects,  
408 ‘eating’ and ‘walking’ being actions). From then on, infants could start exploiting their small semantic seed  
409 and their familiarity with some common syntactic contexts for assigning novel words into categories and  
410 performing syntactic bootstrapping (e.g., ‘Take the’ + ‘gorp’ -> gorp = object; ‘You’re’ + ‘gorping’ -> gorp  
411 = action). Furthermore, according to the semantic seed hypothesis, learners’ willingness to take a leap when  
412 mapping a potential meaning to a new word is a valuable asset. Indeed, their ability to generalize linguistic  
413 patterns from a small set of exemplars (as shown in: <sup>129-132</sup>) has been regarded as their most powerful tool  
414 in the creation of syntactic bootstraps.

415  
416           How do infants use their semantic seed to learn about syntactic contexts? According to a central  
417 account in cognitive and brain sciences, the human brain (including infants’ developing brains) operates by  
418 creating predictions. Everything from perception to action planning and language operates by creating  
419 hierarchical predictions about what happens next. One of the important features of this approach is that the  
420 brain does not need to encode every bit of information it is faced with, but rather, only the difference

421 between its predictions and the actual stimulus - an error signal. As long as everything goes as planned, no  
422 learning occurs<sup>133</sup>. Predictive processing, or error-based learning, has also been suggested to underlie  
423 language acquisition<sup>134–137</sup>. This account suggests that children predict what they will hear next, be it words,  
424 syntactic categories or any other linguistic element, and when these predictions fail, their internal  
425 distributional models are corrected to avoid future errors. This mechanism also ties together the semantic  
426 seed with distributional learning about preceding context. Young children could try to predict what category  
427 of words is most likely to follow, for example, a noun in a noun frame, thus forming a model in which it is  
428 likely to be an object name. In Bernal and colleagues (2010)<sup>138</sup>, 2-year-olds were shown to build on-line  
429 syntactic expectations when listening to spoken sentences. Toddlers' differential brain responses to  
430 expected/grammatical contexts (e.g., "She wants to eat the strawberry") versus unexpected/ungrammatical  
431 contexts (e.g., But she strawberries it) demonstrated the presence of such a predictive-based mechanism.  
432 Learners' predictions, including syntactic bootstraps, are in fact flexible in nature, as they can adapt to new  
433 information. Three- to five-year-old preschoolers have also been shown to change their predictions about  
434 verb and noun contexts when faced with a small amount of recent evidence that their predictions are wrong  
435 <sup>139,140</sup>.

436  
437 In recent years, the semantic seed hypothesis has received support from both computational models  
438 and behavioral experiments aimed at resembling more real-world-like learning scenarios. The processing  
439 and representational mechanisms underlying a computational model allowed researchers to develop a  
440 framework of syntactic bootstraps and evaluate how the input could be processed by the young mind. The  
441 main advantage of such an approach is that the architecture of a model can mimic to some degree the one  
442 of a human infant. As mentioned above, when the first syntactic bootstraps are thought to emerge, infants  
443 only know a handful of words and have limited attentional and memory capacities. Using an algorithm that  
444 relied on very little computational and memory resources, Brusini et al. (2021)<sup>110</sup> showed that a probabilistic  
445 context-based mechanism can be very efficient for the acquisition of syntactic categories when a handful  
446 amount of seed words (words already categorized) are included in the training phase. Their model was  
447 trained to extract two-word contexts in the immediate vicinity of seed words, so that test words would be  
448 categorized based on these local contexts. In line with the semantic seed hypothesis, even with a limited  
449 semantic seed size (e.g., 8 nouns and 1 verb used during the training phase), the vast majority of new nouns  
450 and verbs for which a categorization was attempted were correctly categorized at test (many words occurred  
451 in contexts which were not recognized as informative). Hence, with a small semantic seed, a learner using  
452 this approach would only attempt to categorize new words in a small number of contexts that are familiar,  
453 and remarkably this categorization would be mostly error-free.

454

455 A few experimental studies tested more directly the feasibility of the semantic seed hypothesis by  
456 investigating young children's ability to learn the semantic category co-occurring with novel syntactic  
457 elements (function words; <sup>130-132</sup>). Based on these results, syntactic bootstrapping may well be a  
458 computationally light strategy, where children can construct and use syntactic-semantic links with little  
459 input. That is, similarly to the computational model of Brusini et al., participants were first provided with  
460 a small set of exemplars (e.g., 6 words appearing with each novel syntactic element) that could be used to  
461 make generalizations to novel test words. In Barbir et al. (2023)<sup>132</sup>, French-learning 20-month-old toddlers  
462 were presented with videos of a woman telling short stories in which a small set of familiar nouns co-  
463 occurred with two new morphosyntactic elements, determiners 'ko' and 'ka', along with a broad range of  
464 naturalistic cues that children typically encounter (e.g., gaze cues, pointing, ostensive cues). The new  
465 elements were inserted directly into sentences, replacing the French determiners 'le' and 'la' (e.g., *Ko* rabbit  
466 climbs into *ka* tractor), but they corresponded to a grammatical distinction absent in the participants' native  
467 language: animate vs inanimate. Toddlers were then presented with a test phase where they saw two novel  
468 objects on the screen, an animate and an inanimate, and heard sentences containing novel nouns: the only  
469 cues to the novel nouns' meanings were the determiners 'ko' and 'ka' (e.g., Oh , look at *ko bamoule*). The  
470 results revealed that infants looked longer to the animate image when the sentence contained the animate  
471 determiner, and to the inanimate image when the sentence contained the inanimate determiner. This study  
472 showed that toddlers can learn syntactic-semantic links in under 30 minutes of naturalistic exposure and  
473 quickly use them to learn novel nouns. This positions syntactic bootstrapping as an easily deployable  
474 mechanism that can be applied to novel grammatical elements with little environmental input, and thus as  
475 an invaluable tool for early word learning.

476

## 477 **5. Contemporary word learning theory and the evolution of syntactic bootstrapping**

478

479 In recent years, word learning theory has begun integrating more multi-cue strategies and multi-mechanism  
480 processes for learning, and has been influenced by prominent contemporary cognitive processing theories  
481 (e.g., <sup>36</sup>). These shifts have had a ripple effect into how syntactic bootstrapping is understood, by clarifying  
482 its definition and describing its role in broader word-learning and cognitive-processing frameworks.<sup>8,141</sup>  
483 The first shift in syntactic bootstrapping theory was a clarification as to which cues children could use to  
484 syntactic bootstrap. The initial idea of syntactic bootstrapping was broadly about sentence frames, and yet,  
485 in many studies, sentence frames were narrowly studied through word-based cues to syntax (e.g., how  
486 words were strung together). Recent studies show that toddlers can also syntactic bootstrap off of prosodic  
487 cues to syntactic structure.<sup>88,142</sup> For example, the same three words 'the baby flies' can refer to a baby flying  
488 through the air or little insects, depending on whether the prosodic boundary is between 'baby' and 'flies'



489 (two prosodic groups index a verb structure: [the baby][flies]) or after ‘flies’ (one prosodic group indexes  
490 a noun structure: [the baby flies]). Children’s capacity to use prosody to determine the sentence frame  
491 refines the definition of syntactic bootstrapping to explicitly include different surface-level cues to abstract  
492 syntactic structure. It further suggests that children might use multiple such cues in real-time to syntactic  
493 bootstrap.

494         The second shift was a precise positioning of syntactic bootstrapping in the broader word learning  
495 process. The initial idea of syntactic bootstrapping was broadly as a supplementary strategy for words that  
496 are hard to acquire from perceptual cues alone, notably verbs, and yet, in most studies, syntactic  
497 bootstrapping has been studied as a sufficient mechanism. Recent research has however uncovered the  
498 situations in which syntactic bootstrapping fails, and the limits of syntactic bootstrapping have informed  
499 novel theories about how syntactic bootstrapping may interface with other learning mechanisms. Mental  
500 state verbs are notably some of the hardest verbs to observe perceptually, and yet they are also words for  
501 which syntactic bootstrapping may be insufficient.<sup>39</sup> The syntactic differences between how ‘want’ and  
502 ‘think’ can inform a child that the two belong to different verb classes, but not much more. Yet, combining  
503 syntactic knowledge with pragmatic knowledge about a speaker’s intentions, like whether they are  
504 expressing an indirect request or indirect assertion, could be highly informative for learning.<sup>7</sup> Even for  
505 words that benefit from syntactic bootstrapping alone, children bootstrap selectively depending on the  
506 situation.<sup>139,141</sup> Studies show that preschool children only syntactic-bootstrapped speech from reliable  
507 speakers<sup>139</sup> and appropriate visual contexts<sup>141</sup>. Children’s selective and targeted use of syntactic  
508 bootstrapping specifies its role in the word learning process. It furthermore suggests that children weight  
509 multiple strategies, flexibly using syntactic bootstrapping with or without other strategies to learn new  
510 words.

511         The third shift in syntactic bootstrapping theory was an integration of a standalone mechanism into  
512 a larger cognitive-processing framework. Syntactic bootstrapping was initially defined as an inferential  
513 process from prior knowledge about syntax to the meaning of a novel word, and yet the rise of the predictive  
514 coding theory as a unified model of how the brain processes information has led to a redefinition of the  
515 inferences that underlie syntactic bootstrapping as predictions.<sup>143-148</sup> Predictions, however, differ from  
516 inferences in the computations, and degree of mentalizing, involved. Under the classical rationalist  
517 inference account, a child infers a word’s meaning by reasoning from an abstract structural relation (e.g.,  
518 ‘the bamoule’, ‘the’ + noun, so ‘bamoule’ is likely a noun); under the new predictive coding account, a  
519 child predicts a word’s meaning by tracking statistical probabilities (e.g., ‘the’ so the next word is likely to  
520 be a noun). Predictive coding has been empirically demonstrated across cognitive domains, from low-level  
521 perceptual processing, like vision, to high-level cognitive processing, like language (e.g., for metanalysis:  
522 <sup>149</sup>). Thus, redefining syntactic bootstrapping within a predictive coding framework would redefine

523 syntactic bootstrapping as one manifestation of a domain-general cognitive mechanism for prediction,  
524 simplifying word learning theory.<sup>146</sup> Yet, it is still unknown whether prediction is sufficient, or even  
525 necessary, for syntactic bootstrapping, and whether our current adult-based accounts of predictive coding  
526 are cognitively accurate for developmental populations. Recent computation work on empirical data from  
527 young children suggests that an immature predictive processing model increases explanatory power of  
528 behaviour, over and above traditional adult-based models.<sup>150,151</sup> Together, contemporary word learning  
529 theory and cognitive processing theory are reflected in our current conception of syntactic bootstrapping,  
530 expanding the scope of cues children use when they syntactic bootstrap, contextualising the role  
531 bootstrapping plays in word learning, and redefining the computation processes that underlie syntactic  
532 bootstrapping.

533

### 534 **Summary and future directions**

535

536 Syntactic bootstrapping is an essential mechanism for learning words from limited and noisy input: it  
537 provides evidence for a word's meaning when other evidence is insufficient, and it creates meaning frames  
538 that focus learning on a relevant subset of potential meanings. Recontextualizing syntactic bootstrapping in  
539 the broader word learning theory enabled us to theorize in this paper how toddlers learn so many words in  
540 so little time. First, they likely know more than we have observed empirically prior to their vocabulary  
541 spurt. This knowledge likely includes both word-level knowledge (e.g., zippers are found on clothing and  
542 bags) and word-learning strategies (e.g., syntactic-semantic links). Second, there is likely more evidence in  
543 the environment than we take into consideration. Computational models now enable us to overcome some  
544 limitations by scouring input in fine-grained detail and locating previously overlooked sources of evidence  
545 (e.g.,<sup>152</sup>). Third, there is likely a high degree of flexibility as to how words are learned, such that a wide  
546 range of contexts can offer favourable word-learning opportunities.

547 In addition to its contributions to our understanding of word learning, syntactic bootstrapping  
548 provides a valuable model for future research. Gleitman's theory was initially based on the observation that  
549 children's language production may be limited by the development of other cognitive capacities over and  
550 above language. Today, observations of comprehension are also implicitly or explicitly interpreted as  
551 observations of knowledge. Yet, the behavioural responses we use to measure comprehension (e.g., eye-  
552 gaze, pointing) may also lack one-to-one correspondence with knowledge. It is unclear whether children  
553 are syntactic bootstrapping even earlier than we have observed and our experimental protocols or measures  
554 are just too coarse to detect their knowledge; and whether the same cognitive processes underlie all syntactic  
555 bootstrapping.

556

557 Gleitman's theory also emerged from the study of children's environment as a source of their  
 558 linguistic knowledge.<sup>14,153</sup> The process however may be a closed loop: children's environments influence  
 559 their linguistic knowledge and children in turn influence their environments. Recent studies show that  
 560 children shape their linguistic and extra-linguistic environments; for example, children have been shown to  
 561 look at and touch novel objects more than familiar ones, and this behaviour elicited naming in parents.<sup>154,155</sup>  
 562 Children may try to elicit informative sentence frames from a caregiver or another child, when perceptual  
 563 cues are lacking or when they first encounter a word, for example. Whether and how children shape their  
 564 environments to exploit syntactic information is unknown.

565 Finally, syntactic bootstrapping was initially founded on the interaction between environmental  
 566 cues, innate biases, and inferential reasoning. A large portion of research on how syntactic bootstrapping  
 567 could emerge has been based on identifying minimally sufficient cues for learning in the environment (e.g.,  
 568 <sup>141,43</sup>). On the other hand, only a small portion of research has focused on how other cognitive processes,  
 569 such as attention, could underlie the creation of syntactic bootstraps.<sup>155,157</sup> How the two interact to create  
 570 such a powerful learning mechanism is even less clear (cf. <sup>7</sup>). Research still has a long way to go to fully  
 571 understand how children acquire words with the efficacy that they do. However, syntactic bootstrapping  
 572 has both provided critical answers and modeled how to approach answering unknown questions, almost  
 573 like a research bootstrap. If children can bootstrap their way to learning words, we believe researchers can  
 574 bootstrap their way to uncovering just how they do it.

575

### 576 **Box 1: What is syntax?**

577 Broadly, syntax is the set of structural rules that are used to construct sentences. A simple example is word  
 578 order: in English, it is subject-verb-object ('She eats cake'), and in Japanese, it is subject-object-verb  
 579 ('*Kanojo ga keeki wo tabeteriru*' [She cake eats]).

580

581 Everything that counts as a structural feature of language depends on the theory (e.g., <sup>158-160</sup>). Historically,  
 582 syntactic structure was distinct from morphological structure (e.g., the present progressive morpheme "-  
 583 ing" in English) and discourse structure (e.g., the modal particle '*ne*' that can be used to establish common  
 584 ground between a speaker and listener, in Japanese; see <sup>161</sup>). This separation works well for the structure of  
 585 English, the most structurally studied language, but fails to account for the diversity of structures in the  
 586 world's languages.

587

588 1. Morphological structure: Highly synthetic languages, like Hindi, have complex morphological  
 589 systems, where both structure and meaning are embedded in the morphemes, making it difficult to  
 590 classify elements as syntactic or semantic.<sup>162</sup>

591 2. Discourse structure: Argument drop languages, like Japanese, have complex pragmatic structure,  
 592 where syntactic elements encode broader discourse relations, like speaker intention.<sup>163</sup>

593

594 Recent research has proposed that morphology may be part of a larger morphosyntactic structural  
 595 system,<sup>160,164</sup> and that discourse markers may be whole sentence modifiers.<sup>165,166</sup>

596  
 597 The research on syntactic bootstrapping across the world's languages shows that children can bootstrap  
 598 meaning from morphological markers.<sup>156,167</sup> It also shows that children can fail to bootstrap from the  
 599 presence of syntactic structure, when it is pragmatically infelicitous for the discourse structure (e.g., the  
 600 arguments are present, when they should not be, in an argument drop language).<sup>141,168</sup> Insofar as  
 601 morphological and discourse structure can provide clues to word meanings, we assert that they are likely  
 602 used by children. Whether they are used in the same way as syntax, and how use varies depending on the  
 603 structure of the child's native language is a critical research direction for understanding how syntactic  
 604 bootstrapping works as a general language-learning mechanism.

605

606

### 607 **Box 2: Generalizability of syntactic bootstrapping**

608

609 Syntactic bootstrapping has been observed for a variety of syntactic structures and across different ages,  
 610 but the majority of studies have been conducted with English-learning children (e.g. metanalysis: <sup>1</sup>). The  
 611 literature attests robust syntactic bootstrapping effects in English, and more nuanced effects in other  
 612 languages. For example, both Japanese- and Mandarin Chinese-speaking children and adults syntactic  
 613 bootstrap in some contexts we would expect them to according to the theory, but not in others.<sup>52,54,141,168,169</sup>  
 614 Recent literature reviews have shown how important it is to study language learning across many different  
 615 languages, for our theories (e.g., <sup>170,171</sup>). To understand how syntactic bootstrapping functions as a word-  
 616 learning mechanism, within the larger language learning process, we need more studies in typologically  
 617 diverse languages. We posit the following guidelines for researchers and reviewers to facilitate linguistic  
 618 diversification:

619

620 1. Experiment creatively. The structures that elicit syntactic bootstrapping in English, may be absent or  
 621 pragmatically infelicitous in another language. Modeling studies can help identify which structures  
 622 could elicit syntactic bootstrapping:<sup>152</sup> for example, in Mandarin Chinese, a verb-heavy language, nouns  
 623 and verbs function more similarly than in English, a verb-light language, but there are nonetheless  
 624 distinctive sentence frames (e.g., *Zhe she cha* [This is tea] vs. \**Zhe she pau* [This is run]).

625 2. Value nuance. Syntactic bootstrapping was never intended to be the only word learning strategy  
 626 children use. The situations in which children do and do not syntactic bootstrap are both valuable for  
 627 understanding the mechanism itself. For example, syntactic bootstrapping studies on Mandarin Chinese  
 628 show that the accompanying visual context needs to be pragmatically felicitous for children to  
 629 bootstrap.<sup>141</sup>

630 3. Interpret null results in context. There are theory-driven reasons for which we might observe a null  
 631 effect in a hitherto untested language: a theory built up on English may be overly biased to English. It  
 632 can be difficult to publish studies that diverge from previously observed patterns, even if they are the  
 633 first studies in that language to test an effect, because the first assumption is usually that the research  
 634 was flawed in some way. These studies ought to be published, with ample recognition of the limitation  
 635 of interpretability of the results.

636

637 The recent replicability crisis in psychology has driven large-scale changes in how language development  
 638 experiments are conducted to increase the accuracy of research conclusions. The many changes have  
 639 focused on data quality and quantity. Studies have investigated how to increase the statistical power and  
 640 reliability of developmental studies, and proposed clear guidelines.<sup>192,173</sup> Researchers have also developed  
 641 repositories collecting large datasets, such as WordBank for vocabulary and PeekBank for gaze data, and  
 642 consortia, such as ManyBabies, for conducting multi-lab studies.<sup>174-176</sup> It is important to recognize however  
 643 that data quality and quantity can be distinct from data diversity.  
 644

## 645 References

- 646
- 647 1. Cao, A. & Lewis, M. Quantifying the syntactic bootstrapping effect in verb learning: A  
 648 meta-analytic synthesis. *Dev Sci* **25**, (2022).  
 649 **This metaanalysis on syntactic bootstrapping demonstrates a robust effect, but**  
 650 **reveals limitations on the scope of syntactic structures and languages studied.**  
 651
  - 652 2. Gleitman, L. The Structural Sources of Verb Meanings. *Lang Acquis* **1**, 3–55 (1990).  
 653 **This is Gleitman’s seminal paper proposing and detailing syntactic bootstrapping.**  
 654
  - 655 3. Seidl, A., Hollich, G. & Jusczyk, P. W. Early understanding of subject and object Wh-  
 656 questions. *Infancy* **4**, 423–436 (2003).  
 657
  - 658 4. Jin, K.-S. & Fisher, C. Early evidence for syntactic bootstrapping: 15-month-olds use  
 659 sentence structure in verb learning. In *Proceedings of the 38<sup>th</sup> Boston University*  
 660 *Conference on Language Development* (eds. Orman, W. & Valteau, M.) (Cascadilla  
 661 Press, 2014).  
 662
  - 663 5. He, A. X. & Lidz, J. Verb Learning in 14- and 18-Month-Old English-Learning Infants.  
 664 *Language Learning and Development* **13**, 335–356 (2017).  
 665
  - 666 6. Fisher, C., Gertner, Y., Scott, R. M. & Yuan, S. Syntactic bootstrapping. *Wiley*  
 667 *Interdiscip Rev Cogn Sci* **1**, 143–149 (2010).  
 668
  - 669 7. Hacquard, V. & Lidz, J. On the Acquisition of Attitude Verbs. *Annual Review of*  
 670 *Linguistics* **8**, 193-212 (2022).  
 671 **This review explores how syntactic bootstrapping might interface with other**  
 672 **mechanisms, such as pragmatic bootstrapping.**  
 673
  - 674 8. Havron, N. *et al.* There might be more to syntactic bootstrapping than being pragmatic: A  
 675 look at grammatical person and prosody in naturalistic child-directed speech. *J Child*  
 676 *Lang* **28**, (2023).  
 677
  - 678 9. Rumelhart, D. E., & McClelland, J. L. On learning the past tenses of English verbs. In  
 679 *Parallel Distributed Processing: Explorations in the Microstructures of Cognition (Vol.*  
 680 *2)* (eds. McClelland, J. L. *et al.*,) 216-271 (The MIT Press, 1986).  
 681

- 682 10. Elman, J. L. Finding structure in time. *Cogn Sci* **14**, 179-211 (1990).  
683
- 684 11. Rumelhart, D. E., & Todd, P. M. (1993). Learning and connectionist representations. In  
685 *Attention and performance 14: Synergies in experimental psychology, artificial*  
686 *intelligence, and cognitive neuroscience* (eds. Meyer, D. E. & Kornblum, S.) 3–30 (The  
687 MIT Press, 1993).  
688
- 689 12. Jackendoff, R. What is a Concept, that a Person May Grasp It? *Mind Lang* **4**, 68–102  
690 (1989).  
691
- 692 13. Lidz, J. Children’s use of syntax in word learning. *The Oxford Handbook of the Mental*  
693 *Lexicon* (eds. Papafragou *et al.*) (Oxford University Press, 2022).  
694
- 695 14. Gleitman, L. R., & Newport, E. L. The invention of language by children: Environmental  
696 and biological influences on the acquisition of language. In *Language: An invitation to*  
697 *cognitive science* (eds. Gleitman, L. R. & Liberman, M.) 1–24 (The MIT Press, 1995).  
698
- 699 15. Landau, B. & Gleitman, L. *Language and experience*. (Harvard University Press, 1985).  
700
- 701 16. Locke, J. An essay concerning human understanding, 1690. In *Readings in the history of*  
702 *psychology* (ed. Dennis, W.) 55–68 (Appleton-Century-Crofts, 1948).  
703
- 704 17. Quine, W. V. O. *Word and Object*. (The MIT press, 1960).  
705
- 706 18. Brown, R. W. Linguistic determinism and the part of speech. *The Journal of Abnormal*  
707 *and Social Psychology*, **55**, 1-5 (1957).  
708
- 709 19. Shipley, E. F., Smith, C. S., & Gleitman, L. R. A study in the acquisition of language:  
710 Free responses to commands. *Language* **45**, 322-342 (1969).  
711
- 712 20. Hirsh-Pasek, K., Gleitman, H., Gleitman, L. R., Golinkoff, R., & Naigles, L. Syntactic  
713 bootstrapping: Evidence from comprehension. Paper presented at the *13th Annual Boston*  
714 *University Conference on Language Development* (1988, October).  
715
- 716 21. Naigles, L. Children use syntax to learn verb meanings. *Journal of Child Language*, **17**,  
717 357–374 (1990).  
718 **This study introduced the classic syntactic bootstrapping paradigm used to this day.**  
719
- 720 22. Tincoff, R. & Jusczyk, P. W. Six-Month-Olds Comprehend Words That Refer to Parts of  
721 the Body. *Infancy* **17**, 432–444 (2012).  
722
- 723 23. Bergelson, E. & Swingley, D. At 6-9 months, human infants know the meanings of many  
724 common nouns. *Proc Natl Acad Sci U S A* **109**, 3253–3258 (2012).  
725
- 726 24. Mazuka, R., Jincho, N. & Oishi, H. Development of executive control and language  
727 processing. *Linguistics and Language Compass* **3**, 59–89 (2009).

- 728  
729 25. Havron, N. Why not both? Using multiple measures to improve reliability in infant  
730 studies. *Infant and Child Development* **31**, e2336 (2022).  
731
- 732 26. Wojcik, E. H., Zettersten, M. & Benitez, V. L. The map trap: Why and how word  
733 learning research should move beyond mapping. *Wiley Interdiscip Rev Cogn Sci* **13**,  
734 (2022).  
735
- 736 27. Koenig, P. L. & Naigles, L. R. Prosody influences meaning: Fifteen-month-olds interpret  
737 a novel word as an action. *Infant Behav. Dev.* **19**, 543 (1996).  
738
- 739 28. Shukla, M., White, K. S. & Aslin, R. N. Prosody guides the rapid mapping of auditory  
740 word forms onto visual objects in 6-mo-old infants. *Proc. Natl. Acad. Sci.* **108**, 6038–  
741 6043 (2011)  
742
- 743 29. Johnson, E. K. & Jusczyk, P. W. Word segmentation by 8-month-olds: When speech cues  
744 count more than statistics. *J Mem Lang* **44**, 548–567 (2001).  
745
- 746 30. Ferguson, B., Graf, E. & Waxman, S. R. Infants use known verbs to learn novel nouns:  
747 Evidence from 15- and 19-month-olds. *Cognition* **131**, 139–146 (2014).  
748
- 749 31. Meltzoff, A. N., & Brooks, R. Social cognition and language: The role of gaze following  
750 in early word learning. In *Infant pathways to language: Methods, models, and research*  
751 *disorders* (eds. Colombo, J., McCardle, P., & Freund, L.) 169–194 (Psychology Press,  
752 2009).  
753
- 754 32. Tsuji, S., Jincho, N., Mazuka, R. & Cristia, A. Communicative cues in the absence of a  
755 human interaction partner enhance 12-month-old infants' word learning. *J Exp Child*  
756 *Psychol* **191**, (2020).  
757
- 758 33. Ferguson, B. & Waxman, S. R. What the [beep]? Six-month-olds link novel  
759 communicative signals to meaning. *Cognition* **146**, 185–189 (2016).  
760
- 761 34. Morales, M., Mundy, P., Delgado, C. E., Yale, M., Messinger, D., Neal, R., & Schwartz,  
762 H. K. Responding to joint attention across the 6-through 24-month age period and early  
763 language acquisition. *Journal of applied developmental psychology* **21**, 283-298 (2000).  
764
- 765 35. Seidl, A., Tincoff, R., Baker, C., & Cristia, A. Why the body comes first: Effects of  
766 experimenter touch on infants' word finding. *Developmental science* **18**, 155-164 (2015).  
767
- 768 36. Yu, C. & Ballard, D. H. A unified model of early word learning: Integrating statistical  
769 and social cues. *Neurocomputing* **70**, 2149–2165 (2007).  
770
- 771 37. Swirbul, M. S., Herzberg, O., & Tamis-LeMonda, C. S. Object play in the everyday  
772 home environment generates rich opportunities for infant learning. *Infant Behavior and*  
773 *Development* **67**, 101712 (2022).

- 774  
775 38. Lee, C. & Lew-Williams, C. The dynamic functions of social cues during children's word  
776 learning. *Infant and Child Development* **32**, e2372 (2023).  
777
- 778 39. Hacquard, V. Being pragmatic about syntactic bootstrapping. *J Child Lang* **50**, 1041–  
779 1064 (2023).  
780
- 781 40. Swingley, D. Contributions of infant word learning to language development.  
782 *Philosophical Transactions of the Royal Society B: Biological Sciences* **364**, 3617–3632  
783 (2009).  
784
- 785 41. Feldman, N. H., Myers, E. B., White, K. S., Griffiths, T. L., & Morgan, J. L. Word-level  
786 information influences phonetic learning in adults and infants. *Cognition* **127**, 427–438  
787 (2013).  
788
- 789 42. Christophe, A., Millotte, S., Bernal, S., & Lidz, J. Bootstrapping lexical and syntactic  
790 acquisition. *Language and Speech* **51**, 61–75 (2008).  
791
- 792 43. Arunachalam, S., Escovar, E., Hansen, M. A. & Waxman, S. R. Out of sight, but not out  
793 of mind: 21-month-olds use syntactic information to learn verbs even in the absence of a  
794 corresponding event. *Lang Cogn Process* **28**, 417–425 (2013).  
795
- 796 44. Arunachalam, S. & Dennis, S. Semantic detail in the developing verb lexicon: An  
797 extension of Naigles and Kako (1993). *Dev Sci* **22**, (2019).  
798
- 799 45. Arunachalam, S. & Waxman, S. R. Meaning from syntax: Evidence from 2-year-olds.  
800 *Cognition* **114**, 442–446 (2010).  
801
- 802 46. Yuan, S., Fisher, C. & Snedeker, J. Counting the Nouns : Simple Structural Cues to Verb  
803 Meaning. *Child development* **83**, 1382–1399 (2012).  
804
- 805 47. Gertner, Y. & Fisher, C. Predicted errors in children's early sentence comprehension.  
806 *Cognition* **124**, 85–94 (2012).  
807
- 808 48. Messenger, K., Yuan, S. & Fisher, C. Learning Verb Syntax via Listening: New Evidence  
809 From 22-Month-Olds. *Language Learning and Development* **11**, 356–368 (2015).  
810
- 811 49. Yuan, S. & Fisher, C. 'Really? She Blicked the Baby?' Two-Year-Olds Learn  
812 Combinatorial Facts About Verbs by Listening. *Psychological Science* **20**, 619–626  
813 (2009).  
814
- 815 50. Dautriche, I. *et al.* Toddlers Default to Canonical Surface-to-Meaning Mapping When  
816 Learning Verbs. *Child Dev* **85**, 1168–1180 (2014).  
817



- 818 51. de Carvalho, A., Dautriche, I., Fiévet, A. C. & Christophe, A. Toddlers exploit referential  
819 and syntactic cues to flexibly adapt their interpretation of novel verb meanings. *J Exp*  
820 *Child Psychol* **203**, (2021).  
821
- 822 52. Suzuki, T. & Kobayashi, T. Syntactic Cues for Inferences about Causality in Language  
823 Acquisition: Evidence from an Argument-Drop Language. *Language Learning and*  
824 *Development* **13**, 24–37 (2017).  
825
- 826 53. Jin, S. K. *The role of syntactic and discourse information in verb learning*. University of  
827 Illinois at Urbana-Champaign, 2015.  
828
- 829 54. Lee, J. N. & Naigles, L. R. Mandarin learners use syntactic bootstrapping in verb  
830 acquisition. *Cognition* **106**, 1028–1037 (2008).  
831
- 832 55. Arunachalam, S., Syrett, K. & Chen, Y. X. Lexical Disambiguation in Verb Learning:  
833 Evidence from the Conjoined-Subject Intransitive Frame in English and Mandarin  
834 Chinese. *Front Psychol* **7**, (2016).  
835
- 836 56. Göksun, T., Küntay, A. C. & Naigles, L. R. Turkish children use morphosyntactic  
837 bootstrapping in interpreting verb meaning. *J Child Lang* **35**, 291–323 (2008).  
838
- 839 57. Fernald, A., Zangl, R., Portillo, A. L. & Marchman, V. A. Looking while listening: Using  
840 eye movements to monitor spoken language. *Developmental Psycholinguistics* 97–135  
841 (2008) doi:10.1017/CBO9781107415324.004.  
842
- 843 58. Golinkoff, R. M., Hirsh-Pasek, K., Cauley, K. M. & Gordon, L. The eyes have it: lexical  
844 and syntactic comprehension in a new paradigm. *J. Child Lang* **14**, 23-45 (1987).  
845
- 846 59. Arunachalam, S. Two-year-olds can begin to acquire verb meanings in socially  
847 impoverished contexts. *Cognition* **129**, 569–573 (2013).  
848
- 849 60. He, A. X., Huang, S., Waxman, S. & Arunachalam, S. Two-year-olds consolidate verb  
850 meanings during a nap. *Cognition* **198**, 104205 (2020).  
851
- 852 61. Chen, Y., Latourrette, A. S., Trueswell, J. & Latourrette, A. Evidence for Cross-  
853 situational Syntactic Bootstrapping: Three-year olds Generalize Verb Meaning across  
854 Different Syntactic Frames. In *Proceedings of the Annual Meeting of the Cognitive*  
855 *Science Society*, Vol 45, No. 45. (2023).  
856
- 857 62. Markman, E. M. & Wachtel, G. F. Children's Use of Mutual Exclusivity to Constrain the  
858 Meanings of Words. *Cognitive Psychology* **20**, 121-157 (1988).  
859
- 860 63. Markman, E. M. Constraints children place on word meanings. *Cogn Sci* **14**, 57-77  
861 (1990).  
862

- 863 64. Fisher, C. Structural limits on verb mapping: The role of abstract structure in 2.5-year-  
864 olds' interpretations of novel verbs. *Dev Sci* **5**, 55–64 (2002).  
865
- 866 65. Lidz, J., Gleitman, H. & Gleitman, L. Understanding how input matters: verb learning  
867 and the footprint of universal grammar. *Cognition* **87**, 151-178 (2003).  
868
- 869 66. Gertner, Y. & Fisher, C. Predicted errors in children's early sentence comprehension.  
870 *Cognition* **124**, 85–94 (2012).  
871
- 872 **67.** Fisher, C., Jin, K. S., & Scott, R. M. The developmental origins of syntactic  
873 bootstrapping. *Topics in Cognitive Science* **12**, 48–77 (2020).  
874 **This review discusses thoroughly the evidence and challenges to the structure-**  
875 **mapping account, which proposes that syntactic bootstrapping begins with a bias to**  
876 **map each noun phrase in a sentence onto a participant role in an event.**  
877
- 878 68. Pozzan, L., Gleitman, L. R. & Trueswell, J. C. Semantic Ambiguity and Syntactic  
879 Bootstrapping: The Case of Conjoined-Subject Intransitive Sentences. *Language*  
880 *Learning and Development* **12**, 14–41 (2016).  
881
- 882 69. Gleitman, Cassidy, Nappa, P. & T. Hard words. *Language Learning and Development* **1**,  
883 23–64 (2005).  
884
- 885 70. Papafragou, A., Cassidy, K. & Gleitman, L. When we think about thinking: The  
886 acquisition of belief verbs. *Cognition* **105**, 125–165 (2007).  
887
- 888 71. Dudley, R., Rowe, M., Hacquard, V. & Lidz, J. Discovering the factivity of 'know'. In  
889 *Proceedings of SALT* **27**, 600-619 (2017).  
890
- 891 72. Hacquard, V. & Lidz, J. Children's attitude problems: Bootstrapping verb meaning from  
892 syntax and pragmatics. *Mind Lang* **34**, 73–96 (2019).  
893
- 894 73. White, A. S., Hacquard, V. & Lidz, J. Semantic Information and the Syntax of  
895 Propositional Attitude Verbs. *Cogn Sci* **42**, 416–456 (2018).  
896
- 897 74. Hallé, P. A., Durand, C. & Boysson-bardies, B. De. Do 11-month-old French Infants  
898 Process Articles ? *Language and Speech* **51**, 23-44 (2008).  
899
- 900 75. Höhle, B. & Weissenborn, J. German-learning infants' ability to detect unstressed closed-  
901 class elements in continuous speech. *Dev Sci* **6**, 122–127 (2003).  
902
- 903 76. Shafer, V. L., Shucard, D. W., Shucard, J. L. & Gerken, L. An Electrophysiological  
904 Study of Infants' Sensitivity to the Sound Patterns of English Speech. *Journal of Speech,*  
905 *Language, and Hearing Research* **41**, 874–886 (1998).  
906

- 907 77. Shi, R., Cutler, A., Werker, J. F. & Cruickshank, M. Frequency and form as determinants  
908 of functor sensitivity in English-acquiring infants. *J Acoust Soc Am* **119**, EL61-L67  
909 (2006).  
910
- 911 78. Shi, R. Functional Morphemes and Early Language Acquisition. *Child Dev Perspect* **8**,  
912 6–11 (2014).  
913
- 914 79. de Carvalho, A., Babineau, M., Trueswell, J. C., Waxman, S. R. & Christophe, A.  
915 Studying the real-time interpretation of novel noun and verb meanings in young children.  
916 *Front Psychol* **10**, 274 (2019).  
917
- 918 80. Babineau, M., Shi, R. & Christophe, A. 14-month-olds exploit verbs' syntactic contexts  
919 to build expectations about novel words. *Infancy* **25**, 719-733 (2020).  
920
- 921 81. Höhle, B., Weissenborn, J., Kiefer, D., Schulz, A. & Schmitz, M. Functional elements in  
922 infants' speech processing: The role of determiners in the syntactic categorization of  
923 lexical elements. *Infancy* **5**, 341–353 (2004).  
924
- 925 82. Shi, R. & Melançon, A. Syntactic categorization in French-learning infants. *Infancy* **15**,  
926 517–533 (2010).  
927
- 928 83. Arunachalam, S. & Waxman, S. R. Meaning from syntax: Evidence from 2-year-olds.  
929 *Cognition* **114**, 442–446 (2010).  
930
- 931 84. Arunachalam, S. & Waxman, S. R. Let's See a Boy and a Balloon: Argument Labels and  
932 Syntactic Frame in Verb Learning. *Lang Acquis* **22**, 117–131 (2015).  
933
- 934 85. Bernal, S., Lidz, J., Millotte, S. & Christophe, A. Syntax Constrains the Acquisition of  
935 Verb Meaning. *Language Learning and Development* **3**, 325–341 (2007).  
936
- 937 86. Oshima-Takane, Y., Ariyama, J., Kobayashi, T., Katerelos, M. & Poulin-Dubois, D.  
938 Early verb learning in 20-month-old Japanese-speaking children. *J Child Lang* **38**, 455–  
939 484 (2011).  
940
- 941 87. Waxman, S. R., Lidz, J. L., Braun, I. E. & Lavin, T. Twenty four-month-old infants'  
942 interpretations of novel verbs and nouns in dynamic scenes. *Cogn Psychol* **59**, 67–95  
943 (2009).  
944
- 945 88. de Carvalho, A., He, A. X., Lidz, J. & Christophe, A. Prosody and Function Words Cue  
946 the Acquisition of Word Meanings in 18-Month-Old Infants. *Psychol Sci* **30**, 319–332  
947 (2019a).  
948
- 949 89. Waxman, S. Specifying the scope of 13-month-olds' expectations for novel words.  
950 *Cognition* **70**, B35–B50 (1999).  
951

- 952 90. Fisher, C., Hallb, D. G., Rakowiw, S. & Gleitman, L. *When it is better to receive than to*  
 953 *give: Syntactic and conceptual constraints on vocabulary growth* \*. *Lingua* vol. 92  
 954 (1994).  
 955
- 956 91. Fisher, C., Gleitman, H. & Gleitman, L. R. *On the Semantic Content of Subcategorization*  
 957 *Frames*. (1991).  
 958
- 959 92. Chemla, E., Mintz, T. H., Bernal, S. & Christophe, A. Categorizing words using ‘frequent  
 960 frames’: What cross-linguistic analyses reveal about distributional acquisition strategies.  
 961 *Dev Sci* **12**, 396–406 (2009).  
 962
- 963 93. Chrupała, G. & Alishahi, A. Online Entropy-based Model of Lexical Category  
 964 Acquisition. In *Proceedings of the Fourteenth Conference on Computational Natural*  
 965 *Language Learning* (pp. 182-191) (2010).  
 966
- 967 94. Mintz, T. H. Frequent frames as a cue for grammatical categories in child directed  
 968 speech. *Cognition* **90**, 91–117 (2003).  
 969
- 970 95. Parisien, C., Fazly, A. & Stevenson, S. *An Incremental Bayesian Model for Learning*  
 971 *Syntactic Categories*. (2008).  
 972
- 973 96. Redington, M., Chater, N. & Finch, S. Distributional information: A powerful cue for  
 974 acquiring syntactic categories. *Cogn Sci* **22**, 425–469 (1998).  
 975
- 976 97. Wang, H., Höhle, B., Nihan Ketrez, F., Küntay, A. C. & Mintz, T. H. Cross-Linguistic  
 977 Distributional Analyses with Frequent Frames: the Cases of German and Turkish. In  
 978 *Proceedings of 35th Annual Boston University Conference on Language Development*  
 979 (pp. 628-640). Somerville, MA: Cascadilla Press (2011).  
 980
- 981 98. Weisleder, A. & Waxman, S. R. What’s in the input? Frequent frames in child-directed  
 982 speech offer distributional cues to grammatical categories in Spanish and English. *J Child*  
 983 *Lang* **37**, 1089–1108 (2010).  
 984
- 985 99. Newport, E. L. Maturational constraints on language learning. *Cogn Sci* **14**, 11–28  
 986 (1990).  
 987
- 988 100. Babineau, M., Christophe, A. & Preverbal, A. C. Preverbal infants’ sensitivity to  
 989 grammatical dependencies. *Infancy* **27**, 648-662 (2022).  
 990
- 991 101. Mintz, T. H. Finding the verbs: Distributional cues to categories available to young  
 992 learners. in *Action meets word: How children learn verbs* (eds. Hirsh-Pasek, K. &  
 993 Michnick Golinkoff, R.) 31–63 (Oxford University Press, 2006).  
 994
- 995 102. Hicks, J. P. *The Impact of Function Words on the Processing and Acquisition of Syntax*.  
 996 (2006).  
 997

- 998 **103.** Lidz, J. Learning, Memory, and Syntactic Bootstrapping: A Meditation. *Top Cogn Sci*  
 999 **12**, 78–90 (2020).  
 1000 **This review discusses how memory drives word learning and syntactic**  
 1001 **bootstrapping.**  
 1002
- 1003 104. Trueswell, J. C., Medina, T. N., Hafri, A. & Gleitman, L. R. Propose but verify: Fast  
 1004 mapping meets cross-situational word learning. *Cogn Psychol* **66**, 126–156 (2013).  
 1005
- 1006 105. Medina, T. N., Snedeker, J., Trueswell, J. C. & Gleitman, L. R. How words can and  
 1007 cannot be learned by observation. *Proc Natl Acad Sci U S A* **108**, 9014–9019 (2011).  
 1008
- 1009 106. Wang, F. H. & Trueswell, J. C. Spotting Dalmatians: Children’s ability to discover  
 1010 subordinate-level word meanings cross-situationally. *Cogn Psychol* **114**, (2019).  
 1011
- 1012 107. Wang, F. H. & Trueswell, J. Being suspicious of suspicious coincidences: The case of  
 1013 learning subordinate word meanings. *Cognition* **224**, (2022).  
 1014
- 1015 108. Dautriche, I. & Chemla, E. Cross--situational word learning in the right situations.  
 1016 *Journal of Experimental Psychology: Learning, Memory, and Cognition*, **40**(3), 892–  
 1017 903 (2014).  
 1018
- 1019 109. Yurovsky, D. & Frank, M. C. An integrative account of constraints on cross-situational  
 1020 learning. *Cognition* **145**, 53–62 (2015).  
 1021
- 1022 110. Brusini, P., Seminc, O., Amsili, P. & Christophe, A. The Acquisition of Noun and  
 1023 Verb Categories by Bootstrapping From a Few Known Words: A Computational Model.  
 1024 *Front Psychol* **12**, (2021).  
 1025
- 1026 111. Christophe, A., Dautriche, I., Carvalho, A. De & Brusini, P. Bootstrapping the Syntactic  
 1027 Bootstrapper. *Proceedings of the 40th Annual Boston University Conference on*  
 1028 *Language Development*. Somerville, MA: Cascadilla Press, 75–88 (2016).  
 1029 **This paper offers a detailed account of the semantic seed hypothesis, a proposal**  
 1030 **that was only partially discussed in other prior work.**  
 1031
- 1032 112. Gutman, A., Dautriche, M. I., Crabbé, D. B. & Christophe, D. A. Bootstrapping the  
 1033 Syntactic Bootstrapper: Probabilistic Labeling of Prosodic Phrases. *Dx.Doi.Org*  
 1034 141006190207005 (2014) doi:10.1080/10489223.2014.971956.  
 1035
- 1036 113. Christodoulopoulos, C., Roth, D. & Fisher, C. An incremental model of syntactic  
 1037 bootstrapping. *7th Workshop on Cognitive Aspects of Computational Language*  
 1038 *Learning*, 38–43 (2016).  
 1039
- 1040 114. Gomez, R. L. & Gerken, L. Artificial grammar learning by 1-year-olds leads to specific  
 1041 and abstract knowledge. **70**, 109–135 (1999).  
 1042

- 1043 115. Hohle, B., Schmitz, M., Santelmann, L. M. & Weissenborn, J. The Recognition of  
 1044 Discontinuous Verbal Dependencies by German 19-Month-Olds: Evidence for Lexical  
 1045 and Structural Influences on Children's Early Processing Capacities. *Language*  
 1046 *Learning and Development* **2**, 277–300 (2006).  
 1047
- 1048 116. Marchetto, E. & Bonatti, L. L. Words and possible words in early language acquisition.  
 1049 *Cogn Psychol* **67**, 130–150 (2013).  
 1050
- 1051 117. Saffran, J. R., Aslin, R. N. & Newport, E. L. Statistical Learning by 8-Month-Old  
 1052 Infants. *Science* **274**, 1926–1928 (1996).  
 1053
- 1054 118. Santelmann, L. M. & Jusczyk, P. W. Sensitivity to discontinuous dependencies in  
 1055 language learners : evidence for limitations in processing space. **69**, 105–134 (1998).  
 1056
- 1057 119. Heugten, M. Van & Johnson, E. K. Linking infants ' distributional learning abilities to  
 1058 natural language acquisition. *Journal of memory and language*, **63**, 197-209(2010).  
 1059
- 1060 120. Pinker S. *Language learnability and language development*. Cambridge, MA: Harvard  
 1061 University Press (1984).  
 1062
- 1063 121. Pinker, S. How could a child use verb syntax to learn verb semantics?. *Lingua* **92**, 377-  
 1064 410 (1994).  
 1065
- 1066 122. Gleitman, L. R. & Trueswell, J. C. Easy Words: Reference Resolution in a Malevolent  
 1067 Referent World. *Top Cogn Sci* **12**, 22–47 (2020).  
 1068
- 1069 123. Bergelson, E. & Swingley, D. The Acquisition of Abstract Words by Young Infants.  
 1070 *Cognition* **127**, 391–397 (2013).  
 1071
- 1072 124. Bergelson, E. & Swingley, D. Early Word Comprehension in Infants: Replication and  
 1073 Extension. *Language Learning and Development* **11**, 369–380 (2015).  
 1074
- 1075 125. Parise, E. & Csibra, G. Electrophysiological Evidence for the Understanding of  
 1076 Maternal Speech by 9-Month-Old Infants. *Psychol Sci* **23**, 728–733 (2012).  
 1077
- 1078 126. Syrnyk, C. & Meints, K. Bye-bye mummy – Word comprehension in 9-month-old  
 1079 infants. *British Journal of Developmental Psychology* **35**, 202–217 (2017).  
 1080
- 1081 127. Tincoff, R. & Jusczyk, P. W. Some beginnings of word comprehension in 6-month-olds.  
 1082 *Psych Sci* **10**, 172–175 (1999).  
 1083
- 1084 128. Carey, S. *The Origin of Concepts*. Oxford university press (2009).  
 1085
- 1086 129. Gerken, L. & Boltt, A. Three Exemplars Allow at Least Some Linguistic  
 1087 Generalizations: Implications for Generalization Mechanisms and Constraints.  
 1088 *Language Learning and Development* **4**, 228–248 (2008).

- 1089  
1090  
1091  
1092  
1093  
1094  
1095  
1096  
1097  
1098  
1099  
1100  
1101  
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1121  
1122  
1123  
1124  
1125  
1126  
1127  
1128  
1129  
1130  
1131  
1132
130. Wojcik, E. H. & Saffran, J. R. Toddlers encode similarities among novel words from meaningful sentences. *Cognition* **138**, 10–20 (2015).
131. Babineau, M., de Carvalho, A., Trueswell, J. & Christophe, A. Familiar words can serve as a semantic seed for syntactic bootstrapping. *Dev Sci* **24**, (2021).
132. Barbir, M., Babineau, M. J., Fiévet, A. C. & Christophe, A. Rapid infant learning of syntactic-semantic links. *Proc Natl Acad Sci U S A* **120**, e2209153119 (2023).  
**This paper presents the first experimental test of the semantic seed hypothesis with toddlers, demonstrating their ability to learn rapidly new syntax-semantic links from a short naturalistic video.**
133. Clark, A. Whatever next? Predictive brains, situated agents, and the future of cognitive science. *Behavioral and Brain Sciences* **36**, 181–204 (2013).
- 134.** Babineau, M., Havron, N., Dautriche, I., de Carvalho, A. & Christophe, A. Learning to predict and predicting to learn: Before and beyond the syntactic bootstrapper. *Language Acquisition* **30**, 337–360 (2023).  
**This review discusses both successes and challenges of applying the predictive processing framework to syntactic bootstrapping.**
135. Reuter, T., Borovsky, A. & Lew-Williams, C. Predict and redirect: Prediction errors support children’s word learning. *Dev Psychol* **55**, 1656–1665 (2019).
136. Lin, Y. & Fisher, C. Error-Based Learning: A Mechanism for Linking Verbs to Syntax. In *Proceedings of the Annual Meeting of the Cognitive Science Society* (2017).
137. Chang, F., Dell, G. S. & Bock, K. Becoming syntactic. *Psychol Rev* **113**, 234–272 (2006).
138. Bernal, S., Dehaene-Lambertz, G., Millotte, S. & Christophe, A. Two-year-olds compute syntactic structure on-line. *Dev Sci* **13**, 69–76 (2010).
139. Beretti, M., Havron, N. & Christophe, A. Four- and 5-year-old children adapt to the reliability of conflicting sources of information to learn novel words. *J Exp Child Psychol* **200**, 104927 (2020).
140. Havron, N., de Carvalho, A., Fiévet, A. C. & Christophe, A. Three- to Four-Year-Old Children Rapidly Adapt Their Predictions and Use Them to Learn Novel Word Meanings. *Child Dev* **90**, 82–90 (2019).
141. Imai, M. *et al.* Novel noun and verb learning in Chinese-, English-, and Japanese-speaking children. *Child Dev* **79**, 979–1000 (2008).

- 1133           **This study tests syntactic bootstrapping in English and in two non-Indo-European**  
 1134           **languages, Japanese and Mandarin Chinese, and evidences the situations in which**  
 1135           **children syntactic bootstrap across languages.**  
 1136
- 1137           142. de Carvalho, A., Dautriche, I., Lin, I. & Christophe, A. Phrasal prosody constrains  
 1138           syntactic analysis in toddlers. *Cognition* **163**, 67–79 (2017).  
 1139
- 1140           143. Helmholtz, H. On the Sensations of Tone as a Physiological Basis for the Theory of  
 1141           Music (English trns. Southall, J.P.C) (Dover, 1962).  
 1142
- 1143           144. Rao, R. P., & Ballard, D. H. Predictive coding in the visual cortex: a functional  
 1144           interpretation of some extra-classical receptive-field effects. *Nature neuroscience* **2**, 79-  
 1145           87 (1999).  
 1146
- 1147           145. Friston, K. A theory of cortical responses. *Philosophical transactions of the Royal*  
 1148           *Society B: Biological sciences* **360**, 815-836 (2005).  
 1149
- 1150           146. Babineau, M., Havron, N., Dautriche, I., de Carvalho, A., & Christophe, A. Learning to  
 1151           predict and predicting to learn: Before and beyond the syntactic bootstrapper. *Language*  
 1152           *Acquisition*, 1-24 (2022).  
 1153
- 1154           147. Chang, F., Dell, G. S., & Bock, K. Becoming syntactic. *Psychological Review* **113**, 234  
 1155           (2006).  
 1156
- 1157           148. Lin, Y., & Fisher, C. Error-Based Learning: A Mechanism for Linking Verbs to Syntax.  
 1158           In *The proceedings of the 39th Annual Meeting of the Cognitive Science Society*, 754-  
 1159           759 (UC Merced, 2017).  
 1160
- 1161           149. Ficco, L., Mancuso, L., Manuello, J., Teneggi, A., Liloia, D., Duca, S., ... & Cauda, F.  
 1162           Disentangling predictive processing in the brain: a meta-analytic study in favour of a  
 1163           predictive network. *Scientific Reports* **11**, 16258 (2021).  
 1164
- 1165           150. Nagai, Y. Predictive learning: its key role in early cognitive development. *Philosophical*  
 1166           *Transactions of the Royal Society B* **374**, 20180030 (2019).  
 1167
- 1168           151. Philippsen, A., Tsuji, S., & Nagai, Y. Simulating Developmental and Individual  
 1169           Differences of Drawing Behavior in Children Using a Predictive Coding Model.  
 1170           *Frontiers in Neurorobotics* **16**, 856184 (2022).  
 1171
- 1172           152. Xu, T., Kawasaki, Z., Takida, K., & Tang, Z. A child verb learning model based on  
 1173           syntactic bootstrapping. *IEICE TRANSACTIONS on Information and Systems* **85**, 985-  
 1174           993 (2002).  
 1175
- 1176           153. Gillette, J., Gleitman, H., Gleitman, L. & Lederer, A. *Human simulations of vocabulary*  
 1177           *learning. Cognition* **73**, 135–176 (1999).  
 1178



- 1179 154. Chen, C., Houston, D. M. & Yu, C. Parent–Child Joint Behaviors in Novel Object Play  
 1180 Create High-Quality Data for Word Learning. *Child Dev* **92**, 1889–1905 (2021).  
 1181
- 1182 155. Masek, L. R. *et al.* Where language meets attention: How contingent interactions  
 1183 promote learning. *Developmental Review* **60**, (2021).  
 1184
- 1185 156. de Diego-Balaguer, R., Martinez-Alvarez, A. & Pons, F. Temporal attention as a  
 1186 Scaffold for language development. *Front Psychol* **7**, (2016).  
 1187
- 1188 157. Perkins, L., Feldman, N. H. & Lidz, J. Learning an Input Filter for Argument Structure  
 1189 Acquisition. *Cogn Sci* **46**, e13080 (2022).  
 1190
- 1191 \*\*\* Box 1 \*\*\*  
 1192
- 1193 158. Kayne, R. S. *The antisymmetry of syntax* (The MIT press, 1994).  
 1194
- 1195 159. Cinque, G. *Adverbs and functional heads: A cross-linguistic perspective* (Oxford  
 1196 University Press, 1999).  
 1197
- 1198 160. Koopman, H. J., & Szabolcsi, A. *Verbal complexes* (The MIT Press, 2000).  
 1199
- 1200 161. Fodor, J., & Lepore, E. Impossible words?. *Linguistic Inquiry* **30**, 445-453 (1999).  
 1201
- 1202 162. Singh, R., & Agnihotri, R. K. *Hindi morphology: A word-based description* (Motilal  
 1203 Banarsidass, 1997).  
 1204
- 1205 163. Terada, M. *Incorporation and argument structure in Japanese* (University of  
 1206 Massachusetts Amherst, 1990).  
 1207
- 1208 164. Embick, D. *Contextual conditions on stem alternations*. In Romance Languages and  
 1209 Linguistic Theory (eds. Franco, I., Lusini, S., & Saab, A.) 21-40 (John Benjamins,  
 1210 2012).  
 1211
- 1212 165. Miyagawa, S. *Syntax in the treetops* (The MIT Press, 2022).  
 1213
- 1214 166. Diewald, G. Discourse particles and modal particles as grammatical elements. In  
 1215 *Approaches to discourse particles* (ed. Fischer, K.) 403-425 (Brill, 2006).  
 1216
- 1217 167. Nowenstein, I., Sigurjónsdóttir, S., Yang, C., Ingason, A. K. & Wallenberg, J. The  
 1218 Meaning of Case: Morphosyntactic Bootstrapping and Icelandic Datives. In The  
 1219 Proceedings of the 44<sup>th</sup> annual Boston University Conference on Language  
 1220 Development (eds. Brown, M. M. & Kohut, A.) 402-425 (Cascadilla Press, 2020).  
 1221
- 1222 168. Suzuki, T. Bootstrapping from Case-Marking Morphology in Japanese. *Studies in*  
 1223 *Language Science* **2**, 157-174 (2002).  
 1224

1225 \*\*\*\* Box 2 \*\*\*\*

- 1226
- 1227 169. Haryu, E., & Kajikawa, S. Japanese infants' use of grammatical particles in segmenting  
1228 and syntactically categorizing words. *IEICE Technical Report* **113**, 61-66 (2014).
- 1229
- 1230 170. Singh, L., Rajendra, S. J. & Mazuka, R. Diversity and representation in studies of infant  
1231 perceptual narrowing. *Child Dev Perspect* **16**, 191–199 (2022).
- 1232
- 1233 171. Blasi, D. E., Henrich, J., Adamou, E., Kemmerer, D. & Majid, A. Over-reliance on  
1234 English hinders cognitive science. *Trends in Cognitive Sciences* **26**, 1153–1170 (2022).
- 1235
- 1236 172. Oakes, L. M. Sample Size, Statistical Power, and False Conclusions in Infant Looking-  
1237 Time Research. *Infancy* **22**, 436–469 (2017).
- 1238
- 1239 173. DeBolt, M. C., Rhemtulla, M. & Oakes, L. M. Robust data and power in infant research:  
1240 A case study of the effect of number of infants and number of trials in visual preference  
1241 procedures. *Infancy* **25**, 393–419 (2020).
- 1242
- 1243 174. Visser, I., Bergmann, C., Byers-Heinlein, K., Dal Ben, R., Duch, W., Forbes, S., ... &  
1244 Zettersten, M. Improving the generalizability of infant psychological research: The  
1245 ManyBabies model. *Behavioral and Brain Sciences* **45**, e35 (2022).
- 1246
- 1247 175. Zettersten, M., Bergey, C. A., Bhatt, N. S., Boyce, V., Braginsky, M., Carstensen, A., ...  
1248 & Frank, M. C. Peekbank: Exploring children's word recognition through an open,  
1249 large-scale repository for developmental eye-tracking data. In *Proceedings of the 43<sup>rd</sup>*  
1250 *Annual Meeting of the Cognitive Science Society*, 2950-2956 (UC Merced, 2021).
- 1251
- 1252 176. Frank, M. C., Braginsky, M., Yurovsky, D. & Marchman, V. A. Wordbank: An open  
1253 repository for developmental vocabulary data. *J Child Lang* **44**, 677–694 (2017).
- 1254

#### 1255 **Highlighted references**

- 1256
- 1257 Cao, A. & Lewis, M. Quantifying the syntactic bootstrapping effect in verb learning: A meta-analytic  
1258 synthesis. *Dev Sci* **25**, (2022).
- 1259 *This meta-analysis on syntactic bootstrapping demonstrates a robust effect, but reveals limitations on the*  
1260 *scope of syntactic structures and languages studied.*
- 1261
- 1262 Gleitman, L. The Structural Sources of Verb Meanings. *Lang Acquis* **1**, 3–55 (1990).
- 1263 *This is Gleitman's seminal paper proposing and detailing syntactic bootstrapping.*
- 1264
- 1265 Hacquard, V. & Lidz, J. On the Acquisition of Attitude Verbs. *Annual Review of Linguistics* **8**, 193-212  
1266 (2022).

- 1267 *This review explores how syntactic bootstrapping might interface with other mechanisms, such as*  
1268 *pragmatic bootstrapping.*  
1269
- 1270 Naigles, L. Children use syntax to learn verb meanings. *Journal of Child Language* **17**, 357–374 (1990).  
1271 *This study introduced the classic syntactic bootstrapping paradigm used to this day.*  
1272
- 1273 Imai, M. et al. Novel noun and verb learning in Chinese-, English-, and Japanese-speaking children. *Child*  
1274 *Dev* **79**, 979–1000 (2008).  
1275 *This study tests syntactic bootstrapping in English and two non-Indo-European languages, Japanese and*  
1276 *Mandarin Chinese, and evidences the situations in which children syntactic bootstrap across languages.*  
1277
- 1278 Christophe, A., Dautriche, I., de Carvalho, A., & Brusini, P. (2016). Bootstrapping the  
1279 syntactic bootstrapper. In Proceedings of the 40th Annual Boston University  
1280 Conference on Language Development (pp. 75-88). Somerville, MA: Cascadilla  
1281 Press.  
1282 *This paper offers a detailed account of the semantic seed hypothesis, a proposal that was only partially*  
1283 *discussed in other prior work.*  
1284
- 1285 Fisher, C., Jin, K. S., & Scott, R. M. (2020). The developmental origins of syntactic bootstrapping. *Topics*  
1286 *in Cognitive Science*, 12(1), 48–77.  
1287 *This review discusses thoroughly the evidence and challenges to the structure-mapping account, which*  
1288 *proposes that syntactic bootstrapping begins with a bias to map each noun phrase in a sentence onto a*  
1289 *participant role in an event.*  
1290
- 1291 Lidz, J. (2020). Learning, memory, and syntactic bootstrapping: A meditation. *Topics in Cognitive*  
1292 *Science*, 12(1), 78-90. <https://doi.org/10.1111/tops.12411>  
1293 *This review discusses how memory drives word learning and syntactic bootstrapping.*  
1294
- 1295 Babineau, M., Havron, N., Dautriche, I., de Carvalho, A., & Christophe, A. (2022). Learning to predict  
1296 and predicting to learn: Before and beyond the syntactic bootstrapper. *Language Acquisition*, 1-  
1297 24.  
1298 *This review discusses both successes and challenges of applying the predictive processing framework to*  
1299 *syntactic bootstrapping.*  
1300

1301 Barbir, M., Babineau, M. J., Fiévet, A. C., & Christophe, A. (2023). Rapid infant learning of  
1302 syntactic–semantic links. *Proceedings of the National Academy of Sciences*, *120*(1),  
1303 e2209153119.  
1304 *This paper presents the first experimental test of the semantic seed hypothesis with toddlers,*  
1305 *demonstrating their ability to learn rapidly new syntax-semantic links from a short naturalistic video.*  
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### 1318 **Competing interests**

1319 The authors declare no competing interests.

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### 1321 **Author contributions**

1322 M. Babineau wrote the abstract and sections 3, 4, and designed the figures. M. Barbir wrote the  
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