



HAL
open science

Syntactic bootstrapping as a mechanism for language learning

Mireille Babineau, Monica Barbir, Alex de Carvalho, Naomi Havron, Isabelle Dautriche, Anne Christophe

► **To cite this version:**

Mireille Babineau, Monica Barbir, Alex de Carvalho, Naomi Havron, Isabelle Dautriche, et al.. Syntactic bootstrapping as a mechanism for language learning. *Nature Reviews Psychology*, In press, 10.1038/s44159-024-00317-w . hal-04611468

HAL Id: hal-04611468

<https://hal.science/hal-04611468>

Submitted on 13 Jun 2024

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

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

Mireille Babineau ^{1*}, Monica Barbir ^{2*}, Alex de Carvalho ³, Naomi Havron ^{4,5}, Isabelle Dautriche ⁶, and
Anne Christophe ^{7,8}

¹ Department of Psychology, University of Toronto, Canada

² International Research Center for Neurointelligence (WPI-IRCN), UTIAS, The University of Tokyo;
Tokyo, Japan

³ Laboratoire de Psychologie du Développement et de l'Éducation de l'Enfant (LaPsyDE), CNRS,
Université Paris Cité, Paris, France

⁴ School of Psychological Sciences, University of Haifa, Israel

⁵ Center for the Study of Child Development, University of Haifa, Israel

⁶ Laboratoire de Psychologie Cognitive, Aix-Marseille University, CNRS, Marseille, France

⁷ Laboratoire de Sciences Cognitives et Psycholinguistique, DEC-ENS / EHESS / CNRS, Ecole Normale
Supérieure – PSL University, Paris, France

⁸ Maternité Port-Royal, AP-HP, Faculté de Médecine Paris Descartes, France

Corresponding authors: correspondence concerning this article should be addressed to:

Anne Christophe. Email: anne.christophe@ens.psl.eu; Address of Dr. Christophe: Laboratoire de
Sciences Cognitives et Psycholinguistique, 29 rue d'Ulm, 75005 Paris, France

Mireille Babineau. Email: mireille.babineau@utoronto.ca; Address: Department of Psychology, 100 St.
George Street, Sidney Smith Hall, 4th floor, Toronto, ON (Canada), M5S 3G3

Monica Barbir. Email: monica.barbir@ircn.jp; Address: International Research Center for
Neurointelligence (WPI-IRCN), UTIAS, The University of Tokyo, Tokyo 113-0033, Japan

ORCID: 0000-0001-9940-669X

38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54

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.

Introduction

55
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 learning¹
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 mouse²). 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: ¹). This
74 capacity is called 'syntactic bootstrapping'², 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., ³⁻⁵; for a review: ⁶). 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. ^{7,8}). 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

¹ 'Word learning' throughout the manuscript refers to the acquisition of content words (words that bear meaning): nouns, verbs, adjectives, and adverbs.

² 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 20th 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: ⁹⁻¹¹), or innatist
102 perspectives which were centered on demonstrating how an innate language capacity could underlie
103 learning (e.g., generativism: ¹²). 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 learning¹³: 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.¹⁴⁻¹⁵ 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).¹⁶ 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.¹⁷ A learner³ 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.⁴

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.¹⁸ 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”).¹⁹ 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 (¹⁵; see
149 Figure 2). Their hypothesis was that vision-related words, like the distinction between ‘see’ and ‘look’, may

³ An adult, linguist learner.

⁴ 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.^{20,21} 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).²¹ 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.¹⁵ 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);¹⁹ (2) there are more learning cues in the
181 environment than it appears (Landau & Gleitman study)¹⁵; 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).^{20,2}

184 ¹The 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., ^{22,23}). Furthermore, they revealed that production is subject to additional non-
190 linguistic cognitive constraints (e.g., speech motor control, executive functions: ²⁴), 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., ^{25,26}).

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) ^{27,28} 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) ^{29,30}. 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). ³¹⁻
202 ³³. 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: ³⁴; touch: ³⁵). 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., ³⁶⁻³⁸).

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.³⁹ 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).^{40,41} The acoustic features of phonemes vary greatly depending on the context, such as
216 neighbouring sounds, stress, and speaker.⁴⁰ 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.^{40,41} 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.,⁴²). 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: ^{4,21,43-49}; in French: ^{50,51}; in Japanese: ⁵²; in Korean:⁵³; in
238 Mandarin: ^{54,55}; in Turkish:⁵⁶). 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., ^{57,58}), 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)²¹, toddlers heard these cues while observing
254 events, but in subsequent work (e.g.,^{49,59}), researchers showed that learners' remarkable inference process
255 can even be active in the absence of event observation. Indeed, in Yuan & Fisher (2009)⁴⁹, 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 also⁶⁰).

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-analysis¹, 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.,^{42,51}). 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)⁴² 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. ⁶¹).

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. ⁶²; the whole-object assumption: e.g. ⁶³). 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., ^{2,6,21,64,65}). 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., ^{50,51,66}). 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: ^{67,68}). 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 ⁵⁴; Kannada:⁶⁵). As Fisher and colleagues⁶ 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., ^{2,69}). 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)⁷⁰, 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 ⁷¹; see also ^{7,39,72,73}), 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., ⁷⁴⁻⁷⁷; for a review: ⁷⁸). 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. ⁷⁹). 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; ⁴⁵⁻⁴⁷), but also semantic expectations (e.g.,
339 ^{5,79,83-88}). 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., ^{51,54,56}). For instance, in de Carvalho et al.
341 (2019a)⁸⁸, 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)⁸⁹, 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., ⁹⁰), 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 sophisticated⁶⁸.

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.⁹¹). 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.,^{92–98}). 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 cues⁹⁹. 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 (¹⁰⁰; see also ^{101,102}). As Lidz (2020)¹⁰³ 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;^{104–106}; but see:^{107–}
384 ¹⁰⁹). 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 (¹¹⁰⁻¹¹², see similar proposals: ^{68,94,113}), infants’
389 burgeoning lexicon (their semantic seed) and their notorious ability to track distributional regularities (e.g.,
390 ¹¹⁴⁻¹¹⁹) 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 bootstrapping¹²⁰, 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 ¹²¹), 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., ¹²²), as they would have been learned through rich social
404 and multimodal experiences enabling simple word-to-world mappings (e.g., ^{22,23,123-127}). 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; ¹²⁸). 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: ¹²⁹⁻¹³²) 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 occurs¹³³. Predictive processing, or error-based learning, has also been suggested to underlie
423 language acquisition^{134–137}. 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)¹³⁸, 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 ^{139,140}.

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)¹¹⁰ 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; ¹³⁰⁻¹³²). 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)¹³², 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., ³⁶). 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.^{8,141}
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.^{88,142} 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.³⁹ 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.⁷ Even for
505 words that benefit from syntactic bootstrapping alone, children bootstrap selectively depending on the
506 situation.^{139,141} Studies show that preschool children only syntactic-bootstrapped speech from reliable
507 speakers¹³⁹ and appropriate visual contexts¹⁴¹. 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.¹⁴³⁻¹⁴⁸ 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:
522 ¹⁴⁹). 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.¹⁴⁶ 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.^{150,151} 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.,¹⁵²). 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.^{14,153} 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.^{154,155}
 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 ^{141,43}). 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.^{155,157} How the two interact to create
 570 such a powerful learning mechanism is even less clear (cf. ⁷). 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., ¹⁵⁸⁻¹⁶⁰). 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 ¹⁶¹). 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.¹⁶²

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

593

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

596
 597 The research on syntactic bootstrapping across the world's languages shows that children can bootstrap
 598 meaning from morphological markers.^{156,167} 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).^{141,168} 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: ¹). 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.^{52,54,141,168,169}
 614 Recent literature reviews have shown how important it is to study language learning across many different
 615 languages, for our theories (e.g., ^{170,171}). 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:¹⁵² 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.¹⁴¹

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.^{192,173} 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.¹⁷⁴⁻¹⁷⁶ 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 metanalysis 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 38th 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. Swingle, 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. Maturation 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 130. Wojcik, E. H. & Saffran, J. R. Toddlers encode similarities among novel words from
1091 meaningful sentences. *Cognition* **138**, 10–20 (2015).
1092
- 1093 131. Babineau, M., de Carvalho, A., Trueswell, J. & Christophe, A. Familiar words can serve
1094 as a semantic seed for syntactic bootstrapping. *Dev Sci* **24**, (2021).
1095
- 1096 132. Barbir, M., Babineau, M. J., Fiévet, A. C. & Christophe, A. Rapid infant learning of
1097 syntactic-semantic links. *Proc Natl Acad Sci U S A* **120**, e2209153119 (2023).
1098 **This paper presents the first experimental test of the semantic seed hypothesis with**
1099 **toddlers, demonstrating their ability to learn rapidly new syntax-semantic links**
1100 **from a short naturalistic video.**
1101
- 1102 133. Clark, A. Whatever next? Predictive brains, situated agents, and the future of cognitive
1103 science. *Behavioral and Brain Sciences* **36**, 181–204 (2013).
1104
- 1105 **134.** Babineau, M., Havron, N., Dautriche, I., de Carvalho, A. & Christophe, A. Learning to
1106 predict and predicting to learn: Before and beyond the syntactic bootstrapper. *Language*
1107 *Acquisition* **30**, 337–360 (2023).
1108 **This review discusses both successes and challenges of applying the predictive**
1109 **processing framework to syntactic bootstrapping.**
1110
- 1111 135. Reuter, T., Borovsky, A. & Lew-Williams, C. Predict and redirect: Prediction errors
1112 support children’s word learning. *Dev Psychol* **55**, 1656–1665 (2019).
1113
- 1114 136. Lin, Y. & Fisher, C. Error-Based Learning: A Mechanism for Linking Verbs to Syntax.
1115 In *Proceedings of the Annual Meeting of the Cognitive Science Society* (2017).
1116
- 1117 137. Chang, F., Dell, G. S. & Bock, K. Becoming syntactic. *Psychol Rev* **113**, 234–272
1118 (2006).
1119
- 1120 138. Bernal, S., Dehaene-Lambertz, G., Millotte, S. & Christophe, A. Two-year-olds
1121 compute syntactic structure on-line. *Dev Sci* **13**, 69–76 (2010).
1122
- 1123 139. Beretti, M., Havron, N. & Christophe, A. Four- and 5-year-old children adapt to the
1124 reliability of conflicting sources of information to learn novel words. *J Exp Child*
1125 *Psychol* **200**, 104927 (2020).
1126
- 1127 140. Havron, N., de Carvalho, A., Fiévet, A. C. & Christophe, A. Three- to Four-Year-Old
1128 Children Rapidly Adapt Their Predictions and Use Them to Learn Novel Word
1129 Meanings. *Child Dev* **90**, 82–90 (2019).
1130
- 1131 141. Imai, M. *et al.* Novel noun and verb learning in Chinese-, English-, and Japanese-
1132 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 44th 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 43rd*
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.*
1306

1307 **Acknowledgements**

1308 We thank Ganna Mamonova for helpful comments.

1309 M. Barbir discloses that this paper was written with support of the World Premier International Research
1310 Center Initiative (WPI), MEXT, Japan and the following grants: Japan Society for the Promotion of
1311 Science post-doctoral fellowship grant (grant number P20722), and JSPS Grant-in-aid for Transformative
1312 Research Areas (grant number 20H05919). M. Babineau received support from an Insight Development
1313 Grant from the Social Sciences and Humanities Research Council of Canada (SSHRC). This paper has
1314 also received support from the CNRS through the MITI interdisciplinary programs award to Alex de
1315 Carvalho and from Sciences Po - Université Paris Cité (Fonds Investissements d’Avenir) award to Alex
1316 de Carvalho.

1317

1318 **Competing interests**

1319 The authors declare no competing interests.

1320

1321 **Author contributions**

1322 M. Babineau wrote the abstract and sections 3, 4, and designed the figures. M. Barbir wrote the
1323 introduction, Sections 1, 2, and 5, the discussion, and the boxes. A. C. oversaw conceptualization and
1324 writing. All authors contributed to revising the manuscript.