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Learning Through Processing: Toward an Integrated Approach to Early Word Learning

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Abstract

Children's linguistic knowledge and the learning mechanisms by which they acquire it grow substantially in infancy and toddlerhood, yet theories of word learning largely fail to incorporate these shifts. Moreover, researchers' often-siloed focus on either familiar word recognition or novel word learning limits the critical consideration of how these two relate. As a step toward a mechanistic theory of language acquisition, we present a framework of "learning through processing" and relate it to the prevailing methods used to assess children's early knowledge of words. Incorporating recent empirical work, we posit a specific, testable timeline of qualitative changes in the learning process in this interval. We conclude with several challenges and avenues for building a comprehensive theory of early word learning: better characterization of the input, reconciling results across approaches, and treating lexical knowledge in the nascent grammar with sufficient sophistication to ensure generalizability across languages and development.

Keywords

word learning; language acquisition; lexical processing; linguistic input; infancy; vocabulary growth

1. INTRODUCTION

The English word "infant" derives from the Latin word *infans*, meaning "unable to speak." However, even infants know plenty about language by the time they begin to understand common words, at around 6–9 months of age (e.g., Bergelson & Swingley 2012, Parise & Csibra 2012, Tincoff & Jusczyk 1999). Infants and toddlers connect the language they experience with the world around them before they have understood others' intentions or fully deduced the complex system of sounds and grammar of their language, and while their memory and attention skills are still developing (Bates 1979, Carpenter et al. 1998, Diamond 1985, Fisher & Gleitman 2002, Polka & Werker 1994). Given young children's changing

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knowledge and abilities, a mechanistic theory of language acquisition should consider how infants' and toddlers' representations and inferences shift with age. We examine this shift in representations and inferences within early word learning.

In Section 2, we present a framework that relates language learning and processing through a growing store of linguistic knowledge. This framework explicitly decouples real-time processing from longer-term word learning and separates learning based on accruing language input from that based on shifts in inferential machinery, allowing us to characterize various existing proposals in terms of these changes (see the sidebar titled Computational Models). We then summarize and link common methods for evaluating linguistic knowledge to this long timeline of iterated processing. Throughout, we focus on early word comprehension in particular, though much of what we say readily extends to production and to other levels of linguistic representation.

In Section 3, we propose a specific, empirically testable timeline of major shifts in word learning before age 2. These stages include early brute-force associative learning focusing on concrete nouns; a comprehension boost across word classes that appears aligned with social insights, cognitive improvements, and metalinguistic awareness; and a broader process of using utterance contexts (e.g., linking semantics with syntactic role) to rapidly build and extend word meanings with increasing efficiency.

Our perspective highlights three challenges for developing a full-fledged theory of early word learning, taken up in Section 4. First, while children's linguistic knowledge depends critically on the history of utterances and contexts that they have observed, dense, transcribed longitudinal corpora of naturalistic interaction are rare (Roy et al. 2015, Tomasello & Stahl 2004). Moreover, such corpora and experiments measuring word knowledge are usually collected from nonoverlapping groups of children (though see Bergelson & Aslin 2017, Weisleder & Fernald 2013). Second, novel word learning and familiar word processing studies yield potentially incompatible results, prompting questions about the language knowledge they tap. Third, the question of what early words are—and, relatedly, what the learning problem truly entails—requires careful consideration. To meet these challenges, we recommend (*a*) developing longitudinal designs that tie all four classes of empirical methods together with computational modeling at the level of individual children, (*b*) expanding the set of words tested by in-lab processing studies, and (*c*) carefully considering variability in both forms and meanings.

2. HOW DOES LEXICAL PROCESSING RELATE TO WORD LEARNING?

2.1. A Framework for Learning Through Processing

Proposals linking language processing and learning abound (Bates & Goodman 1997, Carey & Bartlett 1978, Fernald & Frank 2012, Katz et al. 1974, McMurray et al. 2012, Swingley 2010). However, different operationalizations of "processing" and "learning," as well as foci at varying levels of linguistic representation and timescales, have failed to consider possible relationships between processing and learning within a more general framework. Filling this gap, we introduce a rational analysis–based framework (i.e., a framework that defines the core inferential problems, as well as what an optimal learner might do to solve them;

Anderson 1990) to characterize the central computational problems of early word learning. The framework is not intended to be directly testable, but rather helps identify what to test by comparing existing proposals and identifying gaps in our understanding of the process (see Section 3, where we propose specific testable hypotheses). This framework also allows us to relate common empirical methods to the overall process of language acquisition. Furthermore, it provides a way to think about continuity vis-à-vis communicative goals, as well as changes in the data and inferential methods available to a child language learner.

In our conceptualization, a child's language knowledge is represented as a probabilistic decoder (e.g., Serdyuk et al. 2018) that inputs a spoken or signed utterance and the nonlinguistic context and outputs a probability distribution over possible meanings, which then informs the child's behavior (Figure 1). The decoder plays a dual role as (*a*) a model for in-the-moment processing, translating from utterances to meaning in real time, and (*b*) a reflection of the output of learning, as a constantly revised store of linguistic knowledge. The word learning process is iterative: As a listener, the child infers the most likely meaning in a given communicative context (using the current decoder's parameter values, i.e., the current state of their linguistic knowledge), while as a learner the child updates the decoder.

In a crude sense, learning and processing simply alternate: In each instance of language processing (Figure 1), the child observes an utterance U_t and context C_t and must decode them with language knowledge at that timepoint, L_t, to produce a probability distribution over potential meanings, M_t (the Process function; see Figure 1). The highest-probability hypothesis $\widehat{M}_t$ informs the child's behavior B_t. The child then updates the decoder parameters, transitioning from their previous best estimate of the language (L_t) to their new best estimate (L_{t+1}) (the Update function; see Figure 1). Under our framework, learning—expanding the lexicon and adjusting word meanings—is this update process. This simple setup readily handles exposure-driven improvements in both lexical processing and word learning as the child observes more data over time. It also permits the inferential capacities of the child to change, accelerating improvements in learning or lexical processing above and beyond observing more data (i.e., improvements in data efficiency). In all cases, advances in language knowledge from word learning support better processing, though processing may improve independently as well.

This framework centers on the child's role as a language processor. We operationalize processing as the integration of information across linguistic and nonlinguistic input, especially the use of top-down information to overcome challenges in understanding others' speech in a "noisy channel" (Shannon 1948). Mature language processing requires evaluating hypotheses about intended meanings on the basis of both perceptual signals and probabilistic expectations across levels of linguistic representation (Gibson et al. 2013, Levy 2008, Meylan et al. 2021c, Shannon 1951); converging work suggests that this ability emerges in childhood (Rabagliati et al. 2013, Reuter et al. 2021, Yurovsky et al. 2017; though see Snedeker & Trueswell 2004). For example, Yurovsky et al. (2017) find that 3–5-year-olds use scene plausibility when interpreting adult speech, for example, preferring a scene with the more plausible plate of peas and carrots for "I had carrots and bees for dinner."

In Section 3, we offer our own specific hypotheses regarding how real-time processing and learning change over time. But first we provide two examples translating existing proposals into this framework, showing how theories from disparate theoretical backgrounds can be understood in relation to these definitions of learning and processing.

First, Mollica & Piantadosi (2017) describe an "accumulator" model (see also Hidaka 2013) as a null model of word learning where processing and learning remain constant over time and word knowledge grows purely as a function of the frequency with which a child encounters a word. This model posits that (*a*) there is no appreciable contribution of the child's increasing phonological, syntactic, or morphological knowledge over developmental time, either to real-time processing or to learning, and that (*b*) skills like sensitivity to social information make a constant (and possibly null) contribution to processing. In terms of our framework, this means constancy in both the Process and Update functions —the only thing that changes over developmental time is the quantity of data available to the Update function. Mollica & Piantadosi (2017) demonstrate that this null model is sufficient to account for growth curves in parent-reported child vocabulary knowledge, though subsequent work (Bergelson 2020) has challenged its fit to experimental findings (e.g., Bates 1979, Carpenter et al. 1998, Fernald et al. 2006).

Second, McMurray et al. (2012) distinguish between real-time processing as a case of referent selection (looking at a dog when hearing "dog") and longer-term, robust word learning. They argue that the latter occurs only on longer timescales, specifically as a result of associative learning that operates independently from real-time processing. Under their proposal, children can only use mutual exclusivity (the inference that a novel word applies to a novel object in the context of novel and known objects; Markman 1990) in real-time processing. They argue that this dissociation best explains in-lab experiments where 24-month-olds can identify referents for new words by excluding familiar ones, but have difficulty in retaining meanings a few minutes later (Horst & Samuelson 2008). Under our framework, this proposal can be characterized as a change in the Process function (e.g., as children learn to use mutual exclusivity and gain proficiency in real-time processing), coupled with constancy in the Update function (slow associative learning).

Phrasing these two disparate proposals in terms of our framework reveals an underlying similarity between them: Both espouse constancy in word learning (i.e., the Update function), eschewing the possibility of maturational transitions in how children update their language knowledge. The framework opens a broader space of plausible theories of developmental change in word learning: We can posit separate transitions in processing and learning while considering the implications of each for the other. This points to the possibility that how children learn words may change substantially over time, both as children observe more linguistic input and as the inferential mechanisms available to the children themselves change. We address this topic in detail in Section 3, after reviewing how common empirical approaches are readily accommodated by this framework.

2.2. Empirical Methods

We next consider the toolkit of empirical methods available to child language researchers in terms of our framework. This highlights several core challenges in child language research:

the overall sparsity of what can be observed with respect to the process of language development, the strict reliance on behavioral and physiological signals to infer changes in language knowledge, and the vanishingly small scale of the input for in-lab learning studies compared with the larger process of language acquisition.

2.2.1. Testing familiar word knowledge.—

Tests of familiar word knowledge (Figure 2c) aim to evaluate whether young children understand common words. In terms of our framework, such tests evaluate children's knowledge by examining a small number of instances of processing (i.e., test trials) in light of an assumed history of previous language processing (i.e., home language experience) and the concomitant updates to language knowledge that this entails (i.e., learning). Because the child's estimate of word meaning cannot be directly accessed, researchers use proxies: behavioral observables, including what a child looks at or selects in response to an utterance, or measures of unexpectedness, such as electrical signals in the brain.

The most common method for testing word comprehension in infancy involves tracking looking behavior, particularly measures of looking time in response to linguistic input [variably called "looking while listening," "language-guided looking," or the "intermodal preferential looking paradigm"; Fernald et al. 1998, Golinkoff et al. 2013, Swingley 2009 (cf. Visual World Paradigm in adults; e.g., Salverda & Tanenhaus 2017)]. In looking-time experiments, researchers show infants scenes set up with some sort of contrast (e.g., eating versus drinking, a foot versus a banana, a new toy versus a familiar toy), say an utterance (e.g., "Look, she's eating!", "Where's the banana?", "Do you see the block?"), and measure where infants look and for how long (Fernald et al. 1998). Generally speaking, looking at what is being talked about is an automatic process, given the requisite word knowledge: Listeners who know the word "dog" will spontaneously search for one only a few hundred milliseconds after hearing "Look at the dog!" (Fernald et al. 2006, Salverda & Tanenhaus 2017).

A second way to probe word comprehension is to measure correlates of unexpectedness, typically with electroencephalography (EEG). In such experiments, children see and/or hear congruent word pairs (e.g., "shoe-boot") or word–object pairs (e.g., a picture of a ball and the word "ball" spoken aloud), or incongruent pairs (e.g., a picture of a ball and the word "shoe"). Neural responses, such as the N400, are then compared for the congruent versus incongruent pairings (e.g., Forgács et al. 2019, Parise & Csibra 2012). A benefit of both methods is that they directly probe infants' knowledge but require little overt behavioral response, making them suitable for young infants.

A third approach involves instruments like the Computerized Comprehension Task and the Peabody Picture Vocabulary Test (PPVT), which prompt children to select a picture in response to a prompt or produce a word in response to a picture (Dunn et al. 1965, Friend et al. 2012). These approaches often require more action planning than eye movements do, and thus are generally used for children older than 18 months.

2.2.2. Testing novel word learning.—

The methods for experimentally measuring children's receptive knowledge of novel words are essentially the same as those outlined above for familiar word comprehension. The major distinction is that children have no prior history with the specific word in question (Figure 2d). Processing here reflects updates to language knowledge that occur during an exposure or training phase. But, as with familiar word comprehension, both processing and learning rely on the child's broader language knowledge; in other words, while the individual word being taught may be novel, its constituent phonemes or syntactic role within an utterance may reflect broader linguistic knowledge.

New items presented in the exposure phase of novel word learning experiments are typically unusual objects, like dog toys (Horst 2016), or novel actions. The exposure phase in such experiments can include passive exposure to items and utterances (Smith & Yu 2008), explicit teaching (Oviatt 1980, Woodward et al. 1994), situations where infants are supposed to infer labels of unseen objects (Baldwin 1993, Tomasello 2005), and learning trials with selection in the context of known referents (Horst & Samuelson 2008). Participants are exposed to the new items' labels a few dozen times, with test trials (eye tracking or selection based) directly following exposure or shortly thereafter.

A major benefit of novel word learning methods is their ability to manipulate learners' access to syntactic and semantic information for the new words (Arunachalam et al. 2013, Shi 2014, Syrett et al. 2014, Waxman et al. 2009, Zangl & Fernald 2007). In particular, work on syntactic bootstrapping has highlighted the utility of considering how entire utterances connect to the oft-ambiguous world, confirming the importance of syntax in forging such links (Fisher & Gleitman 2002; Fisher et al. 2020; Gleitman 1990; Naigles 1990, 2021; Omaki & Lidz 2015).

2.2.3. Vocabulary assessment.—Caregiver reports of children's vocabulary knowledge [e.g., the MacArthur–Bates Communicative Development Inventory (MCDI); Fenson et al. 1994] provide a holistic proxy for the quantity and kinds of words children can effectively process by asking caretakers to report what they believe their children understand or say (Figure 2e). Like the experimental methods above, caregiver reports are not exhaustive but are constructed to specifically capture a representative sample of children's word knowledge at a specific age.

2.2.4. Analyzing corpora from the home environment.—Recording children's everyday experiences—language input—and their productions is a fourth broad way to investigate word learning (Brown 1973, MacWhinney 2000, VanDam et al. 2016) (Figure 2b). Historically, children's productions in such corpora have been taken as evidence of the state of their linguistic knowledge. More recently, caregivers' behavior (linguistic or otherwise) in these corpora has been either analyzed directly (Bergelson 2020; Bergelson et al. 2018; Casillas et al. 2020, 2021) or used as input for computationally instantiated learning models that test which representations and behaviors can be learned by different learning procedures (Frank et al. 2009a, Goldwater et al. 2009, Perfors et al. 2011, Regier & Gahl 2004). In terms of our framework, longitudinal corpora supply samples of the history of utterances U and contexts C that we expect to inform linguistic knowledge at a given point in development. While not our focus here, children's language productions, too, reflect this knowledge.

3. HOW DO WORD LEARNING AND PROCESSING CHANGE OVER TIME?

In this section, we provide a specific, falsifiable timeline of early word learning and processing as a useful reference point for subsequent empirical work to correct and refine. Ours is not the first proposal of this type (e.g., Bates 1979; Bloom 1993, 2002; Hollich et al. 2000; McMurray et al. 2012; Tomasello 2005; see also the null model in Mollica & Piantadosi 2017). However, growing evidence of early word knowledge (Bergelson & Aslin 2017; Bergelson & Swingley 2012, 2015; Campbell 2018, Kartushina & Mayor 2019; Parise & Csibra 2012; Tincoff & Jusczyk 1999, 2012) necessitates a reconsideration of prior proposals.

Research in the 1980s and 1990s highlighted several types of mechanisms underlying word learning: associative or cue based (Bates & MacWhinney 1989, Plunkett 1997, Smith 2000); socio-pragmatic (Baldwin 1993, Carpenter et al. 1998, Tomasello 2005); and constraint based, with both linguistic and conceptual flavors (Clark & Hecht 1983, Gleitman 1990, Markman 1990). The bulk of the empirical evidence pointed to approximately 18 months as the age when many such mechanisms become available. Subsequent theories have integrated some of these factors and proposed developmental timelines (e.g., Hollich et al. 2000, Naigles 2021, Tomasello 2005).

However, converging research from the past decade, across several languages, has found that infants begin to understand (i.e., correctly identify a referent for) common nouns at age 6 to 9 months, according to both eye tracking and EEG (e.g., Bergelson & Swingley 2012, Kartushina & Mayor 2019, Parise & Csibra 2012). These studies find modest but consistent evidence of word comprehension across infants and items, suggesting that theories need to address how word learning can transpire in infants who lack the previously proposed abilities.

We suggest that early word learning is well characterized as a series of at least three successive phases. The first phase consists of brute-force associations that initiate the lexicon. The second phase is the comprehension boost, wherein new skills foster better word learning capacities (Bergelson 2020). The third phase is leveraging efficiency, whereby children's improved processing lets them more readily harness associative, socio-pragmatic, and conceptual/linguistic knowledge (e.g., Fernald et al. 2006, Hollich et al. 2001, Tomasello 2005). Each can be characterized as changes to the Process or Update function in our framework (Figure 3).

Delineating these phases helps underscore that not all proposed mechanisms of word learning are available to young children. For instance, to our knowledge there is no evidence for cross-situational word learning before 12–14 months (Smith & Yu 2008) and evidence only of immature mutual exclusivity before 17 months (Halberda 2003, Markman 1990, Pomiechowska et al. 2021). Given the converging evidence for comprehension in younger infants, word learning must be possible without those abilities. In contrast, there are clear qualitative improvements in word learning across year two relative to this initial phase, suggesting both newly available learning mechanisms and improved processing efficiency.

3.1. Linguistic Data Crunching and Brute-Force Early Associations (<10 Months)

The earliest words in the receptive lexicon are nouns that pick out individuals, foods, body parts, and common objects, such as "mommy," "banana," "foot," or "ball" (Bergelson & Aslin 2017; Bergelson & Swingley 2012, 2015; Campbell 2018; Kartushina & Mayor 2019; Parise & Csibra 2012; Tincoff & Jusczyk 1999, 2012). Words from other lexical classes (e.g., "uh-oh," "eat") follow a few months thereafter (Benedict 1979, Bergelson & Swingley 2013a). This pattern is crosslinguistically robust according to parental vocabulary assessments (Frank et al. 2021). These early words are notable for at least two reasons. First, they are highly frequent in young infants' input. For example, in a set of daylong audio recordings taken at 6 and 7 months, infants heard the top five concrete nouns more than 750 times over approximately 20 waking hours (Bergelson et al. 2018). Second, while early nouns' referents are not all well-delineated and freestanding objects (e.g., "milk"), they do look alike across instances (e.g., most hands look similar). The high input frequency and perceptual consistency are likely critical for these nouns' early learnability, especially when paired with learners' abilities to generalize across instances. Intriguingly, this highly variable natural exposure permits word learning at ages where deliberate, clear, short-term teaching experiments fail to evince comprehension (e.g., Gonzalez-Barrero et al. 2021, Oviatt 1980; see Section 4.2).

If mutual exclusivity and intention reading are not available in year one, what kinds of skills might be harnessed for word learning in early infancy? Young infants have an increasing interest in faces (Frank et al. 2009b), bringing focus to these frequently named body parts. By 9 months, infants expect labels—but not preferences—to hold across individuals (Henderson & Woodward 2012), inferring words' community-wide consistency. Moreover, 6–9-month-olds exhibit multi-modal categorization skills (e.g., Kadlaskar et al. 2020) and isolate word forms (Johnson 2016). All of these abilities likely facilitate the word-to-referent matching that is central for early-learned nouns in particular.

In contrast, young infants' phoneme inventories and language-specific segmentation strategies are not yet adult-like (Swingley 2009), and their early memory, attention, and social prowess remain highly rudimentary (e.g., Bates 1979, Diamond 1985). These limitations may help explain why concrete nouns, the least ephemeral and most perceptually consistent of lexical categories, constitute first words. They also suggest why early learning is so slow: Young infants lack the capacity for the kind of one-trial learning licensed by more mature cognitive and social skills, and a more developed lexicon.

However, we do not suggest that infants' earliest words are akin to the highly trained, contextually circumscribed, interlocutor-specific abilities that, say, border collies exhibit (Frank 2016, Pilley 2013). Rather, this initial phase of human word learning occurs spontaneously, and the words that are first codified are readily generalized to new tokens and decontextualized contexts (e.g., looking-while-listening experiments). Setting the nature of these representations aside, we emphasize that the words and concepts that infants first link in their receptive lexicons are the result of an intrinsically driven but slow, hardscrabble process (cf. McMurray et al. 2012, Swingley 2010). Critically, early learning contrasts with the relative ease with which later lexical entries (which make use of advancing skills) are both initially added and, eventually, readily retained.

3.2. Comprehension Boost: Cognitive, Social, and Metalinguistic Insights (~12–14 Months)

What was once taken as the onset of word learning around 12 months (Bloom 2002, Tomasello 2005) is better characterized as a qualitative improvement in word comprehension. Indeed, as social, cognitive, and linguistic skills accrue and word production begins, there is a nonlinear improvement in how well infants understand common words, signaling the onset of robust word comprehension (Bergelson 2020). In this phase of word learning, infants understand both concrete nouns and high-frequency words from other lexical classes, like “hi” and “eat” (which occur in a far broader range of linguistic contexts with fewer reliable visual correlates). Notably, this boost does not simply reflect changing language input: Language input remains fairly constant over infancy across measures like word counts and utterance types, while comprehension, particularly as measured by looking-while-listening tasks, improves markedly (Bergelson 2020, Bergelson et al. 2018). The improvement in comprehension is consistent with a learner whose language processing improves while the language input stays largely stable.

What underlies this comprehension boost? As discussed elsewhere (Bergelson 2020), it coincides with advances in social cognition and linguistic representations, as well as with the start of word production. Regarding social advances, breakthroughs in joint attention around 12 months support the insight that others use symbols to refer to the world, which may facilitate content word learning in particular. These social skills are observed in 12–14-month-olds’ ability to track others’ knowledge states (Forgács et al. 2019) and to both produce and follow pointing gestures (Behne et al. 2012, Carpenter et al. 1998). Regarding linguistic representations, 12–14-month-olds have well-specified phonological representations for how words sound (Swingley & Aslin 2002) and can use prosodic and functor-based prediction to facilitate sentence processing (e.g., Babineau et al. 2020). These abilities, in turn, may begin to smooth utterance interpretation (which accelerates further in the third phase), letting infants learn more from each successive utterance they encounter. Such advances, paired with the growing lexicon itself, may speed up the word learning process, bringing more words above the comprehension threshold our methods can detect. Finally, infants typically produce their first words at this age (Frank et al. 2021), which may provide them with a deeper metalinguistic insight into words’ symbolic, representational nature and change caregiver–child conversational dynamics and inferences therein.

In terms of our framework, this phase of word learning predominantly reflects qualitative changes in learning mechanism (i.e., the Update function), along with continuing (and, by hypothesis, causally linked) improvements in utterance processing. Establishing prerequisites of the comprehension boost is an important next step for understanding early word learning, and awaits further multitask, multitimepoint empirical work.

3.3. Leveraging Efficiency (>17 Months)

While less pronounced than the comprehension boost around age one, several word learning advances occur in the second half of year two. By this age, toddlers readily use others’ intentions, syntax, and lexico-conceptual constraints to rapidly guide new word learning, and they process utterances containing familiar words more quickly (Baldwin 1993, Fernald et al. 1998, Fisher et al. 2020, McMurray et al. 2012, Tomasello 2005). But since these are improvements in degree rather than new skills that are wholly absent in 14–17-month-olds, what is actually new at this stage of word learning? We propose that a decrease in the amount of contextual support required for word learning is itself the notable shift, and reflects increased efficiency in two senses: In this phase, children are faster at processing utterances that, for instance, guide their gaze ("Look at the dog!") and in turn garner more information from each utterance they process.

An example of children in this phase needing less word learning support comes from a series of studies building on seminal work by Stager & Werker (1997). They find that, while 14-month-olds struggle to learn two similar-sounding novel words for two new objects without added cues (e.g., noncontrastive phonetic variability, familiar object "warm-ups,") children over 17 months do so readily (Tsui et al. 2019). Similarly, infants struggle with mutual exclusivity before 17 months but not thereafter (Halberda 2003, Markman 1990), though overt social cues can help younger infants succeed in some contexts (Pomiechowska et al. 2021). In each of these cases, while younger children can learn new words in the lab with a certain set of supportive cues, >17-month-olds no longer need them.

Related longitudinal work by Fernald et al. (2006) has explored improving comprehension after year two. They find that as children get older, they are quicker to look at the named target objects relative to when they were younger, which the authors characterize as improved "processing efficiency" in their real-time comprehension task. They also find that individual differences in online word comprehension are strongly related to lexical and grammatical development only toward the end of year two. These results are consistent with a positive feedback loop between efficiently processing known words and successfully learning new ones (Fernald et al. 2006). In line with the novel word learning examples presented above, this efficiency itself is a key advance, letting toddlers rapidly add words across lexical classes to their now quickly growing language stores. In terms of our framework, here the predominant shift is in the Process function (as real-time comprehension accelerates), with knock-on effects for learning (the Update function).

Of course, word learning continues into childhood and beyond. The phases proposed above call for a broader theory of word learning across development that accounts for the range of empirical results in the literature. Recent work in this area (Gutman et al. 2015) has built on the syntactic bootstrapping literature (e.g., Fisher et al. 2020, Gleitman 1990). Christophe and colleagues (Babineau et al. 2021, Gutman et al. 2015) suggest that this process begins with what they call a "semantic seed." Knowledge of a few content words (the seed), sensitivity to phrasal prosody, and initial segmentation abilities in early infancy collectively reveal abstract syntactic categories and the role of function words, which the bootstrapper then continues to build on. This proposal is supported by both computational and empirical results (Babineau et al. 2021, Gutman et al. 2015) and provides an important set of testable claims for further theory development.

Relatedly, recent computational and experimental work has demonstrated that 2–5-year-olds' ability to integrate across different information sources appears relatively stable, while their sensitivity to these sources (i.e., pragmatics and prior knowledge at the utterance, conversational, and long-term scales) improves (Bohn et al. 2021). How and when these sensitivities first arise and come to mutually inform one another are important questions for future work.

Taken together, the three phases proposed here highlight both continuity and qualitative improvement in word learning over early development. Testing our proposal requires two critical next steps. The first is to collect further experimental and observational data from an expanded set of lexical classes, languages, and measures to test the robustness of the proposed phases and ages. The second is to build computational models of this and other proposals within a common framework like the one outlined above (cf. Cristia 2020). Creating theories that incorporate what infants know at different ages will be vital to ensuring plausible generalization to the full task word learners face.

4. CHALLENGES IN UNDERSTANDING EARLY LINGUISTIC KNOWLEDGE

4.1. Quantifying Input to the Learning Process

A major challenge for studies of familiar word learning is that when we measure infants' word knowledge, we generally have very little information about particular infants' experiences with a given set of words. That is, we assume (ideally, informed by corpora; e.g., MacWhinney 2000) that children's experiences are reasonably similar to one another. We then draw conclusions about children knowing or not knowing a word by a particular age without being able to incorporate one of the largest contributors underlying this knowledge: the input from which they learn. Doing so limits our ability to build testable theories about how language input and knowledge are directly connected within learners. Corpora that measure the learning environment and young children's word knowledge are critical for providing information regarding the ground truth of the variability across families and contexts and for testing whether purportedly useful properties for word learning (e.g., words in isolation, bouts of joint attention) reliably predict word knowledge. Thanks to technological advances, measuring improving receptive word knowledge and collecting high-density, longitudinal language samples have recently become more feasible (Casillas & Cristia 2019). Beyond the theory testing that such corpora support, they also let us evaluate how representative small language samples are relative to longer spontaneous interactions.

Intriguingly, studies combining home environment measures with evaluations of children's early lexical knowledge have revealed connections between language input and knowledge even in the earliest stages of comprehension and production. For instance, the overall "referential transparency" of the situations in which words are said in infants' home environments (e.g., "Here's a ball" while mother and infant look at a ball) correlates with how well those same infants understand everyday nouns at the outset of word comprehension at 6 months (Bergelson & Aslin 2017; cf. Yurovsky et al. 2013). With regard to our proposed first phase of word learning, these results are consistent with a brute-force mechanism that capitalizes on the prevalence of particularly clear examples of nouns and referents; the more the child gets, the better the early real-time noun comprehension we observe. In a similar vein, the spatial, temporal, and linguistic distinctiveness of the words, as heard by a single child, has also been found to predict when that child begins to say those words (Roy et al. 2015).

Measuring both input and knowledge within children has also shown that once lexical and grammatical foundations are laid, generalization to new instances readily follows. For example, at least by around 12 months, infants' word comprehension appears just as robust whether they engage in a looking-while-listening task that probes them with images of their own items ("shoe," "cat," etc.) or with other tokens of such items that they have not accrued dozens to thousands of hours of experience with (Garrison et al. 2020). Relatedly, work on the determiners "a" and "the" has found that structural regularities in the input quickly permit children to find generalizations in word usage corresponding to syntactic categories (Meylan et al. 2017).

Collecting dense enough data to characterize young children's everyday experiences with common words is challenging, however. For example, sampling 30 minutes per week would lead to an estimate that a word a child hears 10 times per day has a weekly frequency of between 0 and 205 (Tomasello & Stahl 2004). The imprecision of this range leaves open wildly different accounts of how much of a certain type of input is needed to learn a given word, morpheme, or paradigm. This uncertainty has implications for the type of learner that can acquire these units; more precise estimates can drastically change how much is viably learned via exposure versus inference and generalization. Thus, we find dense corpus building to be a critical way forward for our understanding of lexical development—and language acquisition more broadly.

4.2. Reconciling Lab-Based Learning with Home-Based Learning

Another challenge for early word learning theories is reconciling results across approaches. Generalizing from novel word learning experiments to everyday word learning requires caution on at least two dimensions: persistence of learning and heuristic reliance. In terms of persistence, young children are typically shown new words and their referents for mere minutes in the lab (Carey & Bartlett 1978), leading to learning that fades after 5 minutes, even in preschoolers (Horst & Samuelson 2008). In contrast, infants' experiences with words like "dog" and "hand" (not to mention "of") are plentiful: Infants amass scores of learning instances with early-learned words every day (Bergelson et al. 2018), developing lexical entries slowly over time (Swingley 2010). The effects of this difference between lab-based exposure and home-based experience are strikingly clear in comparing the ages of children who demonstrate familiar word comprehension versus novel word learning in the lab. While an increasing number of studies have found that infants understand common nouns before 10 months, evidence of robust new word learning from a lab-based exposure is limited, even in 1-year-olds (Gonzalez-Barrero et al. 2021, Oviatt 1980), who show robust comprehension of familiar words.

We reiterate that even our best attempts to teach infants words as clearly as possible in a concentrated test session fail, whereas passive, noisy, accumulated exposure over months succeeds. Minimally, this pattern of findings suggests that experience amassed with words in context can counteract limitations in memory, consolidation, and attention that lab teaching tasks face. Typically, controlled lab studies show capacity X at age Y in principle, but generalization to "the wild" is questionable. In contrast, with familiar word learning, it is the messy natural case that emerges before the same knowledge can be readily captured with carefully crafted experiments that teach new words.

In terms of heuristic reliance, results based on learning from brief lab exposure appear to overemphasize children's use of heuristics like mutual exclusivity. For instance, by 17 months (but not earlier without special support; cf. Pomiechowska et al. 2021) infants readily use known words to scaffold new word learning in the lab (Bergelson & Aslin 2017, Halberda 2003, Markman 1990). However, younger infants learn words without mutual exclusivity, and indeed its use varies over later development as well (Lewis et al. 2020). Moreover, mutual exclusivity is less useful for (and less used by) multilingual toddlers (Byers-Heinlein & Werker 2013) and is surmountable for monolinguals learning synonyms, hyponyms, and hypernyms (e.g., "toy" and "ball"). Thus, while mutual exclusivity may aid word learning in a certain set of circumstances, the extent to which it is actually available or useful for everyday word learning is unclear.

To us, these examples call for considering novel and familiar word knowledge within a single framework that considers the linguistic knowledge children already bring to the table in processing new words. Moreover, we encourage a front-and-center consideration of children's age-related capacities and knowledge in driving what kinds of mechanisms are usable and useful for word learning.

4.3. The Nature of Early Word Representations

We next turn to two broader queries: What are words to young children, and how does a singular focus on concrete nouns for objects in English limit our fuller characterization of early lexical knowledge?

4.3.1. Early words are not adults' written words.—Words separated by spaces are not what young children learn. Equating children's and adults' words presupposes that words exist as discrete symbolic entities in children's minds and that language consists of sequential, distinct units (i.e., beads on a string). These common simplifying assumptions should not be taken for granted within children's first language learning.

4.3.1.1. Adults impose lexical structure on child language.: Models of adult–child conversations reveal that adults readily ascribe distinctive, contextually appropriate lexical interpretations to incorrect or indistinct forms produced by young children (Meylan et al. 2021a). For example, a child may use identical sounds approximating /da/ to refer to both *dad* and *dog*, while caregivers interpret them differently based on context. Thus, word knowledge ascribed to children is a function of both the child and the listener. Similarly, speakers often assume that their words call the same ideas to mind in others. In contrast, experimental data from both adults and toddlers point to variability and flexibility in listeners' assumptions about what items are called (e.g., Bergelson & Swingley 2013b, Malt & Sloman 2004).

4.3.1.2. Early words are not beads on a string.: An attractively simple view is that humans communicate by combining words, like threading beads on a string: Each word is a bead, and the meaning can be composed from the sequence of beads. Applied to comprehension, this view suggests that children recognize the communicative intent of others by decoding the speech signal into words, then building up the meaning from the component words. However, this view fails to consider a variety of linguistic phenomena, like clitics and bistable sequences, that point to rich dependency structures within and across words.

English clitics (e.g., "'ll" in "he'll" and "'t" in "can't") function as syntactically independent units, yet they are phonologically dependent on a host word. While the term "contraction" presupposes a beads-on-a-string analysis where the observed phonetic form corresponds to a latent multiword sequence, it seems likely that forms like "can't" (or semiauxiliaries like "gonna") are initially treated as stand-alone forms by child language learners.

Another example of dependencies across words is the bistability of single- versus multiword expressions [Sag et al. 2002; cf. idioms (Titone & Connine 1999)]. For instance, "a lot of" (/ə1ɔdə/) functions as a determiner when used before a noun (=many) but consists of a determiner–noun–preposition sequence. The sequence is not truly fixed, in that "a <unit> of" covers many pseudopartitive constructions ("a bunch of," "a glass of"). Assigning lexical status to the component words alone (i.e., "a," "lot," and "of") overlooks this rich locus of lexical meaning; ignoring the component parts overlooks another.

Such phenomena suggest that characterizing early words as beads on a string oversimplifies word learning. Language learning is not recovering a disconnected inventory of form–meaning units. Rather, it is discovering the many ways components of spoken or signed linguistic gestures can be combined and reused.

So why use words as a unit at all? Doing so highlights the uniqueness of human communicative symbols and provides a useful intuitive shortcut to a nuanced, complex concept. To the first point, even if operationalizing lexical knowledge is hard, children clearly show remarkable prowess in the range and richness of their communicative inventories, in stark contrast to nonhuman primates. Whereas the average 2-year-old English-learning infant in the USA can comprehend ~230 and produce ~50 words by 18 months (Frank et al. 2021), a bonobo reared in a matched, language-rich home environment could understand 70 and produce only 4 words by 24 months [Savage-Rumbaugh et al. 1986; cf. attempts at sign language learning in chimpanzees (Gardner & Gardner 1971)]. This distinction is particularly intriguing in light of comparable performance between human 24-month-olds and nonhuman primates on tasks testing physical cognition (Herrmann et al. 2010). To the second point, "word" is a convenient shorthand for the smallest freestanding, meaning-bearing gesture sequence, as long as its nuances and limitations are not forgotten.

4.3.2. Early words take many forms and many meanings.—Word learning accounts often implicitly assume that children learn to comprehend and produce the lemma (the canonical, uninflected form of a word) by linking the basic form to a single cohesive meaning (e.g., Markman 1990, Trueswell et al. 2013). In reality, for each word, children must learn correspondences between multiple possible word forms and multiple possible meanings.

4.3.2.1. Multiple possible forms.: In many languages, children hear multiple morphologically inflected variants of a word. In English, these include plural markers and possessive clitics for nouns, third-person singulars for verbs (all marked with +/s/, +/z/, or +/ɪz/), past tense +/əd/+/ət/ for verbs, and a progressive marker /ŋ/. Empirical investigation reveals that children do not simply learn a basic form like the singular of a noun or the uninflected form of a verb first. In many cases, the inflected form is actually more common and acquired earlier, as in “peas,” “pants,” and “teeth” (Sanchez et al. 2019). Moreover, morphology varies widely crosslinguistically. For instance, in some languages, some plurals take the unmarked form while the singular is inflected (e.g., Welsh singulative, as in *plant* ‘children’ versus *plentyn* ‘a child’; King 2016). In other cases, words have a latent stem structure (e.g., Semitic trilateral roots) rather than a lexicalized base form (McCarthy 1981).

In some speech communities, children hear many variants of a word within and across talkers that deviate from the lemma but do not change the meaning (e.g., “diapey” and “diaper”). Common nouns in speech to North American English-learning infants include frequent instances of such wordplay; for example, one family used 14 forms for the word “banana” in monthly recordings over a 12-month period (Moore & Bergelson 2021b). Infants must learn that these variants do not change the meaning, eventually distinguishing meaningful variation versus mere wordplay.

4.3.2.2. Multiple possible meanings.: Complicating matters further, many words have multiple context-specific meanings, which can be treated as discrete word senses (Feldbaum 1998) or gradiently related ones (Gangemi et al. 2001). These senses exhibit polysemy (related meanings for the same word form, e.g., “chicken” as an animal versus its meat) or homonymy (unrelated meanings for the same word form, e.g., “bank” of a river versus a financial institution). Corpus analyses reveal that children both hear and use multiple word senses from the youngest ages (Meylan et al. 2021b), consistent with experimental research showing that 3–4-year-olds readily learn polysemous and homonymous words (Floyd & Goldberg 2021, Srinivasan et al. 2019). Mastering polysemy and homonymy too is part of the word learner’s task.

4.3.3. Beyond words for concrete objects in English.—Much of the literature on early word learning (our own work included) focuses on how young English-learning children learn concrete object labels, namely nouns. This singular focus precludes an appropriately generalizable theory of lexical development.

Stating the trivially obvious, the vast majority of first language learners acquire languages other than English. From a typological perspective, English has unusual features, including a relatively large phonological inventory (compared with, e.g., Japanese) and a relatively simple system of morphological inflections (compared with, e.g., Turkish). Word learning in each language doubtlessly has its challenges (Trecca et al. 2021), but whether crosslinguistic variability in the early lexicon is due to the linguistic knowledge to be acquired or the methods used to study it is not yet known. In particular, we note the value of studying non-Indo-European languages, whose typological divergences from the most commonly studied languages hold great promise for expanding our understanding of early word learning

(Casillas et al. 2020, 2021; Cristia et al. 2019; Demuth et al. 2010; Mazuka et al. 2006; Tsuji et al. 2020).

The field's focus on early-learned nouns has multiple underlying motivations. First, words for things are overrepresented in the early vocabulary of English learners (Gentner 1982) as well as learners of other languages (Frank et al. 2021), making them a natural focus of attention. Second, from a methodological standpoint, it is easier to measure children's understanding of such words relative to other lexical classes, particularly function words (but see Babineau et al. 2020, Feiman et al. 2017, Gerken & Mclntosh 1993, Zangl & Fernald 2007). That is, methods like looking while listening test noun knowledge simply by displaying two images depicting nouns paired with a simple utterance like "Where's the dog?" In contrast, testing knowledge of prepositions or even action verbs requires more complex considerations. Such experiments also require greater memory and attention, which can be hard to separate from the challenges of understanding the words themselves (Lidz et al. 2017, Moore & Bergelson 2021a).

Unfortunately, this focus on nouns creates a situation where theories proposed for learning concrete nouns (which can be treated as primarily a mapping problem between word and referent) do not readily extend to other lexical classes (which cannot). These include pronouns (whose referents change with the context of use), predicates (e.g., "all gone," "bigger"), quantifiers (e.g., "some," "all"), and other parts of speech (Rohlfing et al. 2016).

Notably, the meaning of many words may rely more on linguistic rather than nonlinguistic context (Brysbaert et al. 2014), raising further questions about dependencies between words. For instance, quantifiers like "all" may only be acquired once a learner has developed sufficient knowledge of nouns, that is, things that can be quantified (cf. Crain 2017). Likewise, meanings of verbs interact with the words that populate their argument structures (cf. Gentner 1982, Gleitman 1990, Gutman et al. 2015).

The literature's overreliance on concrete nouns, and on the acquisition of English, creates theories that are self-limiting. On one hand, there does seem to be crosslinguistic consistency supporting noun dominance in the earliest lexicon (e.g., Frank et al. 2021), particularly early learning of nouns across languages of varying language families (Bergelson & Swingley 2012, Kartushina & Mayor 2019, Parise & Csibra 2012). On the other hand, both the relative morphological barrenness of English and the methodological challenges of testing other parts of speech suggest that more research is needed to understand the generalizability of lexical acquisition timelines, including those proposed here. Resolving this concern will require a concerted effort to build international, interdisciplinary collaborations to collectively consider how words (and other aspects of linguistic knowledge) are learned across languages and cultures, from a broader range of perspectives (Frank et al. 2021, ManyBabies Consortium 2020, Soderstrom et al. 2020, VanDam et al. 2016).

5. CONCLUSION

Over the first few years of life, children gain an enormous amount of knowledge about their language and the world around them. Word learning is an important part of this growth. It allows infants to integrate information from different levels of linguistic representation, on the one hand, and social and cognitive skills, on the other. As highlighted above, processing and learning words are two sides of the same coin, both relying on iterative inferences across experiences. But the nascent word learner brings less-refined linguistic, social, and cognitive machinery to the table compared with the more experienced one, and nevertheless succeeds in building an early store of lexical items (i.e., common nouns).

As development progresses, infants learn to take better advantage of their language input. That is, initial word learning before 10 months relies on highly frequent and perceptually consistent experiences with words that have clear referents. But as learning and experience continue to accrue, infants learn more from less, using their improving parsing skills, social inferences, and memory to facilitate more efficient word learning of an ever-increasing range of words. Measures of both familiar word knowledge and new word learning help explain how this process unfolds. But integrating these approaches longitudinally alongside measures of the home environment, within children, stands to catalyze our theories and models further. In turn, understanding the earliest stages of human word learning sets the stage for a broad range of extensions. These include applications to clinical conditions where language and development are implicated, other species' communicative systems, and both cognitively plausible and implausible artifical intelligence. Most broadly put, the study of early word learning provides a window to a deeper understanding of the human mind.

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COMPUTATIONAL MODELS

Formal and computational models are vital for building and testing mechanistic models of language learning and processing (Dupoux 2018, Pinker 1979). The first step in building such models is often to create an ideal observer (or rational) model (Anderson 1990, Chater et al. 1998) that characterizes the learning problem and an optimal inferential approach. Phrasing hypotheses as probabilistic computational models puts them into a common language that is more easily understood across psychology, linguistics, computer science, and robotics. Bayesian approaches are particularly helpful for placing diverse proposals in a common space relating hypotheses to data and inductive biases via probabilities (Griffiths et al. 2010). The second step is to revise these models to be increasingly representative of the learning or processing challenge, by adding more realistic inputs (e.g., raw video rather than symbolic representations of context), resource constraints (reflecting attention and memory limits), scales of input and output (approximating the history of children's experience), and interactions with other learning processes. Computational models are becoming increasingly important in bridging the gap between verbal theories and empirical data, by requiring explicit, testable articulation of the implementation and outcomes of complex processes like word learning (Hill et al. 2020).

SUMMARY POINTS

1. Children's language learning and processing build on each other over time, yielding a growing store of knowledge about language that can be characterized with an iterative framework.
2. While children's linguistic knowledge changes as they observe more data with age, the inventory of learning mechanisms they can use also changes. We propose three stages of learning in infancy and toddlerhood: brute-force early associations (before ~10 months), a comprehension boost (12–14 months), and leveraging efficiency (after 17 months).
3. Historically, researchers have had difficulty characterizing children's day-to-day input in the home environment cross-culturally and at scale. New, dense corpora collection efforts intertwined with lab-based tests of processing and caregiver vocabulary reports can help clarify the link between input and language knowledge within and across specific children.
4. Tests of familiar word knowledge and novel word learning tap different dimensions of linguistic knowledge but share a reliance on utterance and nonlinguistic context. Integrating what different approaches reveal as a function of age is likely to strengthen our understanding of the aspects of word knowledge that they reflect.
5. Understanding early word learning requires careful consideration of what children represent in their lexicons, which is not initially the conventional, space-separated words in the adult language. It also requires an appreciation of the task of learning correspondences between multiple possible forms and multiple possible meanings.

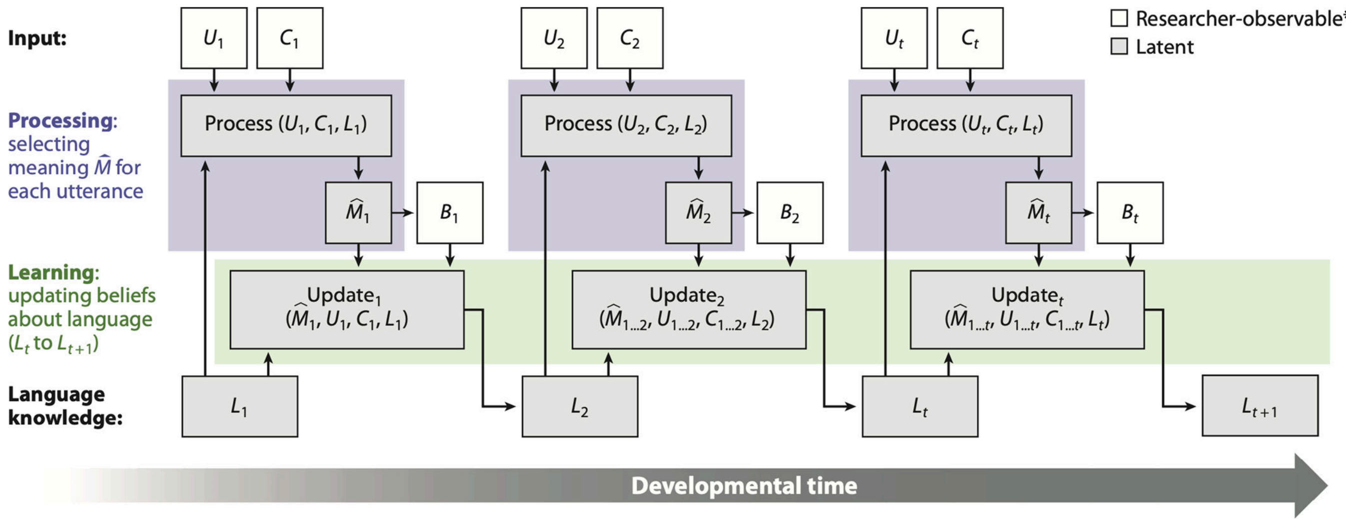

Figure 1.

A framework depicting the relationship among input (utterance U and context C), language knowledge (L), best guess of meaning ($\widehat{M}$), and behavior informed by meaning (B) as processing and learning proceed over developmental time. Function arguments indicate dependencies in the causal graph (i.e., what inputs are used in processing or updating). Blue squares highlight the Process function, and green squares highlight the Update function. The asterisk indicates that utterances, contexts, and behaviors are potentially observable by the researcher, though in practice only snapshots of each are recorded with existing methods (see Figure 2).

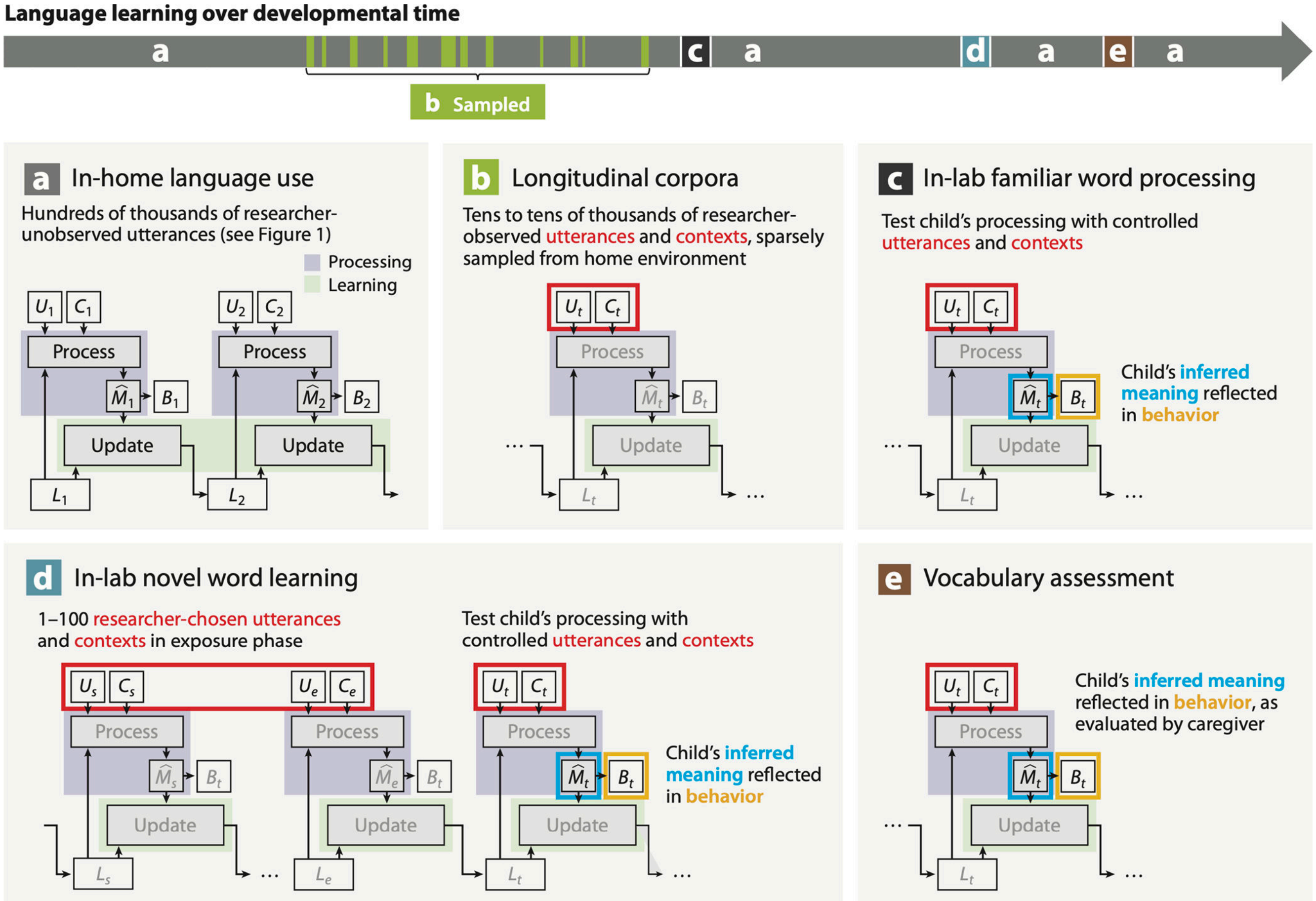

Figure 2.

(*a*) Learning through processing in the home, related to (*b*–*e*) four common methods of early linguistic knowledge assessment. Panel *b* shows longitudinal corpora as an example of a more general method of home recordings. The arrow at the top, representing developmental time, indicates that each of these assessment methods represents a small proportion of a child's history of processing and learning.

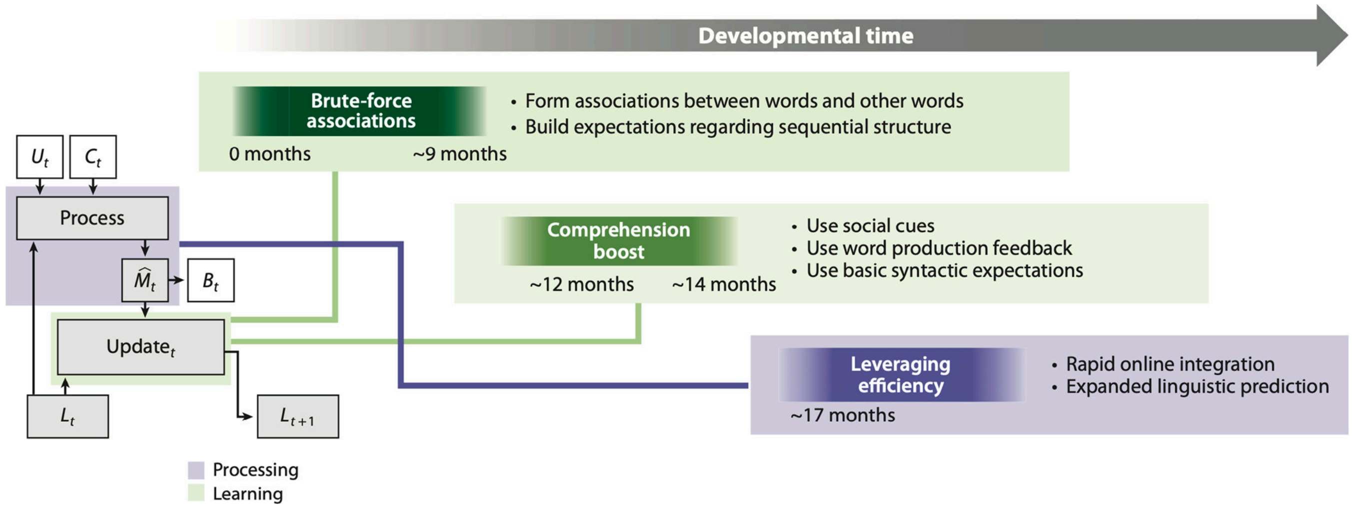

Figure 3.
Changes in word learning between 0 and 2 years, presented in terms of the framework introduced in Section 2.