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Drivers of Lexical Processing and Implications for Early Learning

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Abstract

Understanding words in unfolding speech requires the coordination of many skills to support successful and rapid comprehension of word meanings. This multifaceted ability emerges before our first birthday, matures over a protracted period of development, varies widely between individuals, forecasts future learning outcomes, and is influenced by immediate context, prior knowledge, and lifetime experience. This article highlights drivers of early lexical processing abilities while exploring questions regarding how learners begin to acquire, represent, and activate meaning in language. The review additionally explores how lexical processing and representation are connected while reflecting on how network science approaches can support richly detailed insights into this connection in young learners. Future research avenues are considered that focus on addressing how language processing and other cognitive skills are connected.

Keywords

lexical processing; language acquisition; vocabulary development; network science; word learning

1. INTRODUCTION

The young language learner will encounter millions of ephemeral words in speech during their first few years of life (Hart & Risley 1995). These words complement learning environments containing many sources of linguistic, sensory, and social information. As young children sift through this milieu, they become efficient processors of spoken language. By their first birthday, they can reliably identify the intended referents of many common nouns, and by their second birthday, they can flexibly and rapidly recognize many word meanings. As their skills grow, children start to activate not only intended word meanings in response to speech, but also a range of related words that share similarities in multiple dimensions of sound and meaning. These patterns of shared activation along multiple lexical dimensions reflect the organization of the early lexicon. Given these substantial challenges and impressive early achievements, how does the developing mind activate, retrieve, and represent spoken word meanings? What factors affect the trajectory of

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this developing skill? And how might this skill contribute to ongoing development and later learning outcomes?

This article considers these questions via a selective review of real-time spoken language processing at the single-word level. Lexical processing skill, which describes the mechanisms by which children rapidly interpret spoken strings of sounds and map these sounds onto meaning, is variously termed in the literature “word recognition,” “lexical recognition,” “speech processing,” “lexical processing efficiency,” and “real-time language processing,” as well as other variations on this terminological theme. This review focuses on the drivers of these phenomena primarily in children under the age of 3, with an eye toward probing the nature of early lexico-semantic representation, and on how these early language processing skills support ongoing developmental trajectories and outcomes beyond this age. This review primarily considers language processing in children who are learning a single, spoken language. For excellent reviews on language acquisition in other contexts and in bilingual environments, readers are referred to two other recent *Annual Review of Developmental Psychology* articles (Rowe & Weisleder 2020, Sebastian-Galles & Santolin 2020).

2. FACTORS THAT INFLUENCE REAL-TIME LEXICAL PROCESSING IN YOUNG CHILDREN

The seeming ease and speed with which listeners appear to comprehend a single spoken word belies the enormous complexity of the task. Listeners must often coordinate information from multiple sensory channels to decipher the message. For example, listeners identify potential referents in speech by simultaneously weighing visually present cues about potential referents and auditorily presented words (Tanenhaus et al. 1995). Additionally, listeners coordinate these sensory components of the message with higher-level, top-down sources of information conveying social, pragmatic, syntactic, and discourse constraints in order to activate and retrieve appropriate candidate meanings for the word from memory. Adding yet another layer to this task, language processing can be influenced by other factors that are not part of the immediate message, such as the learner’s lifetime language experience, the ambient noise in the immediate environment, and the listener’s age. The following sections consider several of these drivers of lexical processing. Although various factors are described in isolation below, it is important to note that everyday communication, which occurs in rich contexts, has multiple factors aligning and/or competing simultaneously to drive linguistic interpretation.

Developmental and cognitive scientists have also devised a number of experimental approaches to measure early lexical processing in early childhood, including those that tap into manual, brain-wave, and gaze responses (for overviews of several alternative methods that are not reviewed here, see Friend & Keplinger 2003, Junge et al. 2021, Kemler Nelson et al. 1995). This review focuses primarily on findings arising from gaze-based methods that measure how quickly and/or accurately a child directs their gaze toward a named object or image in response to a spoken label. These language-mediated gaze paradigms are alternatively referred to by several labels, including: the intermodal preferential looking procedure (Golinkoff et al. 1987), the visual world paradigm (Huettig et al. 2011, Tanenhaus et al. 1995), and the looking while listening paradigm (Fernald et al. 2008b). The review below first describes these gaze-based paradigms of lexical processing and then follows with a description of a number of factors that influence real-time lexical recognition.

2.1. Measuring Lexical Processing by Gaze

Researchers have increasingly sought to study mechanisms of lexical processing through gaze measures that quantify children's language-mediated fixations toward labeled images and videos. These methods have increased in popularity due to a number of desirable properties, including the increasing availability of technology to support automated measures of eye movements, low task demands (i.e., no manual or explicit response required), the ease of child engagement (i.e., trials are presented with child-friendly and engaging stimuli and reliable data can be captured in a brief testing session lasting less than 10 min), and a logical connection between the behavior measured and the inferred mechanism (i.e., the speed and accuracy of looking toward a named object is equated with the speed of lexical activation and recognition). Figure 1 illustrates one version of this task and some common measures. In the version of the task depicted (Figure 1a), the participant is initially provided a silent visual preview of two images. Then, a central fixation stimulus appears in the center of the image, accompanied by an attention-getting sound (e.g., "Look!"). This central stimulus remains until the child fixates toward the central stimulus in order to ensure that the child is attentive and fixated in a standard location of the screen (for expanded discussion of benefits of this gaze-contingent version, see Egger et al. 2020). Next, one of the images is named (e.g., "Car!"), and the participant's gaze toward the target and distractor objects is measured at regular time intervals following the target label. To visualize the dynamics of word recognition in response to the named target word, the mean fixations over time across all items and/or participants is then plotted on a time course plot (illustrated in Figure 1b). It is also possible to compute various measures across relevant portions of the time window following target labeling; in this figure, aggregated measures are calculated from the time course using a common time window of 300–1,800 ms after target labeling. Figure 1c exhibits a small subset of the wide range of possible aggregated measures, including average looks to the target, average looks to the distractor, and accuracy (defined as average looks to the target divided by the sum of target and distractor looks).

Gaze responses to named objects in this lexical recognition paradigm can be influenced by a number of factors that are thought to reflect the structure and activation of the lexical system. For example, listeners' gaze toward a named target word (e.g., "dog") is slower when the target image is paired with a unnamed distractor image that is related in meaning (e.g., "cat") compared with a distractor that does not share a semantic relation (e.g., "car") (Bergelson & Aslin 2017, Huettig & Altmann 2005, Yee & Sedivy 2006). This pattern, termed semantic competition or semantic interference, suggests that the listener's lexicon represents the link in meaning between these related concepts such that activation of one concept leads to spreading coactivation of the related concept. Importantly, these gaze-based patterns in semantic interference in young children are validated by findings using other methods, such as electroencephalogram/N400 and head-turn preference procedure methods, that do not rely on the visual presentation of named objects (Faust et al. 1993, Rämä et al. 2013, Torkildsen et al. 2007, Willits et al. 2013). Together, convergent findings from multiple approaches suggest that these connections are not simply an artifact of a gaze-based paradigm where objects may share a visually apparent physical connection that drives semantic interference. Further, gaze-based measures of competition from related distractors can reflect a number of ways in which the learner's lexicon is structured and activated, such as in measuring activation of different kinds of semantic connections at the individual level (e.g., thematic versus categorical relations; Mirman & Graziano 2012) and for phonological neighbors (Allopenna et al. 1998). (For a more extensive discussion of gaze-based language processing methods, see Egger et al. 2020, Fernald et al. 2008b, Golinkoff et al. 2013, Huettig et al. 2011, Swingley 2011, Trueswell 2008.) The following sections highlight a number of factors that drive efficiency in lexical recognition.

2.2. Acoustic Factors

Everyday speech is rapid and variable, often occurring in less-than-ideal listening conditions. While young children build robust lexical processing skills despite these challenges, research suggests that young children may be particularly sensitive to variable acoustic dimensions in speech. For example, a common challenge in early learning environments may be the presence of multiple simultaneous talkers and other sources of noise, either from multiple family members, sources of electronic speech, or the presence of noise pollution (Cohen et al. 1973). Infants increasingly become able to filter out background speech during tasks that involve own-name recognition over the first two years (Newman 2005, 2009, 2011; Newman & Jusczyk 1996), and children who experience enhanced levels of environmental noise show, at least early in development, enhanced abilities to recognize speech in noise. However, prolonged exposure to noise seems to negatively impact recognition skills, and both transient and prolonged noise exposure affects word learning (Erickson & Newman 2017, McMillan & Saffran 2016).

Other features of the early acoustic environment available in child-directed speech (CDS) might support lexical recognition (Singh et al. 2009). For example, CDS is often reported to be slower in tempo than adult-directed speech. Accordingly, toddlers' word recognition is enhanced when words are presented with a slower speech rate (Song et al. 2010) and is less accurate when speech is time compressed (Zangl et al. 2005). By age 2, other phonologically relevant acoustic factors, such as pitch and stress contours, can drive lexical recognition and learning in languages where these features are linguistically relevant (Quam & Swingley 2014), though there can be considerable development in this skill even until age 3 (Ma et al. 2017, Ota et al. 2018, Singh et al. 2014) and potentially beyond. Relatedly, the child's own experience with speakers of multiple dialects can influence word recognition. For example, 24-month-olds who hear both standard-accented and foreign-accented speech at home are slower to recognize words in standard-accented speech, though this difference disappears by 32 months. This developmental pattern suggests that variability in the child's acoustic experience with individual words, as indexed by accent exposure, may cause transient differences in how children recognize words, particularly when children have had less exposure to variability in speech from multiple speakers at younger ages (Buckler et al. 2017). Overall, the young language learner is sensitive to the acoustic variability of words in speech. Across development, children learn to navigate this variability, though this skill is flexible, and are influenced by the dimensions that are most pertinent to the child's own linguistic and acoustic environment.

2.3. Cognitive Factors

Lexical recognition can also be affected by emerging cognitive abilities of the child. Studies in school-aged children and in adults identify connections between spoken word recognition and domain-general cognitive skills such as executive function (Pomper et al. 2021) and working memory (Nitsan et al. 2019). Yet thus far, few studies have explored links between lexical processing and cognitive skills in children under the age of three. Part of the reason for this gap stems from the relative difficulty of identifying robust and standardized cognitive measures that tap into distinct subdomains of cognition at this age (compared with those of older children and adults), although some research is starting to tackle these questions. For example, several studies have suggested that the attentional capacities and interests of the young learner may support lexical processing and word learning (Ackermann et al. 2020, Peters et al. 2021). There is also evidence that lexical recognition skills in toddlerhood may be linked to future growth in cognitive function. This idea is supported by evidence suggesting that the speed of lexical recognition at age 2 is associated with working memory at age 8 (Marchman & Fernald 2008). However, not all domain-general cognitive skills seem to be linked to lexical recognition. Several studies have failed to identify a connection between lexical processing and general information processing skills as indexed through visual reaction time to a nonlinguistic stimulus (Fernald et al. 2006, Lany 2018). In sum, the current findings build on evidence from older age groups that lexical recognition is a cognitively complex skill that is influenced by, and potentially also supports, multiple domain-general mechanisms that interact with cognitive development. However, the state of this evidence is currently preliminary, and much more work is needed in this area. Despite the challenges of assessing cognitive function in infants and toddlers, this gap is still surprising given the theoretical and practical importance of the knowledge to be gained by such efforts. A fuller accounting of how these multiple skills interact across early development could illuminate how advances in early language processing and other cognitive abilities and skills drive each other and could yield potential targets for identifying markers of early risk and future intervention.

2.4. Maturation and Experience

Word recognition skills improve with age and are also tied to the learner's experience. Over the course of the first year, children start to recognize common nouns (Bergelson & Swingley 2012; Tincoff & Jusczyk 1999, 2012). However, the emergence of robust noun-referent mapping skills before 12 months can vary depending on linguistic context and familiarity with the speaker (Bergelson & Swingley 2018, Steil et al. 2021). As children age, they begin to recognize more words, and they do so with increasing speed and accuracy (Bergelson & Swingley 2014, Fernald et al. 1998). For example, 12-to-15-month-olds may start to look reliably toward a named object only after it is completely spoken, but by 18 months can identify the referent of a spoken word from partial phonetic information (Fernald et al. 1998, 2001). This developmental process appears to have a protracted profile, with developmental changes continuing even into adolescence (Rigler et al. 2015).

These developmental changes in lexical processing efficiency are driven both by the overall maturation of the child and by their own learning histories.

Children experience tremendous range in the amount and nature of language input they receive in the early years of life, and this experience can influence lexical processing. Not only do children vary greatly in the quantity of language they hear in their households (Hart & Risley 1995), but also there are many documented differences in the complexity and contingency of these early language experiences between children (Hoff & Naigles 2002, Rowe & Weisleder 2020). These differences are frequently explored within the context of differences in socioeconomic status (SES), as, for a variety of complex reasons, caregivers in higher-SES households are often reported to produce more CDS and speech that shows more variety, complexity, and contingent interaction compared with caregivers in lower-SES households (Rowe 2008). However, even when controlling for SES, there is significant variability in language experience among children (Huttenlocher et al. 1991), and recent cross-cultural investigations highlight the possibility that differences in caregiver speech may be offset by input from other sources, such as from other children in the community (Bunce et al. 2020, Loukatou et al. 2021). Whatever the source of these differences in language input, individual variability in exposure to CDS is associated with the time course of lexical recognition such that young children who tend to hear more child-directed language also exhibit more efficient lexical processing (Fernald et al. 2013, Hurtado et al. 2008, Weisleder & Fernald 2013). Researchers hypothesize that receptive language skills may rely on building robust lexical representations through responsive language experiences that scaffold the child's own attempts to communicate. Postnatal maternal depression and anxiety can similarly pose challenges that affect the quantity and quality of caregiver–child interactions (Brookman et al. 2020a, Clifford et al. 2021), and recent evidence suggests that children with mothers who experience postnatal depression and anxiety also show less robust lexical recognition skills (Brookman et al. 2020b).

Disentangling maturationally driven effects on lexical processing from the language learning history of the child can be difficult. Nevertheless, a few indicators suggest that the child's own biologically driven development may influence gaze-driven measures of lexical processing. For example, latency in initiating a target-directed gaze changes across development. While an adult can typically initiate a saccade toward a visual target within 200 ms (Walker et al. 2000), one- and two-month-olds are significantly slower, taking around 500 ms (Aslin & Salapatek 1975). The latency of this ability reduces markedly across the course of the first year (Gredebäck et al. 2006), after which saccade latency improves slowly and steadily throughout childhood (Fukushima et al. 2000, Salman et al. 2006). It is not known whether and how these developmental changes in saccadic latency may also contribute to gaze-based measures of early lexical processing, particularly across infancy when both saccadic latency and lexical recognition accuracy are changing dramatically. However, given the rapid development of saccade latency in the first year of life, it is possible that gaze-based measures of lexical recognition may potentially underestimate infants' ability to understand word meanings before the age of approximately 12 months.

Other studies have contributed to questions regarding maturational effects on lexical processing by comparing children who were born preterm with those of similar postnatal age and gestational age. For example, Loi and colleagues (2017) found that children who were born preterm were slower to recognize words than children of the same postnatal age but not of the same gestational age. These findings suggest that differences in lexical processing efficiency are at least partially driven by the biological development of the listener, even when controlling for relative amount of language experience.

Together, the evidence suggests that maturational and experiential factors are woven together to afford numerous pathways by which young children may successfully acquire language and highlights many paths that may lead to successful targets for intervention when children experience delays in early learning.

2.5. Lexical Processing as a Window into the Learner's Knowledge

Changes in vocabulary size reflect the growing knowledge of the young learner, and between the ages of one and three, vocabulary size grows explosively. Children start out in this developmental period saying, at most, a handful of words and typically produce at least several hundred (and often thousands) of words by age 3 (Fenson et al. 2007, Mayor & Plunkett 2011). At the same time, there are also tremendous differences between learners. For instance, when measuring vocabulary size using a common parental checklist of early-acquired words [e.g., the MacArthur-Bates Communicative Developmental Inventory (MBCDI)], an 18-month-old at the 10th percentile may be reported to say about 16 words, while another 18-month-old at the 90th percentile would say 277 words—a 17-fold difference (Fenson et al. 1994, 2007). These early differences in vocabulary size between children are connected to lexical processing efficiency such that children with larger vocabularies are also faster to recognize words. This connection appears to be in place at least from 12–15 months of age (Lany et al. 2018), persists across the second year (Donnelly & Kidd 2020; Fernald et al. 2006; Friend et al. 2019; Hurtado et al. 2008; Legacy et al. 2016, 2018; Marchman et al. 2010, 2016; Peter et al. 2019), and continues into preschool age (Koenig et al. 2020, Law & Edwards 2015, Mahr & Edwards 2018). This enduring association between lexical processing and vocabulary size substantiates a strong connection between the learner's knowledge and their ability to interpret words in speech.

In addition to the size of the learner's vocabulary, the structure of the learner's lexicon also affects processing. In other words, children vary widely not only in the number of words that they say but also in which words they learn such that even when two children are reported to say an identical number of words, the composition and structure of their vocabulary may look very different. Such differences in one dimension of vocabulary structure—linkages among word meanings—are illustrated in Figure 2a. Variability in lexical structure can manifest at several levels of granularity. For example, Figure 2a illustrates global differences in semantic vocabulary structure between two children who are matched in total vocabulary size but show striking differences in the overall interconnectivity and clustering of their early vocabulary. These differences can also emerge at a more local level of granularity, as highlighted in Figure 2a, where the shaded area captures differences in expressive vocabulary surrounding a specific word (e.g., "dog") and category (e.g., "animals"). In both of the vocabulary networks in Figure 2a, individual words are represented as nodes or vertices on the graph, while connections between words that overlap in meaning are represented by lines or edges. The graph in Figure 2a, for example, was constructed by initially capturing the productive noun vocabularies of two 18-month-olds using the MBCDI. The nodes on Figure 2a denote the nouns each child says, and the edges represent connections between words that share two or more semantic features according to the norms of semantic features produced in response to noun concepts. There are a number of ways in which this graph-theoretic (also known as network science) approach can characterize connections between words, such as by characterizing links among words that share phonological or orthographic overlap (Siew & Vitevitch 2019, Vitevitch 2021), and among other dimensions of semantic relations among words, such as those captured by semantic association norms (Fourtassi et al. 2020, Hills et al. 2009b), co-occurrence statistics derived from corpora of CDS (Beckage et al. 2011), semantic features (Borovsky & Peters 2019; Hills et al. 2009a,b; Peters & Borovsky 2019; Siew 2019; Yurovsky et al. 2012), or a combination of all of these (Stella et al. 2017). Importantly, the structure depicted by these graphs can be quantified in a variety of ways using network science measures that capture structure at different levels of granularity. Some possibilities include quantifying overall lexical density as the number of links between words (called mean degree), measuring the average lexical distance or number of hops between words (called mean path length), characterizing the overall tendency of a word’s neighbors to also share connections [called the global clustering coefficient (GCC), which measures the proportion of word triplets in a network as being closed, or sharing connections between all three members, versus open, where one pair of words in the triplet does not share a connection with all other members connected], as well as many others (for an introduction to some semantic network measures and their implications, see Borovsky et al. 2021, Steyvers & Tenenbaum 2005).

Importantly, network science methods that illustrate and quantify the structure of the learner’s lexicon open new avenues to explore connections between early vocabulary acquisition and processing. For example, overall global connectivity of the child’s lexicon appears to impact processing, particularly when there is an object that is semantically related to a target word that interferes with lexical processing, as illustrated in Figure 2b (Borovsky 2022, Borovsky & Peters 2019).

Children’s ability to recognize word meanings can also be influenced by the structure of lexical knowledge surrounding that word’s meaning. Before delving into these points further, it is useful to note that lexical processing skills can vary within a child, despite the common shorthand that often characterizes lexical processing as a coherent ability that increases uniformly for a single learner across development. For example, words that parents tend to rate as less frequently known by children at a particular age are recognized less quickly and accurately than those that are frequently understood at the same age (Lany et al. 2018). Similarly, a word’s lexical neighborhood can also impact processing. For example, 30-month-olds with relatively larger vocabularies are slower to recognize words that have many neighbors that share the same phonetic onset as compared with words with sparser phonological neighborhoods (Donnelly & Kidd 2021), and word recognition is more robust when the child knows relatively more words in the same semantic category compared with words that belong to relatively sparser semantic categories (Borovsky 2022, Borovsky & Peters 2019, Borovsky et al. 2016).

One particular advantage of using semantic features to model semantic network structure is that it is possible to quantify connections according to different types of semantic overlap, such as whether words share perceptual, functional, or taxonomic connections in meaning (Peters & Borovsky 2019). This featural approach thereby supports inquiry into what kinds of connections between words drive early learning and processing. For example, Figure 2c illustrates semantic connections among the first 100 nouns that children are reported to produce on the MBCDI. In this case, perceptual features drive a large proportion of the connections among these early-acquired words. Similarly, this structure also affects lexical processing such that toddlers are faster to recognize words that share more perceptual links compared with words with fewer perceptual links (Peters et al. 2021). Children also experience more semantic interference from related category members when those members share many perceptual properties (Arias-Trejo & Plunkett 2010).

Finally, vocabulary size and structure interact with each other and drive lexical processing in interesting ways, as illustrated in Figure 3. Semantic structure can change as children learn more words, which creates more opportunities for words to connect and complex structures to emerge. Individual differences in structure as a function of vocabulary size can be observed in Figure 3a. There is also preliminary evidence that differences in size and structure interact during processing (Figure 3b). For example, a recent study (Borovsky & Peters 2019) explored toddlers' word recognition in semantically related contexts, where enhanced semantic connectivity in the child's lexicon typically results in less accurate recognition due to interference from related competitors during word recognition. While this semantic interference pattern was clear among children overall, interference was enhanced among children with denser lexicosemantic connectivity (higher GCC) and smaller vocabularies (Figure 3b). Together, these findings suggest that as vocabulary size grows, children must devise new ways to prevent interference from related word meanings, potentially by developing enhanced skills in inhibitory control that support the ability to reduce competition among lexical competitors (Chow et al. 2019).

Despite the promising initial evidence that lexical processing can vary within learners according to the structure of their individual lexical neighborhoods, there is still a surprising lack of information on how item-level factors affect processing in infants and toddlers with respect to other variables that are frequently studied in adult psycholinguistic studies, such as frequency, concreteness, iconicity, and age of acquisition. This current gap illustrates a need to develop richer models of the origins and nature of the lexicon early in life, which would in turn connect traditionally disconnected domains of inquiry between adult and child research to support more integrative life span models of continuous growth in language processing skills and lexical representation across time.

3. WHY DO LEXICAL PROCESSING SKILLS MATTER?

The previous section emphasizes that lexical processing skills intersect with many abilities that are driven by the learner's early maturation, experience, and knowledge. Yet the presence of these associations does not make clear why one might care about lexical recognition itself. Aside from the obvious importance of fluent comprehension for facilitating everyday communication, lexical processing skills seem to serve important roles as a predictor of future learning outcomes and a driver of early learning. Both of these ideas are reviewed below.

3.1. Processing Predicts Later Outcomes

Lexical processing skills are connected to concurrent and future language and cognitive skills in children. For example, lexical processing skills in 18-to-24-month-olds have repeatedly been associated with later vocabulary abilities in preschool and school-age children (Borovsky 2022; Marchman et al. 2016, 2018; Newbury et al. 2016; Smolak et al. 2021). Early lexical processing also predicts preschool-age syntactic skills (Peter et al. 2019), suggesting that early abilities in recognizing individual word meanings may help to support and facilitate language skills beyond the single-word level. Lexical processing has also been connected to skills that directly translate to school readiness at ages 4 and 5, just before school entry, including core language skills, receptive vocabulary, and IQ (Koenig et al. 2020, Marchman et al. 2018, Newbury et al. 2016), and to cognitive skills at age 8 (Marchman & Fernald 2008). Similarly, the speed of processing at 18 months of age can also predict the resolution of early language delay status one year later in children who are late talking (Fernald & Marchman 2012). Together, these findings suggest that language processing may be an important and central indicator or ongoing development and may itself support continued growth in language skill.

3.2. How Might Lexical Processing Support Learning?

There are at least several reasonable ways in which lexical processing could support vocabulary learning, and to some extent the codevelopment of these skills is likely bidirectionally related. For example, building a larger vocabulary might support efficient retrieval and recognition of word meanings, which would in turn lead to more robust lexical processing.

Ease of ongoing known word recognition may support ongoing vocabulary building by reducing the cognitive resources needed to interpret known words in speech, which allows the learner more processing slack to focus on learning novel words (Donnelly & Kidd 2020; Friend et al. 2018, 2019; Lany 2018; Marchman & Fernald 2008; Peter et al. 2019). Studies have probed this hypothesis experimentally by presenting children with novel words embedded in phrases like, “Look at the doggie on the deebo!” (Byers-Heinlein et al. 2021, Fernald et al. 2008a). This paradigm explores the idea that children who are more efficient at processing and then directing their attention toward the known item (doggie) may then be better prepared to process and learn a subsequently presented novel item (deebo). Related explanations suggest that efficient lexical processing does not simply allow the listener to update their ongoing representation of ongoing speech but may help the listener to go a step further and generate expectations about the contents of upcoming speech. This account is bolstered by evidence that children and adults with larger vocabularies are faster to use unfolding information in speech (such as an informative verb) to anticipate upcoming objects and reduce competition from related objects (Borovsky et al. 2012; Borovsky &

Creel 2014; Hintz et al. 2017; Kukona et al. 2016, 2022; Mani & Huettig 2012) and also by evidence that predictive processing skill forecasts future vocabulary growth (Gambi et al. 2021a). Finally, some studies have suggested that rather than being driven by an ability to anticipate upcoming words, learning may instead be most effective when a listener generates an incorrect prediction. Error-based learning accounts posit that incorrect predictions provide a type of corrective feedback to the learner that prompts a revision and updating of their linguistic representation and network (Chang et al. 2006, Elman 1990, Ramscar et al. 2013). Some evidence supports error-based accounts during real-time processing in word learning (Reuter et al. 2019), and other work identifies this error-based learning connection only in adults, but not children (Gambi et al. 2021b). Finally, the degree to which lexical processing is tied to other cognitive skills, like working memory, executive function, and attentional skills, is still largely unknown. Tracing connections between lexical processing and cognitive skills may be theoretically useful to expand on accounts of whether and to what degree language-relevant skills emerge from domain-general cognitive mechanisms that may be primary drivers of learning. Nevertheless, there is an expanding body of evidence suggesting that lexical recognition has some role in supporting young learners. Future work is needed that can directly compare and identify potential mechanistic accounts for this relation and disentangle where and when in development these skills may exert a proximal or distal role in ongoing linguistic and cognitive development.

4. FUTURE DIRECTIONS

Researchers studying the emergence of lexical recognition skills are entering a golden age. Developmental scientists are armed with two critical tools: (*a*) a foundational understanding of a sizeable set of parameters that support and modulate a child's ability to fluently interpret words in speech and (*b*) a set of candidate mechanisms for how these skills support ongoing cognitive development. As methods mature and technology for both automated and remote eye tracking becomes increasingly available and affordable, the field is primed to make substantial advances. Below, I sketch out several ideas that seem well-positioned to bear fruit in the coming years.

The first question concerns the nature of the relation between the child's lexical knowledge and processing skills. As reviewed in Section 2.5, there is overwhelming evidence that the speed and accuracy of lexical recognition is connected to the size and structure of the learner's lexicon. Importantly, the recognition process for an individual word is driven by factors beyond the direct knowledge of that word. Although this insight in itself is not new—psycholinguists have sought to map how broader connections among words affect processing in priming studies for half a century (Meyer & Schvaneveldt 1971, Neely 1991)—the extension of this inquiry into the onset of lexical development represents a valuable step. Adults know many tens of thousands of words. Therefore, psycholinguistic studies with adults typically rely on standard estimates of word properties that are assumed to apply equivalently to all individuals in a study. For example, studies of the impact of phonological neighborhood density on processing hinge on estimates of adult lexical neighborhoods in general and not on individual differences in phonological networks surrounding a word (e.g., Vitevitch & Luce 1998). In other words, the phonological neighborhood density measure for a word like "cat" would register as the same value for each participant in the study, despite the fact that the structure of this neighborhood is likely to vary somewhat at the individual level. However, for young children at the outset of lexical acquisition who may only produce a few dozen to a few hundred words, it is possible to gain a detailed and reasonably comprehensive snapshot of their lexical abilities via parental report measures. This early state of learning therefore provides a unique and fertile ground from which to model the early origins of and connections between representation and processing. Thus, scientists are able to explore these questions with a sensitivity to individual detail in the lexicon that is otherwise not practical among adults. Further, given the dramatic growth of vocabulary during this early point in learning, it is possible to model how these connections change as the individual learner's lexicon transforms over the first few years of life (Borovsky 2022).

A secondary but related question concerns how learning and processing are connected. How and when do learning and processing drive each other? Are these two skills two sides of the same coin, or are they driven by separate factors? How might these skills support interconnected developmental cascades across early childhood? The evidence reviewed above suggests an important connection among these phenomena, but the precise relation is likely to be developmentally complex. Answers to these questions not only will support theoretical accounts of language representation and processing but also can identify directions for building effective interventions and early learning curricula. For example, a bidirectional link between processing and learning would suggest that building skills in either vocabulary knowledge or processing is likely to support the other, whereas a unidirectional link would necessitate a more specific intervention target. In turn, these questions are also likely to yield valuable theoretical insights into the mechanisms that support early representation and activation of meaning in language.

Raising the question of intervention requires scientists to evaluate several assumptions that are embedded in this endeavor. The primary element is the need to clearly establish the existence of a causal connection between early lexical processing and future development. Critically, more evidence is required to firmly cement the hypothesis that building lexical processing skills will mitigate poor learning outcomes. At minimum, this question motivates a call for longitudinal work that probes the relation between early lexical processing and longer-term outcomes to enrich the existing work on this topic. An even harder question may be: Is it possible to develop effective therapies to improve spoken word recognition? There is some precedent for the development of a therapy that targets acoustic elements of speech recognition to improve other language and reading skills (Tallal 2013). However, the effectiveness of this particular therapy has been debated (Strong et al. 2011). Similarly, interventions that have sought to improve academic achievement through domain-general cognitive training have also failed to show effective transfer (Melby-Lervåg & Hulme 2013). More generally, there has been skepticism in recent years concerning the potential effectiveness of so-called brain-training programs that aim to boost general cognitive skills from limited training domains (Simons et al. 2016). However, there is evidence that interventions that have a more proximal relation to a particular skill can be effective. Educational scientists have pursued interventions targeting skills that have a direct connection to the target ability, which can improve learning achievement outcomes. For example, interventions that build fluency in word reading skills can lead to growth in reading comprehension skills (Natl. Read. Panel 2000). With this connection in mind, it seems plausible that a parallel connection might exist in younger learners, who could build early language comprehension abilities more generally by targeting fluency in early lexical recognition.

Any research enterprise that seeks to develop interventions needs to employ a rigorous and cautious approach initially informed by longitudinal studies that explore how a variety of factors support lexical processing across development. A number of groups are already advancing or interested in this cause, and there is much value to be gained by coordinated engagement among groups. The large sample sizes needed and many factors involved preclude any single research site from gaining a complete understanding of these questions. Teams of researchers are needed to support this work, along with groups that contribute to the expanding culture of team science, metascience, and prioritizing exploration of these questions in many cultural and linguistic contexts.

In sum, studies of lexical processing in young learners have generated a number of exciting discoveries unraveling the origins and structure of the mental lexicon and delineating the roots of individual differences in early language development. Together, these insights suggest potential pathways for supporting future learning and intervention. Nevertheless, scientists have only begun to scratch the surface of our understanding of lexical processing. There exist many avenues for future inquiries that have the potential to build our fundamental understanding of these abilities and, ultimately, to chip away at foundational questions in early language development to help all learners succeed.

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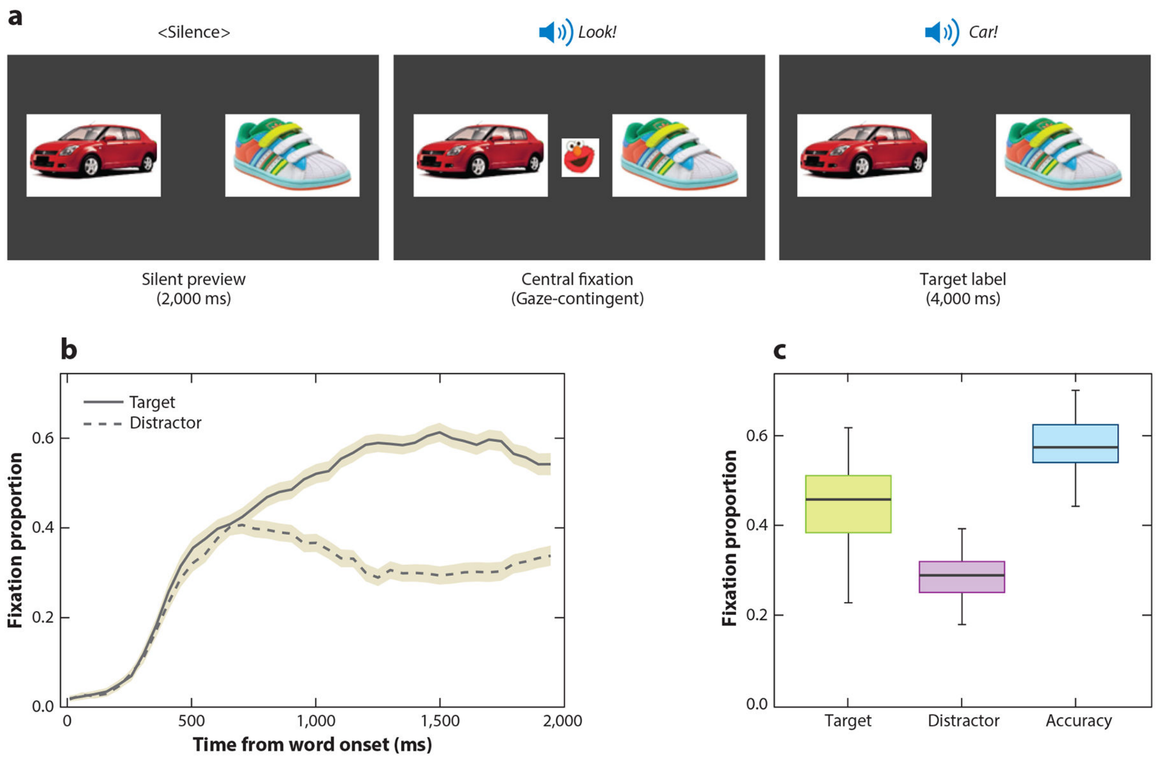

Figure 1.

Illustration of sample task and measures in a gaze-based assessment of lexical processing. (*a*) Illustration of a version of a gaze-based task where images appear in a silent preview, followed by the appearance of a gaze-contingent central stimulus (e.g., "Look!" paired with an image of a cartoon face), which disappears after participant fixation. This is followed by the onset of the spoken word, which (typically) names one of the objects on the screen. (*b*) Illustration of the time course of fixations toward the target and distractor images, starting from the onset of the target naming. In this gaze-contingent version of the paradigm, fixations start at 0, indicating that participants were initially fixating centrally (i.e., not at the target or distractor). (*c*) Boxplots indicating the mean and variance in target and distractor fixations 300–2,000 ms post–label onset, with accuracy representing mean looks to the target divided by mean fixations to the target and distractor.

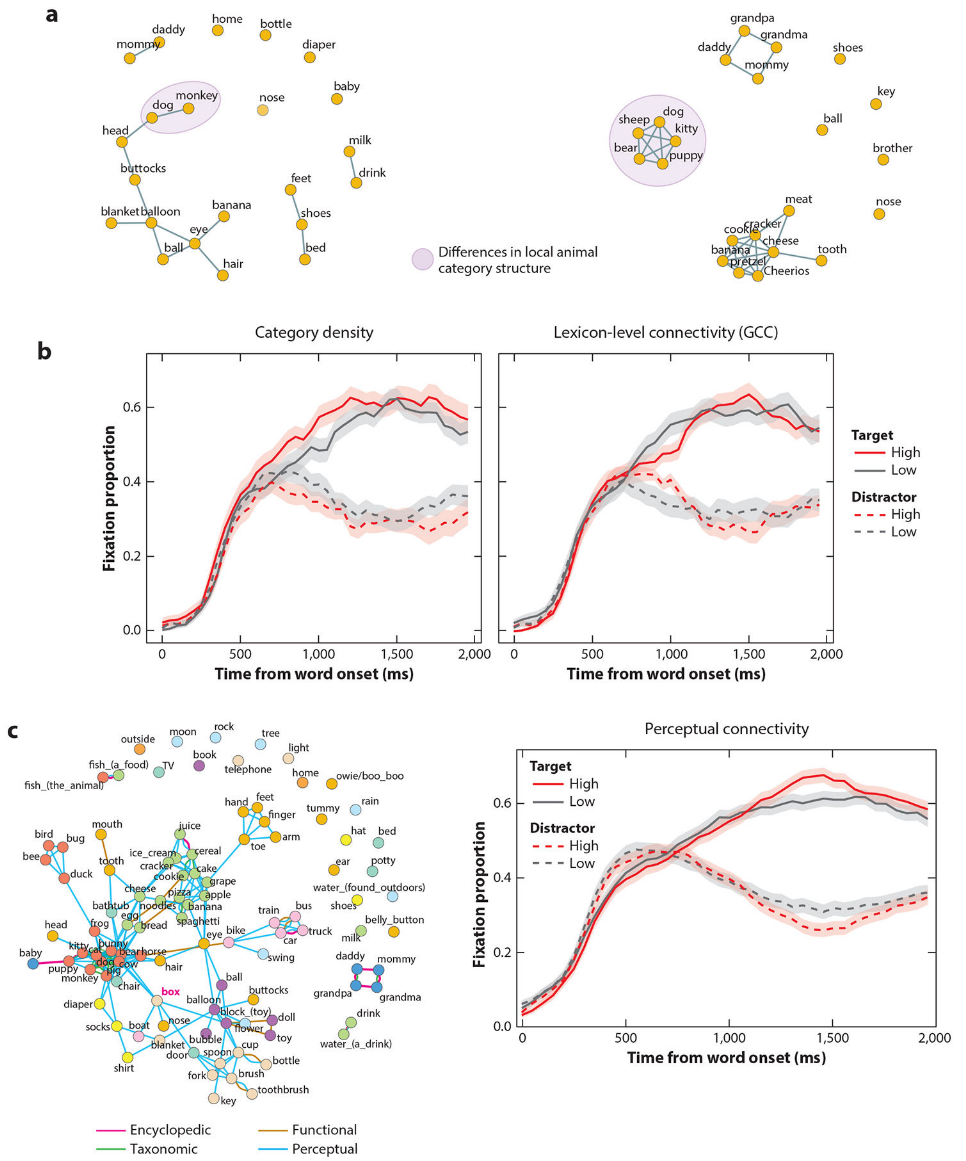

Figure 2.

Semantic structure and its links to processing at several levels. (*a*) Global semantic structure of two 18-month-olds who say the same number of words but show differences in vocabulary structure. Purple areas highlight the differences in local animal category structure. (*b*) Global and local differences in structure influence processing. At 18 months, word recognition is facilitated by higher (versus lower) density category structure, but this pattern is reversed when considering lexicon-level connectivity. (*c*, *left*) Map of types of semantic connections across children's (normative) first 100 spoken words created from data reported in Peters & Borovsky (2019). Perceptual feature connections dominate early. (*c*, *right*) Processing for words with many perceptual connections is facilitated compared with words with fewer perceptual links. Abbreviation: GCC, global clustering coefficient. Panel *b* adapted from Borovsky & Peters (2019) (CC BY 4.0). Panel *c* (*right*) adapted from Peters et al. 2021 (CC BY 4.0).

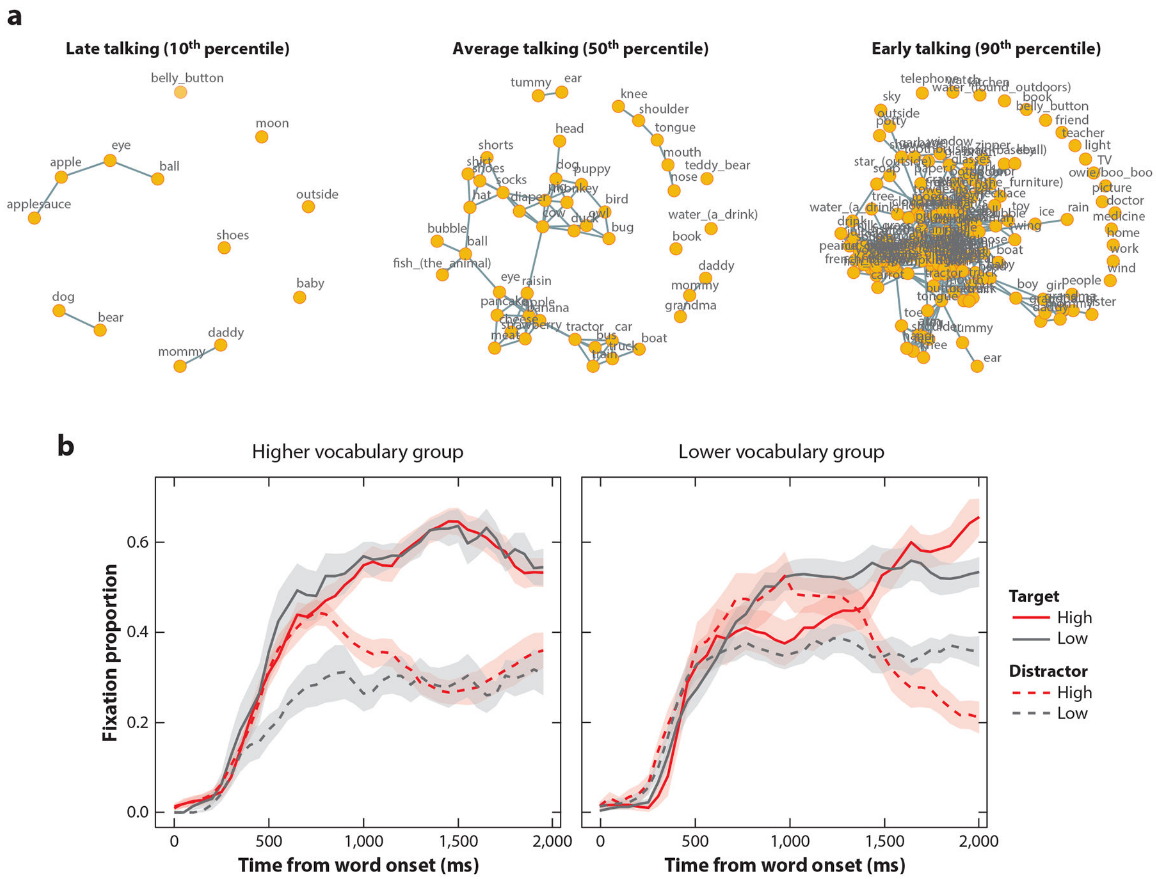

Figure 3.

Semantic network structure of vocabulary as a function of vocabulary size across age and connections to lexical processing. (*a*) Productive noun vocabularies of three 18-month-olds at different expressive vocabulary sizes. (*b*) Processing as a function of vocabulary size and structure in semantically related contexts in 18-month-olds. Vocabulary recognition is less robust overall in 18-month-olds with (*right*) smaller versus (*left*) larger vocabulary sizes. In the lower vocabulary group, there is an extended period of time for the higher connectivity words where target- and distractor-looking are not differentiated, suggesting an extended period of interference from the related distractor. In both vocabulary groups, lower levels of connectivity lead to reduced interference between the target and distractor, as indicated by earlier differentiation of the low-density target relative to the distractor in both plots.