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Toward a Precision Science of Word Learning: Understanding Individual Vocabulary Pathways

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Abstract

Toddlers vary widely in the rate at which they develop vocabulary. This variation predicts later language development and school success at the group level; however, we cannot determine which children with slower vocabulary development in the second year will continue to have difficulty. In this article, I argue that this is because we lack theoretical understanding of how multiple processes operate as a system to create individual children's pathways to word learning. I discuss the difficulties children face when learning even a single concrete noun, the multiple general cognitive processes that support word learning, and some evidence of rapid development in the second year. I present work toward a formal model of the word learning system and how this system changes over time. The long-term goal of this work is to understand how individual children's strengths and weaknesses create unique vocabulary pathways that enable us to predict outcomes and identify effective interventions.

Keywords

word learning; individual differences; formal models

Learning even a single new word is a time-extended task that requires successfully integrating numerous complex processes (D'Souza, D'Souza, & Karmiloff-Smith, 2017; Hoff, 2006; Samuelson & McMurray, 2017). Not surprisingly, typically developing children vary widely in their rate of vocabulary development. These differences predict later cognitive achievements, including school success (Duff, Reen, Plunkett, & Nation, 2015; Snowling, Duff, Nash, & Hulme, 2016). The general course of early vocabulary development is well documented—from receptive understanding as early as 4 months to the sharp upswing in the number of words comprehended (Bergelson, 2020) and produced (Fenson et al., 1994) by the end of the second year. Despite what we know from diary studies of individual vocabulary development, the field lacks theoretical understanding of how multiple processes operate as a system to create *individual* trajectories of word learning—and this is problematic if we are to translate research into effective interventions for at-risk children.

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Making headway on this issue requires understanding at the level of individual developmental pathways. With this goal in mind, I begin this review by briefly examining the literature on our ability to predict vocabulary and language trajectories from early measures of performance. Next, I discuss the difficulties children face during the task of learning even a single concrete noun, the many general cognitive processes that support word learning, and some evidence that these processes develop rapidly in the second year. Understanding the diverse pathways in which these components are integrated and mutually influential in early language development is critical to making a difference in the lives of children with language delay.

Toward this end, my colleagues and I are using a formal model to capture the complexities of the word learning system and its changes in the second year. Our account allows us to understand how strengths and weaknesses in underlying processes such as working memory and novelty detection shape the learning of individual words and the growing vocabulary. In this article, I also discuss the possibilities such formal accounts present for understanding, predicting, and supporting children's vocabulary development.

Predicting Toddler Trajectories Requires Understanding Basic Processes

The productive vocabulary of a 24-month-old can range from 0 to 600+ words (see Figure 1). While most typically developing 24-month-olds (oval) produce thousands of words by the time they enter school (green arrow), some have late-emerging language difficulties (orange arrow). Of the late talkers (children below the 15th percentile for their age and gender; circle), a large proportion bloom to average levels of vocabulary by school entry (blue arrow) but have weak language through adolescence (Henrichs et al., 2011; Rescorla, 2011; Snowling et al., 2016). The remaining late talkers continue to have difficulty (red arrow), often being diagnosed with developmental language disorder (Bishop et al., 2016; McGregor, Goffman, Van Horne, Hogan, & Finestack, 2020).

Many epidemiological and small-scale studies have documented these trajectories (Rescorla, 2011), but attempts to predict school-age outcomes from toddler language, demographic differences, birth effects, and other risk factors have not yielded strong consensus (Bishop, Price, Dale, & Plomin, 2003; Dale, Price, Bishop, & Plomin, 2003; Law, Boyle, Harris, Harkness, & Nye, 2000; Rowland, 2020). Thus, while the common trajectories of early vocabulary development are well documented, we cannot predict which trajectory an individual child will follow. This hampers the effective use of support services (Rowland, 2020), an increasing problem in the context of decreasing social service budgets.

One possible cause of this lack of predictive power is that the risk factors most commonly assessed do not tap into the basic cognitive processes increasingly understood as foundational to robust vocabulary and language development. Much research documents the relation between language delay and weak cognitive processes, such as poor working memory, poor procedural memory, and slow speed of processing (Fernald & Marchman, 2012; Lum, Conti-Ramsden, Page, & Ullman, 2012; Rescorla, 2011; Vugs, Hendriks, Cuperus, & Verhoeven, 2014). But we do not know how the many complex cognitive processes essential for word learning—processes for isolating and remembering word forms,

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finding visual referents in complex scenes, and creating robust mappings—interact and change from infancy through childhood. Nor do we know enough about how these processes and the necessary inputs—language, social interaction, visual experience—shape the developmental course for individual children.

Multiple Word Learning Processes Cascade to Create Developmental Pathways

Word learning draws on many processes and is shaped by numerous kinds of input. Factors that predict word learning and early language development include language context in the home (Hoff, 2006) and measures characterizing parent-child interactions, such as amount of joint attention (Tomasello, 1988), amount of contingent responding by parents (Donnellan, Bannard, McGillion, Slocombe, & Matthews, 2020), and the sustained attention of the child (Yu, Suanda, & Smith, 2019). Even if we narrow our focus to concrete object names, which make up about half of early vocabularies and set the stage for learning other kinds of words, including adjectives and verbs, many complex processes are involved.

As depicted in Figure 2, to pick up a new food and have a bite when mom says, “Try some of the banana,” the toddler must build a representation of what is where in the scene to determine what the new word refers to and make an initial word-object mapping. This requires finding the critical word form in the speech stream, recognizing the known objects, and identifying potential referents in the visual array, tasks that are supported by statistical learning, visual exploration, and object-recognition processes. Selecting the referent of the novel word is supported by detecting relative novelty and existing lexical knowledge. Furthermore, transitioning from the initial association of the word and the object to encoding a robust vocabulary entry requires recalling, elaborating, and consolidating the association over many subsequent exposures, as well as generalizing to new instances. Thus, explanations of early object-name learning must bring together processes spanning visual and auditory perception, attention, categorization, and memory, among others.

Moreover, such explanations must be dynamic, that is, they must capture how these processes work together in real time and transform over longer time scales as these processes change significantly during the second year. For example, at the time scale of an individual experimental task, in work on cross-situational word learning, 12- and 14-month-olds track co-occurrence statistics over many ambiguous presentations of words and objects to make up to four new word-object mappings (Smith & Yu, 2008). Similarly, at the developmental time scale, children’s processing of visual novelty changes in the context of words in the second year: Nine- to 14-month-olds habituate to objects seen repeatedly and show an increasing bias to look at the more novel of two objects presented in silence, but the addition of a word slows this (Mather, Schafer, & Houston-Price, 2011). Fifteen- to 21-month-olds show stronger initial novelty biases and higher levels of preference for novelty overall, but these are also reduced in the context of words (Mather et al., 2011). Twenty-two-month-olds look more to novel objects than known ones or prefamiliarized novel objects, and attend to the most novel object in the context of a word (Mather & Plunkett, 2012). These developmental changes in word-looking dynamics are likely critical in that they are

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the building blocks of biases like mutual exclusivity (Mather, 2013; McMurray, Horst, & Samuelson, 2012) that are thought to be essential in the rapid formation of new word-object mappings—a process that is less robust in late-talking children (Alt & Plante, 2006; Weismer, Venker, Evans, & Moyle, 2013).

Word-object mapping processes also change over a similar time frame. Eighteen-month-olds show a strong novelty bias in referent-selection tasks, choosing the most novel object in an array regardless of whether a familiar well-known or novel word is used (Kucker, McMurray, & Samuelson, 2018, 2020). However, between 18 and 24 months, the balance between selections based on novelty and word knowledge shifts, with 24-month-olds selecting referents of known items on request and novel items only when novel words are used (Grassmann, Schulze, & Tomasello, 2015; Kucker et al., 2020; Mather, 2013; McMurray et al., 2012). These changes are also reflected in retention of new mappings, which becomes more robust from 24 to 30 months and is influenced by factors such as the strength of word knowledge (Kalashnikova, Mattock, & Monaghan, 2016; Kucker et al., 2020). Again, these referent selection abilities are less robust in late-talking children (Alt & Plante, 2006; Weismer et al., 2013).

Changes in word-referent abilities are further supported by children's ability to remember the objects they have seen and to form and remember new word-object links. Here, too, development is significant in the second year: 20-month-olds can learn new word-object mappings from presentations spaced over several trials, whereas 16-month-olds need presentations to be in immediate succession (Vlach & Johnson, 2013). In older, preschool-aged children, word learning is predicted by object and word recognition memory, and by memory for new word-object links (Vlach & DeBrock, 2017). Finally, in studies using looking-while-listening procedures with 18- and 20-month-olds, the speed with which children process word forms and word-object mappings changes, and early speed of processing predicts vocabulary at 24 months and beyond (Fernald & Marchman, 2012).

Clearly, a child's vocabulary development is jointly determined by changes across many processes that are themselves changing over time. This fits with the variability in vocabulary development since differences in any of the underlying processes, the input to those processes, or the word learning context could produce differences between the vocabularies of any two children. However, input and processes could come together in many ways to create similarities in outcome. That is, potential redundancies across the system of inputs and processes that support vocabulary development can provide a means by which an individual's relative strengths compensate for weaknesses. Some children receive much language input, are good at tracking statistics, and form new mappings readily. Other children get less input but sustain attention on objects longer, leading to better retention of the mappings they do make. Because these differences can cascade over time, a child who receives less input initially but retains more mappings may process new words faster, encode and elaborate information from presentations faster, and end up with a larger vocabulary at age 2. Thus, the relevant processes likely interact and cascade over development in many possible ways to produce robust—or weak—vocabulary development.

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A complete theory of vocabulary development, one with the ability to predict the future course of individual children to guide effective intervention, requires understanding development at the level of these individual pathways. This is a daunting prospect: Even the simplified word learning problem in Figure 2 suggests that we must account for the interaction of a diverse set of cognitive processes that are changed over time by their own action. For this reason, my colleagues and I have turned to formal models that provide a principled way to track the many moving parts of the early word learning system. We have successfully used these models to capture developmental change at the group level across many early word learning tasks and phenomena (Samuelson, Spencer, & Jenkins, 2013). Our approach can also provide a principled way to predict individual children's vocabulary pathways.

A Dynamic Theory of the Multiple Processes of Word Learning

Our model—Word-Object Learning via Visual Exploration in Space (WOLVES)—instantiates a theory of how the early noun vocabulary develops from creating initial mappings between words and objects to building robust vocabulary entries. It focuses on the processes by which children visually explore and represent possible referents in a scene, map these to individual word forms, and solidify these initial mappings over repeated presentations. In WOLVES, visual exploration of task input is supported by two neural pathways (see Figure 3, red box). Visual information about object features is processed via a feature pathway (light green) that connects early visual fields to feature attention and working memory fields, ultimately binding features and spatial information in scene fields. Information about where visual inputs are located in space is processed by a spatial pathway (dark green) that connects early visual fields to spatial attention and working memory fields, binding feature and spatial information in the scene fields (for information on the relation to the dorsal/ventral distinction in neuroscience, see Schneegans, Spencer, & Schöner, 2016).

Along the featural pathway, working memory and novelty detection consolidate representations of attended objects and redirect attention to novel features of a scene. Along the spatial pathway, spatial working memory helps track which locations have been previously attended. Together, these pathways build and update a representation of the current visual scene in terms of what objects are where (Johnson, Spencer, Luck, Schöner, 2009). In addition, featural information about the currently attended object is passed along the featural pathway into word-object mapping fields that map object features to words in real time. This representation then supports the formation of initial associations between words and objects that, with repeated presentations, builds into a vocabulary of long-term memories for words and referents (see Figure 3, green box; Samuelson, Smith, Perry, & Spencer, 2011).

We recently used WOLVES to capture data from the original demonstration of infants' cross-situational word learning (Smith & Yu, 2008; Figure 4A), and from 11 other studies on this type of word learning in adults and children (Bhat, Spencer, & Samuelson, 2020), as well as from studies documenting changes from 9 to 22 months in novelty detection and habituation in the context of words (Bhat, Samuelson, & Spencer, 2021).

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This work provides insight into how processes of visual exploration, object recognition, working memory, novelty detection, and association learning jointly influence early word-object learning and vocabulary development. For example, children who learn more words in a cross-situational word learning task (termed stong learners; cf. Yu & Smith, 2011) tend to have fewer, longer fixations during training trials. We situated WOLVES in the same task as children and measured the same variables—total looking time to the target versus the distractor at test, and numbers and lengths of fixations during training. WOLVES captures both the proportion of children who are strong and weak learners (Figure 4B), and the differences in length of fixation and number of fixations (Figure 4C) seen in studies (Yu & Smith, 2011). Furthermore, these individual differences are tied to a parameter in WOLVES that modulates the strength of spatial attention. Stronger spatial attention allows the system to process information from each spatial location more quickly and drives it to explore more spatial locations; thus, it spends more time shifting attention from location to location in the visual scene and less time focused on object features. This leads to less learning because objects are not attended to long enough to create robust memories.

On another time scale, WOLVES demonstrates that a change in the parameter controlling the speed of memory decay captures the finding that as memory for word-object mappings increases between 12 months and 5 years (Vlach & DeBrock, 2017), so does cross-situational word learning performance (Figure 4D). WOLVES shows that as memory decay slows, the initial mappings between words and objects formed on each trial are active longer, and are more likely to be refreshed in subsequent trials and to grow in strength (Bhat et al., 2020). Thus, older children's slower memory decay creates mappings that support long-term encoding more effectively.

These two examples illustrate the use of a formal model to shed light on how individual differences in processes such as spatial attention and memory affect the formation of word-object mappings and their long-term memories. Combinations and interactions of individual differences in these processes would create more variability between children's word learning performance. Having both strong spatial attention and fast memory decay would be particularly problematic because children would be unlikely to form robust representations of objects and may not build upon the ones they do manage to form. These toddlers would likely need many presentations of a word-object mapping to retain it.

However, there could also be cases of compensation. If fast spatial attention were paired with strong working memory, even short bouts of sustained attention might be enough to create representations of objects that can be mapped to words. The ability to manipulate the strength of these processes in WOLVES opens new avenues for exploring and understanding how children's individual strengths and weaknesses create variability in word learning. It also opens the door to supporting learning and boosting individual children's developmental outcomes via interventions targeted to specific strengths and weaknesses. For example, a late-talking child with fast spatial attention could be supported by simplifying the learning context, resulting in less competition for spatial attention and less opportunity for the system to move quickly from location to location. In contrast, a late-talking child with weaker memory might benefit more from massed presentations of word-object mappings.

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These changes and individual differences can also be considered developmentally to understand variability in trajectories of vocabulary growth. In WOLVES, as word-object mappings build, they can influence how the system visually explores a scene (Bhat et al., 2020). Thus, the word-object mappings that a child with fast spatial processing creates can help slow spatial attention and thereby support the formation of new object representations and word-object mappings, creating a positive feedback loop. In this way, an intervention aimed at attention might have implications for both attention and memory, and we can start to see how the system might change itself and create its own pathway for vocabulary development.

Beyond offering new insights on the multiple processes that support word learning and individual differences in vocabulary development, formal models such as WOLVES provide opportunities for intervention. Prior computational models have examined individual differences in early word learning. In one study, researchers manipulated parameters to simulate differences in children’s ability to form associations and their phonological short-term memory abilities, capturing aspects of early vocabulary development (Li, Zhao, & Mac Whinney, 2007). Similarly, in another study (McMurray, Horst, & Samuelson, 2012), researchers examined how changes to parameters controlling, for example, learning rate and inhibition in their dynamic associative model captured the relation between speed of processing and vocabulary growth (Fernald & Marchman, 2012).

Formal models being are also being used to evaluate the success of intervention techniques in cases of atypical development (see Thomas et al., 2019, for a review). In one study, researchers examined how two interventions implemented at two developmental times affected a model of reading designed to simulate dyslexia, providing insight on why one intervention was more effective (Harm, McCandliss, & Seidenberg, 2003). In another, researchers used population modelling with formal models of past tense acquisition to examine the basis of persistent versus resolving language delay (Thomas & Knowland, 2014). Finally, in yet another study, researchers combined examination of individual differences with tests of interventions in a case study approach (Best et al., 2015). Models were created to capture the individual profiles of two children who had difficulties finding words and then were tested in possible interventions to predict children’s outcomes.

These examples support the prospect of characterizing individual children’s patterns of strengths and weaknesses in the basic processes that support word learning, creating models that capture those patterns, and then generating hypotheses about which interventions are best suited for a particular child. Proposed interventions could be tested on models to determine the most optimal ways to maximize outcomes and support learning, creating personalized intervention plans fit to individual children. Of course, creating models of individual children’s development and individualized interventions would require extensive work. In the case of WOLVES, this would include incorporating additional aspects of the word learning system, such as more developed word form representations and processes capturing the sequential nature of speech. It would also require work with a large range of stakeholders to integrate other language learning risk factors and ensure that interventions are practical and robust. Nevertheless, combining formal process-level theories such as WOLVES with extensive longitudinal studies of the multiple processes supporting early word learning should provide the means to understand and predict individual children's word learning pathways.

Conclusion

Learning individual words and building a vocabulary depend on multiple factors that are likely interrelated. Differences in these factors—in the amount of input children receive and the quality of their language interactions with parents and carers; in their ability to sustain attention, remember objects, and create mappings; in their individual interests, temperaments, and learning motivation—will create differences in individual children's developmental pathways. For some children, small weaknesses in these factors—say, low levels of attention combined with suboptimal input—combine to cause delayed word learning and language development. For other children, weakness in one factor may be compensated for by strength in another. The field has amassed an impressive and crucial list of the factors that matter. Now we need to put these factors together—in their full complexity—to understand how they interact to create the developmental trajectories of *individual* children. This will require using detailed theories and formal models, of which WOLVES is just one approach. These theories and models, combined with experimental and observational studies that seek to measure and put together the elements we know matter, will allow us to predict individual developmental trajectories and make a difference in the lives of individual word learners.

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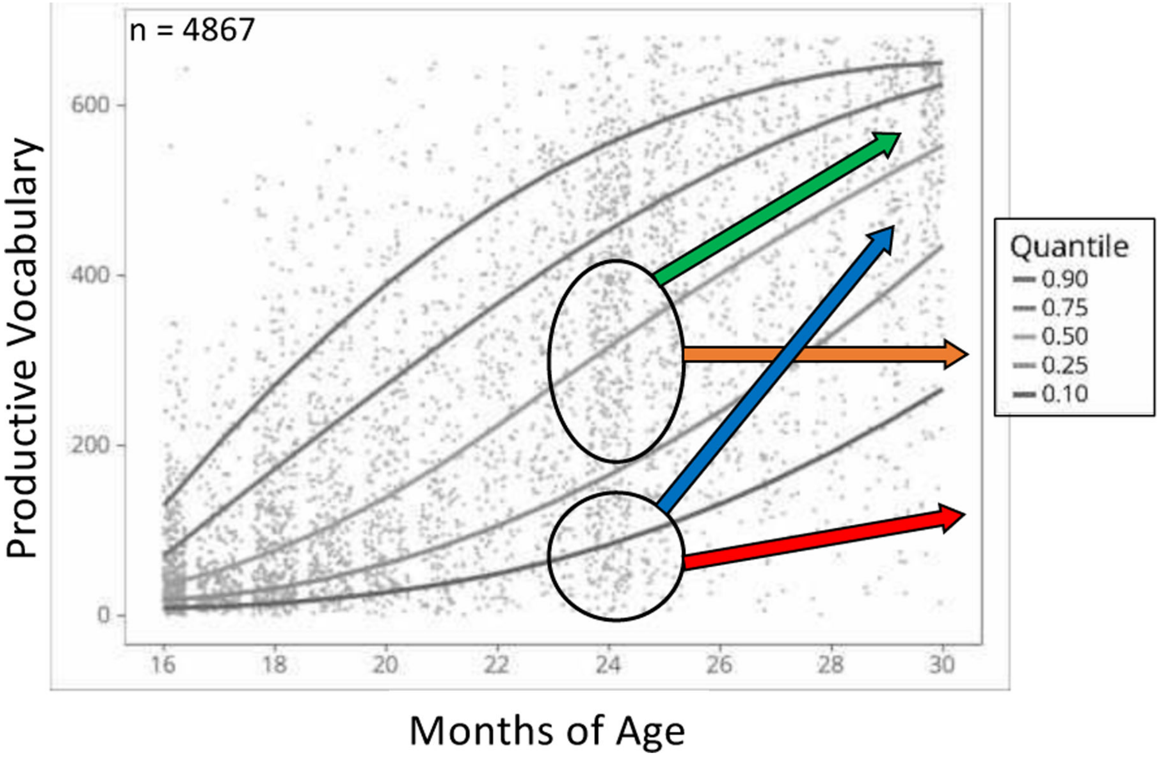

Figure 1.

Normative vocabulary development based on parent report with the MacArthur-Bates Communicative Development Inventories (MBCDI) Words & Sentences.

From Wordbank (http://wordbank.stanford.edu/contributors); Frank, Braginsky, Yurovsky, & Marchman, 2017.

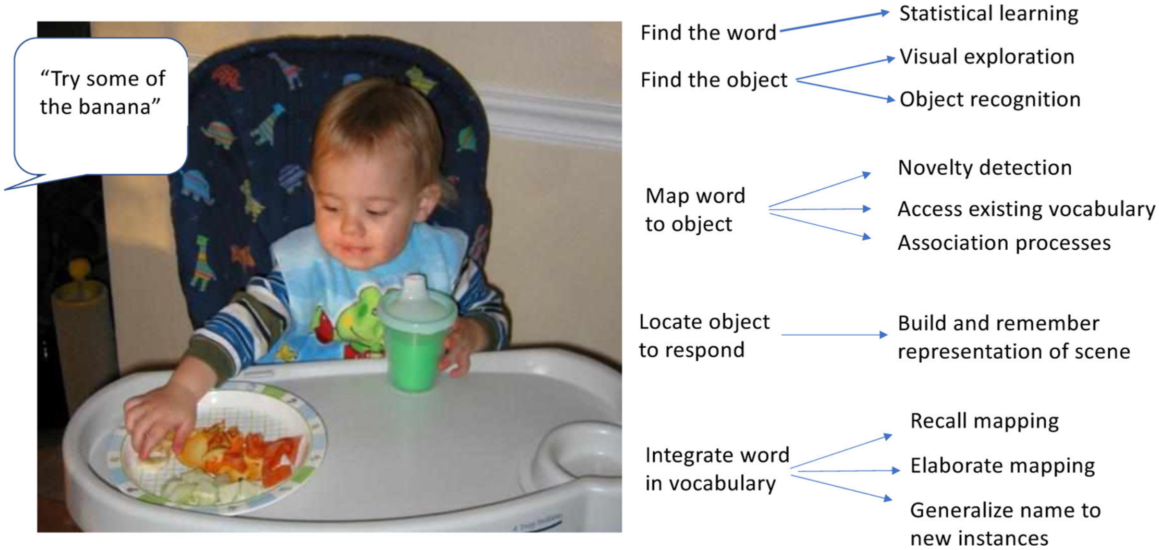

Figure 2.

Illustration of the challenging context and some of the multiple complex cognitive processes involved in learning even a single concrete noun. To respond to the parent's suggestion, the child must find both the word in the auditory stream and the object in the visual scene, then form an initial link between the two that can be recalled later for strengthening and elaboration.

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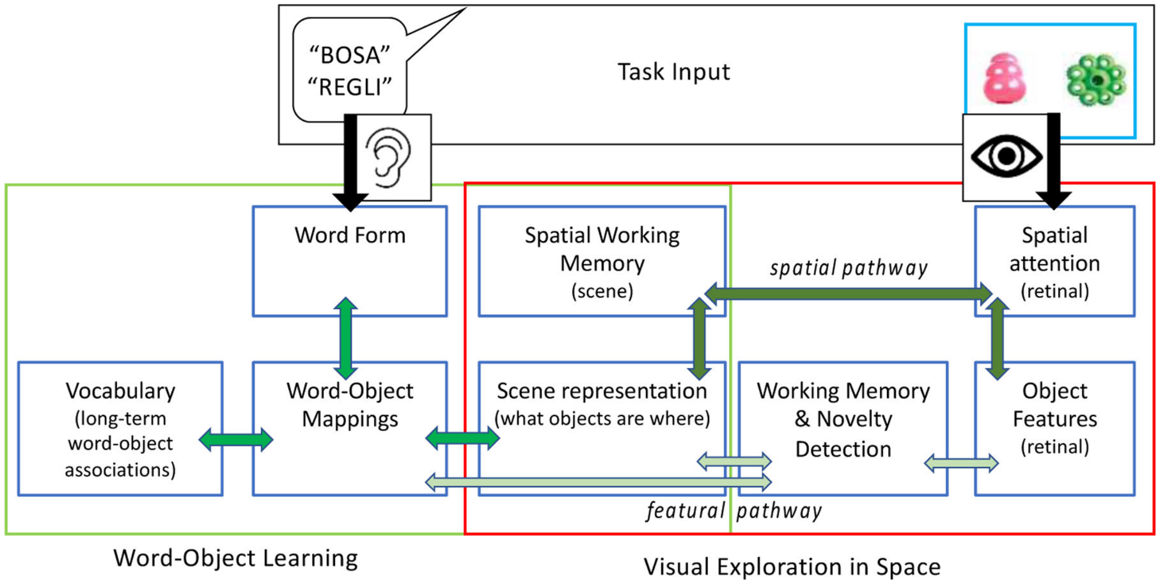

Figure 3.

A schematic of the Word Object Learning via Visual Exploration in Space (WOLVES) model. This formal account captures the processes by which children visually explore and form representations of what objects are where in a scene, map referent objects to word forms, and via repeated presentations, build these initial mappings into the long-term memories of word-object associations that are the basis of a vocabulary. WOLVES integrates to previous models: the Word-Object Learning model (WOL, green box; Samuelson et al., 2011) and the Visual Exploration in Space model (VES, red box; Johnson et al., 2009). For details and model equations, see Bhat et al., 2020).

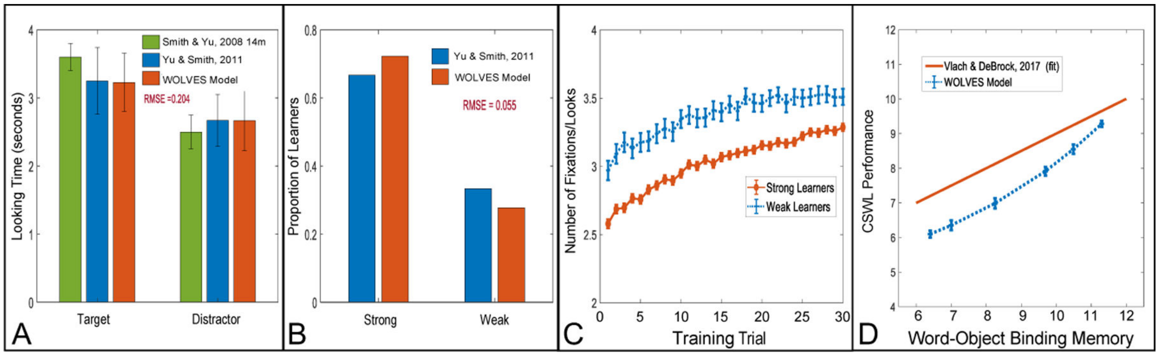

Figure 4.

WOLVES captures individual differences in Smith and Yu's (2008) cross-situational word learning task and over development. Panel A shows the proportion of looking to the target and the distractor for 14-month-olds from Smith & Yu (2008; green bars), Yu and Smith (2011; blue bars), and individual model runs (red bars). Panel B shows the proportion of 14-month-olds from Yu and Smith (2011; blue bars) and individual model runs (red bars) classified as strong and weak learners. At the time scale of the experiment, WOLVES shows that the difference between strong and weak learners is critically related to the number of fixations produced trial to trial over the course of training (C), while on the time scale of development, WOLVES captures the relation between memory for word-object mappings and cross-situational word learning (C).

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