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Origins of vocabulary variability: A scoping review of infant cognitive processes in relation to word learning and vocabulary development

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ABSTRACT

The role early vocabulary plays in later language development and academic success has been widely acknowledged, and common developmental trajectories are known. Nevertheless, how general cognitive processes support individual trajectories of vocabulary development is not well understood. We explored this issue via a scoping review covering literatures on the relations between nine general cognitive processes (visual processing, visual/spatial attention, attention shifting, sustained attention, visual working memory, novelty detection, object recognition, statistical learning, and declarative memory) and vocabulary development. Processes were selected based on their instantiation in a successful neural-process model of word learning. Auditory processing and discrimination was also reviewed to inform future theory and model development. Systematic database searches were conducted for each process. Papers returned from three databases were screened, reviewed, and the relevant information for each process extracted. While the final number of included papers was limited, we found some evidence of links between nine of the processes and vocabulary development. Evidence of processing differences in children at risk for language impairment was also found for three processes. We discuss the revealed relations and gaps in the literature. We also provide a critical appraisal of the literature and implications for both theory and future work, highlighting the need for integrative longitudinal work and the usefulness of formal models in examining how multiple processes interact to support development.

The role that early vocabulary plays in children's language development and later academic success has been widely acknowledged (Bishop et al., 2016; Hohm et al., 2007; J. Lee, 2011; Rescorla, 2011). Early receptive and expressive vocabulary predict children's language abilities during preschool and school years (Feldman et al., 2005; Fernald & Marchman, 2012; Rescorla, 2011; Rescorla et al., 2000), as well as later school performance (Duff et al., 2015; Snowling et al., 2016). The common trajectory of vocabulary development, from early comprehension to first word production and vocabulary expansion, to an extensive number of words in the productive vocabulary at school entry, is well documented. Likewise, a host of studies have documented factors related to slower vocabulary development at the group level including gender, a family history of language difficulties, and lower socioeconomic status (Hoff, 2006; Reilly et al., 2010). However, understanding of individual growth trajectories of vocabulary development remains elusive (Auza-Benavides et al., 2024; Marino & Gervain, 2019; Rowland, 2020; Samuelson, 2021).

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As depicted in the right of Fig. 1, there is great variability in the size of children's early vocabularies. While most 16-month-olds are reported by parents to produce 50 or fewer words, some are reported to produce upwards of 600. Likewise, while most 30-month-olds know more than 400 words, some are still reported to produce fewer than 100. Further, while many children who show initial strength in vocabulary development will continue with positive growth (green arrow), some will stall out during the process and enter schooling with smaller than average vocabularies (orange arrow). Likewise, some late talkers, toddlers below the 15th - 30th percentile for their age and gender in productive vocabulary, will eventually catch up to their peers (blue arrow), but others will continue to struggle, with some eventually gaining a diagnosis of Developmental Language Disorder (DLD[1]; Bishop et al., 2016; McGregor et al., 2020; Rescorla et al., 2000; red arrow). Understanding the nature of these individual trajectories, and why they differ among children, is of paramount importance, not only for making predictions about a child's later language and literacy development (Rowe et al., 2012), but also for choosing and creating innovative and appropriate interventions to help children achieve future success and reach their full potential.

The mechanisms that help most children build their vocabulary with surprising speed and efficiency are still not well understood (D'Souza et al., 2017; Mareschal et al., 2007; Samuelson, 2021; Smith, 2005). One reason for this is that the building block of vocabulary—learning a single lexical entry that can be elaborated over time—is influenced by multiple factors ranging from but not limited to input, social engagement, and basic cognitive processes. Consider even the simple case of an infant learning the name for a concrete object in the context of mealtime. When mom introduces a new food by saying ‘try some of the pita’ (Fig. 1, left), finding and identifying the correct target sounds and words in the speech stream will require processes of auditory processing/discrimination and statistical learning. As the child attempts to map the identified words to a referent they must visually explore their environment; thus, visuospatial attention, attention shifting, as well as visual processing, object recognition and novelty detection are critical. Statistical learning may also build mappings via the co-occurrence of word forms and objects. Further, the creation of robust representations requires sustained attention, and the child will need to keep all the relevant information in working memory during this process. Finally, declarative memory is crucial not only for retaining mappings that are created, but also for gaining access to already existing knowledge in the process of creating associations with new knowledge and elaborating an initial mapping into a robust vocabulary entry.

Differences between children in the operation of any of these processes could potentially explain differences in vocabulary outcomes. Further, these processes do not operate in isolation, but as part of a system such that the action of one will impinge on the others. For example, a child who fails to sustain attention on a referent object is unlikely to form a strong working memory of that object and may have difficulty detecting the novelty of other objects introduced to the scene. Importantly, however, the action of the system can also be such that weaknesses in one process can be compensated in by others; thus, stronger declarative memory allowing better access to the vocabulary and learning by exclusion might compensate for weaker statistical learning of co-occurrence statistics. Understanding the origins of variability in vocabulary development thus requires examination of multiple cognitive processes, how they act together to support word learning, and how this evolves over vocabulary development. To the extent that the same processes are acting on similar input across individuals, word learning and vocabulary development should be stable across individuals. However, the fact that word learning and vocabulary development are influenced by multiple factors, means that individual children's vocabulary trajectories will follow individual pathways of development.

Thus, understanding vocabulary development requires understanding a complex system of multiple interacting processes that change over time. As a step in this direction, this review seeks to examine what is known about how each of the multiple cognitive processes underpinning early word learning contribute to variability between children in their vocabulary development. We selected the specific processes to review based on a promising theoretical approach that specifies how cognitive processes such as attention, statistical learning and memory, among others, dynamically interact in the service of word learning, Bhat et al. (2022a, 2022b) Word Object Learning via Visual Exploration in Space (WOLVES).

A theoretical account of the multiple processes supporting word learning

WOLVES is a formal process model of word learning based on known principals of neural dynamics (for model equations and a detailed account of its operation see (Bhat et al., 2022a, 2022b; Bhat et al., 2023a, 2023b). WOLVES was developed by combining a model of word-object mapping and categorization (Faubel & Schöner, 2008; Samuelson & Faubel, 2016) with a model of visual exploration (Johnson et al., 2009; Perone & Spencer, 2013a, 2013b; Schneegans, Spencer, & Schöner, 2016). Thus, it instantiates a theory of how children build an early noun vocabulary from initial mappings between words and objects, specifying the processes by which they explore a visual scene, represent objects in that scene, form word-object mappings, and solidify those mappings over repeated presentations. As depicted in Fig. 2, visual processing and exploration of a naming scene is supported by two neural pathways (for information on the relation to the dorsal/ventral distinction in neuroscience see Schneegans, Spencer, Schoner, and The DFT Research Group, 2016). A feature pathway (light green) processes visual information about object features by connecting early visual fields to feature attention and working memory fields. This ultimately results in the binding of features and spatial information in scene fields. A spatial pathway (dark green) processes information about where things are located in space by connecting early visual fields to spatial attention and working memory fields. This pathway binds feature and spatial information into a scene representation.

Along the featural pathway, working memory and novelty detection create representations of the objects the child attends to,

[1] Note that while the literature prior to 2016 uses Specific Language Impairment (SLI) to refer to children with difficulties apparently constrained to language learning, we use the Developmental Language Disorder (DLD) to refer to this group, in line with the recent consensus in the field.

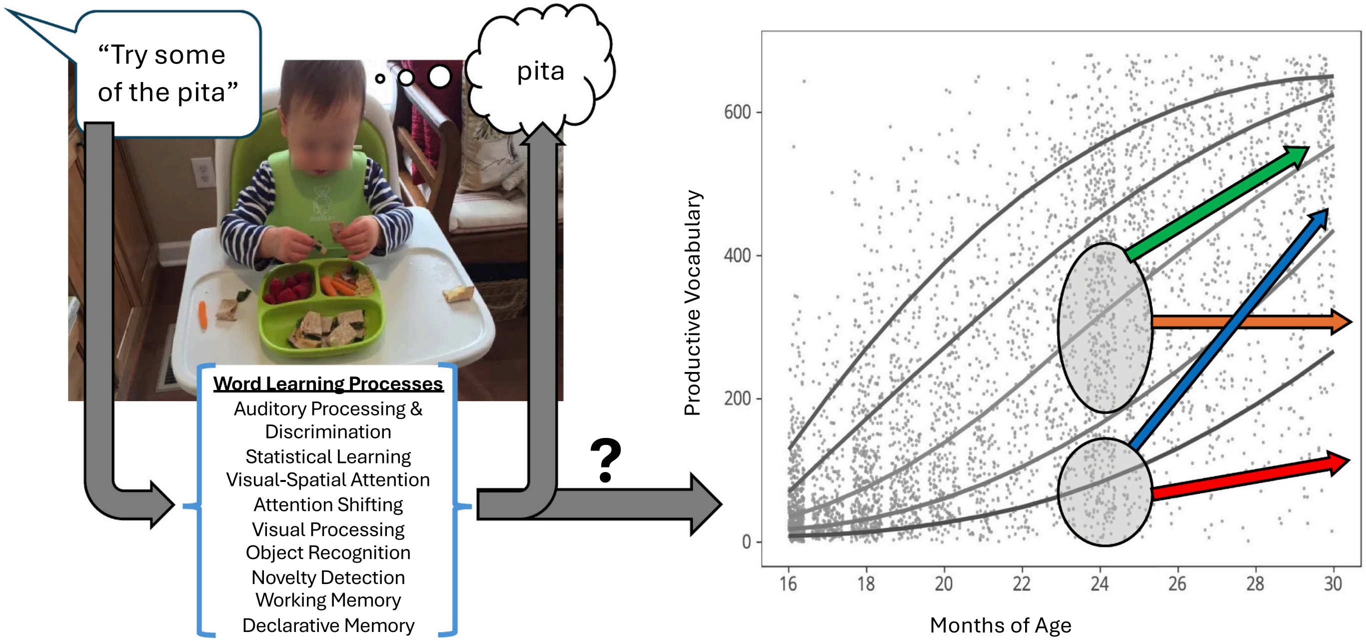

Fig. 1. Motivating question for the review: How does infant processing relate to variability in children’s vocabulary development?

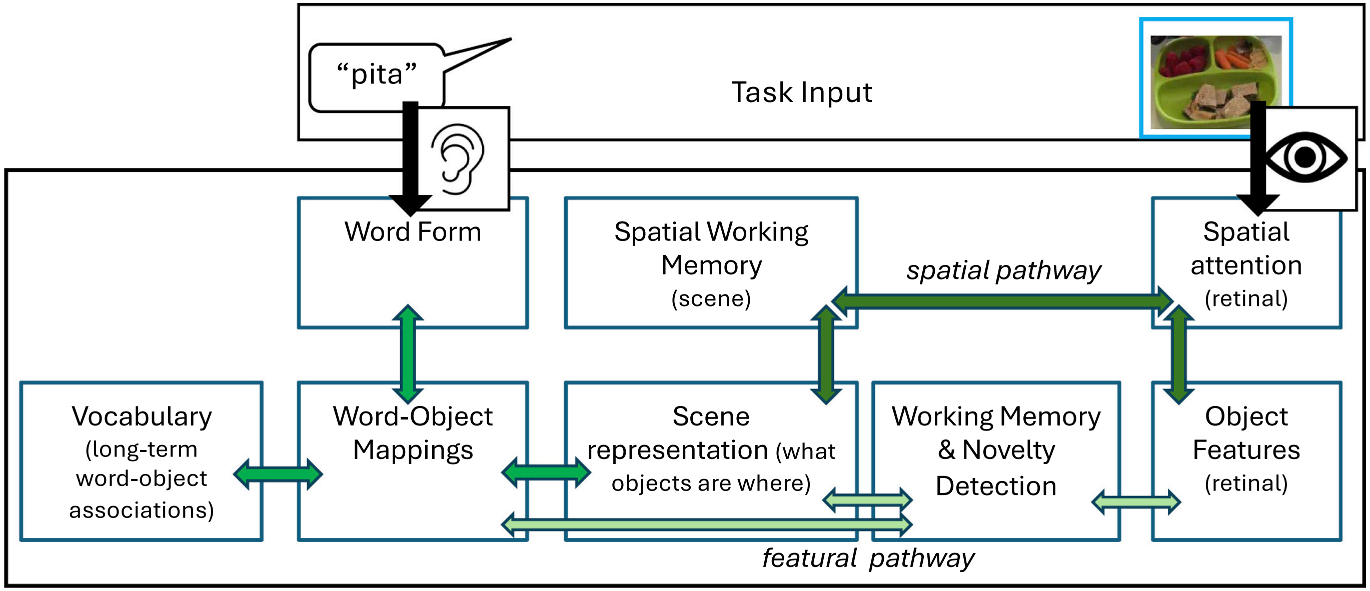

Fig. 2. A schematic of the Word Object Learning via Visual Exploration in Space (WOLVES) model. This formal account captures the processes by which children visually explore and form representations of what objects are where in a scene, map referent objects to word forms and, via repeated presentations, build these initial mappings into the long-term memories of word-object associations that are the basis of a vocabulary. Auditory input is processed and encoded by fields on the left of the diagram while those on the right encode features of the visual input and where those features are located in space. A scene representation field binds object features via shared spatial locations to create a representation of what is where in a task. When an object is attended at the same time an auditory input is processed an initial word-object mapping is formed. These are strengthened with repeated presentations into long-term vocabulary entries.

supporting object recognition and attention shifting to novel features of a scene. Likewise, along the spatial pathway, spatial working memory helps track which locations have been previously attended. Together, these pathways build and update a representation of what objects are where in the visual scene. At the same time, featural information about the currently attended object is passed along the featural pathway into fields that map features to words. Over repeated presentations, statistical learning turns these associations into a vocabulary of long-term declarative memories for words and objects.

WOLVES has successfully captured data from seven child and five adult studies of word learning and is the only developmental account of the processes by which children use the co-occurrence of words and objects over multiple naming episodes to create lexical entries (Bhat et al., 2022a, 2022b). It also outperformed two competitor models in direct comparisons (Bhat et al., 2022a, 2022b) and met a gold standard of model evaluation by generalizing to new data and tasks (Bhat et al., 2023a, 2023b). WOLVES also makes testable predictions that have been supported in studies with both adults (Bhat et al., 2024; Samuelson et al., 2023) and children (Samuelson et al., 2024) and provides new insight on how auditory and visual information are integrated in the process of word learning (Bhat et al., 2023a, 2023b). While there are other models of word learning, few have articulated the processes involved in word learning to the same extent as WOLVES or been applied to sets of infant data showing the importance of basic cognitive processes in word learning (e.g., Smith & Yu, 2013; Vlach & Johnson, 2013; Yu & Smith, 2011, see Bhat et al., 2022a, 2022b for review). Further, WOLVES is the only model that autonomously explores its environment and can be situated in the exact same tasks as infants and children, providing the exact same measures of visual exploration and learning as participants (see https://dynamicfieldtheory.org/dft_case_studies/wolves/ for more information and videos of the model in action).

To date, WOLVES has been applied to object name learning. However, nouns comprise nearly half of early vocabularies (Bates et al., 1994) and set the stage for learning other kinds of words such as adjectives and verbs (Kersten & Smith, 2002; Mintz & Gleitman, 2002). Thus, we felt that WOLVES provided a strong theoretical basis to select processes to review in service of understanding how general cognitive processes interact to support early vocabulary development. Further, review of how the processes incorporated in WOLVES relate to vocabulary development may have implications for how the theory it instantiates relates to the building of vocabulary from individual word-learning episodes.

The present paper

The goal of this paper, then, is to contribute to a better understanding of what shapes variability between individual children in vocabulary development via a scoping review covering literatures on the relations between the nine processes instantiated in WOLVES (see bold list in left column of Table 1) and vocabulary development. A secondary goal is to inform further theory and model development in two ways. First, rather than building a vocabulary as children do, in prior simulation work WOLVES has been started with an initial vocabulary that new words have been added to. Thus, reviewing how the processes instantiated in WOLVES relate to vocabulary growth will provide critical information for future work simulating vocabulary growth trajectories in WOLVES. Second,

Table 1
Paper counts for each of the ten searches including the initial literature review and systematic searches.

	Returned in Initial Google Search			Returned in Systematic Search					Final Total Reviewed	
Process	Reviewed	Excluded	Included	Screened	Excluded	Assessed for Eligibility	Excluded	Included	Duplicates (Google & Systematic)	Included
Visual Processing */Discrimination*	3	1	0	153	148	5	0	2	0	3*
Visual/Spatial Attention	1	0	0	170	157	13	7	3	0	3
Attention Shifting	4	2	0	16	12	4	1	0	0	0
Sustained Attention	11	2	0	299	276	23	11	2	0	2
Visual Working */Short-Term Memory*	27	6	3	26	17	9	4	0	0	3
Novelty Detection	1	0	1	28	22	6	3	3	1	3
Object Recognition / *Memory*	4	2	2	167	154	13	4	9	2	9
Statistical Learning	18	8	1	388	362	26	14	3	1	3
Declarative Memory	4	1	0	363	326	37	21	3	0	3
Auditory processing / Discrimination	13	8	3	847	816	31	14	4	2	5
Totals	86	30	10	2457	2290	167	79	29	6	34

Note. Bold terms in leftmost column are search terms based on the processes instantiated in WOLVES. Italics indicate additional search terms added to specific searches based on returns in the literature. Auditory processing/ Discrimination was added as a search term with a goal of informing future model development. *One paper originally returned in the search on object recognition was later moved to visual processing/discrimination.

while WOLVES is presented with auditory input when learning new words, to date this has been done via representations of whole words, rather than auditory features. Thus, review of the relation between auditory processing and discrimination and vocabulary development can inform the evolution of this aspect of the model and theory.

Our research question is how does infant processing relate to variability in children's vocabulary development. We took a scoping review approach due to the number of areas of work we wished to examine. We focus on studies of infants and toddlers (0 to 3-years-of-age) because this is the developmental period when word learning is taking off, but also when the massive plasticity in the system provides a unique opportunity to potentially boost the activity of individual processes and impact the trajectory of the system. We completed a systematic search on each process following the guidance of (Arksey and O'Malley, 2005; see also Peters et al., 2020). The individual reviews are presented below, followed by a discussion integrating the results across the examined processes, the implications for the theory of word learning and vocabulary development instantiated in WOLVES, and suggestions for future work in the area.

Methods

Our review is largely written in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-analysis extension for Scoping Reviews (PRISMA-ScR Tricco et al., 2018). However, we did not register a protocol for the review prior to beginning the work. Nevertheless, we include the PRISMA-ScR checklist in Appendix A to be as transparent as possible about our methodology.

The work reported here is a subset of a larger project seeking to understand the relation between individual cognitive processes, vocabulary development and later diagnosis of Developmental Language Disorder (DLD). For this reason, the searches included terms related to language delay or DLD (e.g., “Developmental Language Disorder” or “Late Talker”) and did not stipulate an age cutoff. We include here only papers on infants and children between 0 and 3 years of age and thus not work on older children with a diagnosis. We decided to include papers targeting children at risk for language impairment in the current paper as the kinds of tasks used to measure these processes in infants and toddlers can differ substantially from those used with older children who have a diagnosis. Thus, comparison is facilitated by reviewing papers with younger groups together. The findings examining the relation between early word learning processes and atypical developmental trajectories are reported in (Theofilogiannakou & Samuelson, 2026).

All searches were conducted between October 2022 and May 2023. The selected processes were initially explored using Google scholar to test preliminary keywords and search criteria. Separate searches were then conducted in EBSCO (PsychInfo, Medline) and Scopus electronic databases, using the exact same keywords, Booleans and filters for all databases. The initial searches in Google scholar, in combination with the assistance of the Academic Librarian for Social Sciences, determined our selection of keywords and Booleans.

We used multiple specific search terms because some of the processes have multiple names in the literature (i.e., “novelty detection” OR “novelty preference”). We also truncated with wildcards to capture similar terms with the same root word (e.g., vis* processing). As an example, the search terms for attention shifting were:

> (dld OR "developmental language disorder" OR “sli” OR "specific language impairment" OR “language impairment” OR “language disorder” OR "late talkers" OR "vocabulary development" OR "word learning" OR "language development" OR "language delay" OR "Cognitive Development" OR "Reading Development" OR "Perceptual Development" OR "Perceptual Motor Development") AND **"attention shift*" OR “shift of attention”)**

Several trial searches were conducted to ensure the terms and methodology used were the best possible fit for each process. These resulted in the addition of “short term memory” to the working memory search, “object memory” to the object recognition search, and “visual discrimination” to the visual processing search. Appendix B provides full keyword combinations and Booleans for each process.

Articles were filtered by date (2000-present), language (English) and source type (journal articles), resulting in a total of 3816 papers in the combined searches used as the basis for this paper and Theofilogiannakou and Samuelson (2026). The filtered results for each process were then exported to a designated Zotero (Version 6.0.26) folder which was used to identify and resolve duplicates. The remaining results were uploaded to Rayyan (Ouzzani et al., 2016), a web tool specialized for conducting systematic reviews as a separate review for each process.

The first author screened each title and abstract and decided whether papers would be included or excluded based on predetermined exclusion criteria (see Appendix C). Note that we included ‘word learning’ as a term in our searches to maximize relevant returns, however, because we are interested in how the processes that support word learning relate to vocabulary development specifically, we excluded papers that included only a measure of word learning and not also a measure of overall vocabulary. Whether a paper was included in the current set of reviews versus that on children diagnosed with DLD was based on the age of the sample (0 to 3-years of age in this paper) and thus determined after extraction of those data. Exclusion criteria were the same across all processes, except for ‘Wrong Methodology’, which was only applied to ‘Auditory Discrimination/Processing’ to exclude neurophysiological studies. This additional criterion was introduced for this process because the initial return significantly exceeded reviewing capacity, and to align it to the behavioral focus of the other reviews. Retrospective analyses that covered multiple datasets and did not include details of the tasks used to elicit the data were excluded (see Data extraction and coding below). Review papers were only used to provide context for results from primary source journal articles. Papers that only measured receptive, expressive or narrative language skills generally, without a clear vocabulary measure, or that measured reading, were not included. Only results from monolingual participants were included in our review.

All excluded papers were labelled with a reason for exclusion, or ‘maybe’ if there was doubt about exclusion. The second author reviewed all studies tagged as ‘maybe’ and a random selection totaling 397 (36.5%) of all the papers across searches, included for a first screening. Papers tagged as 'maybe' and any conflicts (less than 1% across all searches) were discussed, and a common decision was reached to determine the set of papers included for full text reviewing.

Data extraction and coding

The first author extracted data from all reviewed papers via a specified data extraction form. First, basic information about the study including author name, publication date, aim, age groups, populations (e.g., typically developing, late talker) and number of participants per group were extracted. Studies that included ages not included in the scope of this review were then excluded. Next, details of the standardized measures, questionnaires and parental checklists as well as the experimental tasks were extracted. Finally, the results of the experimental tasks were extracted. The second author extracted data from approximately 17% of the papers. Any conflicts were discussed until resolved. The summaries are available at: https://osf.io/5dyrq/?view_only=eb5d716d1335492ca94868b78e2e12e0

To answer our research question, the first author began by writing a short summary of the findings from each paper based on the extracted data. Summaries for all reviewed papers for a process were gathered, and similarities and differences in findings across papers were noted, as were themes that appeared in multiple papers (e.g., differences in findings related to age, or auditory v. visual processing). Once the summaries for all papers in a review were completed, the text was compiled into a complete draft addressing the research question with respect to that process. These initial drafts were then reviewed, and possible edits noted by the second author, who referred to the extracted data and papers as needed. Edits were discussed resulting in joint revisions and final drafts of each process review.

Results

Fig. 3 provides a PRISMA flowchart of the process used to identify studies for this review. The left side of the flowchart is an overview across all the individual process searches, including total number of papers, summed across all searches, for each step. The middle columns of Table 1 provide corresponding numbers for each individual search. Tables providing numbers of papers excluded at intermediate steps in the process (e.g., screening) and by criteria for each search are provided in the Supplementary Materials (https://osf.io/5dyrq/?view_only=eb5d716d1335492ca94868b78e2e12e0). Table 2 provides a summary of the answers to our research question for each process. The full reviews of the literature for each process are presented below.

Visual processing

Visual processing in the context of word learning refers to the perception of the details, patterns and shapes of things in the naming environment. Given that many of the first words children learn are names for concrete visible objects (Bergelson et al., 2019; Bergelson & Aslin, 2017; Cartmill et al., 2013; Clerkin & Smith, 2022; Tamis-LeMonda et al., 2019), this process could be an important factor for successful word learning and vocabulary building, supporting referent selection and the creation of word-object mappings.

Three papers were returned in the search. Kobaş et al. (2022) found that in a sample of full- and pre-term 12- to-16-month-old infants visual processing mediated the relation between gross motor development and word comprehension, as measured with a Turkish adaptation of the MacArthur-Bates Communicative Development Inventories (MBCDI; Fenson, 2007). Visual processing also mediated the relation between fine motor skills and early communicative behavior, but not word comprehension. Slone et al. (2019) used head cameras to explore 15-month-olds' views of objects during free play and their vocabulary growth, using the original MBCDI parental checklist. They found that children with higher variability in self-generated object views showed greater growth in their productive vocabulary at 21 months of age. Borgström et al. (2016) used ERP to explore Swedish 20-month-olds' visual object processing in a fast-mapping task. They found a measure of encoding speed and quality (visual Nc) during word-referent learning was predictive of responses to violations of previously seen mappings (N400 incongruity effect). However, they did not find this correlated with parent reported vocabulary size, measured using a Swedish adaptation of MBCDI; and suggested existing vocabulary and visual object processing abilities separably influence fast-mapping. Thus, while our searches did not come across many studies focusing on visual processing in relation to vocabulary development, the few studies we found suggest a relation between aspects of visual processing and vocabulary. Nevertheless, more studies, and especially longitudinal projects, are needed to better understand the direction of a potential relation between visual processing and vocabulary.

Visual/spatial attention

Visual/spatial attention refers to the cognitive process filtering out distractions to focus on relevant information in the visual/spatial field. There is a substantial history of work exploring the role of visuospatial attention in vocabulary development including studies of infant attention to faces, parent-child joint attention, attention to aspects of the spatial environment, and object attention (see, e.g., Bakeman & Adamson, 1984; Bruce et al., 2022; Butterworth & Cochran, 1980; Carpenter et al., 1998; Tomasello & Farrar, 1986). The significance of visual attention is consistently acknowledged, but the exact role it plays in children's vocabulary development is unclear (see, e.g., Akhtar & Gernsbacher, 2007; C. Lee & Lew-Williams, 2023).

Our search revealed papers examining children's attention to their parents' face, and joint attention of parents and children to objects, that suggest facilitation of vocabulary development. Salley et al. (2013) used a distractibility paradigm to explore 11-month-old infants' visual attention to a speaker in relation to their later vocabulary and multi-word productions, using the MBCDI. They found

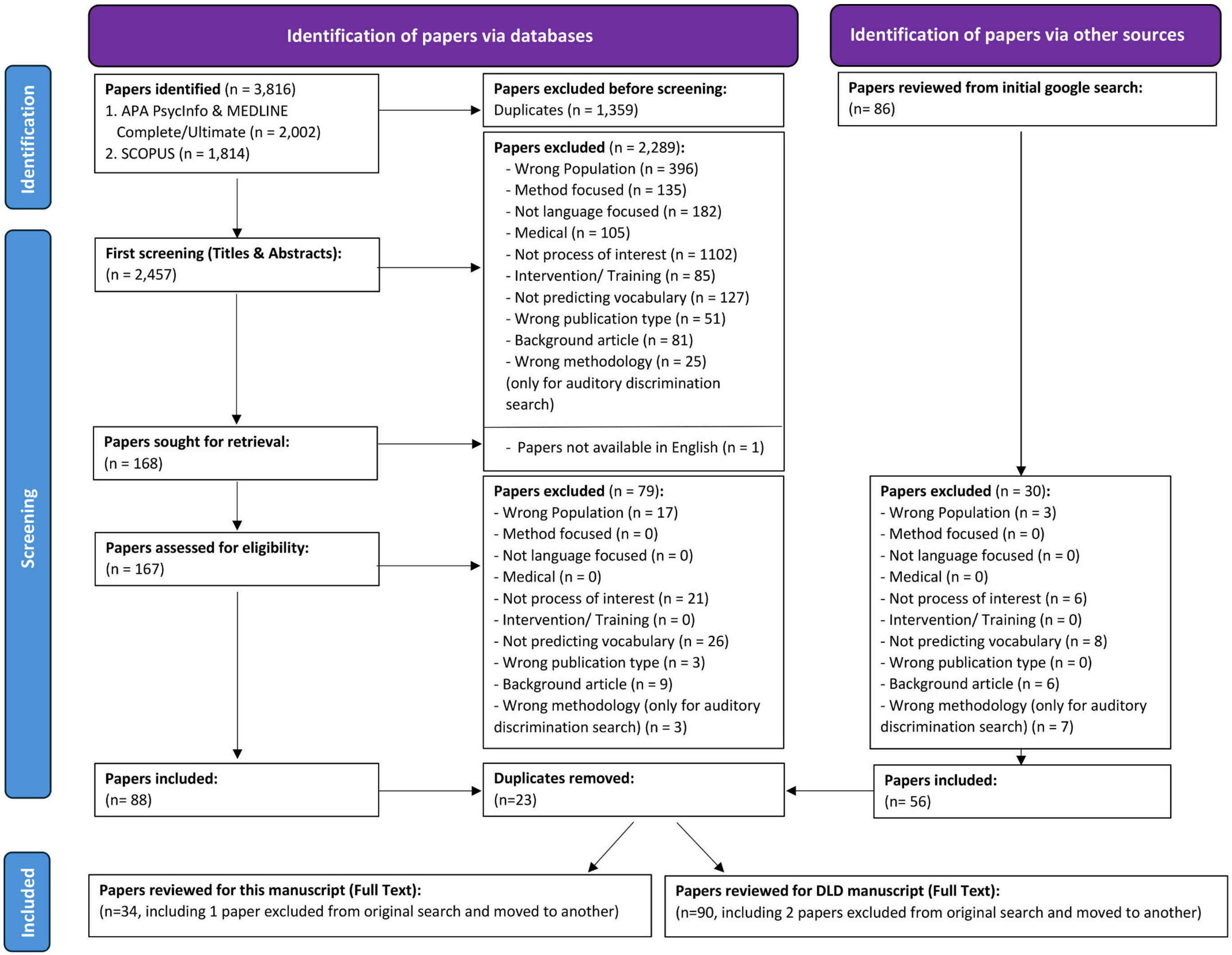

Fig. 3. PRISMA flowchart to identify studies included in the larger review project that includes both this manuscript and the parallel manuscript on older children with a DLD diagnosis (Theofilogiannakou & Samuelson, 2026). Note these numbers are the total across the 10 processes. See tables in the supplemental materials for information about the individual reviews.

Table 2
Summary of findings for each of the ten reviews.

Process	Size of lit. relating infant processing to vocabulary development	Relation between process and word learning and/or vocabulary development
Visual Processing */Discrimination*	Limited (3)	Possible relation to vocabulary development
Visual/ Spatial Attention	Limited (3)	Attention to faces and objects related to vocabulary development
Attention Shifting	None	
Sustained Attention	Limited (2)	Tentative relation to vocabulary development
Visual Working */Short-Term Memory*	Limited (3)	Weak positive evidence of relation to 36mo vocabulary that is not maintained
Novelty Detection	Limited (3)	Potential positive relation to vocabulary development
Object Recognition / *Memory*	Small (9)	Ability increases and features used change as vocabulary grows
Statistical Learning	Limited (3)	Auditory: Positive relation Visual: tentative
Declarative /Long-Term Memory	Limited (3)	Positive relation to vocabulary development
Auditory processing / Discrimination	Small (5)	Positive relation to learning and vocabulary

Note: Ranges used for categorization of the literature: limited < 5, small = 5–9, papers.

children who displayed the lowest levels of distractibility had larger vocabularies 7 months later and produced more multi-word combinations. However, the effect of joint attention at 14 months on later vocabulary diminished when children's initial communication development was controlled in statistical models. Relatedly, a longitudinal study by Bruce et al. (2022) found that 10-month-olds' visual attention to a puppet that drew focus away from the experimenter's face was negatively correlated with their receptive vocabulary as measured with the Peabody Picture Vocabulary Test Fifth Edition (PPVT- & Dunn & Dunn, 2019) at 3, 4, 6 and 9 years of age.

Concerning infants' attention to objects and its relation to vocabulary development, while several recent studies examine how attention to objects facilitates word learning, we found just one that included a measure of vocabulary. Abney et al. (2020) used the MBCDI, and found 9-month-olds' proportion of looking at objects during play sessions with their parents was positively correlated with their vocabulary size at 12 and 15 months of age. Overall, then, a small recent literature building on historic precedent provides longitudinal findings suggesting a link between infants' visual attention and vocabulary development.

Attention shifting

During language interactions there are many potential targets of infants' attention—the other people in the interaction and the objects and other referential targets referred to by speakers, being two critical things. A learner's ability to move the focus of their attention between relevant aspects of an interaction is likely to be related to their ability to determine the correct referent for a novel word. Indeed, 4-to-5-year-old children's attention shifting has been linked to artificial language learning abilities (Kapa & Colombo, 2014) and 9–11-year-old's language ability has been linked to their ability to shift attention between dimensions (Hill & Wagovich, 2020). Despite this, our search did not return any papers examining the relation between infant attention shifting and vocabulary, so this may be a fruitful area of future work.

Sustained attention

Learning new words requires sustained attention to auditory and visual inputs to create robust representations of the word-form and object to be mapped. The development of auditory attention in infancy has been studied using measures such as heart rate (Gomes et al., 2000; Richards, 2004). Heart rate decreases can also indicate sustained attention on visual stimuli, but this is often also measured by coding looking or manual handling behaviors (Ruff, 1986). Not surprisingly, infant auditory attention to speech has been shown to be related to vocabulary (see e.g., Vouloumanos & Curtin, 2014). On the visual side, referent identification is supported by infant interactive partners and the establishment of joint attention on named objects (e.g., Baldwin, 2014; Tomasello & Farrar, 1986; Yu & Smith, 2017). However, recent work on visual attention with older children suggests it is infant sustained attention—prolonged stabilization of attention on a visual object—that might particularly benefit learning of new words (Davidse et al., 2011; Kapa et al., 2017; NICHD Early Child Care Research Network, 2003).

Our search only yielded one paper that linked sustained attention to vocabulary in infant and toddlers. Yu et al., (2019), found that 9-month-olds' visual sustained attention alone, and in combination with their joint attention, in dyadic play was a significant predictor of their vocabulary as measured with the MBCDI, at 12 and 15 months. One other paper returned in our search but at the edge of our age range showed the opposite relation. Masek et al. (2022) found that language ability, specifically verbal comprehension and expressive language, each measured at age 3 predicted 4-year-old sustained attention as measured by a continuous performance task.

The lack of research in this area is particularly striking given work examining developmental changes in auditory sustained attention over infancy (see Gomes et al., 2000; Richards, 2004, for review), and reveals a research gap of great potential. Longitudinal studies would be especially critical, to investigate the directionality of the relation suggested in the papers we reviewed.

Visual working memory

Working memory, our ability to temporarily retain and manipulate information appropriately while on a task, is typically divided into separate verbal and visuo-spatial subsystems, each with limited capacity. There are several studies suggesting a relation between verbal short-term or working memory and vocabulary (e.g., Chrysochoou et al., 2013; Gathercole et al., 1999; Henry & MacLean, 2003; Michas & Henry, 1994). A more open question is whether there are relations between infant visual/visuo-spatial working memory systems and vocabulary development.

Limited infant research has explored whether different variants of visuo-spatial and visual working memory associate with early vocabulary development. Rose et al. (2009) found that 12-month-olds' working memory, as measured via a visual paired-comparison task, was a significant predictor of vocabulary, as measured with the PPVT, at 36 months. A subsequent study, using the same vocabulary measure, found that 3-year-old children who were better able to recognize faces after brief familiarization had better vocabulary and verbal fluency at the same timepoint (Rose et al., 2015). However, when their vocabulary was assessed 10 years later with the same measure, this relationship was no longer significant. Similarly, Choudhury et al. (2007), found significant differences in the novelty preferences of 6-and 9-month-old infants with and without a family history of DLD in a Visual Habituation/ Recognition Memory (VH/RM) task with face stimuli. However, no significant associations were found between the VH/RM and vocabulary at 12 or language at 16 months of age, as measured by MBCDI and Preschool Language Scale (PLS-3) respectively.

Overall, two of the studies returned in our search suggest a potential relationship between early visual working memory and early vocabulary, and another suggests differences in working memory between children with and without a family history of DLD. Thus, while the literature suggests a tentative relation between visual working memory in the infancy and toddlerhood period and vocabulary development, it is not conclusive and deserves further examination.

Novelty detection

Children's attraction to novelty may help them learn new words via biases such as mutual exclusivity (e.g., Merriman et al., 1989, see also Mather, 2013a, 2013b). Novelty detection is also the basis of many early measures of cognitive development such as preferential looking and visual habituation tasks, as well as visual speed of processing tasks (e.g., Rose et al., 2009). Critically, while both word learning biases like mutual exclusivity and visual speed of processing tasks tap children's ability to determine what is novel in a context, they are not equivalent. Visual speed of processing tasks, for example, use a visual habituation paradigm during which participants are led to detect a visual change in stimuli following a familiarization/habituation stage. Thus, in these studies, novelty is defined in the moment based on the prior presentation of some stimuli making others more novel. In contrast, in the context of referent selection, fast-mapping, or disambiguation tasks, participants are introduced to one stimulus that should be familiar based on out of the lab experiences, and one novel stimulus (e.g., a picture of a ball, and a picture of a novel object constructed just for the experiment) along with a novel word, and children's mapping of the novel word to the novel object is measured. Thus, these tasks draw on familiarity or knowledge established over the timescale of declarative memory. Here, we focus on papers examining visual novelty detection in VH/RM tasks, reserving tasks based on declarative memory for that section.

Colombo et al. (2004) conducted a longitudinal study assessing the degree to which infants' looking to novel and familiar stimuli is predictive of later vocabulary growth. Infants were administered a VH/RM task monthly between the ages of 3 and 9 months. Children's productive vocabulary skills were measured at 12, 18 and 24 months using the MBCDI. They found that a higher novelty preference score earlier in development, specifically the aggregation of 4- and 6-month scores, was associated with better vocabulary at 12, 18 and 24 months. More recently, Marino and Gervain (2019) used a French adaptation of MBCDI and showed that French 9-month-old infants' attention to novelty in a similar task was a significant predictor of their receptive, but not productive, vocabulary at 12-, 14- and 18-, but not 24 months-of-age. The authors note that fewer children participated at the last timepoint, which could have hampered the findings.

The Choudhury et al. (2007) study reviewed in the visual working memory section, included a VH/RM task that revealed differences in novelty preferences between 6-to-9-month-old infants with and without a family history of DLD. This effect was significantly driven by a familiarity preference demonstrated by nearly half of the infants with a family history of DLD, suggesting the possible need for more processing time in this group. Nevertheless, no significant relation was revealed between early visual processing and later vocabulary or expressive language at 12 or 16 months.

Overall, then, in this limited literature there is a tentative suggestion of a relation between visual novelty detection, measured in habituation paradigms, and vocabulary development but there is some ambiguity across studies. Given, however, that novelty detection has been suggested to be the basis for fast mapping, which has been clearly linked to vocabulary development (Grassmann et al., 2015) and suggested to be an area of weakness for children with language impairment (Alt & Plante, 2006; Kucker & Seidler, 2023), this may yet be an area that might be fruitfully explored in the future.

Object recognition / memory

The role of object recognition and object memory in early word learning and vocabulary development could take multiple forms. Mapping a novel word to a referent has been argued to involve first recognizing other objects as already having names (Golinkoff et al., 1994; Merriman et al., 1989), while generalizing that new word to novel instances would require recognition that an object is a member of a named category. While not extensive, our searches revealed a growing body of work exploring the link between object recognition and early vocabulary development, suggesting a strong relation.

Smith (2003) found that 17- to 25-month-olds with larger vocabularies (100–200 words), as measured with the MBCDI, were better able to recognize both rich (toys that included many color and shape features of the object category) and sparce (greyscale Styrofoam caricatures composed of 2 to 4 component shapes) representations of common objects in both name comprehension and free play tasks. Furthermore, only children with larger vocabularies were able to recognize sparce caricatures of previously presented novel objects. Similarly, using the same vocabulary measure, Smith and Jones (2011) showed that as 18- to-30-month-olds' vocabularies increased, so did their recognition of sparse object representations, and their tendency to use them appropriately during symbolic play (see also, James et al., 2014). Relatedly, Pereira and Smith (2009) showed changes in the object features children between 16- and 29-months of age need to recognize common objects. Children with 50 or fewer object names in their productive vocabulary as measured by the MBCDI, base recognition on local details of objects (e.g., the face of a dog, the grill of a car) whereas those who said more than 150 object names used global shape information. Yee et al. (2012) used the same vocabulary measure and further showed that this ability to recognize objects based on global shape information came earlier in vocabulary development than children's ability to quickly generalize names to novel objects by similarity in shape (e.g. the 'shape bias' Landau et al., 1988), an ability that has been related to accelerations in vocabulary development (Samuelson, 2002; Smith et al., 2002). Further, Jones (2003) found that late talking toddlers, defined in this study as those below the 30th percentile in MBCDI vocabulary for their age, focused on texture when generalizing novel names in contrast to age-matched typically developing toddlers who focused on shape. Finally, Borgström et al. (2019) showed that 20-month-olds' ability to recognize objects by their silhouette, as measured by an ERP incongruity signal, was related to their expressive language at 6-to-7-years using a composite score that included productive vocabulary measured with a Swedish adaptation of the MBCDI.

Beyond the size of vocabulary, the kinds of words children know have also been shown to be related to object recognition. Using the MBCDI, Perry et al. (2016) showed that while the size of 24-month-olds' vocabulary was related to their ability to retain names for novel objects, it was the composition of their vocabulary that was related to their ability to remember object features. Perry and Saffran (2017) used the same vocabulary measure, and showed that 21-month-olds with smaller productive shape vocabularies were less able to recognize versions of common objects in which another feature was made atypical (a cow that was pink instead of black-and-white).

Overall, even though the size of the literature addressing the link between infant object recognition and vocabulary development is small, a clear relation is emerging. Children with larger vocabularies consistently perform better in object recognition tasks, recognizing sparse representations of objects more efficiently. This ability may also be related to children's ability to use attention to shape in service of word learning, an ability apparently lacking in those struggling to build vocabulary. Nevertheless, more research, especially longitudinal studies, are necessary to explore the nature of this relation and confirm whether change in object perception abilities support vocabulary development or vice-versa.

Statistical learning

According to Erickson & Thiessen (2015, p. 67), "statistical learning refers to learning on the basis of some aspect of the statistical structure of elements of the input, primarily their frequency, variability, distribution and co-occurrence probability." In a seminal study, Saffran et al. (1996) showed that typically developing 8-month-old babies used the transition probabilities between syllable sequences (e.g., how likely one sound was to follow another) in fluent speech of an artificial language to segment word like units after only 2 min of listening experience. This statistical learning ability is not unique to linguistic stimuli (Saffran et al., 1999). Further, Graf Estes et al. (2007) found that 17-month-old infants familiarized with an artificial language similar to that of Saffran et al. (1996) could link extracted words to novel objects. These findings were supported by Pelucchi et al. (2009) who showed that 8-month-old English-learning infants could discriminate between real Italian words with high and low internal transition probabilities (HTP or LTP words), and preferred HTP words, which Hay et al. (2011), showed they could map to novel objects.

Recent papers returned in our search also suggest a strong positive relationship between auditory statistical learning and vocabulary development[2]. Shoaib et al. (2018) used the MBCDI, and found that 20-month-old children with smaller vocabularies were able to learn mappings between HTP, but not LTP, words and objects whereas children with larger vocabularies failed to map HTP words and showed only marginal learning of LTP. Frost et al. (2020) found a significant positive relationship between 17-month-olds' statistical learning performance and their concurrent and later vocabularies using a UK adaptation of the MBCDI. Related studies have also shown a positive relation between auditory statistical learning and aspects of lexical processing that may contribute to vocabulary development such as lexical-phonological access, lexical semantic-access and lexical-processing efficiency (Lany et al., 2018; Mainela-Arnold & Evans, 2014).

We also found one paper that suggests a possible relation with visual statistical learning. Using a task with repeating trials of colored shapes, Bettoni et al. (2022) found that 7-month-old infants and peers at a high risk of language learning impairment both learned sequences of colored shapes in an infant-controlled visual habituation statistical learning task. However, infants in the high-risk group did not learn in a rule-based visual statistical learning task.

Overall, then, this small literature does suggest a relation between auditory statistical learning and vocabulary development. And one study hints that children with and without a family history of language learning impairment may differ in aspects of visual statistical learning. However, for both auditory and visual statistical learning, the small number of studies and the lack of longitudinal

[2] We limit our review to papers that, like Saffran et al. (1996), measure implicit learning of language units (words, grammatical structures) from sequences of smaller units (syllables, words) containing statistical regularities. Studies of probabilistic prediction tasks (e.g., the Weather Prediction Task), are not included.

studies examining statistical learning and its relation to vocabulary in the early years, make this a fruitful area for future research.

Declarative/long-term memory

The ability to recognize an object may facilitate word learning by indicating which potential referents in a visual scene already have known labels. Long term memory for objects or words may also support word learning via exclusion. Further, to the extent that building vocabulary requires the long-term retention of new word-object mappings, we might expect general measures of declarative memory (DM) to be related to vocabulary development. Not surprisingly, then, several studies have revealed a link between DM and children's vocabulary.

Kolling et al. (2010) used the Developmental Test for 6-month to 6-year-olds (ET 6–6; Macha & Petermann, 2008) which includes a receptive language dimension comprising of vocabulary and sentence understanding. They found receptive language differences between clusters of 12-, 18-, and 24-month-olds who demonstrated differences in a deferred imitation task that required infants to repeat a modeled action after a delay. Similarly, Sundqvist et al. (2016) showed that deferred imitation performance at 9 months was predictive of productive vocabulary at 16 months of age as measured via the Swedish adaptation of the MBCDI. Vlach and DeBrock (2019) further found that children's recognition memory as measured by the Woodcock Johnson Cognitive Battery significantly predicted learning of new word-object mappings above and beyond age. Notably, vocabulary measured by the PPVT was not similarly predictive. Thus, a small literature suggests a clear link between declarative memory and vocabulary development, however the need for further studies and longitudinal data to confirm the directionality of this relation is highlighted once more.

Auditory processing/discrimination

Clearly for children learning an oral language, word learning and vocabulary development require processing of auditory information and discrimination of the various sounds that communicate meaning. It is not surprising, then, that this search returned the most papers (847). This was beyond the reviewing capabilities of the team, thus as indicated in the methods, we narrowed the scope to papers including behavioral, rather than neurophysiological, data, aligning this section with the other sections that also focus on behavioral measures.

Using a two-alternative forced choice task with different or same syllables, Lalonde and Holt (2014), showed that receptive vocabulary size as measured by the Receptive One-Word Picture Vocabulary Test (ROWPVT; Martin & Brownell, 2010) explained significant variance in speech discrimination performance in typically developing 2-year-old children. In the other direction, infants' speech discrimination abilities also explain variance in later vocabulary and language development. Uhler et al. (2022) used the Conditioned Head Turning (CHT) procedure to assess 9-month-old Normal Hearing (CNH) and Hard of Hearing (CHH) children on two speech contrasts (/ba-da/, /a-i/) at three intensity levels. Regardless of hearing group membership, infants who could discriminate the contrasts demonstrated better language development on a parental vocabulary checklist (MBCDI) and the Mullen Scales of Early Learning (MSEL) at 16 and 24 months. These children also showed both better expressive and receptive abilities at 30 months as measured by the MSEL.

In a study including infants both with and without a family history of DLD, Benasich and Tallal (2002) found that infants who did not have a family history of DLD had significantly better auditory discrimination than those with a family history of DLD. Further, they found infants who at 6- to 9-months had poorer discrimination abilities when tested with two tones presented at short (e.g., 8 ms) interstimulus intervals (see Benasich & Tallal, 1996), had significantly worse vocabulary outcomes at 16- and 24-months-of-age as measured by the MBCDI (see also Benasich et al., 2002). Likewise, Choudhury et al. (2007), also mentioned above, found that 6-to-9-month-olds with a family history of DLD performed significantly worse than their peers without a family history of DLD in a rapid auditory processing (RAP) task, and that 6-to-9-month-old rapid auditory processing abilities significantly predicted 12- and 16-month-old language scores above and beyond family history of DLD. Thus, multiple behavioral studies exploring infant auditory processing in relation to vocabulary development, most of which were longitudinal, suggest the presence of a positive relation, especially when looking at rapid auditory processing performance.

Discussion

The goal of this review is to contribute to a better understanding of what shapes variability in individual children's vocabulary development by examining literature on the relations between a set of general cognitive processes that support early word learning and vocabulary development. Nine of the reviewed processes were selected based on a successful theory of word learning instantiated in a neural process model (WOLVES, Bhat et al., 2022). A secondary goal was to inform future theory and model development by providing more detail on how the processes in WOLVES relate not just to word learning, but also to vocabulary development, and by also reviewing auditory processing/discrimination as this process is less well articulated in WOLVES. We conducted separate scoping reviews of each process using the same methodology. Below we integrate the findings from across the 10 reviewed literatures, appraise the literature, and discuss implications for theory. We then briefly discuss suggestions for future work.

Summary of findings

Our scoping review revealed that for the majority of the processes we examined, the extant literature relating them to word learning or vocabulary development was limited. Of the ten processes, object recognition, and auditory processing/discrimination constituted small literatures (although for the last of these, inclusion of neurophysiological measures would have potentially made it a very substantial literature). Both evidenced positive relations to vocabulary development. The literatures on visual/spatial attention, visual processing, sustained attention, novelty detection, statistical learning and declarative memory were all limited, but each of these suggests that there is a relation, although for statistical learning the relation was clear with auditory stimuli and less well evidenced for visual. There is also some suggestion of a relation between early visual working memory and vocabulary, but some disagreement in the literature about whether this is maintained beyond the early stages of vocabulary development. Finally, we did not find any papers examining the relation between attention shifting and vocabulary development in the 0- to 3-years age range.

Within several of the reviewed literatures, we found a few studies examining the relation between infant processing and word learning or vocabulary development in children at risk for language impairment. The limited literatures we reviewed suggested that children at risk for language impairment due to a family history or being late talkers show less robust novelty detection and auditory discrimination, which were both linked to poorer vocabulary outcomes, and differences in the features used to recognize objects in word learning tasks. These children also show more difficulty with visual working memory, and while the Choudhury et al. (2007) paper we reviewed found no links between infant visual working memory and childhood vocabulary, recent review papers suggest a link may exist (Pickering et al., 2021; Vugs et al., 2013). Our review also suggests a potential relation between visual statistical learning abilities and language impairment. Relatedly, Lammertink et al. (2017) concluded that there is a clear auditory statistical learning deficit in children with DLD at both the word segmentation and in the grammatical structure level. And, Obeid et al. (2016) drew a similar conclusion in a review that included tasks with visual stimuli.

Our review did not return any papers examining the relation between vocabulary development in children at risk for language impairment and infant visual processing, visual/spatial attention, declarative memory, attention shifting or sustained attention. The lack of papers examining links between attention shifting and vocabulary with either children at risk for language impairment or the general population, was particularly surprising given work showing that older children diagnosed with DLD have poorer attention shifting abilities relative to typically developing controls (Theofilogiannakou & Samuelson, 2026). Indeed, in a study of children just above the range included in our review, Aljahlan and Spaulding (2019) found that 3-to-5-year-old children with DLD, who differed significantly from age-matched peers in vocabulary, were more affected than their typically developing peers when demands on attention shifting are increased.

Likewise, it is surprising there were no studies examining the relation between sustained attention and vocabulary development in children at risk for language impairment given that a large and active literature has examined differences in sustained attention in children diagnosed with DLD (see Theofilogiannakou & Samuelson, 2026, for review). Indeed, a meta-analysis by Ebert and Kohnert (2011) concluded that there are clear deficits in both auditory and visual sustained attention for children with DLD compared to their TD peers. And Kapa and Plante's (2015) review showed performance in both modalities is significantly impacted in children with DLD compared to their TD peers. However, there are also arguments that sustained attention might play a different role in the development of children with DLD compared to typical development (McGregor et al., 2022a; Smolak et al., 2020).

Overall, the nine reviews with returns included findings from a total of 34 papers with a range of 1–9 papers per review. Thus, while the field of infant word learning and vocabulary development is substantial, studies examining the relation between this set of processes and vocabulary development are only a small portion. One reason for this may be that the processes we selected for review were based on a theory of word learning that focuses on building vocabulary out of mappings between *visual* referents and word forms. Indeed, three of our search terms included 'visual', and one (object recognition) implied visual stimuli. We contend the focus on visual processes is justified by the fact that in the age range of interest (0–3 years) most experimental methods are dependent on visual processing, thus our understanding of children's vocabulary development in this range is filtered through their visual processing abilities. Nevertheless, the limited return we found may reflect the field discounting the role of processing visual input as critical to understanding early vocabulary development. Relatedly, of the five processes that did not include 'visual' or imply objects (attention shifting, sustained attention, novelty detection, statistical learning and declarative memory) all but one (statistical learning) *only* returned papers with visual stimuli. This suggests that the field does see it as worthwhile to investigate how these processes act on visual stimuli to support vocabulary development. This point notwithstanding, we did find evidence of some relation between vocabulary development and all but one of the nine processes motivated by the model, suggesting, that even with its focus on visual stimuli, the theoretical account we used as a basis for selecting processes to review is well grounded in the literature.

Critical appraisal

One issue we encountered, with which many researchers in these literatures will be familiar, is that it is not clear where one processing step starts and another ends, nor that the tasks we use to measure these processes are in any sense 'pure'. Our initial work to find the best keywords for our systematic searches quickly made apparent that definitions of processes are not consistent and often ambiguous within and across literatures. For example, it can be unclear what the distinction is between object recognition and declarative memory and how we can be sure a task is measuring one and not the other. Likewise, the timescales used to define the memory processes we reviewed are not always well delineated with short-term memory running into working memory which in turn runs into declarative memory; and all could be influenced by the prior attentional processes that select the information entering the memory processing stream. Similarly, visual processing tasks are clearly often influenced by memory or processes like novelty detection that cause some stimuli to be attended more than others. And in relation to vocabulary development, there is also evidence that growing vocabulary influences the action of these processes, with, for example, older children who have larger vocabularies showing better sustained attention (Masek et al., 2022).

A related issue involves how tasks are related to processes. We found that different tasks were used to measure the same processes, both across and within literatures, however, the blurred line between processes also means we found cases where the same task was used to measure different processes. For example, the ‘Rose’ visual paired-comparison task (Rose et al., 2009) came up in searches as a measure of both novelty detection and visual working memory, as did the similar VH/RM task that was used by Choudhury et al. (2007). To the extent that both tasks require processing of represented stimuli that are held in memory, this is not surprising. But again, it can make it difficult to know what distinguishes children with robust and weak vocabulary development and can mean that related findings reported in different literatures are not always synthesized.

Another issue is that there are inconsistencies in how terms are used. A clear example involves statistical learning. There are a range of uses of ‘statistical learning’ in the literature including as a topic of study (Siegelman et al., 2017) and as a mechanism of learning (Frost et al., 2015). Thus, it is likely our search missed many papers relevant to the question of how the ability to track the statistical distribution of regularities in input might be related to vocabulary. Indeed, work on cross-situational word learning (CSWL), the ability to learn new word-object mappings from multiple individually ambiguous naming events, has proposed tracking the statistics of which words and which objects co-occur as a potential basis for learning (see Bhat et al., 2022, for review). Yet, our search did not return any of these papers, and there is evidence that children's ability to learn words in CSWL tasks is related to vocabulary (Vlach & DeBrock, 2019) and that children with DLD do not learn words in CSWL tasks in the same way that their typical peers do (McGregor et al., 2022). Our review, then, likely underrepresents the importance of visual statistical learning for early word learning and vocabulary development; a limitation that may also be seen more generally across the field to the extent that others of the processes we investigated are not used consistently.

A final issue that emerged in most of our searches is the significant lack of longitudinal studies observed. These studies are an incredibly powerful tool to explore relations between cognitive processes and vocabulary development, and we expected to have come across significantly more of them, especially since we were investigating the first years of life, when so many fast changes take place. Even though most of our findings suggest the existence of relations between the processes in question and vocabulary development, longitudinal data are essential to confirm these, and furthermore, to determine their nature and directionality.

Theoretical implications

Overall, the finding of relations between nearly all the processes we examined, and vocabulary development suggests that the theory of word learning instantiated in WOLVES does have the potential to shed light on variability in children's vocabulary development. While WOLVES has proven to be a robust model of how children make new mappings between words and objects, the focus of work with the model has not been on vocabulary development. This review suggests next steps for modeling work might be to capture specific findings reviewed here such as the Colombo et al. (2004) and Marino and Gervain (2019) data. Relating stronger novelty detection abilities to larger subsequent vocabulary in the model would be a concrete way to expand WOLVES beyond learning of individual words. This would require running simulations that mimic exposure to many potential word-referent pairs over longer timeframes to examine how specific processes contribute to the development of not just individual word-object mappings but also to an accumulated set of ‘known’ words.

Likewise, the reviewed literature showing auditory processing/discrimination abilities in infants are related to vocabulary development clearly suggests the importance of expanding this component of the theory and model to better understand vocabulary development (and we suspect, word learning). Work in this direction is already underway, focused on implementing a theoretically motivated representation of auditory inputs and capturing existing data on infant auditory statistical learning abilities in an expanded WOLVES model. The literature reviewed here provides several studies that could serve as simulation targets for later steps capturing the relation between auditory discrimination abilities and vocabulary.

Suggestions for future work

These reviews suggest a number of fruitful areas for future work. The fact that we did find evidence of relations between processing of visual information and vocabulary development suggests that differences between individuals in visual processing may be a useful avenue for future work on variability in vocabulary development (see D'Souza et al., 2026 for a similar argument). In terms of specific processes, the relation of visual/spatial attention, object recognition, and auditory statistical learning to vocabulary development all emerged as (relatively) established areas of work. However, only one, object recognition, returned a paper examining children at risk for language impairment, suggesting that the extension of this work to at-risk populations may be worthwhile. Visual processing/discrimination, sustained attention, novelty detection and declarative memory all had limited returns but those returns each provided some suggestion of a relationship between these processes and vocabulary development, making them fruitful areas for future work. These may also be areas that could benefit from studies examining variability by testing children at risk for language impairment, as only novelty detection returned a paper that included this population. Visual working memory and visual statistical learning had limited returns and were less clearly linked to vocabulary development or word learning, and attention shifting had no return. For both visual working memory and attention shifting, however, there is evidence of a relation in older children (for visual working memory see Pickering et al., 2021, for attention shifting see Theofilogiannakou & Samuelson, 2026), suggesting it may be worth pursuing these areas more.

Furthermore, the interaction between the processes reviewed above and input related factors, such as the quantity and quality of language input, which have been acknowledged to be essential for vocabulary development (Mahr & Edwards, 2018; Rowe, 2012), could also be a crucial area for future research. More knowledge about these interactions could provide critical insights and even potentially help address gaps in our understanding concerning their individual relations to vocabulary development. Relatedly, we were surprised that our search did not return more recent papers examining the relation between joint attention and vocabulary development. Recent work has examined relations between parent-child interactions with objects and word learning (e.g., Suanda et al., 2019), but only one paper we found linked this to vocabulary (Salley et al., 2013). Thus, more work in this area could be fruitful. Furthermore, this is a potential area where empirical and modeling work could be combined. Perone and Spencer (2013b) simulated the effect of parent interaction with objects on infant visual processing in a precursor model to WOLVES, and Spencer et al. (2026) propose using DFT models to examine the influence of dyadic joint attention on infant's development.

Beyond examining the contributions of these processes individually, a critical avenue of future work will be to understand how they come together as a system to influence both individual moments of word learning and their accumulation into trajectories of vocabulary development. A *developmental pathway* may be defined as the route, or chain of events, through which a new structure or function forms. Most human behaviors depend on the joint operation of multiple processes, so the pathway by which they develop is likely to be multi-causal and to have unexpected dependencies. To the extent that the formation of a function depends on multiple common processes that are reciprocally interdependent, pathways will be stable across individuals. However, because developmental pathways are multi-causal and time-dependent, each child's pathway will be the unique creation of their particular abilities, endowment, experiences, interests, context, and prior learning (Bishop, 1997; Siugzdaite et al., 2020). Early word learning and vocabulary development are prime examples of this, depending on multiple processes that unfold over time and yielding variable vocabulary trajectories over development. Better understanding of how multiple processes cascade to create an individual child's vocabulary development pathway would enable more effective assessment and intervention and is critical to advancing the field. For this reason, the field needs to embrace examination of how multiple processes dynamically interact to shape individual instances of word learning and how these cascade to create individual vocabulary development trajectories.

Formal models can play a critical role in this work. In prior work we have shown how parameters in WOLVES relate to differences in children's learning. For example, a parameter that modulates the strength of spatial attention relates to the length and number of fixations infants produce when visually exploring stimuli in a word learning task, and another parameter controlling how quickly memories decay captures relations between children's memory abilities and word learning (e.g., Vlach & DeBrock, 2019; see Bhat et al., 2022). WOLVES then provides an opportunity to explore how these, and other, cognitive processes interact to create variability in vocabulary development by exploring how combinations of parameter values capture differences in children's word learning and vocabulary development profiles. Combining longitudinal studies that capture differences between individuals and over time in multiple cognitive processes, with simulation studies capturing these empirical findings, would be particularly powerful in examining the system of interacting cognitive processes during individual moments of word learning, and how the results shape future moments of learning to create variable trajectories of vocabulary development.

Conclusions

Overall, our review showed positive relations between vocabulary development and eight (of nine) general cognitive processes operating on, mostly, visual input. Examination of these processes was based on a recent successful model of early word learning, thus supporting the usefulness of this model for understanding the word learning system. Future modeling work should transition beyond understanding learning of word-object mappings to the examination of how children build a vocabulary out of individual words. Likewise, our review confirmed the role of auditory processing/discrimination in the early stages of vocabulary development and thus suggests expansion of the auditory processing components of the model could be critical.

The review also pointed to a few areas of concern in the literature; distinctions between processes are not always clear nor are the relations between tasks and the individual processes they purport to measure. These issues reflect the fact that the processes in question operate as a system to jointly support vocabulary building, a fact that is not always apparent in a literature that tends to look at processes individually. The issue of determining how specific individual processes influence development is particularly difficult when attempting to establish the cause of children's vocabulary building difficulties and may ultimately hamper the development of interventions. This is an area, we believe, where strong theoretical accounts implemented in formal models, can help. Capturing the data from some of the reviewed literatures in WOLVES would inevitably require tuning of model parameters, and perhaps some adjustments to the theoretical approach. This process, however, can reveal the role that specific model components play both individually and as part of the larger system in development. In addition, once a model has been shown to reproduce a set of data, it is possible to test the effects of individual processes by changing model parameters (see for example, Bhat et al., 2022; Li et al., 2007; McMurray et al., 2012). This method can then show the range of outcomes a given process can produce, potentially revealing the basis for differences between groups of children.

Beyond modeling work, our review revealed several areas where future empirical work would be beneficial, including, but not limited to, examination of visual processing/ discrimination, sustained attention, novelty detection and declarative memory in children at risk for language impairment. That said, to the extent that each of the literatures we reviewed were small or limited, continued work to understand how all of these processes contribute to vocabulary development across the spectrum of children's abilities would be beneficial. We would argue, however, that a program of research that combined rigorous empirical work and formal simulations might provide the most insight into the origins of variability in vocabulary development.

Statement on use of generative AI

The authors declare that generative AI was not used in any aspect of preparation of this manuscript.

Author contributions CRediT statement

NT and LS conceptualized this scoping review. NT and LS screened the papers in two phases and extracted the data from the papers. NT organized the data management. NT and LS came to joint consensus about the data. NT and LS curated the data. NT wrote original drafts of all manuscript sections. LS provided feedback, review and editing. LS drafted the visualization in the graphical abstract. NT provided feedback. All authors approved the submitted version.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.dr.2026.101291.

Appendix B. Preferred reporting items for systematic reviews and meta-analyses extension for scoping reviews (PRISMA-ScR) checklist

Section	Item	Prisma-ScR checklist item	Reported on page #
Title			
Title	1	Identify the report as a scoping review.	1
Abstract			
Structured summary	2	Provide a structured summary that includes (as applicable): background, objectives, eligibility criteria, sources of evidence, charting methods, results, and conclusions that relate to the review questions and objectives.	Abstract
Introduction			
Rationale	3	Describe the rationale for the review in the context of what is already known. Explain why the review questions/objectives lend themselves to a scoping review approach.	6
Objectives	4	Provide an explicit statement of the questions and objectives being addressed with reference to their key elements (e.g., population or participants, concepts, and context) or other relevant key elements used to conceptualize the review questions and/or objectives.	6
Methods			
Protocol and registration	5	Indicate whether a review protocol exists; state if and where it can be accessed (e.g., a Web address); and if available, provide registration information, including the registration number.	7
Eligibility criteria	6	Specify characteristics of the sources of evidence used as eligibility criteria (e.g., years considered, language, and publication status), and provide a rationale.	7
Information sources*	7	Describe all information sources in the search (e.g., databases with dates of coverage and contact with authors to identify additional sources), as well as the date the most recent search was executed.	7
Search	8	Present the full electronic search strategy for at least 1 database, including any limits used, such that it could be repeated.	8 and Appendix B
Selection of sources of evidence[†]	9	State the process for selecting sources of evidence (i.e., screening and eligibility) included in the scoping review.	8–9
Data charting process[‡]	10	Describe the methods of charting data from the included sources of evidence (e.g., calibrated forms or forms that have been tested by the team before their use, and whether data charting was done independently or in duplicate) and any processes for obtaining and confirming data from investigators.	9–10
Data items	11	List and define all variables for which data were sought and any assumptions and simplifications made.	9–10
Critical appraisal of individual sources of evidence[§]	12	If done, provide a rationale for conducting a critical appraisal of included sources of evidence; describe the methods used and how this information was used in any data synthesis (if appropriate).	9–10
Synthesis of results	13	Describe the methods of handling and summarizing the data that were charted.	9–10
Results			

(continued on next page)

(*continued*)

Section	Item	Prisma-ScR checklist item	Reported on page #
Selection of sources of evidence	14	Give numbers of sources of evidence screened, assessed for eligibility, and included in the review, with reasons for exclusions at each stage, ideally using a flow diagram.	Fig. 3
Characteristics of sources of evidence	15	For each source of evidence, present characteristics for which data were charted and provide the citations.	9–23
Critical appraisal within sources of evidence	16	If done, present data on critical appraisal of included sources of evidence (see item 12).	9–23
Results of individual sources of evidence	17	For each included source of evidence, present the relevant data that were charted that relate to the review questions and objectives.	9–23
Synthesis of results	18	Summarize and/or present the charting results as they relate to the review questions and objectives.	9–23
Discussion			
Summary of evidence	19	Summarize the main results (including an overview of concepts, themes, and types of evidence available), link to the review questions and objectives, and consider the relevance to key groups.	23–26
Limitations	20	Discuss the limitations of the scoping review process.	26–28
Conclusions	21	Provide a general interpretation of the results with respect to the review questions and objectives, as well as potential implications and/or next steps.	27–33
Funding			
Funding	22	Describe sources of funding for the included sources of evidence, as well as sources of funding for the scoping review. Describe the role of the funders of the scoping review.	NA

JBI = Joanna Briggs Institute; PRISMA-ScR = Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews. From: Tricco AC, Lillie E, Zarin W, O'Brien KK, Colquhoun H, Levac D, et al. PRISMA Extension for Scoping Reviews (PRISMAScR): Checklist and Explanation. Ann Intern Med. 2018;169:467–473. doi:10.7326/M18-0850.

[*] Where *sources of evidence* (see second footnote) are compiled from, such as bibliographic databases, social media platforms, and Web sites.

[†] A more inclusive/heterogeneous term used to account for the different types of evidence or data sources (e.g., quantitative and/or qualitative research, expert opinion, and policy documents) that may be eligible in a scoping review as opposed to only studies. This is not to be confused with *information sources* (see first footnote).

[‡] The frameworks by Arksey and O'Malley (6) and Levac and colleagues (7) and the JBI guidance (4, 5) refer to the process of data extraction in a scoping review as data charting.

[§] The process of systematically examining research evidence to assess its validity, results, and relevance before using it to inform a decision. This term is used for items 12 and 19 instead of "risk of bias" (which is more applicable to systematic reviews of interventions) to include and acknowledge the various sources of evidence that may be used in a scoping review (e.g., quantitative and/or qualitative research, expert opinion, and policy document).

Appendix C. Search keywords, booleans & papers numbers for review screening

(1) APA PsycInfo, MEDLINE Complete (2) SCOPUS

1. (dld OR "developmental language disorder" OR sli OR "specific language impairment" OR "language impairment" OR "language disorder" OR "late talkers" OR "vocabulary development" OR "word learning" OR "language development" OR "language delay" OR "Cognitive Development" OR "Reading Development" OR "Perceptual Development" OR "Perceptual Motor Development") AND **"statistical learning".**

Filters: time (2000−2023), source types (academic journals), language (English).

505 results, 311 results – > 388 after duplicates – > 26 included.

428 duplicates.

2. (dld OR "developmental language disorder" OR sli OR "specific language impairment" OR "language impairment" OR "language disorder" OR "late talkers" OR "vocabulary development" OR "word learning" OR "language development" OR "language delay" OR "cognitive development" OR "reading development" OR "perceptual development" OR "perceptual motor development") AND **"sustained attention".**

Filters: time (2000–2023), source types (academic journals), language (English).

(1) 276, (2) 120 – > 299 after duplicates – > 23 included.

97 duplicates.

3. (dld OR "developmental language disorder" OR sli OR "specific language impairment" OR language impairment" OR "language disorder" OR "late talkers" OR "vocabulary development" OR "word learning" OR "language development" OR "language delay") AND (**"attention shift*" OR "shift* of attention")**

Filters: time (2000–2023), source types (academic journals), language (English).

(1) 17, (2) 14 – > 16 after duplicates – > 4 included.

15 duplicates.

4. (dld OR "developmental language disorder" OR sli OR "specific language impairment" OR "language impairment" OR "language disorder" OR "late talkers" OR "vocabulary development" OR "word learning" OR "language development" OR "language delay") AND (**"visual working memory" OR "visual short term memory"**).

Filters: time (2000–2023), source types (academic journals), language (English).

(1) 16, (2) 22 – > 26 after duplicates – > 9 included.

12 duplicates.

5. (dld OR "developmental language disorder" OR sli OR "specific language impairment" OR "language impairment" OR "language disorder" OR "late talkers" OR "vocabulary development" OR "word learning" OR "language development" OR "language delay") AND (**"novelty detection" OR "novelty preference").**

Filters: time (2000–2023), source types (academic journals), language (English).

(1) 20, (2) 22 – > 28 after duplicates – > 6 included.

14 duplicates.

6. (dld OR "developmental language disorder" OR sli OR "specific language impairment" OR "language impairment" OR "language disorder" OR "late talkers" OR "vocabulary development" OR "word learning" OR "language development" OR "language delay") AND (**"vis* attention" OR "spat* attention").**

Filters: time (2000–2023), source types (academic journals), language (English).

(1) 125, (2) 128 – > 170 after duplicates – > 13 included.

83 duplicates.

7. (dld OR "developmental language disorder" OR sli OR "specific language impairment" OR "language impairment" OR "language disorder" OR "late talkers" OR "vocabulary development" OR "word learning" OR "language development" OR "language delay") AND **("declarative memory" OR "long-term memory").**

Filters: time (2000–2023), source types (academic journals), language (English).

(1) 208, (2) 306 – > 363 after duplicates – > 37 included.

151 duplicates.

8. (dld OR "developmental language disorder" OR sli OR "specific language impairment" OR "language impairment" OR "language disorder" OR "late talkers" OR "vocabulary development" OR "word learning" OR "language development" OR "language delay") AND (**"auditory processing" OR "auditory discrimination"**).

Filters: time (2000–2023), source types (academic journals), language (English).

(1) 613, (2) 716 – > 847 after duplicates – > 31 included.

482 duplicates.

9. (dld OR "developmental language disorder" OR sli OR "specific language impairment" OR "language impairment" OR "language disorder" OR "late talkers" OR "vocabulary development" OR "word learning" OR "language development" OR "language delay") AND (**"vis* processing" OR "vis* discrimination"**).

Filters: time (2000–2023), source types (academic journals), language (English).

(1) 76, (2) 123 – > 153 after duplicates – > 5 included.

46 duplicates.

10. (dld OR "developmental language disorder" OR sli OR "specific language impairment" OR "language impairment" OR "language disorder" OR "late talkers" OR "vocabulary development" OR "word learning" OR "language development" OR "language delay") AND **("object recognition" OR "object memory"**).

Filters: time (2000–2023), source types (academic journals), language (English).

(1) 146, (2) 52 – > 167 after duplicates – > 13 included.

31 duplicates.

Appendix D. Exclusion criteria

Exclusion Criteria	Description
Wrong publication type	Anything not a journal article (e.g., book chapters, commentaries)
Background article	Articles not analysing primary data (e.g., meta-analysis, reviews, synthesis; note some of these kept and used as background reading.
Wrong Population	Articles which only recruited participants outside the TD or DLD populations (e.g., ASD, Dyslexia, motor disorders, bilinguals, adults, animals) or included children older than 3-years.
Intervention/ Training	Articles introducing/ assessing a specific training or intervention.
Not language	Articles focused on the process of interest, but that did not relate the process to any language measures.
Method focused	Articles focused on introducing/assessing a specific method (e.g., battery, tasks).
Not vocabulary	Articles focused on the process of interest, including language measures, but not exploring a direct relationship with vocabulary.
Medical	Articles focusing on medical issues or procedures (e.g., vitamin deficiency, medicine efficiency, surgeries)
Not process of interest	Articles involving other processes, parental factors, neurobiology, unrelated themes, brain organization, music, the process of interest as a mediator, factors influencing the process of interest (not language), mechanisms but not relations etc
Wrong methodology	Studies including only neurophysiological, and no behavioral measures. Note: only used for auditory discrimination/processing search

Data availability

Research Link Provided

Summaries of reviewed articles, Infant Origins of Vocabulary Variability (Reference data) (OSF)

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