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Shared Developmental Principles in Spoken and Written Language During Infancy

Robert Craig Titzer

drtitzer@infantlearning.com

Infant Learning Company https://orcid.org/0009-0001-2398-8459

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Shared Developmental Principles in Spoken and Written Language Learning During Infancy

Robert C. Titzer[1]*

[1] Infant Learning Company, Louisville, TN, USA

* Correspondence: Robert C. Titzer drtitzer@infantlearning.com

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Abstract

Contemporary theories increasingly characterize infants as active learners who detect regularities, generate predictions, integrate information across sensory modalities, and reorganize knowledge through experience. These perspectives raise a developmental question that earlier theories provided little reason to ask: can written language function as natural visual language information during infancy? This paper synthesized predictions from six contemporary perspectives on learning and development and compared them with historical evidence and findings from a parent-report dataset of 778 records. Analyses examined associations among age of introduction, frequency, duration, and variety of early written language experience, written word reading, receptive and expressive spoken language, and parent-reported engagement. Despite differing mechanisms, the six perspectives converged on similar predictions: earlier, more frequent, more sustained, and more varied meaningful experience should support stronger learning, and written and spoken language should show reciprocal developmental relationships. The empirical findings were broadly consistent with these predictions. Earlier program introduction ($p = .039$) and greater program use frequency ($p < .001$) were independently associated with higher written word reading after controlling for age at testing and the other predictor. Longer duration and greater material variety were also associated with higher written word reading after controlling for age (partial rho = .189 and .182, respectively; both $p < .001$). Written word reading was positively associated with both receptive and expressive spoken language (Spearman rho = .46 and .48, respectively; both $p < .001$). Among 332 children who began at 6 months or younger, 331 (99.7%) were reported to enjoy or love the program. Taken together, contemporary theory, historical evidence, and the observed developmental patterns provide a scientific basis for continued investigation of written language as natural visual language information during infancy.

Keywords: infant learning; written language acquisition; spoken language acquisition; language development; infant directed text; multisensory learning; early literacy; audiovisual language learning

Introduction

Theoretical perspectives in developmental science have changed substantially over the past several decades. Contemporary theories increasingly describe infants as active learners who detect patterns, integrate information across modalities, generate predictions, update expectations, and reorganize their knowledge through meaningful experience (Thelen and Smith, 1994; Saffran et al., 1996; Bahrick and Lickliter, 2000; Bahrick et al., 2004; Christiansen and Chater, 2008; Miller, 2022). These advances have changed not only how development is explained, but also which developmental questions warrant scientific investigation. One such

question is whether written language can function as natural visual language information during infancy.

Language acquisition is among the most remarkable achievements of early development. Within only a few years, infants learn a language system whose forms bear little inherent resemblance to the objects, actions, events, and relationships they represent. Spoken words do not reveal their meanings simply by being heard. Infants must detect recurring sound patterns, determine where words begin and end, relate those patterns to referents, and gradually infer increasingly complex linguistic structure. Spoken language is therefore itself an arbitrary symbolic system, although its early acquisition is commonly regarded as natural while its written representation is treated as fundamentally different.

Research over the past several decades has shown that infants do not solve this challenge through hearing alone. From early in development, they integrate information across sensory modalities. Studies of audiovisual speech demonstrate that young infants can combine what they hear with what they see in a talking face (Patterson and Werker, 2003; Lewkowicz and Hansen-Tift, 2012), particularly when relevant visual information is presented in developmentally accessible ways. These findings establish an important principle—visual language information can contribute to spoken language learning during infancy.

This principle raises a broader scientific question. If visual information can contribute to spoken language learning as early as two months of age (Patterson and Werker, 2003), what other forms of visual information might also contribute, and what additional information might they provide? The question is not simply whether vision can support language learning, but whether different visual sources provide complementary information about linguistic forms, meanings, and structure.

Objects and events help infants determine what spoken words refer to and how those referents participate in actions and relationships. Facial expressions provide emotional and social information, while eye gaze and gestures direct attention and communicate intentions and meanings. Visible speech provides visual information directly linked to spoken language. Sign languages demonstrate that complete natural languages can be conveyed visually, although they are independent linguistic systems rather than visual representations of spoken language. Written language differs from these other visual sources because it provides stable, persistent, segmented, and structured visual representations of the spoken language infants are already learning. In this sense, written language is distinctive—spoken words have visual partners that not only represent the same words, but can also provide additional information about them. These sources are not interchangeable; each provides information that may support different aspects of language learning. Written language may therefore offer another source of natural visual language information during infancy.

Visible speech demonstrates that infants can integrate visual information directly linked to spoken language during infancy. Once that principle is established, the scientific question becomes whether written language provides another source of natural visual language information during infancy. Many articulatory movements occur inside the mouth and cannot be fully observed, different speech sounds can produce similar visible movements, and the visual signal disappears almost immediately. Listeners therefore integrate visible speech with auditory information, linguistic context, semantic knowledge, and prior experience (Birulés et al., 2023).

Unlike visible speech, which provides transient visual information about articulation, written language evolved to provide stable visual representations of spoken language. Word boundaries remain visible, lexical forms can be compared across repeated encounters, and morphological relationships can be detected through recurring visual patterns. Homophones that sound identical may remain visually distinct, while related words often preserve visible similarities. Written language sometimes retains information about words that can be lost in spoken language. These stable properties may complement the transient information available from speech by allowing infants repeated opportunities to compare visual and auditory language forms across experiences (Dehaene, 2009; Morin, 2018).

In the present paper, natural visual language information refers to meaningful, perceptually accessible visual information that represents the same language infants are acquiring through spoken language. Written language is proposed as one such source. Written words can serve as visual partners to spoken words, representing the same words visually while also providing stable and structured information about them. Written language can therefore be understood not only as something children learn, but also as information they can learn from. The information it provides depends on the writing system and the specific language or languages being learned. Consequently, the present framework predicts that the developmental consequences of early written language experience should vary across languages and writing systems while reflecting the same underlying developmental principles.

When experienced simultaneously with meaningful spoken language, written words provide repeated opportunities for infants to compare visual and auditory language forms, extract statistical regularities, generate predictions, and refine those predictions over time.

The present paper examines whether multiple contemporary theories of learning and development independently generate predictions consistent with this proposal and whether those predictions correspond to developmental patterns observed in a large parent-report dataset.

Spoken language is acquired through extensive experience with meaningful whole words and utterances in recurrent social contexts (Hart and Risley, 1995), long before infants can identify or explain their component sounds or grammatical rules. For example, a toddler may say, "I goed over there," demonstrating that the child has inferred a productive grammatical pattern even though the child has never heard that form, does not know the term past tense, and could not explain the underlying morphological rule (Marcus et al., 1992; Pinker, 1999). The pattern has been learned before it can be described explicitly.

Knowledge of spoken language has long been evaluated in this way. Young children's understanding is inferred from their ability to use language meaningfully, not from their ability to explain the rules that underlie it (Oller et al., 2012). Contemporary developmental theories view learning as something that develops gradually as children detect meaningful patterns through experience. From this perspective, a young child who can consistently identify written words or demonstrate their meanings has already learned something important, even if the child cannot explain the spelling, sound, or word structure patterns involved. Earlier theoretical perspectives, however, generally assumed that successful reading depended upon mastery of prerequisite component skills and explicit decoding procedures (van Kleeck and Schuele, 2010). Within such frameworks, accurate responses to written words during infancy would not have satisfied prevailing criteria for genuine reading because they occurred before children could demonstrate the component skills considered necessary (van Kleeck and Schuele, 2010). The

present framework therefore suggests that contemporary developmental theories change not only how early written language learning might occur, but also how evidence of that learning should be interpreted.

Written language has often been introduced in the reverse order, beginning with letter names, letter sounds, phonological awareness, and explicit decoding procedures before children receive extensive opportunities to connect visible words directly with meaningful language.

The present paper examines this question by asking whether predictions derived from contemporary developmental theories are consistent with parent-reported developmental outcomes among infants and toddlers who experienced developmentally adapted written language, referred to here as *infant directed text*, during everyday interactions. The theoretical framework focuses on six complementary perspectives: the intersensory redundancy hypothesis, statistical learning, predictive processing theory, Bayesian learning theory, dynamic systems theory, and Oller's growth-spiral account of language development. Together, these perspectives generate converging predictions concerning developmental timing, quantity of experience, variety of experience, and relationships between written and spoken language outcomes.

Why Contemporary Developmental Theories Generate Different Predictions

Scientific theories do more than explain development. They shape which questions researchers ask, which hypotheses appear plausible, and which observations count as meaningful evidence. Historically, reading readiness and maturational perspectives emphasized developmental preparedness and prerequisite skills (Morphett and Washburne, 1931; Gesell and Ilg, 1946) while Piagetian stage theory emphasized qualitatively different cognitive capacities emerging across development (Piaget, 1952), and nativist accounts emphasized biologically specialized capacities for spoken language while distinguishing it from culturally acquired written language (Chomsky, 1965; Pinker, 1994). Although these perspectives differed substantially in their assumptions, together they reinforced a developmental sequence in which meaningful written language was expected to occur later rather than during infancy. Contemporary theories increasingly recognize domain-general processes that detect regularities, coordinate information across modalities, generate predictions, and update knowledge through experience. This broader perspective makes it scientifically reasonable to ask whether written language can engage learning mechanisms already active during infancy.

Christiansen and Chater's (2008) account of language evolution provides an especially useful basis for this reconsideration. They proposed that language has been shaped through cultural evolution to fit pre-existing human learning capacities, rather than requiring the brain to have evolved specifically for the detailed structure of language. Their argument concerns spoken language, but it establishes a broader principle—culturally transmitted systems must remain learnable by the perceptual, attentional, memory, and learning capacities of human brains. More generally, this perspective predicts that information that better matches the perceptual, attentional, memory, and learning capacities of developing brains should be learned more efficiently than information that is less compatible with those capacities (Christiansen and Chater, 2008, 2016; Chater and Christiansen, 2018).

A similar logic applies to the historical development of written language. Writing systems are also culturally evolved systems transmitted across generations (Dehaene, 2009). Forms that people could not reliably perceive, distinguish, remember, or learn would be unlikely to persist (E. J. Gibson, 1969; Christiansen and Chater, 2008; Dehaene, 2009). Contemporary accounts

likewise suggest that writing systems have progressively adapted to constraints imposed by the human visual and cognitive systems, becoming increasingly compatible with efficient perception and recognition through cultural evolution (Changizi and Shimojo, 2005; Dehaene, 2009; Morin, 2018). Written language may therefore reflect constraints imposed by human perception, attention, learning, and memory, providing a principled basis for investigating whether written language, when presented as infant directed text, can provide meaningful visual language information. Together, these complementary perspectives suggest that both spoken language and writing systems have been shaped through cultural evolution to fit human perceptual, cognitive, and learning constraints. The present framework extends this logic by asking whether that evolutionary fit has developmental consequences during infancy when written language is experienced simultaneously with meaningful spoken language.

The original hypothesis grew from a straightforward extension of established multisensory learning principles (Ruff and Kohler, 1978; Rose and Ruff, 1987; Ruff, 1989) and from Edelman's theory of neuronal group selection (Edelman, 1987). The multisensory reasoning led to the question of whether infants would learn language more effectively if they could both see and hear the same words, while Edelman's emphasis on experience-dependent neural selection sharpened the developmental question by drawing attention to the timing of those experiences. If coordinated patterns of sensory experience can strengthen developing neural organization (Edelman, 1987), and infants often learn more effectively when meaningful information is synchronized across sensory systems (Bahrick and Lickliter, 2000), then language learning might also benefit when written language is presented together with meaningful spoken language, actions, gestures, objects, and touch. The proposal therefore began as a developmental question about whether an additional, coordinated source of language information could support learning.

Although the contemporary theories reviewed below differ in their assumptions and primary mechanisms, they independently converge on a common prediction—infants learn most effectively from experiences that are meaningful, structured, repeated, and perceptually accessible. It is this convergence of independent theoretical perspectives—not any single theory—that provides the rationale for considering whether written language may function as natural visual language information during infancy.

The historical significance of this convergence extends beyond the present hypothesis. For much of the twentieth century, influential developmental perspectives generally provided little theoretical motivation for investigating written language during infancy. Contemporary developmental frameworks, while differing substantially in their mechanisms and explanatory principles, now converge on predictions that make such investigation scientifically reasonable. Rather than reflecting a change in a single theory, this shift illustrates a broader transformation in developmental thinking, in which changing theoretical assumptions have opened questions that earlier frameworks provided little reason to ask.

Dynamic systems theory provided the original theoretical framework for the present proposal. The intersensory redundancy hypothesis, statistical learning, predictive processing, and Bayesian approaches either emerged later or became substantially more influential after the proposal was developed. Although these frameworks differ in their assumptions and primary mechanisms, they converge on a broad expectation—infants learn from information that is meaningful, structured, reliable, repeated, and accessible to their developing perceptual and attentional systems.

The frameworks are therefore treated as complementary rather than competing. The intersensory redundancy hypothesis explains how synchronized multisensory events guide early attention. Statistical learning explains how infants extract recurring distributions and relationships. Predictive processing describes how prior experience shapes expectations about incoming information. Bayesian approaches formalize how learners combine prior expectations with new evidence under uncertainty. Dynamic systems theory explains how these processes alter subsequent behavior and reorganize relations among the child, caregiver, task, and environment. Oller's growth-spiral account explains how meaningful linguistic accomplishments can provide a basis for subsequent learning, allowing established knowledge to bootstrap additional linguistic mappings as development proceeds. Together, they provide a continuous account of how attention, learning, and development interact across infancy.

The sections below follow a consistent structure: they identify each theory's central mechanism, derive predictions for written language from principles that were not originally developed to address written language, and specify the empirical pattern expected if written language functions as natural visual language information during infancy.

The Intersensory Redundancy Hypothesis

The intersensory redundancy hypothesis (Bahrick and Lickliter, 2000; Bahrick et al., 2004) proposes that when the same information is presented simultaneously across multiple sensory modalities, infants preferentially attend to the properties shared across those modalities. During early development, attentional resources are limited, making synchronized multimodal information particularly effective for directing attention toward meaningful environmental structure. Rather than competing for attention, temporally coordinated audiovisual information often increases the attentional salience of amodal information, making information shared across spoken and written language more likely to be processed together and facilitating perceptual learning (Bahrick and Lickliter, 2000; Bahrick et al., 2004; Bahrick et al., 2010).

From this perspective, synchronized written and spoken language may provide a previously underexplored form of intersensory redundancy. Spoken words convey linguistic information through audition, while simultaneously presented written words provide stable visual representations of those same linguistic units. Because both modalities specify the same underlying language information, their temporal correspondence is predicted to direct infants' attention to meaningful linguistic relationships, including relationships among written words, spoken words, and meaning.

Accordingly, the intersensory redundancy hypothesis predicts that synchronized written and spoken language should direct infants' attention to linguistic information shared across modalities, making those relationships more salient during early learning (Bahrick and Lickliter, 2000). Because attention determines which information becomes available for subsequent learning (Bahrick and Lickliter, 2000), early differences in attention may influence later statistical learning, prediction, and language development. This attentional advantage may be especially important when the information to be learned is complex, because intersensory redundancy has been shown to facilitate attention and learning under conditions of increased task difficulty (Bahrick et al., 2010). Greater attention to shared linguistic relationships should create additional opportunities for detecting recurring language patterns and integrating information across experiences. Applied to written and spoken language, the hypothesis therefore predicts

that their temporal coordination may direct infants' attention toward meaningful linguistic structure and facilitate subsequent language learning.

Statistical Learning

Statistical learning refers to the capacity to detect regularities in the distribution and co-occurrence of events. Infants use this capacity across sensory modalities and learning domains, including auditory, visual, action, and emotional information (Fiser and Aslin, 2002; Kirkham et al., 2002; Ruba et al., 2022; Saffran, 2020; Compostella, 2024). In language, statistical learning helps infants discover structure in continuous input by tracking which elements reliably occur together, which sequences are probable, and which boundaries are supported by changes in transitional probability (Saffran, 2020).

The classic demonstration by Saffran et al. (1996) showed that eight-month-old infants could segment word-like units from a continuous artificial speech stream after brief exposure. The stream contained no pauses marking word boundaries. The only reliable cues were the statistical relationships among syllables. Syllables within a word occurred together more predictably than syllables spanning word boundaries. Infants learned these conditional relationships and later distinguished the recurring units from less probable sequences.

Language learning involves several forms of statistical learning. Transitional probability learning can help infants detect likely boundaries in continuous speech by tracking which elements reliably follow one another (Saffran et al., 1996). Distributional learning uses the frequency and variability of elements across experience, including patterns in speech sounds (Kuhl et al., 1992; Kuhl, 2004). Cross-situational learning can track recurring relations between words and potential referents across different encounters (Smith and Yu, 2008), while conditional learning captures relationships in which the occurrence of one element provides information about another (Saffran et al., 1996). Statistical learning is therefore not a single task or one laboratory effect. It is a family of domain-general processes through which learners extract structure from repeated experience (Saffran et al., 1996; Fiser and Aslin, 2002; Kirkham et al., 2002; Saffran and Kirkham, 2018; Saffran, 2020).

Statistical learning also occurs across multiple levels of spoken language development (Saffran and Kirkham, 2018; Saffran, 2020; Compostella, 2024) rather than proceeding one linguistic level at a time. Infants simultaneously encounter regularities relevant to speech segmentation, word forms and meanings, morphology, and grammatical structure, allowing learning at different levels to develop concurrently and potentially inform one another (Saffran and Wilson, 2003; Saffran and Kirkham, 2018; Saffran, 2020). The same principle generates an important prediction for written language. From a statistical learning perspective, if infants experience written and spoken language together, learning about written language need not begin with the first word they demonstrably read. The first observable language milestone typically does not mark the beginning of the learning process (Swingley, 2008; He and Arunachalam, 2017). By the time infants understand or produce their first spoken words, they have already acquired substantial knowledge about the sound structure, statistical regularities, segmentation, and meanings of spoken language. If written language learning is influenced by similar developmental principles, the first observable demonstration of written word reading would likewise be expected to reflect learning that has accumulated over many earlier experiences. Before that observable milestone, infants may already be learning visual regularities, relationships between written and spoken words, word boundaries, recurring letter patterns, and

relationships among words and grammatical forms. As with spoken language, the first demonstrated word may therefore reflect learning that has been developing across multiple levels over time rather than the beginning of the learning process itself. Repeated experience plays a central role in this process.

Frequency effects are among the most robust findings across language learning (Ambridge et al., 2015). More frequent linguistic forms and structures are generally acquired earlier and more reliably than less frequent ones, suggesting that repeated experience plays a fundamental role in language acquisition across a wide range of linguistic contexts (Hart and Risley, 1995; Ambridge et al., 2015). If written language provides infants with additional meaningful opportunities to encounter linguistic forms, increasing the frequency of those experiences should likewise strengthen learning through the same domain-general developmental mechanisms.

Written language adds forms of regularity and distinction that are difficult or impossible to observe in the auditory signal alone. Spoken language unfolds serially and disappears quickly, yet infants and young children nevertheless discover recurring relationships among words from this transient input and from the contexts in which different forms occur. This is a remarkable developmental achievement because much of the relevant structure must be inferred across experiences rather than directly observed. For example, children learn relationships among forms such as *dog, dogs, dog's,* and *dogs'*, including plural and possessive uses, from spoken language and context even though these forms cannot be simultaneously inspected in speech. Written language makes the shared word and its changing forms visually available for comparison. Other distinctions are not available in the auditory form at all. Children can learn to understand and appropriately use *to, two,* and *too* from spoken language and context even though the three words sound the same, and they may do so before explicitly understanding that these are three distinct words. Written language makes those distinctions visible. In this way, written language can provide additional stable and structured information about relationships and distinctions that children are already learning from spoken language, potentially making some of the underlying structure more accessible without requiring explicit instruction.

Analogous to infant directed speech, infant directed text refers here to written language presented in forms adapted to infants' developing perceptual and attentional abilities. Initially, this includes making written words perceptually accessible and coordinating them with spoken language and meaning so that the visual forms can become linguistically meaningful.

Infant directed text may therefore increase both the number and clarity of statistical relationships available to the learner. Repeated pairing of a spoken word with the same written form creates a cross-modal co-occurrence pattern. Encountering the same word across different fonts, colors, books, videos, speakers, and situations provides opportunities to detect invariant structure across surface variation, consistent with Gibsonian accounts of perceptual learning (J. J. Gibson, 1966; E. J. Gibson, 1969, 1971). Recurring visual patterns across related words may likewise make lexical and morphological structure available for statistical discovery.

Recent evidence concerning infant object-name learning provides a complementary account of how previously established knowledge may support rapid acquisition of new information. Clerkin and Smith (2022) found that visual referents of early-learned object names were pervasively present across infants' everyday mealtime experiences, whereas the corresponding spoken names occurred much less frequently. They proposed that repeated visual experience can establish robust representations of object categories into which new information, such as a

spoken name, may be incorporated when the established representation is reactivated, potentially from a single learning episode or a small number of experiences. Applied to written language, this mechanism raises the possibility that learning need not begin anew for each form of linguistic information. Once an infant has established information about a referent or its spoken name, a consistently paired written form may become associated with those existing representations. Simultaneous written and spoken presentation may also support associations between the visual and auditory forms of a word. As these relationships develop, previously learned information about referents, spoken forms, or written forms may provide a basis for learning additional information, allowing learning in one part of the developing language system to support learning in another.

Statistical learning generates clear predictions. Greater frequency of meaningful written and spoken pairings should be associated with stronger learning because each encounter supplies another observation of the relevant regularities. Greater duration of experience should matter because statistical evidence accumulates over time. Greater variety should support generalization because stable linguistic relations encountered across changing contexts can be separated from incidental perceptual features.

Statistical learning also predicts relationships between written and spoken outcomes. When visual forms, auditory forms, and meanings repeatedly co-occur, learning in one part of the system can constrain learning in another. Stable written forms may provide additional evidence about lexical identity and boundaries, while a growing spoken vocabulary supplies meanings to which written forms can be mapped. Reciprocal developmental relations between written and spoken language are therefore theoretically expected.

Predictive Processing

Predictive processing describes perception and learning as ongoing attempts to anticipate incoming information (Clark, 2013). The learner does not passively record sensory input. Prior experience generates expectations. Incoming information is compared with those expectations, and mismatches provide signals for updating the developing model (Clark, 2013).

Early language learning is particularly well suited to this account. Speech is rapid and transient, requiring infants to anticipate likely continuations before all relevant information is available (Clark, 2013; Köster et al., 2020). Recurrent words, prosodic patterns, social routines, and event sequences allow expectations to become progressively more accurate (Clark, 2013; Köster et al., 2020). Within predictive processing accounts, confirmed predictions strengthen useful representations, whereas prediction errors provide informative signals for revising developing internal models (Clark, 2013). Repeated cycles of prediction, feedback, and updating therefore become central mechanisms through which increasingly accurate linguistic expectations emerge (Clark, 2013; Köster et al., 2020).

Written language can provide stable, segmented, persistent, and structured visual language information during this process (Dehaene, 2009). Unlike spoken language, which unfolds rapidly and disappears, written words remain available for inspection, comparison, and repeated encounters. These properties provide repeated opportunities for infants to compare visual and auditory language forms, generate increasingly accurate predictions, detect recurring patterns, and refine those predictions over time (Clark, 2013). A spoken word disappears as it is produced, whereas its written form can remain present. When the same visual form repeatedly accompanies the same spoken word and meaning, it provides a reliable cue for anticipating the auditory event. The relationship may also be bidirectional, with written language experience shaping predictions during spoken language processing (Huettig and Pickering, 2019).

This stability may be especially relevant to segmentation. Infants hearing continuous speech must infer where one word ends and another begins (Saffran et al., 1996; Saffran, 2020), while written language makes many lexical boundaries spatially visible (Dehaene, 2009). Across synchronized written and spoken experiences, visible boundaries can provide additional evidence about how the transient auditory stream is organized. For example, when an infant repeatedly hears the phrase *arms up* while simultaneously seeing the written words presented separately, the visible spacing provides an additional stable cue to the underlying linguistic structure. Infants can see the spaces between written words. They need not explicitly understand the purpose of those spaces or apply a rule about word boundaries (Saffran et al., 1996; Saffran, 2020). As emphasized by predictive processing accounts, the brain can use reliable patterns in the environment to generate predictions without requiring explicit knowledge of those patterns (Clark, 2013; Köster et al., 2020). The consistent visual separation of written words may therefore provide additional information about where one word ends and another begins, even before infants understand the function of spaces in written language. Because written words remain visually separated, repeated experience may also strengthen the representation of individual lexical units. In contrast to continuous speech, where word boundaries must be inferred from transient auditory input, written language provides persistent visual segmentation that may facilitate the development of increasingly precise representations of individual words (Huettig and Pickering, 2019).

The instructional videos used in this study were also intentionally designed to be highly structured and predictable. Across learning episodes, infants repeatedly experienced the same sequence in which they heard the target word, saw its written form, and then observed its meaning demonstrated. This consistent organization provided a stable learning framework while multiple aspects of the experience were intentionally varied across exemplars, including speaker, intonation, font, word color, background color, and demonstrations of meaning. Each target word was spoken twice. Usually the two instances used different speakers; when the same speaker was used, intonation was varied. From a predictive processing perspective, this combination of stable relational structure and intentional variability may have supported increasingly accurate predictions about the relationships among spoken words, written words, and their referents while also providing evidence that those relationships remained stable across changing perceptual features (Clark, 2013; Köster et al., 2020). Predictive processing also clarifies the role of meaningful feedback. When an infant sees *clap*, hears *clap*, and observes or performs the action, the event provides several ways to test an expectation. When a prediction is confirmed, prediction error is reduced, whereas a mismatch provides information for revision (Clark, 2013; Köster et al., 2020). Repeated coordinated experiences thus create cycles of prediction, feedback, and refinement.

Predictive processing predicts effects of timing, quantity, and variety. Earlier introduction allows predictions to influence subsequent attention and learning over a longer developmental period. Greater frequency provides more opportunities for cycles of prediction, feedback, and updating. Greater variety tests whether learned relationships generalize across different speakers, fonts, backgrounds, materials, and everyday contexts. Repeated agreement between written and spoken information should also increase the precision, or confidence, of predictions about corresponding spoken words and meanings (Clark, 2013). Within the present framework, reciprocal developmental relationships between written and spoken language are expected because each modality provides complementary evidence about the same underlying linguistic forms and meanings, allowing predictions generated in one modality to be refined through experience in the other.

Bayesian Learning

Bayesian approaches describe learning as probabilistic inference under uncertainty (Gopnik and Tenenbaum, 2007). Learners bring prior expectations to new evidence and update the relative probability of alternative interpretations. Infants need not perform conscious calculations—this framework formalizes how accumulated evidence changes which hypotheses are best supported (Gopnik and Tenenbaum, 2007).

Word learning presents a classic problem of uncertainty—a novel word heard in a complex scene could refer to an object, an action, a property, a part, or the entire event (Quine, 1960; Gopnik and Tenenbaum, 2007). Any single encounter may be ambiguous. Across encounters, however, some interpretations receive repeated support while others do not. Cross-situational evidence can gradually constrain the mappings that best explain the observations (Smith and Yu, 2008).

Multiple language environments make this problem more complex but also reveal the adaptability of probabilistic learning (Zinszer et al., 2018). Infants and children can revise expectations such as mutual exclusivity when the linguistic environment provides evidence that more than one label may refer to the same object. Priors are therefore not fixed rules. They are expectations calibrated by experience (Gopnik and Tenenbaum, 2007; Zinszer et al., 2018). Each

coordinated experience with spoken and written language provides another observation from which probabilistic expectations can be updated.

Synchronized written and spoken language provides an additional source of evidence. When a stable written form, spoken form, and referent repeatedly occur together, confidence that they participate in the same linguistic relation should increase. A single pairing may provide weak evidence, whereas repetition across contexts strengthens the mapping. Variation is also informative because it reveals which properties remain constant as fonts, colors, speakers, positions, and situations change.

Written language may further reduce uncertainty about distinctions that speech alone specifies incompletely. Homophones can remain ambiguous in the auditory signal but distinct in print. Related words can preserve visible similarities even when their pronunciations differ. For example, *sign* and *signature* share a visible pattern that reflects their relationship, although the shared letters are pronounced differently in the two words. Written language can therefore provide stable visual information about relationships among words that may be less apparent from speech alone. Visible word boundaries may also constrain alternative segmentations of continuous speech. Each additional source of structured evidence can narrow the range of plausible interpretations without explicit instruction.

Bayesian learning therefore predicts cumulative and graded outcomes. Learning need not proceed at a constant rate. As accumulating evidence narrows the range of plausible interpretations, prior knowledge can make new observations increasingly informative, allowing substantial learning from relatively little evidence (Tenenbaum et al., 2011). Earlier introduction permits more observations to shape subsequent expectations. Greater frequency and duration increase the available evidence, while greater variety supports generalization by showing that the relevant relation survives changes in context. Written and spoken outcomes should be related because evidence from both modalities contributes to a shared probabilistic model of linguistic forms and meanings.

Dynamic Systems Theory

The preceding theories offer explanations of how infants learn from experience. Dynamic systems theory addresses a different question—how repeated learning experiences reorganize development itself. Rather than focusing on a single mechanism, it explains how interactions among the child, caregiver, task, and environment produce new developmental patterns over time (Thelen and Smith, 1994; Smith and Thelen, 2003). This broader perspective provides a natural bridge from mechanisms of learning to mechanisms of developmental change.

Dynamic systems theory (Thelen and Smith, 1994; Smith and Thelen, 2003) explains development as a process of continuous reorganization that emerges through interactions among multiple components rather than through the maturation of isolated abilities. Perception, action, attention, memory, caregiver behavior, and characteristics of the environment continually influence one another, allowing small developmental changes to alter subsequent learning opportunities.

Applied to the present framework, synchronized spoken and written language represents another component of the developing learning environment. Visible words become one additional source of meaningful information that interacts with spoken words, caregiver behavior, visual attention, object exploration, and social interaction. As these interactions accumulate across everyday

experiences, small changes in one component may influence subsequent learning in others, producing developmental trajectories that differ from those expected when spoken language alone is available.

Accordingly, dynamic systems theory predicts that developmental outcomes should depend not only on the presence of written language, but also on the age at which meaningful experiences begin, the quantity of those experiences, and the variety of contexts in which they occur. Earlier experiences provide more opportunities for interactions among developing systems. Greater quantities of experience allow those interactions to accumulate over time. Greater variety promotes increasingly flexible developmental organization across changing situations. Within the present framework, these principles predict reciprocal developmental relationships between spoken and written language that emerge through repeated developmental interactions rather than through isolated learning events.

Oller's Growth-Spiral Account

The preceding theories explain how infants attend to information, extract regularities, generate expectations, update those expectations, and reorganize development through repeated experience. Oller's growth-spiral account addresses the next developmental question—once meaningful linguistic accomplishments emerge, how do those accomplishments support increasingly advanced learning?

Instead of viewing each new achievement as an endpoint, Oller proposes that successful language use creates opportunities for additional learning, allowing development to accelerate as previously acquired knowledge becomes available for subsequent accomplishments (Oller, 2022).

Applied to the present framework, and consistent with Oller and colleagues' broader account of language development (Oller et al., 2012), early learning about written language may likewise become part of the foundation supporting subsequent spoken and written language development. Initial understanding of a small number of written words may facilitate learning additional written words, strengthen relationships between spoken and written forms, and provide increasingly rich opportunities for detecting linguistic structure across subsequent experiences.

Accordingly, Oller's growth-spiral account predicts that earlier meaningful accomplishments should support increasingly rapid subsequent learning. Earlier introduction provides more time for developmental spirals to emerge. Greater quantities of meaningful experience provide additional opportunities for successful accomplishments to accumulate. Greater variety expands the range of situations in which established knowledge can support new learning. Within the present framework, these principles predict reciprocal developmental relationships between spoken and written language that strengthen as each accomplishment becomes the basis for subsequent developmental change.

Shared Developmental Predictions

Although these theories differ substantially in their mechanisms, historical origins, and the developmental questions they address, they converge on a remarkably similar set of developmental predictions. Each framework addresses a different aspect of development—how attention is directed, how regularities are extracted, how expectations are generated and updated, how repeated experiences reorganize development, and how successful accomplishments support subsequent learning—yet all independently predict that earlier, meaningful, repeated, and varied

experiences should promote stronger developmental outcomes. Their agreement is scientifically informative precisely because it emerges independently rather than through shared theoretical assumptions. The empirical analyses that follow therefore evaluate a broader pattern of theoretical convergence rather than the predictions of any single developmental framework.

These converging theories also predict that increasingly robust linguistic representations should support progressively more efficient language processing (Fernald et al., 2006; Christiansen and Chater, 2008, 2016; Clark, 2013; Oller, 2022), suggesting that early written language experience may ultimately influence the speed and automaticity with which spoken and written language are recognized and integrated.

Scientific confidence is often strengthened when independent theoretical perspectives converge on similar predictions despite differing assumptions and explanatory mechanisms. Such convergence, often described as consilience, has long been regarded as strengthening scientific confidence because independent explanatory approaches arriving at compatible predictions reduce the likelihood that their agreement is merely coincidental (Whewell, 1840/1847; Wilson, 1998).

The present framework is also relatively parsimonious because it relies primarily on developmental mechanisms already established independently of written language and introduces few novel theoretical claims specific to written language. It does not require a specialized mechanism for infant reading. Rather, it proposes that perceptual and domain-general learning processes already operating during infancy are compatible with written language, and that infants can simultaneously learn the written language system and learn from it, just as they simultaneously learn spoken language and learn from spoken language. As knowledge develops across written language, spoken language, and meaning, information acquired through either form of language may influence subsequent learning through the other, allowing reciprocal developmental relationships to emerge from the earliest stages of learning.

The analyses that follow therefore examine whether the developmental patterns observed in the dataset correspond to these shared theoretical predictions.

Materials and Methods

Participants

Participants were parents of infants and young children who had been exposed to an early language program designed to present written language and spoken language in a temporally coordinated manner. The initial dataset contained 778 records. In families reporting on more than one child, one child was randomly selected for inclusion in analyses requiring independent observations, and additional children from the same family were excluded from those analyses. Families were invited to participate through an email distributed to program users. The recruitment email requested participation from families who had used the program videos at least five times per week for a minimum of two months and had English as the primary language spoken in the home. However, reported use varied, and 216 of the 778 records indicated video use fewer than five times per week. These responses were not subsequently excluded on the basis of reported frequency of use. The questionnaire separately asked whether English was the child's first language; 736 respondents answered yes, 28 answered no, and 14 did not provide a response. These responses were also not used as a basis for exclusion.

Participants were recruited through program enrollment and voluntarily provided information about their child's language development. Families did not receive compensation of any kind for participation, including no payment, no free products, no discounts, and no other incentives. Children ranged from early infancy through early childhood, from 3 months to 72 months of age at the time of testing, allowing examination of language outcomes across a broad developmental range. Parents provided informed consent for participation as part of the data collection process. All procedures involving human participants were conducted in accordance with ethical standards.

The dataset analyzed in this study was independently maintained and secured by Dr. Golshan (University of California, San Diego), who provided access following data collection. Dr. Golshan also performed the random selection of one child per family for analyses requiring independent observations. The author was not involved in original data storage, management, or selection procedures.

Ethics Approval and Consent to Participate

The data analyzed in this study were previously collected in 2010 through voluntary parent or legal guardian questionnaires completed by families who had purchased and used the early language program. Parents or legal guardians provided information voluntarily as part of the data collection process. Because the participants were minors, all developmental information was provided by parents or legal guardians. The study involved no direct researcher interaction with children or families for research purposes, no experimental manipulation imposed by the researcher, and no procedures beyond families' prior use of the educational materials in natural home settings. Children who responded to parent-administered activities did so within ordinary parent–child interactions at home rather than through researcher-administered testing.

Formal child assent was not obtained. Infants and very young children were not developmentally capable of providing formal assent. Older children participated only through ordinary parent-administered activities conducted in home settings and did not provide research data directly to the researcher. Findings were analyzed and reported in aggregate in a manner designed to protect participant privacy and wellbeing. The project was treated at the time as a voluntary parent questionnaire and program evaluation dataset for which formal Institutional Review Board approval was not considered necessary.

Materials and Procedure

The early language program, developed by the author, consisted of videos, books, and word cards presenting infant directed text, together with guidance for parents on how to use the materials during everyday interactions. These materials were designed to allow babies to perceive visual and auditory aspects of language together within meaningful contexts.

Videos presented written words in large, high-contrast text, with visual highlighting progressing from left to right as each corresponding word was spoken. Isolated written words were shown more than once in succession by a range of speakers, including girls, boys, women, and men across different ages, usually by different speakers or, when the same speaker was used, with clearly varied intonation. These initial instances were typically followed by short, meaningful phrases or sentences in which the same word was used in context, while the child viewed video segments depicting the meanings of the words. Many segments also included simple, developmentally appropriate interactive prompts (e.g., encouraging the child to clap, wave, or

touch body parts such as their nose or ear), supporting engagement and reinforcing word–meaning mappings.

Parents could use the videos in two ways that fit naturally within many everyday family routines. One was during periods when parents were occupied and unlikely to be providing direct language interaction. The other involved joint media engagement, in which parents watched with their child and enriched the experience by touching named body parts, helping the child perform actions, pausing the video to reinforce meanings, or showing corresponding objects in the child's environment. Research on active co-viewing indicates that such parental scaffolding can support young children's word learning and transfer of information from video to the real world (Strouse and Troseth, 2014; Strouse et al., 2018).

Across the videos, books, and word cards, nonessential perceptual features such as font, color, size, background, and design were systematically varied while the identity of the word and its underlying meaning remained stable. This variability was intended to support the extraction of invariant written word forms across changing visual contexts, consistent with theories of perceptual learning emphasizing the detection of invariant structure across variable input (J. J. Gibson, 1966; E. J. Gibson, 1969). Auditory variability was also included through the use of multiple speakers and varied intonation, allowing children to hear the same words across a range of voices. Together, these visual and auditory variations were designed to help infants map written language, spoken language, and meaning across changing surface features.

The objects, actions, and events used to demonstrate each word's meaning were also varied, so that the same underlying meaning was represented across multiple visual exemplars rather than through repeated presentation of a single instance. This approach may have helped reduce ambiguity in word–referent mapping by allowing children to compare across instances and eliminate incorrect interpretations, thereby supporting more efficient learning of word meanings.

This design was also informed by prior experimental findings indicating that infants' responses can be influenced by motor patterns independent of representational knowledge (Smith et al., 1999). For example, repeated responding to a fixed spatial location can increase the likelihood of subsequent responses to that same location, even when task-relevant information changes (Smith et al., 1999). To minimize the influence of such motor biases and to ensure that responses reflected recognition of written words rather than learned response patterns, parents were instructed to vary the spatial position of words across trials. For example, when two words were presented, the target word could appear on the left on one trial and on the right on another, or above the alternative on one trial and below it on another.

In addition, parents were encouraged to engage children in interactive question-based exchanges (e.g., "Which word says clap?"), allowing learning to occur through active responding and feedback, consistent with protoconversational turn-taking frameworks in early development (e.g., Bruner, 1983). These interactive motor activities were also informed by theoretical perspectives suggesting that engaging multiple sensory and motor systems concurrently may support learning by recruiting distributed neural pathways, thereby strengthening the integration of perceptual, motor, and cognitive processes (Edelman, 2007).

Parents were also instructed to assess their child's ability to recognize written words. Testing procedures involved presenting written words without accompanying auditory cues and asking children to indicate meaning through observable responses such as looking, pointing, acting, vocalizing, or saying the word, selecting between alternatives, or indicating the referent (e.g.,

touching body parts corresponding to the word's meaning). Children responded using whatever motor and language abilities were available to them at their developmental level. Parents were instructed to vary visual features and spatial location across trials to ensure that recognition reflected generalized knowledge rather than memorization of specific visual instances or response patterns.

According to the operational definition used in this study, infants had to consistently recognize individual written words. Because color, background, and other visual features were not reliable cues to word identity, consistent recognition depended primarily on discriminating the visual shapes of the words.

Parent reports that did not include an interpretable numeric estimate (e.g., statements such as "too many to count" or "reading at a second grade level") were excluded from quantitative analyses because they could not be interpreted consistently.

Program use varied across families in terms of age of onset, frequency of use, and duration. Frequency measures primarily reflected video viewing, although families also reported use of books and word cards.

Measures

Parent reports were used to assess children's written word reading, receptive language, expressive language, and exposure to the program. Parent-report measures are widely used in developmental research and are considered reliable and valid indicators of early language development when appropriate procedures are used (e.g., Dale, 1991; Fenson et al., 2007; Marchman and Fernald, 2008). Parents observe their children across a wide range of naturalistic settings and over extended periods of time, allowing them to report on behaviors that may not be captured in brief assessments.

In the present study, parents were provided with specific guidance for assessing written word reading, including testing across variations in font, color, and context, and using observable response formats such as pointing, acting, or selecting between alternatives. These procedures were designed to ensure that reported responses reflected consistent recognition of written words and their meanings, rather than responses based on incidental perceptual features such as font color, background color, size, or material. Parent report is particularly well suited to early development, where children's performance in brief testing sessions may underestimate their knowledge, and where structured parent-administered procedures have been shown to yield results comparable to those obtained in controlled assessments when clear guidelines are provided (Dale, 1991; Fenson et al., 2007; Marchman and Fernald, 2008).

The primary variables included age of program start, frequency and duration of use, material variety, written word reading, receptive language, and expressive language. Frequency was operationalized primarily as weekly video viewing, duration as months of use, and variety as the number of material categories used weekly (videos, books, and word cards).

Written word reading was operationally defined as the consistent recognition of written words with meaning across variations in visual presentation, including differences in font, color, and context, when the written word was presented without accompanying auditory cues. Receptive and expressive language were assessed using parent-reported estimates of words understood and words produced.

Data Analysis

Analyses examined associations among written word reading, age at testing, age of program start, frequency, duration, and material variety. Pearson and Spearman correlations were used as appropriate; partial Spearman correlations controlled for age in duration and variety analyses. Variety analyses required complete frequency data for all program materials and use of at least one material category. Group comparisons and regression analyses were conducted as described below.

Where appropriate, analyses controlled for chronological age to account for developmental differences. Additional subgroup analyses were conducted to examine outcomes associated with earlier versus later program start and with higher versus lower levels of program use. Regression analyses were conducted to examine the independent contributions of age at testing, age of program start, and program use frequency to written word reading and spoken language outcomes.

Results

Analyses were conducted on one child per family. Cases with missing values were excluded from the relevant analyses.

Distribution of Written Word Reading

Among children whose parents reported testing written word recognition and provided numeric responses ($N = 525$), 470 children (89.5%) were reported to read at least one word. The number of written words read varied widely across individuals, ranging from no words to at least 1,000 words. In addition, 242 children (46.1%) were reported to read 25 or more words, 74 children (14.1%) were reported to read 100 or more words, 10 children (1.9%) were reported to read 500 or more words, and 5 children (1.0%) were reported to read at least 1,000 words. The distribution of the number of written words read across these children is shown in Figure 1.

Age of Program Start, Frequency, and Written Word Reading

To examine predictors of written word reading while accounting for developmental differences, a regression analysis was conducted using age in months. The model predicted log-transformed written word reading from age at testing, age of program start, and total weekly frequency of program use. The analysis included 522 children with complete data on these variables.

Age at testing was positively associated with written word reading ($p < .001$), indicating that older children read more words, as expected. Earlier age of program start was independently associated with higher levels of written word reading after controlling for age at testing and program use frequency ($p = .039$). Greater frequency of program use also independently predicted higher levels of written word reading ($p < .001$). These findings indicate that both earlier age of program start and greater experience were associated with higher levels of written word reading. Results of the regression analysis are presented in Table 1.

Duration and Variety of Experience

Longer duration was associated with higher written word reading, words understood, and words said (all Spearman $p < .001$), and each association remained significant after controlling for age: reading (partial rho = .189, n = 523, $p < .001$), understood (rho = .115, n = 627, p = .004), and said (rho = .123, n = 635, p = .002).

Greater material variety was associated with higher written word reading (n = 473, Spearman rho = .217, p < .001) and remained significant after controlling for age (partial rho = .182, p < .001). Variety was also positively associated with words understood and words said in zero-order analyses, but neither remained significant after age was controlled.

Developmental Trajectory Among Very Early Starters

To examine outcomes following very early experience, a subgroup of children who began the program before 5 months of age and were tested by their parents was analyzed (n = 161). Written word reading in this subgroup showed a developmental progression across age at testing. Written word reading by age at testing among children who began before 5 months of age is presented in Table 2. Median written word reading before 12 months of age was 4 words. This level is comparable to early expressive vocabularies reported at this age and suggests that written word recognition can emerge alongside, and in some cases prior to, spoken word production under conditions of early and consistent exposure.

Across age groups, median written word reading increased with age, with particularly large gains observed among children 24 months and older. However, substantial variability was observed within age groups, indicating that outcomes were not uniform even under early experience conditions.

High-Fidelity Early Starters

A high-fidelity early starter subgroup was defined as children who began the program before 5 months, were tested by their parents for written word recognition, used the program's videos at least 10.5 times per week (the midpoint of the program's recommended once- or twice-daily schedule), and also used the program's books and word cards.

Written word reading was observed early in development within this subgroup and showed substantial variation across age. Median written word reading was 4 words among children younger than 12 months, 30 words at 12–17 months, and 22.5 words at 18–23 months. Among children 24–35 months, only two children in this subgroup had reached this age range. One was reported to read 500 words, and the other was reported to read 1,000 words.

Considerable variability was observed within age groups, indicating that outcomes were not uniform even under early and consistent exposure. Nevertheless, measurable levels of written word reading were present even among the youngest children, with higher levels emerging as age increased.

Receptive and expressive spoken language also increased across age in this subgroup. Written word reading and spoken language outcomes by age among high-fidelity early starters are presented in Table 3.

Developmental Patterns Across Age

Patterns of written and spoken language across age groups are shown in Figure 2, highlighting variation across developmental stages. These data reflect cross-sectional observations rather than longitudinal trajectories, but provide a visual representation of how written word reading, words understood, and words said tend to increase across developmental time.

Engagement, Interest, and Enjoyment

Parent-reported engagement was high overall and varied by age of program start. Engagement remained above 90% among children who began at 18 months or younger and was lower among children who began at 19 months or older. Engagement by age of program start is shown in Table 4.

Interest and enjoyment ratings showed a clear age-of-start pattern, with the strongest positive ratings among the earliest starters. Among children who began at 6 months or younger, 51.6% were reported to love the program and 48.1% were reported to enjoy it; only 0.3% were reported to dislike it, and none were reported to hate it. Among children who began at 19 months or older, 25.7% were reported to love the program, 63.7% to enjoy it, 8.8% to dislike it, and 1.8% to hate it. Detailed interest patterns across age groups appear in Table 5.

Across groups, the proportion of children reported to love the program decreased from 51.6% among those who began at 6 months or younger to 25.7% among those who began at 19 months or older, while overall enjoyment remained high, with the vast majority of children reported to either enjoy or love the program.

Among children who began before 5 months of age, 52.6% were reported to love the program (120/228), and 99.6% were reported to either enjoy or love it (227/228). These rates were similar among children who began at 5–6 months, of whom 50.0% were reported to love the program (52/104) and 100.0% were reported to either enjoy or love it (104/104), with no statistically significant difference between groups (Fisher's exact $p = .723$ for "loved it"; $p = 1.000$ for "enjoyed or loved"). By contrast, among children who began at 7 months or later, 33.0% were reported to love the program (131/397), indicating that the most pronounced decline in highly positive engagement occurred after the first 6 months (Fisher's exact $p < .001$ for comparison with <5 months).

Differences across age of program start were statistically significant for engagement, interest, and enjoyment (all $p < .0003$).

Parent-Reported Future Impact of the Program

Parents reported overwhelmingly positive perceptions of the program's impact on their child's future development. The proportion reporting a very positive impact decreased as age of program start increased.

The proportion of parents reporting no impact remained low across all groups, ranging from 1.7% to 4.5%. Responses were concentrated in the positive and very positive categories, and no parent selected negative options for this item. Ratings of future impact across age groups are summarized in Table 6.

Associations Between Written Word Reading and Spoken Language

Written word reading was positively associated with both receptive and expressive spoken language. Children with higher levels of written word reading tended to understand more spoken words ($n = 461$, Pearson $r = 0.23$, Spearman $rho = 0.46$, $p < .001$) and to say more spoken words ($n = 465$, Pearson $r = 0.44$, Spearman $rho = 0.48$, $p < .001$).

Additional Observations for Children 37–72 Months of Age

Among children older than 36 months, written word reading continued to increase with age. When grouped by age, average reported reading levels were approximately 420 words for children 37–40 months, 520 words for 41–45 months, 610 words for 46–50 months, and 720 for children older than 50 months. Individual variability remained high within age groups, including reports of both relatively low and very high word counts.

These values should be interpreted cautiously due to smaller sample sizes and variability in reported outcomes. However, the overall pattern is consistent with the broader developmental trends observed in younger children, with higher levels of written word reading associated with increasing age.

Summary of Findings

Across analyses, written word reading was associated with age, earlier program start, greater frequency and duration, greater material variety, and stronger spoken language outcomes. Earlier start predicted higher reading independent of age and frequency; duration and variety remained associated with reading after controlling for age.

Discussion

The present findings contribute to a growing body of evidence suggesting that written language may function as natural visual language information when introduced alongside meaningful spoken language during infancy. Although no single study can resolve this question, the present findings are notable because they converge with several largely independent sources of evidence. Historical observations, contemporary developmental theories, research on audiovisual language learning, reciprocal relationships between written and spoken language (Eklund et al., 2018; Huettig and Pickering, 2019), and the developmental patterns observed in the present study all point toward the same scientific question—under what developmental conditions can written language contribute to early language learning during infancy?

This convergence is theoretically important because these lines of evidence arose largely independently. Historical reports of infants responding to written words were documented long before contemporary theories of statistical learning, predictive processing, Bayesian learning, or intersensory redundancy became influential. Likewise, those theoretical frameworks were developed to explain broad aspects of perception, learning, and development rather than written language specifically. Yet together, these frameworks predict that developmentally accessible, meaningful, structured, and repeatedly experienced information should facilitate learning. The proposal that written language can be experienced alongside meaningful spoken language during infancy is consistent with those theoretical predictions.

The present findings also converge with a broader body of research examining early written language experiences. Collectively, these studies have reported that some infants and toddlers exposed to enriched written language environments acquired meaningful written word knowledge without formal rule-based instruction, and in some cases appeared to discover regularities linking written and spoken language through experience (e.g., Terman, 1918; Doman, 1964; Söderbergh, 1977; Baghban, 1984; Kamada, 1997; Titzer, 1998; Cohen and Söderbergh, 1999; Inan, 2010). Although these reports vary in methodology and most involve relatively small samples, they consistently indicate that the natural acquisition of written language during infancy is possible under at least some developmental conditions. Yet these

observations did not lead to a sustained program of scientific research on written language learning during infancy.

This absence is particularly striking because some researchers were already challenging traditional assumptions about how early reading could begin. Fowler (1962), for example, experimentally examined reading with a two-year-old child, while Durkin's (1966) longitudinal work showed that children who learned to read before school maintained later reading advantages over comparable children matched on age, sex, IQ, and socioeconomic factors. Nevertheless, systematic research did not continue backward into infancy. At the same time, highly publicized claims that babies could be taught to read became associated with approaches such as Doman's (1964), but these claims emerged within a scientific climate in which reading was generally expected to follow developmental readiness and mastery of prerequisite skills, often including letter naming, and in which beginning reading instruction too early was sometimes considered ineffective or even harmful (Morphett and Washburn, 1931; see Hanson and Farrell, 1995, for discussion of these historical assumptions). Prevailing conceptions of reading may have created an additional barrier because babies reading words, or even sentences, could be discounted as evidence of genuine reading when children could not demonstrate the component skills considered prerequisite for reading (van Kleeck and Schuele, 2010). Collectively, this history suggests that the absence of sustained research during infancy may reflect not an absence of relevant observations, but the theoretical assumptions through which those observations were interpreted.

The present framework therefore does not depend on any single theoretical perspective. Instead, it evaluates whether several influential theories independently generate compatible predictions regarding written language during infancy. Because these frameworks address different developmental questions rather than different versions of the same explanation, their convergence provides a broader scientific rationale for investigating written language as one potential source of natural visual language information rather than viewing it solely as a later academic skill.

The reciprocal developmental processes emphasized by dynamic systems theory are also consistent with broader transactional perspectives on development, which likewise describe development as emerging through continuous interactions between children and their caregiving environments (e.g., Belsky, 1984; Sameroff, 2009). Although these perspectives differ in emphasis and scope, their convergence further illustrates how multiple independent developmental frameworks now point toward similar expectations regarding the value of rich, responsive learning environments during infancy.

This broader shift is also consistent with Edelman's (1987) perspective that neural development is shaped through meaningful experience and the selective strengthening of successful patterns of neuronal activity. From this perspective, repeated coordinated spoken and written language experiences during infancy might be expected to strengthen and refine neural systems supporting language (Edelman, 1987). This possibility may be especially relevant during infancy, a period of heightened neuroplasticity in which experience can shape the organization of developing neural systems (White et al., 2013; McLaughlin et al., 2019; Peyton et al., 2022). Earlier coordinated experience with spoken and written language may therefore provide more opportunities for these representations to become integrated as language systems develop. Whether such experiences contribute to more efficient neural organization remains an empirical question. As developmental science has increasingly emphasized experience-dependent learning,

attention, and active engagement, the learning conditions surrounding language have themselves become scientifically important (Miller, 2022). Contemporary theories therefore encourage investigation not only of what infants learn, but also of which developmental environments best support learning.

One implication concerns how written language is introduced. Infants ordinarily encounter spoken language as meaningful whole words and utterances embedded in objects, actions, gestures, touch, repetition, and responsive interaction, whereas written language has often been introduced through letter names, letter sounds, phonological awareness, and decoding before extensive experience connecting visible words with meaning. The present study examined a different developmental environment: written and spoken words were paired within meaningful multisensory interactions during ordinary family routines, without requiring infants to begin with explicit rules or isolated components. The findings therefore raise the possibility that how and when written language is introduced may substantially influence how it contributes to early language development.

The empirical findings are likewise consistent with these theoretical expectations and provide a natural transition from theory to observation. Earlier introduction, greater frequency of experience, longer duration of experience, and greater variety of meaningful written language experiences were each associated with stronger developmental outcomes. Positive associations between written word reading and both receptive and expressive spoken language were also observed. These associations are consistent with the predicted reciprocal developmental relationships between written and spoken language, but the present data cannot establish directionality. Within this framework, written language may provide infants with an additional, systematically related source of information about the same language they are already learning through speech. These findings cannot establish causality, but they identify developmental patterns that correspond closely to predictions generated independently by multiple contemporary theories.

Considered together, these findings are noteworthy because they correspond closely to developmental predictions derived independently from several complementary theoretical perspectives rather than from a single explanatory framework. Because each framework addresses a different developmental question, the overall developmental pattern is more informative than any individual result and provides a broader theoretical rationale for continued investigation of the influence of written language on language learning and overall development.

In this study, 331 out of 332 babies who began simultaneously seeing and hearing words either loved or liked the experience according to their parents, while one baby disliked it, and no babies hated it. As children began seeing and hearing words at later ages, they were less likely to love it and more likely to dislike or hate it. Attention and positive engagement are not merely incidental reactions to learning materials. They influence which information infants continue to process and for how long, thereby increasing opportunities to form predictions, minimize prediction error, and refine developing internal models over repeated experiences (Bahrick and Lickliter, 2000; Bahrick et al., 2004; Kidd et al., 2012; Clark, 2013). Caregivers also respond contingently to infants' attention and engagement, often adapting, extending, and elaborating interactions in response to children's cues (Smith and Yu, 2008; Mason et al., 2019; Masek et al., 2021; Phillips et al., 2025). Within a dynamic systems perspective, these reciprocal interactions continuously reorganize relationships among the infant, caregiver, and learning environment, creating

additional opportunities for meaningful, repeated, and varied learning experiences (Thelen and Smith, 1994; Smith and Thelen, 2003).

An important implication concerns the nature of infant reading itself. Within the present framework, recognizing a written word is not viewed as an isolated visual skill. Like understanding a first spoken word, recognizing a written word reflects the coordinated operation of perceptual, attentional, memory, linguistic, cognitive, motor, communicative, and social processes. The developmental significance therefore lies less in the printed word itself than in what successful recognition reveals about the developing language system.

Naturally, several limitations should be considered. The present study relied on parent-reported data, and causal conclusions cannot be drawn from correlational evidence alone. Parents differed in the amount, frequency, and variety of experiences they provided, and unmeasured variables may also have contributed to the observed associations. Nevertheless, the findings were not limited to isolated reports of unusually high achievement. Systematic developmental patterns emerged across multiple predictors, and their close correspondence to independently derived theoretical predictions strengthens the scientific rationale for continued investigation while underscoring the need for prospective, experimental, and longitudinal research.

Some reassurance comes from convergence with an independent prospective evaluation by Hare, Baldwin, and Okoth (2013) in a predominantly low-income sample using the same materials. At the one-month assessment, 54.55% of caregivers reported that their child loved the materials, 33.33% reported that their child definitely liked them, and 12.12% reported that their child sort of liked them; no caregiver reported that their child disliked the materials. At the final assessment, 81% of responding caregivers reported that their child had learned to read some words. These outcomes were also based on caregiver report, and the final assessment was subject to substantial attrition. Nevertheless, broadly similar reports obtained independently in a socioeconomically different sample provide useful converging evidence.

Additional converging evidence comes from a separate observational study of 71 children aged 10–23 months. Children with at least seven months of experience with the same early language program obtained substantially higher examiner-administered standardized spoken language scores than a comparison group matched on socioeconomic status. Mean overall language scores were 119.97 in the enrichment group and 100.57 in the comparison group, a 19.40-point difference corresponding to a very large between-group effect of approximately $d = 1.78$ (Johnson and Titzer, 2026, manuscript submitted for publication).

The same study also found a very large between-group difference on the Bayley-III Cognitive scale, with mean scores of 112.10 in the enrichment group and 87.86 in the comparison group, a difference of 24.24 standard-score points and an effect size of approximately $d = 1.84$. A separate manuscript reporting these cognitive findings will be submitted shortly. Taken together, the convergence of parent-reported developmental patterns, standardized language assessment, and cognitive outcomes across different measures provides an additional form of consilience and broadens the scientific question beyond language. These findings raise the possibility that meaningful early written language experience may be associated not only with language development, but also with broader cognitive development. Because these studies were observational, however, the between-group differences do not establish causality.

Future Research

The broadest question for future research is whether developmental science has overlooked the role of written language as natural visual language information during infancy. This question is larger than whether infants can recognize written words. It asks whether written language, when made meaningful and easy for infants to perceive during a period of especially rapid spoken language development, can provide another source of information that helps them learn language.

A first priority is to determine the conditions under which meaningful written language experience during infancy most strongly supports development. Research should examine how timing, frequency, duration, variety, meaningfulness, synchrony, perceptual accessibility, and caregiver interaction shape the reciprocal relationships between written and spoken language over time. Repeated assessment of both forms of language could help identify when these relationships first emerge, how they change with experience, and which early learning conditions lead to the strongest developmental outcomes.

A second major question concerns how these effects occur. If written language contributes to development, research should determine what infants are learning from it and how that learning affects what they are able to learn next. Written words may help infants notice linguistic structure, provide stable representations of words that disappear quickly in speech, make word boundaries easier to detect, strengthen connections among written forms, spoken forms, and meanings, and provide additional opportunities to discover regularities within language. Behavioral and neurodevelopmental research could also examine whether early experience changes how efficiently spoken and written language are recognized and integrated. More specific possibilities, including changes in visual attention or sensitivity to shape, can be examined within this broader question of how early written language experience influences learning.

Another central question is when and under what conditions these developmental effects are most likely to occur. Timing, frequency, duration, variety, meaningfulness, synchrony, perceptual accessibility, and caregiver interaction should be treated as important features of infants' learning experiences rather than simply details of an intervention. Experimental studies will be valuable, but they should also measure the experiences individual infants actually receive. The important question is not simply whether written language was presented, but what information was available to the infant, when it became available, how often it was experienced, and whether it was meaningful enough to support learning.

Cross-linguistic research can provide especially informative tests because different languages and writing systems make different aspects of language visible. Alphabetic, syllabic, and logographic writing systems, as well as relatively transparent and opaque orthographies, make different relationships among written language, speech, word structure, and meaning available to learners. Comparing learning across these languages and writing systems could help identify which effects reflect broad principles of human learning and which depend on particular properties of a language or orthography. Multilingual infants may provide especially valuable opportunities for understanding how written language helps learners distinguish among different linguistic patterns while also recognizing meanings that are shared across languages.

Finally, one of the most important questions for future research concerns what very early written language learning may mean over the longer course of development. Contemporary theories of

learning and development generally predict that early learning influences later learning because what infants already know changes what they can notice, predict, understand, and learn next. This prediction is also consistent with evidence that words acquired earlier are generally processed more rapidly and that early spoken language processing efficiency is related to subsequent language development (Juhasz, 2005; Fernald et al., 2006). Early written and spoken language knowledge may therefore become mutually reinforcing—growth in one can support learning in the other, while each new accomplishment can make later learning easier (Eklund et al., 2018; Huettig and Pickering, 2019). When meaningful written language experience begins during infancy and continues under conditions that support learning, the present account therefore predicts that early advantages may accumulate and become increasingly important over time.

Future longitudinal research should test this prediction directly and identify the conditions under which these advantages are sustained or amplified. Timing, frequency, duration, variety, meaningfulness, and quality are likely to matter because limited or inconsistent experience may provide little opportunity for cumulative effects to develop. If reciprocal relationships between written and spoken language begin during infancy, even relatively small differences in when meaningful written language first becomes available could ultimately contribute to much larger differences as learning builds upon earlier learning. Establishing whether this occurs, and under what conditions, could have important implications not only for written and spoken language development, but for a much broader question: how the experiences we provide during the earliest months of life can help children learn, develop, and thrive.

Conclusion

The present findings are broadly consistent with the proposal that written language may function as natural visual language information when introduced alongside meaningful spoken language during infancy. More importantly, the observed developmental pattern corresponds closely to predictions derived independently from multiple representative developmental frameworks, historical observations, research on audiovisual language learning, and evidence concerning reciprocal relationships between written and spoken language. This convergence provides a stronger scientific rationale for continued investigation than any single line of evidence considered in isolation.

No single study can determine the developmental role of written language. However, when several independent lines of evidence point toward the same scientific question, that convergence provides a strong rationale for continued investigation. Contemporary developmental theories increasingly emphasize that infants learn by integrating meaningful information across sensory modalities, detecting statistical regularities, generating predictions, updating expectations, and continuously reorganizing knowledge through experience. The present framework proposes that written language may participate in these same developmental processes when introduced in ways that resemble the meaningful contexts through which spoken language is naturally acquired.

This paper integrates contemporary developmental theory, historical observations, and empirical findings into a coherent developmental framework that generates specific, testable predictions concerning the role of written language during infancy.

If future research continues to support these predictions, written language may come to be viewed not solely as a school-based academic skill that children eventually learn, but also as a

source of structured language information from which they can learn during development. Written language may therefore constitute one component of the broader language environment available to infants during the earliest stages of development. The present findings therefore support continued investigation of written language as natural visual language information during infancy.

Data Availability Statement

The de-identified data supporting the findings of this study are available from the corresponding author upon reasonable request, subject to appropriate protections for participant privacy and confidentiality.

Ethics Statement

The data analyzed in this study were previously collected in 2010 through voluntary parent or legal guardian questionnaires completed by families who had purchased and used the early language program. Parents or legal guardians provided informed consent for participation. The project was treated at the time as a voluntary parent questionnaire and program evaluation dataset for which formal Institutional Review Board approval was not considered necessary.

Author Contributions

RCT: Conceptualization, methodology, original program development, formal analysis, interpretation, writing—original draft, and writing—review and editing. The author approved the final manuscript and accepts responsibility for the work.

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Conflict of Interest

RCT developed the early written and spoken language program and materials examined in this study and retains a financial interest in related educational materials through Infant Learning Company, a small family-owned business.

Generative AI Statement

The author declares that OpenAI ChatGPT, GPT-5.6 Sol (OpenAI, https://chatgpt.com) was used for light proofreading, spelling, and grammar correction, and citation and reference checking.

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Figure Captions

Figure 1. Distribution of reported written word reading among tested children.

Figure 2. Growth of written and spoken language across age groups.

Tables

Table 1. Regression predicting log-transformed written word reading from age at testing, age at program start, and total weekly program use.

Predictor	Direction	p value
Age at testing	Positive	< .001
Age of program start	Earlier start associated with higher reading	0.039
Total weekly program use	Positive	< .001

Table 2. Written word reading by age at testing among children who began before 5 months of age.

Age at testing	*n*	Mean	Median	Range
Under 12 months	32	15.3	4.0	0–282
12–17 months	85	29.1	10.0	0–250
18–23 months	38	28.4	16.25	0–145
24 months and older	6	271.2	57.5	2.5–1,000

Table 3. Written word reading and spoken language across age among high-fidelity early starters.

Age at testing	*n*	Mean words read	Median words read	Mean words understood	Median words understood	Mean words said	Median words said	Range (read)
Under 12 months	11	7.0	4.0	38.2	20.0	5.6	2.0	0–25
12–17 months	26	45.9	30.0	210.4	120.0	115.3	60.0	0–250
18–23 months	20	33.5	22.5	310.7	250.0	210.6	150.0	0–145
24–35 months	2	750.0	750.0	600.0	600.0	750.0	500.0	500–1,000
36–72 months	0	-	-	-	-	-	-	-

Table 4. Engagement by age of program start.

Age of program start	*N*	Engaged %	Not engaged %
6 months or younger	335	91.9	8.1
7 to 12 months	172	93.6	6.4
13 to 18 months	108	93.5	6.5
19 months or older	111	82.9	17.1

Table 5. Interest by age of program start.

Age of program start	***n***	**Completely disinterested %**	**Disinterested %**	**Interested %**	**Completely interested %**
6 months or younger	332	0.6	4.5	59.3	35.4
7 to 12 months	175	0.6	6.3	63.4	29.7
13 to 18 months	112	0.9	6.2	64.3	28.6
19 months or older	111	0.0	12.6	72.1	15.3

Table 6. Parent-rated future impact by age of program start.

Age of program start	***n***	**Very negative**	**Negative**	**No impact %**	**Positive %**	**Very positive %**
6 months or younger	337	0	0	3.0	35.9	61.1
7 to 12 months	173	0	0	1.7	46.8	51.4
13 to 18 months	111	0	0	4.5	48.6	46.8
19 months or older	113	0	0	4.4	49.6	46.0

Figures

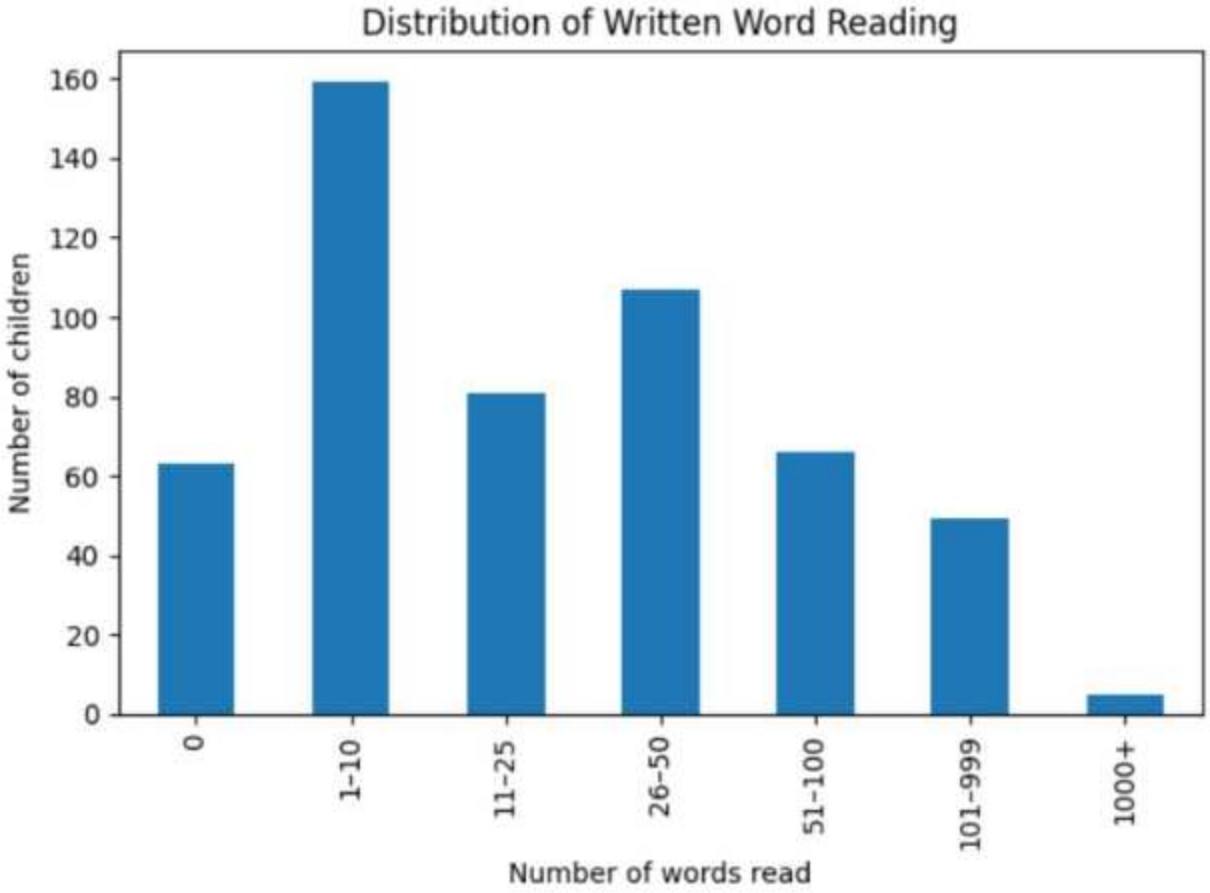


Figure 1

Distribution of reported written word reading among tested children.

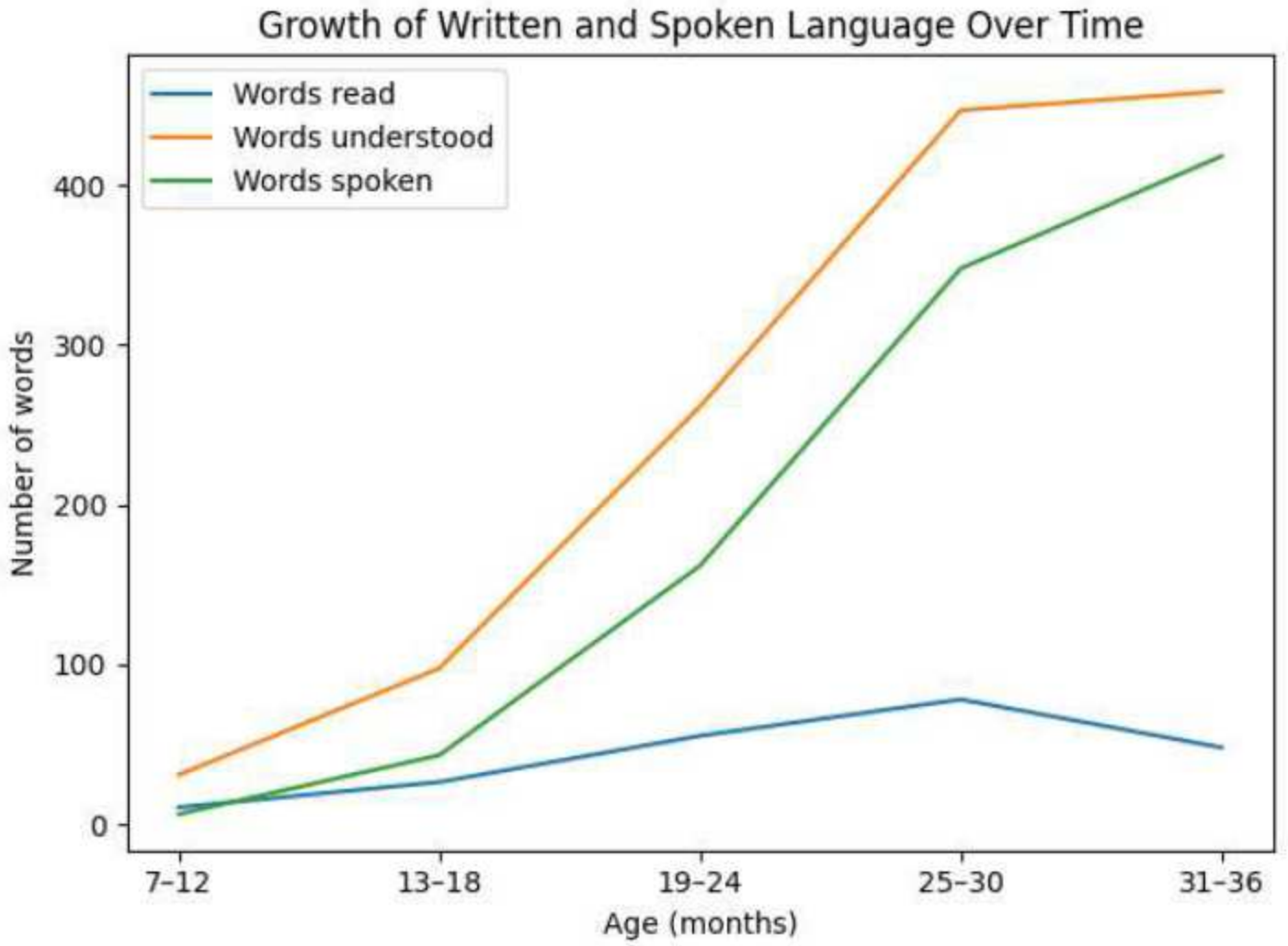


Figure 2

Growth of written and spoken language across age groups.