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Christina Blomquist
University of Iowa

Bob McMurray
University of Iowa

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WAR OF THE WORDS: DEVELOPMENT OF INTER-LEXICAL INHIBITION IN TYPICAL CHILDREN

by

Christina BlomquistBob McMurray

A thesis submitted in partial fulfillment of the requirements
for graduation with Honors in the Speech Pathology and Audiology

Bob McMurray
Thesis Mentor

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Amanda Van Horne
Speech Pathology and Audiology Honors Advisor

War of the Words:

Development of Inter-Lexical Inhibition in Typical Children

Christina Blomquist

The University of Iowa

Abstract

Spoken word recognition requires accessing the target word in the mental lexicon. It is now well known that as acoustic information unfolds over time, similar-sounding lexical candidates (e.g., *cap* and *cat*) compete until the disambiguating information (i.e., the last sound) is perceived and one word “wins”. As the word is activated it inhibits similar-sounding competitors. While this inter-lexical inhibition between words has been demonstrated in adults (Dahan, Magnuson, Tanenhaus, & Hogan, 2001; Luce & Pisoni, 1998), it is unclear how it develops. The present study used an eye-tracking paradigm to examine this inhibition in school-aged children. Participants heard words and matched them to their picture from a screen containing four pictures. Words were manipulated with cross-splicing to briefly activate a competitor and observe the resulting interference on the target word. Eye-movements to each picture were monitored to measure how strongly words compete during recognition. We found that both 7- to 8-year-old children and 12- to 13-year old children made fewer fixations to the target when the onset of the target word (e.g., *cap*) came from a competitor word (e.g., *ca(t)p*) than from a nonword (e.g., *ca(ck)t*). This suggests that activation of the competitor led to inhibition of the target word, resulting in less activation of the target word. There were differences in this marker of inhibition across age groups, suggesting that lexical competition undergoes developmental change even in the later years of childhood. Analyses of assessments of language, reading, perceptual reasoning, and general inhibition reveal a potential relationship between inter-lexical inhibition and reading fluency, but none with vocabulary or general inhibition.

Keywords: lexical competition, online lexical processing, spoken word recognition

War of the Words:

Development of Inter-Lexical Inhibition in Typical Children

Introduction

Research on language acquisition and individual differences has elucidated the critical role of vocabulary in language ability, reading acquisition, and academic achievement (Bleses, Makransky, Dale, Højen, & Ari, 2015; Duff, Reen, Plunkett, & Nation, 2015; Lee, 2011). Vocabulary size in early childhood predicts subsequent language achievement (Lee, 2011), reading accuracy and comprehension (Duff et al., 2015), and educational outcomes (Bleses et al., 2015). This makes understanding the process of acquiring a vocabulary of critical importance for understanding outcomes. However, the development of the lexicon involves not just the acquisition of lexical knowledge, but also gains in lexical processing (Fernald, Pinto, Swingley, Weinberg, & McRoberts, 1998; Fernald, Perfors, & Marchman, 2006; Rigler, Farris-Trimble, Greiner, Walker, Tomblin, & McMurray, 2015; Sekerina & Brooks, 2007).

While vocabulary knowledge is often quantified as the number of acquired words and the set of factual knowledge associated with each word, lexical processing refers to how this knowledge is accessed and used. This is an important distinction, as proficiency in language not only requires effective acquisition of lexical knowledge, but also relies on efficient access of lexical representations (Leach & Samuel, 2007). Child language research has historically focused on investigating the former (for review, see Golinkoff & Hirsh-Pasek, 2006). Consequently, there is substantially less work on how the skill of lexical processing develops (though see: Fernald et al., 1998; Fernald et al., 2006; Rigler et al., 2015; Sekerina & Brooks, 2007; Swingley, Pinto, & Fernald, 1999).

In the last 30 years, lexical processing research with typical adults has led to consensus on several basic principles regarding the process of accessing spoken words in the lexicon. These include the incremental nature of processing, simultaneous activation of lexical candidates, and competition between words (Weber & Scharenborg, 2012). More recent research has utilized this work with adults as an empirical and theoretical foundation for investigating of lexical processing in children. This suggests that, in many ways, spoken word recognition in children resembles that in adults. Children process speech incrementally, immediately activating similar-sounding lexical candidates. However, at the same time, there are clearly developmental changes in this process (Fernald et al., 1998; Fernald et al., 2006; Rigler et al., 2015; Sekerina & Brooks, 2007), raising the question of what exactly is being tuned over development.

In adults, there is evidence that inhibitory connections between words play a role in lexical competition during word recognition (Dahan et al., 2001; Luce & Pisoni, 1998). While this inter-lexical inhibition has been suspected to be involved in lexical competition in children, there is a lack of clear behavioral evidence. The present study seeks to investigate the potential role of inhibition in lexical competition during spoken word recognition in children, and whether this inhibition may serve as a mechanism for change in the dynamics of lexical competition across development.

Spoken Word Recognition

Spoken words unfold over time. As a result, in the early moments of listening to a word, there is inadequate information to identify the target word. This problem arises in perception of nearly every word, since any given word shares a similar onset with multiple other words. This cognitive “problem” is referred to as the problem of temporary ambiguity (Marslen-Wilson, 1987). Research on spoken word recognition with adults demonstrates that to deal with this

temporary ambiguity, listeners activate a set of words that match the available acoustic information at any moment of time (Marslen-Wilson, 1987). During periods of ambiguity, this set might be large (since many words will match the partial input), but it is reduced over time as more information is available. This has been established empirically with measures like cross-modal priming and eye-tracking that are sensitive to early states in processing. Such measures reveal that multiple lexical candidates are active immediately, and these words are considered simultaneously in parallel with each other until they can be ruled out by following acoustic information (Allopenna, Magnuson, & Tanenhaus, 1998; Dahan & Gaskell, 2007; Frauenfelder, Scholten, & Content, 2001; Marslen-Wilson & Zwitserlood, 1989). Most importantly for the present proposal, a number of studies suggest that partially activated lexical candidates actively inhibit each other (Dahan et al., 2001), and this competition depends on how many similar words are activated in the lexicon (Luce & Pisoni, 1998).

This competition among words plays out over the course of milliseconds. As a result, understanding lexical processing at this level requires measures that are sensitive to the dynamics of this competition. Eye-tracking in the Visual World Paradigm (VWP) (Allopenna et al., 1998; Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy, 1995) has been useful in detailing the time course of lexical competition. In the VWP, participants hear a spoken word and select its referent on a computer screen containing pictures of the target and competitors. During the task, eye movements to each picture referent are recorded to measure how strongly each word is considered over time.

Allopenna et al. (1998) offered one of the earliest applications of this technique to spoken word recognition. In this study, adult listeners heard words, like *sandal*, and selected the referent from an array of several pictures while their eye movements to each picture were monitored.

The presented pictures included the target (e.g., *sandal*), a competitor with a similar onset, also known as a cohort (e.g., *sandwich*), a rhyme competitor (e.g., *candle*), and a phonologically unrelated object (e.g., *parrot*). Starting around 200 msec¹ after onset of the spoken word, listeners fixated on the target and cohort competitor pictures more often than the unrelated object. This demonstrated that eye movements were sensitive to changes in lexical activation starting at the onset of the word. Shortly after this notably higher proportion of target and cohort activation, fixations to the cohort were suppressed, ultimately leading to the final fixation of the target word.

In this way, the VWP offers detailed information about the dynamics of lexical activation in spoken word recognition. Studies investigating the fine-grained details of lexical competition dynamics have led to a clearer understanding of how this processing occurs in adults (Allopenna et al., 1998; Dahan & Gaskell, 2007; Dahan et al., 2001; Frauenfelder et al., 2001). More recently, questions related to the development of this processing have been addressed using similar techniques with children. This research on the development of spoken word recognition has the potential to illuminate the relationship between real-time processing of language and overall language ability (McMurray, Samelson, Lee, & Tomblin, 2010; Fernald & Marchman, 2012; Marchman & Fernald, 2008). More specifically, a description of developmental change in language processing may help to understand when and how atypical patterns of processing appear in childhood, and how these processing differences may be related to impairments in language and reading.

Development of Spoken Word Recognition

¹ 200 msec is the duration of time needed to plan and launch eye-movement (Viviani, 1990).

Studies investigating the dynamics of spoken word recognition in children are largely rooted in eye-tracking research done with adults. The VWP, commonly used in adult studies, has been adapted to study spoken word recognition in young children (Fernald et al., 1998). Most notably, Fernald and colleagues have developed an eye-tracking paradigm for infants from 15 to 30 months of age known as the “looking-while-listening” (LWL) paradigm (Fernald et al., 1998; Fernald, Swingley, & Pinto, 2001; Swingley et al., 1999). In this paradigm, infants see pictures of two objects and hear a spoken word referring to one of them. Mean reaction time and mean proportion of fixations to the correct picture are used as measures of efficiency of word recognition.

Using this paradigm, Swingley, Pinto, and Fernald (1999) concluded that 24-month-old children’s responses were delayed when the competing word overlapped with the onset of the target word (e.g., *doll* when the target is *dog*), showing that children, like adults, monitor speech incrementally. In another study with 18- and 21-month-olds, Fernald, Swingley, and Pinto (2001) demonstrated that even younger children recognize partial words (the first 300 ms of a word) as quickly and reliably as whole words, suggesting that lexical access in children is incremental and immediate, as in adults.

While these gross aspects of lexical processing in children reflect general characteristics of mature, adult processing, spoken word recognition by children also differs from adults in several ways. Throughout the second and third years of life, processing gradually increases in speed and efficiency (Fernald et al., 1998; Fernald et al., 2006). For example, longitudinal work by Fernald et al. (2006, 2008) examined children from 15 to 25 months of age. This longitudinal study revealed that speed and accuracy in spoken word recognition increased significantly

between the 15- and 25-months of age, and that this efficiency is correlated with later language outcomes.

While rapid gains in processing efficiency are evident in the early years, there is also evidence that this development continues into later childhood and even adolescence (Rigler et al., 2015; Sekerina & Brooks, 2007). Sekerina and Brooks (2007) extended this development to the age 5, showing clear differences in processing efficiency between 5-year-olds and adults in a 4-referent version of the VWP. Relative to the children, adults showed faster fixations to the target. Along with this difference in target activation, children demonstrated longer lasting competitor activation before suppressing them to baseline looking levels. Neurophysiological data from event-related potential recordings during spoken word recognition suggest gains in speed of word recognition between the ages of 7 and 9, but not past the age of 9 (Ojima, Matsuba-Kurita, Nakamura, & Hagiwara, 2011). These results suggest that development of spoken word recognition extends until at least the age of 9.

Rigler et al. (2015) further extended the timeline of development into adolescence. In this study, the dynamics of competition during spoken word recognition in 9-year-old and 16-year-old children were assessed through the four-picture referent version of the VWP. Compared to the 9-year-olds, 16-year-olds showed earlier activation of the target. Additionally, the older children showed less activation of competitors. The combination of these findings suggest that gains in efficiency of processing extend into the teenage years, and these gains involve not only faster target activation, but also differences in how children deal with competing words. It is clear from the available evidence that the efficiency and competition dynamics of spoken word recognition undergo a rather protracted timeline of development.

It is also becoming evident that this development of processing is fundamental to language development. Specifically, the relationship between lexical processing and language ability seems to take on a predictive nature. Fernald and Marchman (2008, 2012) have presented evidence for a predictive relationship between early lexical processing and later language outcomes. Marchman and Fernald (2008) found that measures of spoken word processing (LWL) and vocabulary size predicted linguistic and cognitive skills at 8 years of age, with only some of this relationship being accounted for by the involvement of working memory. These results suggest that the predictive validity of early lexical processing and vocabulary measures on later language ability may extend into the school-age years. Further, in a study of 18-month-old children classified as “late talkers,” Fernald and Marchman (2012) showed that more efficient spoken word recognition at 18 months predicted accelerated vocabulary growth in the following year. These findings provide evidence to the view that early differences in processing efficiency lead to consequences in later language learning.

Additional research into the relationship between efficiency of lexical processing and vocabulary growth provide further evidence that differences in processing are related to language ability (Fernald et al., 2001; Fernald et al., 2006; Law & Edwards, 2015). Fernald et al. (2001) investigated the potential relationship between differences in processing efficiency and productive vocabulary, finding that children with faster reaction times were more accurate in word recognition and had larger productive vocabularies. Fernald et al. 2006 extended this by showing that efficiency in lexical processing was associated with rate of vocabulary growth, finding that 25-month-old children that exhibited faster and more accurate performance in spoken word processing also showed more accelerated vocabulary growth across the second year. Similarly, Law and Edwards (2015) showed that children between 30 and 46 months of

age with larger expressive vocabularies were also faster at identifying familiar words. Moreover, when hearing a novel word, children with larger vocabularies also looked more quickly and consistently to the picture of an unfamiliar object when they heard an unfamiliar word, suggesting that vocabulary size and familiar recognition efficiency are related to a child's ability to map novel words to novel objects. Additionally, Bion, Borovsky, and Fernald (2012) found that 18-, 24-, and 30-month-olds' proportion of looking time to a novel object when a novel word was heard was related to their success in retention of the novel word, as well as their vocabulary size. These findings regarding the influence of lexical processing on the mapping of words to objects implicates processing efficiency in word learning.

It is clear that early individual differences in lexical processing are related to, and even predictive of, language ability. Moreover, it is possible that these differences in processing eventually give rise to the atypical patterns of processing observed in children with language and reading impairments (Desroches, Joanisse, & Robertson, 2006; Dollaghan, 1998; Mainela-Arnold, Evans, & Coady, 2010; McMurray et al., 2010). Studies of children with developmental language disorder (also referred to as specific language impairment, or SLI) reveal that difficulties with language may stem from differences in dealing with competitor activation during processing (Mainela-Arnold et al., 2008; McMurray et al., 2010). Mainela-Arnold et al. (2008; see also Dollaghan, 1998) investigated the nature of lexical representations in children with and without SLI through the use of a forward gating task in which participants heard words presented in successive fragments of the auditory stimulus that became longer as the experiment went on. After each fragment, participants verbally responded with their best guess as to the identity of the word they heard, and their responses were coded as either correct or incorrect. There were no significant group differences in effects of word frequency or neighborhood

density on the children's ability to activate words beginning with the perceived first sound and their ability to isolate the target word based on acoustic fragments. However, the children with SLI seemed to consider multiple lexical candidates (correct and incorrect) at significantly later gates compared with chronological age-matched peers. This difference suggests that children with SLI may be more vulnerable to competing words during processing, even in the later stages.

Similarly, McMurray et al. (2010) used the VWP to investigate the dynamics of competition during spoken word recognition by adolescents with a wide range of language skills. Adolescents with poor language abilities showed fewer looks to the target and more looks to competing words. After running various TRACE simulations, it appeared that simple changes in processing speed were not able to account for these differences related to adolescent language ability (McMurray et al., 2010). Therefore, it may be that atypical patterns of processing in later childhood derive from differences in dynamics of lexical competition. This research describing the set of deficits in lexical competition related to language impairment further emphasizes the importance of understanding the development of the overall efficiency and fine-grained dynamics of spoken word processing and the its relationship with the development of language.

The Role of Lateral Inhibition in Lexical Competition

With growing evidence for the development of lexical processing and its association with language development, an important question remains: what processing mechanisms are tuned via developmental to achieve more efficient lexical processing? One possible mechanism is *lateral inhibition* between words in the lexicon. Lateral inhibition is an aspect of lexical competition, specifically referring to competition between words via inhibitory lateral connections.

Lateral inhibition may underlie a key phenomenon observed in multiple studies of spoken word recognition: lexical interference. For example, words with denser neighborhoods take longer to recognize compared to words with sparse neighborhoods (Luce & Pisoni, 1998). This interference in speed of recognition is due to an increased number of potential competitors. Interference from competing words hinders activation of the target word over and above limitations from temporal ambiguity (Dahan & Gaskell, 2007). There is clear evidence of this interference effect from studies demonstrating the influence of neighborhood density on speed of spoken word recognition (Luce & Pisoni, 1998; Vitevitch & Luce, 1998; Vitevitch, Luce, Pisoni, & Auer, 1999). This lexical interference is thought to derive from inhibition among words (Dahan et al., 2001, Luce & Pisoni, 1998; McClelland & Elman, 1986).

Using a stimulus manipulation introduced by Marslen-Wilson and Warren (1994; see also Street & Nigro, 1979), Dahan et al., (2001) offered the clearest evidence that these interference effects derive from interactions between specific words (e.g., lateral inhibition). In this paradigm, auditory stimuli are manipulated to temporarily boost activation of a competitor word to then observe its effects on the target. For example, a target word (*bud*) is cross-spliced with the onset of a competitor (*bug*) so that the coarticulatory information in the vowel of the onset misleads the listener as to the correct word (*bug*). After this temporary period of competitor activation boost, the release burst of the final sound (/d/) reveals the true target word. If there is lateral inhibition between words, then this splicing manipulation should favor the competitor word (*bug*), briefly inhibiting the target word (*bud*). This initial suppression would then have to be resolved when the final, disambiguating sound is heard, leading to more difficulty fully activating the target.

Dahan et al. (2001) presented these spliced stimuli to adult participants while recording eye-movements using the VWP. Fixations to the picture of the target word were slower when the stimulus was spliced to boost competitor activation. Target fixations in this condition were slower relative to a condition in which the intact word was presented, as well as a control condition in which the coarticulatory mismatch caused by splicing in the onset of nonword (*bub*) did not activate another word, since there was no lexical candidate to activate. This effect of splicing condition was even observed when the picture of the activated competitor (*bug*) was not displayed on the screen, suggesting that this interference is not driven by a decision-level process that was specific to the task. Instead, this interference must derive from properties of the lexicon, providing strong evidence that lateral inhibition is involved in the observed interference effect.

Although this lateral inhibition is thought to be an underlying cause of interference during these kinds of spoken word recognition paradigms, it may also be useful for efficient lexical processing. When listening to typical speech input, inhibition among words can contribute to speed of recognition by suppressing competitors more rapidly. Given that inter-lexical inhibition may play a part in word recognition efficiency, it is also plausible that it could be an underlying mechanism of developmental gains in processing efficiency. Similarly, differences in lateral inhibition may contribute to individual differences in resolution of lexical competition observed in populations with language and/or reading impairments (Desroches et al., 2006; Dollaghan, 1998; McMurray et al., 2010).

Of course, for such effects to emerge developmentally, they must be adaptable with experiences. Recent research suggests this is the case: inhibition in lexical competition is plastic and can change with short-term training in adults (Kapnoula & McMurray, 2016). The plasticity

of this inhibitory system in lexical competition points to an exciting potential real-world application of word processing research. This suggests that development of lexical processing dynamics can be tuned by language experience, and this component of processing could serve as a potential focus of intervention in atypical development. Children also have to solve the problem of lexical interference during spoken word recognition, with this interference effect due to neighborhood density (Mani & Plunkett, 2011; Swingley & Aslin, 2007). This suggests that some form of inhibition may be present. However, the methodological paradigms previously used to investigate lexical competition in children, including gating tasks (Mainela-Arnold et al., 2008; Dollaghan, 1998) and pause detection (Henderson, Weighall, Brown, & Gaskell, 2013), do not allow for description of fine-grained detail of the dynamics of this processing in real time.

The Present Study

The present study set out to investigate the real-time dynamics of lexical competition during spoken word recognition by children. We evaluated inhibition between words using the VWP/splicing design of Dahan et al. (2001). Similar to the original use of this paradigm with adults, a splicing manipulation of word stimuli was used to cause interference between a competitor word with temporarily boosted activation and the target word. There were three splicing conditions, all of which ultimately led to perception of the same target word (e.g., *cap*). In the *word-splice* condition, the onset from a recording of the competitor word was spliced onto the release burst of the target word (*ca_p*). In the *matching-splice* condition, the onset and the release burst of the auditory stimulus came from different recordings of the same word (*ca_{pp}*). In order to control for the fact that the *word-splice* condition resulted in the co-articulatory formant information in the vowel mismatching with the final sound, and thus resulting in a poor acoustic example of the target word, we also compared it with a *nonword-splice* condition in which the

onset (taken from an exemplar of a nonword, like *cack*) mismatched the release burst (*ca_{ck}p*), but did not activate another word.

These stimuli were presented to the participant in the VWP. After hearing the word, the participant selected the referent from a set of four pictures, one of which represented the target word, and none of which were the competitor. Looks to the target picture were considered an index of the word's activation in the lexicon. The difference in target fixations between the *nonword-splice* and *word-splice* conditions reflects interference above and beyond effects of subphonemic mismatch, meaning the remaining interference of target activation is due to lateral inhibition between words.

Participants were typically developing children from two age groups: 7- to 8-year-olds and 12- to 13-year-olds. These ages were chosen for several reasons. First, children's abilities to categorize speech sounds is still developing between 3 and 7 years (Nittrouer, 2002; McMurray, Danelz, Rigler, & Seedorf, submitted), meaning the processing of speech input continues to develop into the early school-age years. Further, research from our lab suggests that lexical development extends even into adolescence (Rigler et al., 2015). Rigler et al. (2015) demonstrated differences in the dynamics of spoken word recognition between 9-year-olds and 16-year-olds, suggesting that this was evidence for a slow developmental timeline for spoken word recognition processes. Consequently, mechanisms of developmental change in lexical processing efficiency would be quite likely to continue developing into adolescence.

If inhibitory processes play a role in the development of lexical competition, it is possible this development would extend into later childhood as well, since cognitive processes like executive function and inhibitory control continue to develop into puberty, and possibly beyond (Welsh & Pennington, 1998), and there are qualitatively distinct academic experiences across

age groups. The younger age range includes children in the early years of elementary education, while the children in the older age range have experienced several years of formal schooling. A shift to more formal and complex language of instruction occurs between these stages of schooling. Primarily, after the first few years of schooling, children shift from learning to read to reading to learn. This shift in reading instruction is combined with the introduction of academic language, leading to language skills becoming more complex and abstract. Comparing age groups with these clear differences in language experience and ability enables the detection of any developmental differences in the dynamics of language processing, if developmental changes indeed exist.

Differences between age groups would suggest developmental change in the lateral inhibition involved in lexica competition. Our hypothesis was that such inhibitory competition processes would be observed in children, since the effects of this competition has been indirectly observed in previous studies (Henderson et al., 2013; Mani & Plunkett, 2011; Swingley & Aslin, 2007). We also hypothesized that we would observe differences in the involvement of inter-lexical inhibition in the dynamics of processing, because existing evidence on the development of lexical processing dynamics suggests it extends into adolescence (Rigler et al., 2015).

We also investigated the relationship of this inter-lexical inhibition with other abilities. Specifically, we assessed vocabulary, reading skills, non-verbal reasoning, and domain-general inhibition. It is plausible that there would be an association between lexical processing dynamics and vocabulary development, given the studies finding a predictive relationship between early lexical processing and later vocabulary development (Fernald & Marchman, 2012; Marchman & Fernald, 2008). Considering that atypical patterns of processing have been observed in children

with dyslexia, there may be a relationship between the lexical processing and reading skills as well (Desroches et al., 2006).

This study also included measures of non-verbal reasoning and general inhibition were included also, in order to determine whether age-related differences can be attributed to differences in more general cognitive processes. The inclusion of a general inhibition measure also allows for investigation into whether inter-lexical inhibition is related to a more general inhibitory mechanism, or whether is it specific to the language system.

Method

Participants

Forty-six children participated in this study. Participants were recruited from two age groups: 7- to 8-year-olds (N=23, 12 female) and 12- to 13-year-olds (N=23, 13 female). Participants were recruited through a university-wide email. Four were excluded from analysis due to issues with eye-tracking; three due to technical problems, and one due to very few fixations to any of the objects, this left 21 in each age group. A small number of subjects were excluded from analyses of the additional tasks and assessments as they did not complete one or more measures (general inhibition [6], vocabulary [1], reading ability [9], reading fluency [10], and nonverbal reasoning [10]). All parents reported that their child was a native monolingual English speaker, had normal or corrected-to-normal vision and normal hearing, and was typically developing with no known speech, language, or other cognitive concerns. Participants received \$30. Following an IRB approved protocol, written informed consent was obtained from the parents of the participating children and children underwent a verbal assent procedure.

Design

A VWP task was used to investigate lexical inhibition as in Dahan et al. (2001). On each trial, the participant saw 4 pictures on a computer screen, heard a word, and then selected the picture referent of that word while eye-movements were monitored. Stimuli were constructed from 14 word pairs. Each pair included a base word (e.g., *bat*). The base word was manipulated to create the three different splicing conditions as in Dahan et al. (2001): 1) the *matching-splice* condition in which the onset was taken from a different recorded exemplar of the base word (*bat*); 2) the *word-splice* condition in which the onset was from another word with overlapping onset (*back*); and 3) the *nonword-splice* condition in which the onset was from a nonword (*bap*; see Appendix A for list of all words and nonwords used). Each base word was paired with a cohort competitor with one phoneme overlap at onset (e.g., for *bat*, *bead*). This was done to prevent participants from identifying the target picture based on the initial phoneme alone, before hearing the critical coarticulatory mismatch carried by the vowel.

To construct the four objects seen on each trial, each word pair was combined with another word pair, resulting in seven sets of four words. Sets were constructed following three different lists, each of which had unique arrangements of word pairs; no word sets were identical across lists. The word sets were carefully constructed to ensure that the two word pairs in each set did not share phonological or semantic characteristics. In this way, when a word from one pair was presented as a target, the two words in the other pair served as unrelated distractors in that trial. The competing word for the base word never appeared on the screen.

Each word in a set served as the target an equal number of times. As a result, a base word was presented as a target in half of the trials, while the other half of trials had the competitor as the target. Each base word was presented as the target three times in each of the splicing conditions. Each competitor word was spliced in three ways as well: once with the

onset from another recording of the competitor word (e.g., *bead*), and twice with the onset of two different nonwords (*beeb*, *beeg*). Each competitor word was presented three times in each of the three splicing conditions as well, yielding a total of 252 trials.

Following the VWP task, participants conducted the spatial Stroop task to measure inhibition (see below). After the end of the spatial Stroop task, participants were given the PPVT-IV, WRMT subtests (Word Attack, Word Identification, and Oral Reading Fluency), and the WASI-II subtests (Block Design and Matrix Reasoning). All assessments were administered by a researcher trained to administer standardized tests. Participant responses were recorded online and scored offline.

Standardized Assessments

Participants also completed a number of standardized assessments of vocabulary, reading, and nonverbal reasoning. These scores were used to check for group differences in these abilities, as well as investigate potential relationships between these abilities and inter-lexical inhibition.

Vocabulary was assessed using the Peabody Picture Vocabulary Test (PPVT-IV; Dunn & Dunn, 2012). For all participants, standard scores were either average or above average (mean = 116, $SD = 11.8$; $Range = 96$ to 143), and all vocabulary scores were greater than the clinical threshold for language impairment (i.e., 1 SD below the mean. The younger group (7- to 8-year-olds) had an average standard score of 119 ($SD = 12.7$), and the older group (12- to 13-year-olds) averaged 113 ($SD = 10.1$), which approached significance ($t(43) = 1.98$, $p = 0.053$). The fact that the younger children were more advanced than the older children suggests that this difference is not of concern, as it is in the opposite direction of development. Additionally, raw PPVT scores reveal that the older children still have significantly greater *absolute* language ability: the

younger group's mean raw score was 152 ($SD = 16.39$) and the older group scored 188 ($SD = 9.87$), $t(43) = 8.30$, $p < 0.001$.

Reading ability and fluency were assessed for each participant using the Woodcock Reading Mastery Tests, specifically the Word Attack, Word Identification, and Oral Reading Fluency subtests. Scores for Word Attack and Word Identification were combined into a composite score of word reading ability. In the word reading ability composite score, the younger group averaged 105 ($SD = 13.0$, $Range = 85$ to 130) and the older group averaged 103 ($SD = 11.5$, $Range = 82$ to 125), $t(35) = 0.646$, $p = 0.522$. In reading fluency, the standard scores for the younger group averaged 110 ($SD = 11.1$) and the older group averaged 113 ($SD = 14.0$), $t(34) = 0.523$, $p = 0.604$. Thus, the two age groups were matched in terms of relative reading ability and fluency.

Nonverbal reasoning was assessed by administering the Block Design and Matrix Reasoning subtests of the Wechsler Abbreviated Scale of Intelligence (WASI-II). The two subtests' t-scores were combined into a composite score. The younger group's composite scores averaged 54 ($SD = 6.90$) and the older group averaged 51.9 ($SD = 9.64$), $t(35) = 0.834$, $p = 0.410$. Thus, the two age groups were matched in relative nonverbal reasoning ability.

Visual World Paradigm Test of Inter-Lexical Inhibition

Auditory Stimuli. Auditory stimuli were selected from a larger set of word stimuli used in Kapnoula and McMurray (2016), which used the subphonemic mismatch paradigm to study word learning. Words were selected from this larger set based on their appropriateness for children. In order to determine which words would be understood by the youngest participants in this study (7-year-olds), we used the on-line child corpus calculator created by Storkel and Hoover (2010) to determine the frequency of each word. The calculator is a collection of two

corpuses of productive language from kindergarten and first grade children, so the resulting word frequency represents the log of the raw frequency of occurrence across both corpuses. Words were initially selected based on whether log frequency was greater than 2 (100 times within the child corpus). This yielded nine word sets, which was an insufficient number to ensure generalization of behavioral results to words not used in the study. We thus loosened the criteria to include eight words that did not have a frequency of 2, but were deemed acceptable as appropriate for this age range: *bait*, *bead*, *bark*, *fog*, *heap*, *root*, *shed*, *mug*. This yielded a total of 14 word pairs.

Auditory stimuli were recorded by a male native speaker of American English in a sound-attenuated room using a Kay CSL 4300B A/D board at 44100 Hz. Each stimulus was excised from a recording of the word spoken in a carrier phrase (e.g., “He said *cap*”). One hundred milliseconds of silence were added to the beginning of each stimulus, and they were normalized to the same intensity. For each word, multiple tokens were recorded from which the tokens with the strongest coarticulation were selected for splicing. All stimuli were spliced at the zero crossing closest to the onset of the release. Following Dahan et al. (2001), the onset of the word (from the initial consonant through the vowel and plosive closure) was either consistent or inconsistent with the release burst of the final sound of the target word (e.g., *cap*). There were three splicing conditions: a *matching-splice* condition in which the onset and release burst of the auditory stimulus came from another recording of the same word (*cap*), a *word-splice* condition in which the onset was from the recording of the competitor word (*cat* for *cap*; *cat*), and a *non-word splice* condition in which the onset was from an exemplar of a nonword (*cack* for *cap*; *ca_ck*; see Appendix A for a list of words and nonwords). Cohort competitor stimuli were also

spliced (e.g., *cord* for *cap*), with the only difference being that each target word was spliced with itself and two nonwords (e.g., *cor_ad*, *cor_bd*, *cor_gd*).

Visual Stimuli. Visual stimuli were developed using a standard lab procedure to ensure that they were clear and representative of the word they were intended to represent (Apfelbaum, Blumstein, & McMurray, 2011; McMurray et al., 2010). For each word, five to ten images of each word were downloaded from a commercial clipart repository. These images were then viewed by a group of three to five undergraduate and graduate student lab members, who arrived at a consensus of which image was the most representative image. This image was subsequently edited slightly to ensure a prototypical depiction of the word. Finally, all images were approved by a member of the laboratory with extensive experience using VWP (see Appendix B for a list of the visual stimuli).

Procedure. After informed consent, participants were familiarized with the 28 pictures used in the VWP task. They saw each picture along with its orthographic label. If a child expressed confusion regarding the meaning of the word, the experimenter explained the definition of the word and its connection to the picture stimulus, ensuring that the child was confident in their knowledge of the word before moving on to the task. Next, the padded chin and forehead rest used for the eye-tracker was adjusted to a comfortable position. The experimenter then calibrated the desktop mounted eye-tracker.

Next, the participant was given written and verbal instructions as well as an opportunity to ask questions about the experimental task. At the beginning of each trial, participants saw four pictures in the four corners of the monitor along with a red dot in the center. This lasted 500 ms and was intended to familiarize the participant with the objects and their locations on that trial, thus minimizing eye movements due to visual search. After that, the circle turned blue,

which cued the participant to click on it (with a computer mouse) to start the trial. This oriented the participant's eyes and the mouse to the center of the screen at trial onset. The blue circle disappeared after the participant clicked on it and an auditory stimulus was played through headphones. The participant then clicked on the matching picture, and the trial ended as soon as they clicked on one of the pictures. Participants were encouraged to take their time and be as accurate as possible.

Eye-tracking recording and analysis. In the VWP task, eye movements were recorded with a desktop mounted SR Research EyeLink 1000 eye-tracker. Both corneal reflection and pupil were used whenever possible. A standard 9-point calibration was used. Every 20 trials, a drift correction procedure was performed to maintain calibration. If the participant failed a drift correction, the eye-tracker was recalibrated. Eye movements were processed using a similar procedure to McMurray et al. (2010). Point of gaze was sampled at every 4 ms starting at the onset of each trial (after the central fixation point) and continuing until the participant clicked on a picture. These data were automatically classified into saccades, fixations, and blinks using the default psychophysical parameters. Adjacent saccades and fixations were combined into a "look" that began at the onset of the saccade and ended at the offset of the fixation. In mapping the looks onto specific pictures, the boundaries of objects were extended by 100 pixels to account for any noise in the eye track. This did not result in overlap between objects, with the neutral space between pictures being 124 pictures vertically and 380 pixels horizontally.

General Inhibition Task

A spatial Stroop test was used to measure domain general inhibition. Similar to the classic color-word Stroop task, in this paradigm the stimulus has one dimension that is pertinent to the response, while another dimension is irrelevant and can interfere. In the spatial Stroop

task, an arrow appears on the computer screen with a particular direction (right or left) and a location (left or right side of the screen). The two screen locations were crossed with the two arrow directions for four total types of trials (two *congruent*: right arrow on right side, left arrow on left side; two *incongruent*: right arrow on left side, left arrow on right side). The order of trial types was randomized and each trial type repeated 24 times, resulting in 96 total trials. Upon seeing the arrow, the participant presses either the right or left arrow key depending on the direction of an arrow, while ignoring what side of the screen the arrow is on. When arrow direction and screen location are incongruent (e.g., arrow pointing left on the right side of the screen), the reaction time for response is typically longer. Individuals with better inhibitory function should show less interference as they are better able to inhibit the irrelevant dimension.

Results

Our analysis begins with an analysis of mouse click responses (accuracy) and reaction time in order to determine the participants' general ability to complete the task successfully. Only the experimental trials (e.g., those trials in which one of the target words was a stimulus) were included in all of the analyses. Consistent with prior studies, we also eliminated the small number of trials in which subjects did not select the correct target. Regarding the eye-movement data, we first analyzed target activation in the *matching-splice* condition in order to describe differences in the pattern of target fixation across age groups. Second, we analyzed target fixations across splicing conditions to determine whether there was evidence for inter-lexical inhibition in school-aged children. This analysis was followed by an investigation into potential differences in inter-lexical inhibition across age. Finally, we used Pearson correlation coefficients to relate language, reading, non-verbal reasoning, and general inhibition to the eye-tracking data.

Mouse Click Analysis

Across all trials and all splice conditions, 7- to 8-year-olds selected the target at an average of 99.5% correct ($SD = 0.626\%$). 12- to 13-year-olds averaged 99.3% correct ($SD = 0.832\%$), $t(40) = 0.915$, $p = 0.336$. Therefore, participants in both groups were highly accurate. We carried out a two-way, repeated measures analysis of variance (ANOVA) to assess accuracy as a function of splicing condition (*matching-splice*, *word-splice*, *nonword-splice*) and age group. Accuracy did not differ significantly between splicing conditions ($F < 1$) nor between experimental groups ($F < 1$). In addition, the Splicing Condition \times Group interaction was not significant ($F = 1.217$, $p = .301$).

Next, we examined RT (computed on correct trials only). Here, a two-way ANOVA similar to that conducted with accuracy revealed a significant effect of age group, $F(1,40) = 34.448$, $p < 0.001$. 7- to 8-year-old participants had significantly slower RTs ($M = 1888$ msec, $SD = 358$) than 12- to 13-year-olds ($M = 1389$, $SD = 155$). There was also a significant effect of splicing condition ($F(2,80) = 17.81$, $p < 0.001$), but the Splicing Condition \times Age Group interaction was not significant ($F(1, 80) = 1.543$, $p = 0.22$). Post-hoc comparisons revealed that participants were significantly faster in the *matching-splice* ($M = 1,585$ ms) than in the *nonword-splice* ($M = 1,678$ ms), $t(41) = -7.426$, $p < 0.001$, and the *word-splice* ($M = 1652$ ms), $t(41) = -3.865$, $p < 0.001$, conditions. There was no significant difference in RTs between the *nonword-splice* and *word-splice* conditions, $t(41) = -1.448$, $p = 0.115$. Thus, the RTs suggest that younger children are slower than the old, and that there was some sensitivity to mismatch (in general).

Eye-Movement Analysis

Between-group differences in target fixations. We began our analysis of the eye-tracking data by describing the differences across age groups in target activation in normal listening circumstances (i.e., *matching-splice* condition). It is important to characterize the age-related differences in normal target activation prior to investigating potential differences in the fine-grained details of lexical competition, like inter-lexical inhibition. In order to determine whether developmental changes in such inhibition processes are related to increased efficiency in lexical processing, we must first assert that lexical processing is indeed becoming more efficient throughout this age range. To do this, we characterized changes in efficiency of target activation across the two age groups. Visual comparison of the pattern of target fixations across age groups (Figure 1A) shows that the proportion of looks to the target by the older group increases more quickly and ultimately reaches a higher level in relation to the younger group.

We examined these differences statistically by fitting a four-parameter logistic function to the data for each participants' target fixations in *matching-splice* condition experimental trials (Figure 1B). This function (Equation 1) has four parameters that serve as descriptors of the time (t) course of processing. The lower asymptote, or baseline (b), is the point at which the function starts. The upper asymptote, or peak (p), is the asymptotic level of looking at the end of the time course of fixations. The crossover point (c) is the time point when the function crosses the midway point between baseline and peak. Finally, the slope (s) defines the rate of change in the function measured at the crossover point.

$$P(\textit{target}) = \frac{p-b}{1+\exp\left(\left(\frac{s}{p-b}\right)\cdot(c-t)\right)} + b \quad (1)$$

This equation was fit to each subject's data using a constrained gradient descent technique that minimized the least-squared error between the data and the function. Once we

had estimated these parameters for each participant, we compared them across age groups using t tests.

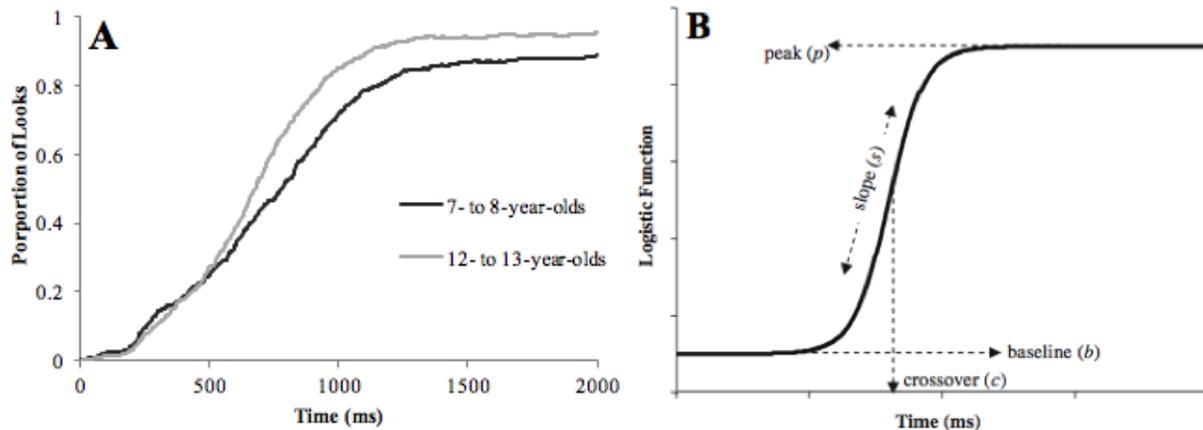


Figure 1. Time Course of Fixations to Target in Matching-Splice Condition and Logistic Function. Proportion of looks to the target in *matching-splice* condition for both groups (A). Time 0 msec indicates the trial onset. The function and parameters used for curve-fitting of the time course of looks to target in *matching-splice* conditions (B). A 4-parameter logistic function was used to characterize each subjects' curve, defined by upper and lower asymptotes, crossover point, and slope.

Fits using the logistic function were very good with an average R^2 of 0.995 ($SD = 0.008$, $Max = 0.999$, $Min = 0.95$). Table 1 reports the results of between sample t tests for each as a function of age. Baseline (b) showed little difference across age groups, as this reflects the amount of eye movements prior to the onset of the auditory stimulus. However, the younger group had a significantly later crossover, as well as significantly lower peak fixations (p) of the target. The younger group also had shallower slopes, but this difference was only marginally significant. Thus, we see clear developmental effects on target fixations in this task.

Table 1. Results of Curve-Fitting Analysis Examining the Time Course of Fixations to Target in Matching-Splice Condition. Mean parameter values (*SD*) for each of the analyses are shown for 7- to 8-year olds and 12- to 13-year-olds, along with the results of *t* tests (assuming unequal variance) comparing estimates between the two age groups ($* = p < .05$).

Logistic Parameter	<i>M (SD)</i>		<i>t</i>	<i>p</i>
	7- to 8-year-olds	12- to 13-year-olds		
Peak (<i>p</i> ; proportion)	.885 (.077)	.942 (.061)	2.649	.012*
Crossover (<i>c</i> ; ms)	716 (93)	648 (75)	-2.581	.014*
Slope (<i>s</i> ; Δ proportion/ms)	.001 (.0002)	.002 (.002)	1.983	.061
Minimum (<i>b</i> ; proportion)	.016 (.032)	.011 (.034)	.399	.692

Evidence of inter-lexical inhibition. We next asked if there was evidence for lexical interference in school-aged children overall, replicating the analyses of Dahan et al. (2001). We computed the proportion of looks to the target as a function of time for each of the three splicing conditions (Figure 2). As in previous studies (Dahan et al., 2001; Kapnoula & McMurray, 2016; Kapnoula, Packard, Gupta, & McMurray, 2015), we observed an effect of splicing condition: The *matching-splice* shows the highest proportion of looks, followed by the *nonword-splice* and *word-splice* conditions.

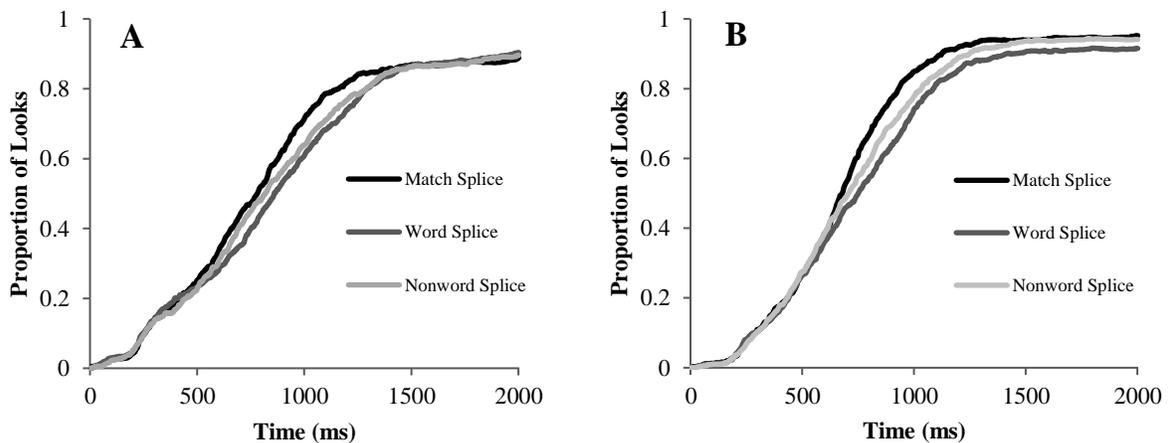


Figure 2. Time Course of Fixations to Target Across Splicing Conditions. Proportion of looks to the target per splice condition for the 7- to 8-year-olds (A) and the 12- to 13-year-olds (B). Time 0 ms indicates the trial onset.

In order to compare these differences statistically, we computed the average proportion of fixations to the target between 600 ms and 1,400 ms poststimulus onset. The average proportion of fixations was calculated at a later time window as well, between 1,400 and 2,000 ms poststimulus onset, to examine potential differences in amount of final asymptotic fixations to the target². Using the area-under-the-curve method, we calculated the average proportion of target fixations for each time window in each splicing condition. These averages were then analyzed using separate two way, repeated-measures ANOVA examining age group and splice condition (for each time window³. Separate ANOVAs were run for the area-under-the-curve estimates for each time window.

In the initial time window (600-1,400 ms), we found a significant effect of age group, $F(1,40) = 26.861, p < 0.001$. We also found a significant effect of splicing condition, $F(2,80) = 56.929, p < 0.001$, but no significant Splicing Condition \times Age Group interaction, $F(2,80) = 0.211, p = 0.810$. Post-hoc comparisons reveal that, in the initial time window, the difference between the *matching-splice* and the *nonword-splice* conditions was significant, $t(41) = 6.658, p < 0.001$, suggesting that participants were immediately sensitive to subphonemic mismatch. The most important comparison was the difference between the *word-splice* and *nonword-splice* conditions, which indicates an effect of inter-lexical inhibition beyond any effect of coarticulatory mismatch. In the initial time window, the difference between *word-splice* and

² We chose the initial time window (600-1,400) and late time window (1,400-2,000) to distinguish between the initial effects of interference and later, lasting effects. The 600ms onset was chosen to be consistent with previous studies from our lab using subphonemic mismatch paradigm (Kapnoula & McMurray, 2016; Kapnoula et al., 2015). This onset was chosen because the duration of the presplice stem lasts approximately 400 ms, then adding the 200 ms needed to plan an eye movement. The 1,400-ms time point was chosen based on the point at which participants' eye-movements reached asymptotic final activation. The 2,000 ms offset was chosen to allow for measurement of final target activation during a sufficient duration of time (600 ms) to ensure that the level of final activation was reached.

³ It is inadvisable to include time as a factor in the ANOVA since adjacent time bins are not independent samples.

nonword-splice conditions was also significant, $t(41) = -4.539$, $p < 0.001$; children looked significantly less at the target in the *word-splice* condition than the *nonword-splice* condition. These results demonstrate a clear effect of splicing manipulation, providing evidence of interference between target and competitor above and beyond any effect related to subphonemic mismatch. These results replicate findings from adult studies of inter-lexical inhibition (Dahan et al., 2001; Kapnoula & McMurray, 2016; Kapnoula et al., 2015), suggesting that this additional interference is evidence of inter-lexical inhibition during spoken word processing by school-aged children.

Analysis of the later time window revealed a significant effect of age group, $F(1,40) = 8.356$, $p = 0.006$. Although the effect of splicing condition alone was not significant, $F(2,80) = 2.031$, $p = 0.138$, there was a significant Splicing Condition \times Age Group interaction, $F(2,80) = 3.589$, $p = 0.032$, in the final asymptotic target fixations. Post-hoc comparisons compared the *word-splice* and *nonword-splice* (the critical marker of inhibition) within each age group. The older group showed significantly less fixations to the target in the *word-splice* condition than the *nonword-splice* condition, $t(41) = 2.714$, $p = 0.013$, while the younger group did not, $t(41) = -0.423$, $p = 0.677$. The difference in fixations between the *word-splice* and *nonword-splice* conditions represents the estimated final level of interference on target activation from the temporarily boosted activation of the competing word. Thus, this finding suggests that the older children exhibited a lasting interference from competitors, while the younger children did not. Only the younger group fully recovered from the inter-lexical inhibition imposed on the target from the activated competitor (implying that the interference is weaker).

An alternative explanation of this finding is that the presence of lasting interference in older children and the lack there of in the younger children is due to the younger children paying

less attention to the details to the auditory signal, and therefore are less sensitive to the splicing manipulation. To address this, we compared the subphonemic mismatch effect—that is the difference between the *matching-splice* and *nonword-splice* conditions—across age groups. We found no group differences in sensitivity to subphonemic mismatch in either time window (initial time window: $t(40) = -0.013, p = 0.99$; late time window: $t(40) = 0.023, p = 0.609$). Therefore, the difference between the age groups must derive from a difference in how each age group deals with the temporary boost of competitor activation in the *word-splice* condition.

Individual Differences

Finally, we asked if these age-related changes in the effects of inter-lexical inhibition were related to performance on language, reading, and perceptual reasoning assessments, as well as performance on a general inhibition task. Pearson's correlation coefficients were calculated for each assessment/task score and the inter-lexical inhibition effect in each time window. Inter-lexical inhibition was quantified as the target fixations in the *word-splice* condition subtracted from fixations in the *nonword-splice* condition.

We also used linear regression to further investigate the potential associations between eye-movement data and performance on additional assessments/tasks accounting for the effects of age. With the exception of oral reading fluency, we found no significant relationships between assessment scores and inter-lexical inhibition, so we focus primarily on the simple correlations which are shown in Table 2. Scatter plots of the data are presented in Figure 3.

With a few exceptions, few large correlations were observed. First, while there seemed to be no relationship between PPVT scores and inter-lexical inhibition in the initial time window, there appeared to be a potential relationship with inhibition in the later time window. However, an inspection of the scatter plot suggested that this correlation was driven predominantly by one

outlier. Removal of this participant from analysis led to a much smaller, and non-significant association between vocabulary score and inter-lexical inhibition in the later time window ($r = 0.264$). Furthermore, a two-level hierarchical regression predicting inter-lexical inhibition in the later time window revealed that, when age is taken into account, there is a non-significant association between PPVT and inter-lexical inhibition ($R^2 = 0.10$; $B = -0.001$; $F(1,37) = 1.541$, $p = 0.222$). It is important to note that all variation of vocabulary scores among subjects is within the high end of vocabulary ability (standard scores: $mean = 117$, $SD = 11.8$; $Range = 96$ to 143). This means that if the role of inter-lexical inhibition is more influential in children with lower language abilities, then this relationship would not be detected within the high-performing sample of this study.

The composite score of the single-word reading subtests of the WRMT (Word Identification and Word Attack) did not show any significant correlations with inter-lexical inhibition in the initial nor later time window. Regarding the Oral Reading Fluency (ORF) subtest, there was an association between reading fluency performance and inter-lexical inhibition in the initial time window that approached significance. This correlation was robust even when an outlier subject was removed. We ran a two level hierarchical regression predicting inter-lexical inhibition in the initial time window. On the first step, age was added to the model and accounted for 0.7% variance ($B < 0.001$; $F(1,30) = 0.213$, $p = 0.648$). On the next step, ORF was added to the model. It accounted for 10% of the variance over and above the effect of age ($B = -0.001$; $F(1,29) = 3.011$, $p = 0.093$). This finding suggests that oral reading fluency is associated with degree of inter-lexical inhibition in the earlier part of spoken word recognition.

Perceptual reasoning, as measured by WASI-II, did not have a significant association with inter-lexical inhibition. While the association between WASI-II composite scores and inter-

lexical inhibition in the later time window appeared to be approaching significance, a two-level hierarchical regression predicting inter-lexical inhibition in the later time window revealed that, when age is taken into account, there is a non-significant association between perceptual reasoning and inter-lexical inhibition ($R^2 = 0.087$; $B < 0.001$; $F(1,29) = 0.011$, $p = 0.918$).

Similarly, no significant associations were found between performance on the general inhibition task and the inhibition effect in the fixations. This suggests that executive function processes, like nonverbal reasoning and general inhibition, may not be related to inhibition processes between words in the lexicon. It appears that inter-lexical inhibition is specific to the language system.

Table 2. *Correlation Coefficients Between Inter-Lexical Inhibition and Other Assessments/Tasks.* Analyses were done with all subjects that completed the given task. Thus, some subjects were excluded from a given analysis if he/she did not complete the task during the session. The stated n represents the number of subjects included in each analysis.

Assessment/Task	Pearson's correlation coefficient (r) per time window	
	Initial (600-1,400 ms)	Later (1,400-2,000 ms)
PPVT-IV (n=40) ^a	-.143	-.264
WRMT – Word Composite (n=34)	-.075	-.151
WRMT – ORF (n=33)	-.292	-.157
WASI-II – MR+BD Composite (n=33)	-.082	-.256
Spatial Stroop Z Score (n=37)	.057	-.019

^aSubject classified as outlier (>2.5 *SD* above mean) excluded from analysis

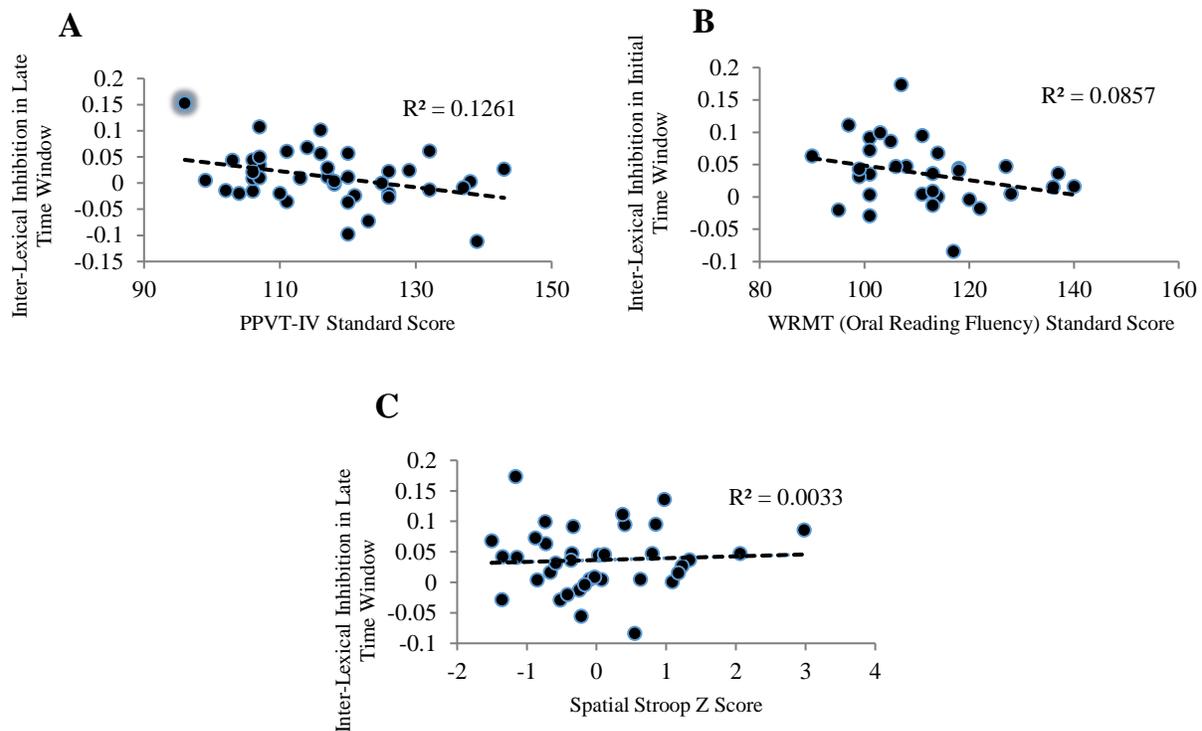


Figure 3. Associations Between Inter-Lexical Inhibition and Vocabulary, Reading fluency, and General Inhibition. (A) Scatter plot showing relationship between inter-lexical inhibition and vocabulary scores. Correlation is primarily driven by an outlier subject (shaded). (B) Scatter plot showing marginally significant relationship between inter-lexical inhibition and oral reading fluency scores. (C) Scatter plot showing no significant relationship between inter-lexical inhibition and spatial Stroop Z scores (measure of general inhibition).

Discussion

This study asked whether inter-lexical inhibition was involved in lexical competition during spoken word recognition by school-aged children and whether this process undergoes development in childhood between the ages of 7 and 13. We addressed these questions via an eye-tracking paradigm (VWP) that recorded looks to the target word, which was presented in three different splicing conditions: *matching-splice*, *word-splice*, and *nonword-splice* conditions designed to isolate inter-lexical inhibition. The *word-splice* condition resulted in a temporary boost of activity for a competitor word that then inhibited activation of the target word. It is

important to note that this competitor word was not present on the screen, so any observed inhibition effects are attributable to inhibition between words in the lexicon.

Analyses of the difference in fixations between the *word-splice* and *nonword-splice* conditions revealed evidence of inter-lexical inhibition influencing spoken word recognition in both age groups. Analysis of fixations in the later part of the time course revealed a difference in the resolution of lexical interference across age groups. Specifically, the younger group fully recovered from this inter-lexical inhibition while the older group did not. Analyses of individual differences in vocabulary, reading, and other cognitive abilities (perceptual reasoning and general inhibition) lead to the finding of a potential link between inter-lexical inhibition and reading fluency, as well as reveal potential limitations of the present study and directions for future research.

Development of Inter-Lexical Inhibition

This difference in the dynamics of lexical competition suggests that changes in inter-lexical inhibition are implicated in the development of spoken word recognition. While previous studies of development of lexical processing have focused on changes in efficiency of processing (Fernald et al., 1998; Fernald et al., 2006; Sekerina & Brooks, 2007) and competition dynamics (Rigler et al., 2015), the findings from this study pinpoint a specific mechanism (i.e., inter-lexical inhibition) as plausible mechanism for the development of efficiency in spoken word recognition.

As in Rigler et al. 2015, we found notable age-related differences in the dynamics of target activation during processing of normal word stimuli (i.e., *matching-splice* condition). Specifically, the older group showed significantly more efficient activation of the target, fixating to the target earlier and more quickly. In contrast to Rigler et al. (2015), the older children in our

study showed more fixations to the target at the end of the time course in comparison to the younger children, suggesting development of the resolution of lexical competition as well as development of initial target activation.

It is evident from these findings that efficiency in lexical processing develops in the school-age years, and this development may be linked to changes in underlying competition processes. This study supports the idea that changes in inter-lexical inhibition during lexical competition plays a role in developing more efficient, adult-like lexical processing abilities. From our results, it appears that the older children are not able to resolve the lexical interference caused by temporary activation of a competitor as well as the younger children. There are two aspects of this finding that may seem counterintuitive. First, the inter-lexical inhibition effect was observed late in the time course, much later than the initial perception of co-articulatory mismatch. Second, the difference in inter-lexical inhibition seems to go in the opposite direction, with the older children showing seemingly less efficient resolution of lexical competition than the younger children.

With regards to the timing of the effect, this result could actually be expected, as similar results were found in a previous study investigating the effects of short-term training on the dynamics of lexical competition (Kapnoula & McMurray, 2016). Kapnoula and McMurray (2016) used the same splicing paradigm in the VWP to examine the differences in spoken word recognition across two groups that underwent a short-term training. In the high competition (HC) group, the training was designed to heighten competition between similar-sounding words, while the training low competition (LC) group was not. Kapnoula and McMurray (2016) found that the primary difference in spoken word recognition between groups was that HC group was significantly better at recovering from the interference of a lexical competitor than the LC group.

Subsequent TRACE simulations showed that the manipulation of lexical inhibition produced similar patterns of processing, with only a small effect occurring during the co-articulation and large differences in the extent to which the target word was successfully suppressed by the competitor later in the time course. Therefore, the simulation results suggested that the observed group differences in inter-lexical inhibition impact the efficiency of interference resolution (Kapnoula & McMurray, 2016). The consequences of differences in inhibition were much more apparent later in the trial, when both target and competitor had been partially activated. It may be that the effect of inter-lexical inhibition appears not in the overall magnitude of interference, but rather the way in which listeners resolve interference.

When the findings of Kapnoula and McMurray (2016) are taken into account, we can begin to understand the difference in inter-lexical inhibition across age groups. While age of the participant had little effect early in the time course of processing, more significant age-related differences were observed later in the time course, similar to the group-related differences in Kapnoula and McMurray (2016). The pattern of inter-lexical inhibition effect in the older children resembles the performance of the LC group, which suggests that, similar to the LC group, the older children had more difficulty recovering from lexical interference, which included inhibition imposed on the target by the temporarily boosted competitor.

As mentioned previously, this result seems counterintuitive, as we could expect that the older children would have more efficient resolution of lexical interference, just as older children show more efficient resolution of lexical competition in normal spoken word recognition (as in the *matching-splice* condition and Rigler et al., 2015). This raises an important question: if developmental changes in the dynamics of lexical competition are adaptive and assumedly lead

to more efficient processing, why do the older children to have more difficulty dealing with this lexical interference?

One possible explanation is that this lasting interference is a consequence of older children having a more expansive lexicon with more robust word representations. The activation of richer representations of words and the more developed connections between words may result in stronger lateral inhibition being imposed on similar-sounding words in the lexical network. If this were the case, the temporary activation boost of a competitor would lead to more robust suppression of the target word, leading to increased difficulty activating the target and suppressing the competitor later in the time course. It is also likely that the misleading co-articulatory information led to activation of not only the competitor (e.g. *cat*), but also longer words with a similar beginning (e.g. *cattle*, *category*). The cumulative inhibitory effect of these activated words on the target word could also lead to more trouble dealing with lexical interference and ultimately activating the target.

Another potential explanation is that this lasting effect of lexical interference in older children is a product of more flexible competition processes. Rather than stronger interference from competing words leading to more interference, it may be that the lasting interference is due to dampening of inhibition of these competitors. This dampening of inter-lexical inhibition would allow for multiple lexical candidates to remain more available to subsequent activation. This strategy would be adaptive in situations in which the perception of the target word is unreliable and may be subject to revision (c.f., Brouwer, Mitterer, & Huettig, 2012; McMurray, Tanenhaus, & Aslin, 2009). These situations could include adverse listening circumstances such as listening to speech in background noise or accented speech. In this way, the flexibility and plasticity of inter-lexical inhibition would be useful in adjusting the word recognition system to

be best prepared for difficult listening contexts. This explanation is supported by the findings of Kapnoula and McMurray (2016), which demonstrated the experience-dependent plasticity of inter-lexical inhibition in adults. It is possible that gains in lexical processing efficiency are a result of increasing flexibility of processing.

Regardless of the underlying cause of this difference in inter-lexical inhibition, it is clear there are age-related differences in the real-time processes by which words interact with each other during spoken word recognition. If these processes, such as lateral inhibition, are amenable to learning, as seen in Kapnoula and McMurray (2016), then the finding that these processes undergo developmental changes may have significant implications for how we understand and study development of language processing in general. If the real-time processes underlying spoken word recognition are malleable, then developmental changes in processing could be conceptualized as a long-term outcome that is the result of short-term changes in the language system.

It is important to note that changes in lateral inhibition are not the only mechanisms by which language processing can develop in childhood. Changes in the quality of bottom-up mappings between input representation and words may also play a role (McMurray, Horst, Samuelson, 2012). McMurray et al. (2012) proposed that changes in word recognition efficiency may derive from long-term learning processes, like associative learning, influencing mappings between phonological and semantic representations formed through word learning over development. This model suggests that processing speed is related to the weakness of irrelevant associations in the lexical network, stating that smaller (better pruned) irrelevant connections support faster word processing. The present study's findings suggest that, while associative

learning may influence processing efficiency, changes in the parameters that control competition dynamics (i.e., lateral inhibition) may also be involved in development of lexical competition.

Just as bottom-up processes may be involved, development of top-down knowledge and attentional processes may also improve processing speed. Seeing that inhibitory control continues to develop through later childhood (e.g., Welsh & Pennington, 1998), a critical question arises: Could changes in lateral inhibition in the lexical network simply be a result of gains in more general inhibitory abilities? In the present study, we found no association between inter-lexical inhibition and performance on a measure of general inhibition (i.e., spatial Stroop task). This finding suggests that differences in lateral inhibition involved in lexical competition is not related to differences in general inhibitory ability, and therefore must be specific to the language system. For this reason, it is important to distinguish between lateral inhibition and top-down inhibition that is implicated in executive function. While development of the plasticity of attention-based forms of inhibition may also be relevant for language ability (Novick, Hussey, Teubner-Rhodes, Harbison, & Bunting, 2014), the contributions of these two types of inhibition to language development may be independent of each other.

The contributions of lateral inhibition may be applicable to understanding and addressing impairments related to atypical patterns of processing, like developmental language disorder (McMurray et al., 2010) or dyslexia (Ziegler & Muneaux, 2007). Specifically, these disorders have been associated with inefficient resolution of interference from activated competitors, including the effects of lateral inhibition. In developmental language disorder, interference from competition appears primarily at the end of word processing, suggesting that these individuals have more difficulty in suppressing competitors and fully activating the target word. Taking into account that lateral inhibition is changing as a result of both short-term training and long-term

development, it is possible that the combination of disadvantageous experiences and altered developmental trajectories may lead to the atypical, inefficient patterns of lexical processing observed in certain populations. Furthermore, if the underlying mechanisms of this processing are amenable to learning, then it may be possible to design interventions that train individuals to better manage lexical competition, consequently leading to better language outcomes.

Implications for Individual Differences in Language and Reading

Since atypical patterns of lexical processing have been observed in populations with language and reading disorders, it can be inferred that these differences in processing are related to language and reading ability (Desroches et al., 2006; McMurray et al., 2010; Ziegler & Muneaux, 2007). There is also evidence that early processing abilities are predictive to later language outcomes (Fernald & Marchman, 2012; Marchman & Fernald, 2008). The present study sought to further elaborate on the relationship between individual differences in lexical processing and language and reading ability. Contrary to expectations, we found no notable associations between individual differences in inter-lexical inhibition and performance on vocabulary scores. These results seem to coincide with findings from Law, Mahr, Schneeberg, and Edwards (2017) who found that children with larger vocabularies were not quicker or more accurate to reject any particular type of competitor (e.g., semantic, phonological, unrelated). Since inter-lexical inhibition is required to reject phonological or semantic competitors, but not unrelated ones, Law et al. (2017) concluded that vocabulary size was not associated with inhibition of competing lexical items.

Before disregarding the potential relationship between individual differences in dynamics of lexical processing and overall language ability, it is important to consider certain limitations of this study that could have limited our power to detect this relationship. First, the number of

subjects was rather small for an investigation of individual differences. As seen in Table 2, many of the correlations between inter-lexical inhibition and assessment scores followed a similar trend (negative values), but only a few associations reached marginal levels of significance. Moreover, when age is controlled for in analyses, these associations do not remain significant. It is possible that the resulting correlation values would be significant if they continued to present in larger samples. It may be that a larger sample of subjects is required in order to detect these relationships between lexical processing dynamics and overall language ability.

More importantly, the narrow distribution of language ability in the present study may also be a limiting factor in investigating the potential link between language processing and ability. All of our participants had vocabulary scores in the average to above-average range. The effects of individual differences in lexical processing dynamics may manifest differently at the lower end of the language scale in comparison to the observed effects at this range. While limiting in an individual differences perspective, this lack of variability in language ability also allows us to more precisely attribute the observed differences in lateral inhibition to development, not language ability. It is possible that the language outcomes of children who are at-risk of language difficulties (i.e., low socioeconomic status (SES), developmental language disorder) are more dependent on aspects of processing efficiency than children with stronger language skills. It is likely that environmental factors, such as SES, contribute to individual differences in processing and language ability. Studies have shown that there are significant disparities in language processing efficiency between higher- and lower-SES families as early as 18 months (Fernald, Marchman, & Weisleder, 2013), and these differences may last into young adulthood (Troyer & Borovsky, 2017). From these finding, it is clear that quantity and quality of

early language experience should be considered when investigating the development of lexical processing and its potential influence on language development.

While the results of the present study show no significant relationship between inter-lexical inhibition and vocabulary, we did find a marginally significant association with oral reading fluency. It seems that the degree of lateral inhibition in the initial period of lexical processing is potentially related to reading fluency. More fluent readers show less interference from inter-lexical inhibition early in processing. This finding can be interpreted in a few ways. One possible explanation is that the dynamics of spoken word processing may serve as a foundation for automaticity and fluency in reading written words. On the other hand, it may be that automaticity in reading aids in the development of more efficient spoken word processing. Recent work from our lab suggests that there is a common underlying factor contributing to the processing efficiency of word recognition across both spoken and written modalities (Goodwin, Blomquist, & McMurray, in preparation). Specifically, the speed and amount of target activation in spoken word recognition is significantly related to these measures of target activation in written word recognition. This finding provides further evidence for the potential relationship between spoken word processing and the development of reading abilities. This relationship warrants further investigation in future studies, as such research would lend to a better understanding of how oral language ability contributes to reading acquisition.

This study showed clear evidence for the involvement of lateral inhibition in lexical competition during spoken word recognition by school-aged children. Additionally, we found developmental differences in how lateral inhibition was used to resolve lexical competition. The inhibitory processes involved in competition resolution later in lexical processing seem to be changing even into later childhood. The plasticity of this inter-lexical inhibition provides not

only an explanation for how gains in lexical processing efficiency arise in development, but also a plastic mechanism underlying lexical processing that may be amenable to interventions specifically-designed to address atypical patterns of processing in individuals who struggle with language.

Appendix A

List of Words and Nonwords Used in Splicing Conditions

Matching-splice <i>(bat condition)</i>	Word-splice <i>(back condition)</i>	Nonword-splice <i>(bap condition)</i>
bait	bake	bape (beɪp)
bat	back	bap (bæp)
bug	bud	bub (bʌb)
cap	cat	cack (kæk)
dot	dock	dop (dɒp)
fork	fort	forp (fɔrp)
heap	heat	heak (hik)
mug	mud	mub (mʌb)
net	neck	nep (neɪp)
park	part	parp (pɑrp)
pick	pit	pip (pɪp)
rod	rob	rog (rɒg)
shake	shape	shate (ʃeɪt)
soup	suit	sook (suk)

Appendix B

List of Images Used in the Visual World Paradigm Task

Target Word	Cohort
bait	book
bat	bead
bug	bark
cap	cord
dot	dad
fork	fog
heap	hood
mug	milk
neck	nut
park	pig
pick	plug
rod	root
shake	shed
soup	sword

References

- Allopenna, P., Magnuson, J. S., & Tanenhaus, M. K. (1998). Tracking the time course of spoken word recognition using eye movements: Evidence for continuous mapping models. *Journal of Memory and Language*, 38, 419–439. <http://dx.doi.org/10.1006/jmla.1997.2558>
- Apfelbaum, K. S., Blumstein, S. E., & McMurray, B. (2011). Semantic priming is affected by real-time phonological competition: Evidence for continuous cascading systems. *Psychonomic Bulletin & Review*, 18, 141–149. <http://dx.doi.org/10.3758/s13423-010-0039-8>
- Bion, R. A. H., Borovsky, A., & Fernald, A. (2013). Fast mapping, slow learning: Disambiguation of novel word-object mappings in relation to vocabulary learning at 18, 24, and 30 months. *Cognition*, 126, 39–53. <http://dx.doi.org/10.1016/j.cognition.2012.08.008>
- Bleses, D., Makransky, G., Dale, P. S., Højen, A., & Aktürk Ari, B. (2016). Early productive vocabulary predicts academic achievement 10 years later. *Applied Psycholinguistics*, 37, 1461-1476. <http://dx.doi.org/10.1017/S0142716416000060>
- Brouwer, S., Mitterer, H., & Huettig, F. (2012). Speech reductions change the dynamics of competition during spoken word recognition. *Language and Cognitive Processes*, 27 (4), 539-571. <http://dx.doi.org/10.1080/01690965.2011.555268>
- Dahan, D., & Gareth Gaskell, M. (2007). The temporal dynamics of ambiguity resolution: Evidence from spoken-word recognition. *Journal of Memory and Language*, 57, 483–501. <http://dx.doi.org/10.1016/j.jml.2007.01.001>
- Dahan, D., Magnuson, J. S., Tanenhaus, M. K., & Hogan, E. (2001). Subcategorical mismatches and the time course of lexical access: Evidence for lexical competition. *Language and Cognitive Processes*, 16, 507–534. <http://dx.doi.org/10.1080/01690960143000074>

- Desroches, A. S., Joanisse, M. F., & Robertson, E. K. (2006). Specific phonological impairments in dyslexia revealed by eyetracking. *Cognition, 100*, B32–B42. <http://dx.doi.org/10.1016/j.cognition.2005.09.001>
- Dollaghan, C. (1998). Spoken word recognition in children with and without specific language impairment. *Applied Psycholinguistics, 19*, 193–207. <http://dx.doi.org/10.1017/S0142716400010031>
- Duff, F. J., Reen, G., Plunkett, K., & Nation, K. (2015). Do infant vocabulary skills predict school-age language and literacy outcomes? *Journal of Child Psychology and Psychiatry, 46* (8), 848-856.
- Dunn, L. M., & Dunn, D. M. (2012). Peabody Picture Vocabulary Test (PPVTM-4). New York, NY: Pearson Education Inc.
- Fernald, A., & Marchman, V. A. (2012). Individual differences in lexical processing at 18 months predict vocabulary growth in typically developing and late-talking toddlers. *Child Development, 83*, 203–222. <http://dx.doi.org/10.1111/j.1467-8624.2011.01692.x>
- Fernald, A., Marchman, V. A., & Weisleder, A. (2013). SES differences in language processing skill and vocabulary evident at 18 months. *Developmental Science, 16* (2), 234-248. <http://dx.doi.org/10.1111/desc.12019>
- Fernald, A., Perfors, A., & Marchman, V. A. (2006). Picking up speed in understanding: Speech processing efficiency and vocabulary growth across the 2nd year. *Developmental Psychology, 42*, 98–116. <http://dx.doi.org/10.1037/0012-1649.42.1.98>
- Fernald, A., Pinto, J. P., Swingle, D., Weinberg, A., & McRoberts, G. W. (1998). Rapid gains in speed of verbal processing by infants in the second year. *Psychological Science, 9*, 228–231. <http://dx.doi.org/10.1111/1467-9280.00044>
- Fernald, A., Swingle, D., & Pinto, J. P. (2001). When half a word is enough: Infants can recognize spoken words using partial phonetic information. *Child Development, 72*,

1003–1015. <http://dx.doi.org/10.1111/1467-8624.00331>

Frauenfelder, U., Scholten, M., & Content, A. (2001). Bottom-up inhibition in lexical selection:

Phonological mismatch effects in spoken word recognition. *Language and Cognitive Processes, 16*, 583–607. <http://dx.doi.org/10.1080/01690960143000146>

Golinkoff, R. M., & Hirsh-Pasek, K. (2006). Baby wordsmith: From associationist to social sophisticate. *Current Directions in Psychological Science, 15*, 30–33. <http://dx.doi.org/10.1111/j.0963-7214.2006.00401.x>

10.1111/j.0963-7214.2006.00401.x

Goodwin, C., Blomquist, C., & McMurray, B. (in preparation). The development of real-time lexical processing for spoken and written input: Implications for reading outcomes.

Henderson, L., Weighall, A., Brown, H., & Gaskell, G. (2013). Online lexical competition during spoken word recognition and word learning in children and adults. *Child Development, 84* (5), 1668-1685. <http://dx.doi.org/10.1111/cdev.12067>

Kapnoula, E. C., & McMurray, B. (2016). Training alters the resolution of lexical interference: Evidence for plasticity of competition and inhibition. *Journal of Experimental Psychology: General, 145* (1), 8-30. <http://dx.doi.org/10.1037/xge0000123>

Psychology: General, 145 (1), 8-30. <http://dx.doi.org/10.1037/xge0000123>

Kapnoula, E. C., Packard, S., Gupta, P., & McMurray, B. (2015). Immediate lexical integration of novel word forms. *Cognition, 134*, 85–99. <http://dx.doi.org/10.1016/j.cognition.2014.09.007>

2014.09.007

Law II, F., & Edwards, J. (2015). Effects of vocabulary size on online lexical processing by preschoolers. *Language Learning and Development, 11* (4), 331-355. <http://dx.doi.org/10.1080/15475441.2014.961066>

10.1080/15475441.2014.961066

Law II, F., Mahr, T., Schneeberg, A., & Edwards, J. (2017). Vocabulary size and auditory word recognition in preschool children. *Applied Psycholinguistics, 38* (1), 89-125. <http://dx.doi.org/10.1017/S0142716416000126>

<http://dx.doi.org/10.1017/S0142716416000126>

Leach, L., & Samuel, A. G. (2007). Lexical configuration and lexical engagement: When adults

- learn new words. *Cognitive Psychology*, 55, 306–353. <http://dx.doi.org/10.1016/j.cogpsych.2007.01.001>
- Lee, J. (2011). Size matters: Early vocabulary as a predictor of language and literacy competence. *Applied Psycholinguistics*, 32, 69-92. <http://dx.doi.org/10.1017/S0142716410000299>
- Luce, P. A., & Pisoni, D. B. (1998). Recognizing spoken words: The neighborhood activation model. *Ear and Hearing*, 19, 1–36. <http://dx.doi.org/10.1097/00003446-199802000-00001>
- Mainela-Arnold, E., Evans, J. L., & Coady, J. A. (2008). Lexical representations in children with SLI: Evidence from a frequency-manipulated gating task. *Journal of Speech, Language, and Hearing Research*, 51, 381–393. [http://dx.doi.org/10.1044/1092-4388\(2008/028\)](http://dx.doi.org/10.1044/1092-4388(2008/028))
- Mani, N., & Plunkett, K. (2011). Phonological priming and cohort effects in toddlers. *Cognition*, 121, 196–206. <http://dx.doi.org/10.1016/j.cognition.2011.06.013>
- Marchman, V. A., & Fernald, A. (2008). Speed of word recognition and vocabulary knowledge in infancy predict cognitive and language outcomes in later childhood. *Developmental Science*, 11(3), F9–F16. <http://dx.doi.org/10.1111/j.1467-7687.2008.00671.x>
- Marslen-Wilson, W. D. (1987). Functional parallelism in spoken word recognition. *Cognition*, 25, 71–102. [http://dx.doi.org/10.1016/0010-0277\(87\)90005-9](http://dx.doi.org/10.1016/0010-0277(87)90005-9)
- Marslen-Wilson, W. D., & Zwitserlood, P. (1989). Accessing spoken words: The importance of word onsets. *Journal of Experimental Psychology: Human Perception and Performance*, 15, 576–585. <http://dx.doi.org/10.1037/0096-1523.15.3.576>
- McClelland, J. L., & Elman, J. L. (1986). The TRACE model of speech perception. *Cognitive Psychology*, 18, 1–86. [http://dx.doi.org/10.1016/0010-0285\(86\)90015-0](http://dx.doi.org/10.1016/0010-0285(86)90015-0)
- McMurray, B., Danelz, A., Rigler, H., & Seedorff, M. (Submitted). *Speech categorization*

develops slowly through adolescence.

- McMurray, B., Horst, J. S., & Samuelson, L. K. (2012). Word learning emerges from the interaction of online referent selection and slow associative learning. *Psychological Review, 119*, 831–877. <http://dx.doi.org/10.1037/a0029872>
- McMurray, B., Samuelson, V. M., Lee, S. H., & Tomblin, J. B. (2010). Individual differences in online spoken word recognition: Implications for SLI. *Cognitive Psychology, 60*, 1–39. <http://dx.doi.org/10.1016/j.cogpsych.2009.06.003>
- McMurray, B., Tanenhaus, M. K., & Aslin, R. N. (2009). Within-category VOT affects recovery from "lexical" garden paths: Evidence against phoneme-level inhibition. *Journal of Memory and Language, 60* (1), 65-91. <http://dx.doi.org/10.1016/j.jml.2008.07.002>
- Nittrouer, S. (2002). Learning to perceive speech: How fricative perception changes, and how it stays the same. *Journal of the Acoustical Society of America, 112*, 711–719. <http://dx.doi.org/10.1121/1.1496082>
- Novick, J. M., Hussey, E., Teubner-Rhodes, S., Harbison, J. I., & Bunting, M. F. (2014). Clearing the garden-path: Improving sentence processing through cognitive control training. *Language, Cognition and Neuroscience, 29*, 186–217. <http://dx.doi.org/10.1080/01690965.2012.758297>
- Ojima, S., Matsuba-Kurita, H., Nakamura, N., & Hagiwara, H. (2011). The acceleration of spoken-word processing in children's native-language acquisition: An ERP cohort study. *Neuropsychologia, 49*, 790-799. <http://dx.doi.org/10.1016/j.neuropsychologia.2011.01.007>
- Rigler, H., Farris-Trimble, A., Greiner, L., Walker, J., Tomblin, J. B., & McMurray, B. (2015). The slow developmental timecourse of real-time spoken word recognition. *Developmental Psychology, 51* (12), 1690-1703. <http://dx.doi.org/10.1037/dev0000044>.
- Sekerina, I. A., & Brooks, P. J. (2007). Eye movements during spoken word recognition in

- Russian children. *Journal of Experimental Child Psychology*, 98, 20–45. <http://dx.doi.org/10.1016/j.jecp.2007.04.005>
- Streeter, L. A., & Nigro, G. N. (1979). The role of medial consonant transitions in word perception. *The Journal of the Acoustical Society of America*, 65, 1533–1541. <http://dx.doi.org/10.1121/1.382917>.
- Swingley, D., & Aslin, R. N. (2007). Lexical competition in young children's word learning. *Cognitive Psychology*, 54, 99–132. <http://dx.doi.org/10.1016/j.cogpsych.2006.05.001>
- Swingley, D., Pinto, J. P., & Fernald, A. (1999). Continuous processing in word recognition at 24 months. *Cognition*, 71, 73–108. [http://dx.doi.org/10.1016/S0010-0277\(99\)00021-9](http://dx.doi.org/10.1016/S0010-0277(99)00021-9)
- Tanenhaus, M. K., Spivey-Knowlton, M. J., Eberhard, K. M., & Sedivy, J. C. (1995). Integration of visual and linguistic information in spoken language comprehension. *Science*, 268, 1632–1634. <http://dx.doi.org/10.1126/science.7777863>
- Troyer, M., & Borovsky, A. (2017). Maternal socioeconomic status influences the range of expectations during language comprehension in adulthood. *Cognitive Science*, 41 (3), 1-29. <http://dx.doi.org/10.1111/cogs.12488>
- Vitevitch, M. S., & Luce, P. A. (1998). When words compete: Levels of processing in perception of spoken words. *Psychological Science*, 9, 325–329. <http://dx.doi.org/10.1111/14679280.00064>
- Vitevitch, M. S., Luce, P. A., Pisoni, D. B., & Auer, E. T. (1999). Phonotactics, neighborhood activation, and lexical access for spoken words. *Brain and Language*, 68, 306–311. <http://dx.doi.org/10.1006/brln.1999.2116>
- Viviani, P. (1990). Eye movements in visual search: Cognitive, perceptual, and motor control aspects. In E. Kowler (Ed.), *Eye movements and their role in visual and cognitive processes: Reviews of oculomotor research* (Vol. 4, pp. 353–383). Amsterdam, Netherlands: Elsevier.

Weber, A., & Scharenborg, O. (2012). Models of spoken-word recognition. *Wiley*

Interdisciplinary Reviews: Cognitive Science, 3 (3), 387-401. <http://dx.doi.org/>

10.1002/wcs.1178

Welsh, M., & Pennington, B. (1988). Assessing frontal lobe functioning in children: Views from developmental psychology. *Developmental Neuropsychology*, 4, 199 –230. <http://dx.doi.org/10.1080/87565648809540405>

Ziegler, J. C., & Muneaux, M. (2007). Orthographic facilitation and phonological inhibition in spoken word recognition: A developmental study. *Psychonomic Bulletin & Review*, 14, 75–80. <http://dx.doi.org/10.3758/BF03194031>