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The slow developmental timecourse of real-time spoken word recognition

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Abstract

This study investigated the developmental timecourse of spoken word recognition in older children using eye-tracking to assess how the real-time processing dynamics of word recognition change over development. We found that nine-year-olds were slower to activate the target words and showed more early competition from competitor words than 16 year olds; however, both age groups ultimately fixated targets to the same degree. This contrasts with a prior study of adolescents with language impairment (McMurray et al, 2010) which showed a different pattern of real-time processes. These findings suggest that the dynamics of word recognition are still developing even at these late ages, and differences due to developmental change may derive from different sources than individual differences in relative language ability.

Keywords

spoken word recognition; lexical development; eye-tracking; language impairment; visual world paradigm; adolescence; real-time processing

Introduction

Research on language is often divided between research on the mature (adult) language user and the young language learner (child). These research programs differ on far more than

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age. Developmental studies typically emphasize intra- and inter- individual differences in language performance and linguistic knowledge, often as a function of age, but also across individuals (e.g., language impairment). These differences are attributed to change that unfold over the course of months and years, as key properties of language are learned (what we term *developmental time*). In contrast, adult psycholinguistics typically places less emphasis on knowledge or capacities, and instead focuses on language processing, mechanisms of comprehension and production that unfold over milliseconds (*situation time*). While both theoretical (McMurray, Horst, & Samuelson, 2012) and empirical work (Bion, Borovsky, & Fernald, 2013; Fernald, Perfors, & Marchman, 2006; Snedeker & Trueswell, 2004) have begun to bridge these divides, our understanding of how real-time language processing changes over development is limited, particularly in older children and adolescents.

Work on spoken word recognition in adults is motivated by the problem of temporary ambiguity (Marslen-Wilson, 1987). Because words unfold over time, at early moments there is insufficient information to unambiguously identify a target word. This ambiguity is present even if the input (at that moment) is *acoustically* unambiguous; rather it is a consequence of the fact that for any given word, multiple words share the first few phonemes. For example, when listeners hear the beginning of a word (e.g., the *sa-* in *sandal*), multiple lexical candidates (*sandal, sandwich, sack*) are consistent with it until more input arrives. Given this ambiguity, listeners are faced with two strategies – make an early commitment to several items (and deal with the resulting competition), or avoid this competition by waiting until the end of the word to access the lexicon.

Research on typical adults offers some consensus for early commitment and competition. Listeners cope with temporary ambiguity by immediately activating words that are consistent with whatever portion of the input has been heard, making partial commitments to multiple words (including their meanings; Allopenna, Magnuson, & Tanenhaus, 1998; Marslen-Wilson & Zwitserlood, 1989). These activated lexical candidates compete with each other (Dahan, Magnuson, Tanenhaus, & Hogan, 2001; Luce & Pisoni, 1998), and as the signal unfolds, words that are no longer consistent with the input drop out of consideration (Dahan & Gaskell, 2007; Frauenfelder, Scholten, & Content, 2001; Marslen-Wilson, 1987). By the end of the word, [typically] only one candidate remains that matches the auditory signal.

The process unfolds over milliseconds in what we term *situation-time*, the time scale at which real-time cognition, perception and action take place. Processes at this timescale underlie momentary processes like making a decision, perceiving a scene, or in this case, recognizing a word. They may or may not result in any long term changes to the system. This term contrasts with the slower scale of *developmental-time*, the longer time scale of development over months and years. Such processes underlie learning and developmental change, the large scale changes and tuning of the lexical system that unfold with language development (McMurray et al., 2012).

This dynamic competition among words solves an important cognitive problem by helping listeners make rapid, but flexible, decisions about the input in the face of temporary ambiguity. This problem is quite distinct from the perceptual or phonological problems of identifying categories from variable acoustic input, and is commonly described as part of lexical (not perceptual) processing. There are also competition processes at higher levels of the system (e.g., spreading activation among semantic associates), but the competition driven by temporary ambiguity (phonological similarity) is the first place where lexical representations are thought to be engaged.

This dynamic competition process happens over the course of milliseconds; as a result, detecting these differences requires online measures that are sensitive to these dynamics like gated stimuli, cross-modal priming, or eye-tracking in the visual world paradigm (VWP). In the VWP, (Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy, 1995) participants hear a spoken word and select its referent from a computer screen containing pictures of the target and lexical competitors. While they do this task, eye-movements to each object are monitored to measure how strongly different interpretations of an input are considered at each point in time. In Allopenna et al. (1998), adults heard words like *sandal* while the experimenters monitored their eye-movements to pictures representing a target (e.g., *sandal*), a cohort competitor that matched phonologically at word-onset (e.g., *sandwich*), a rhyme competitor that matched phonologically at word-offset (e.g., *candle*), and a phonologically unrelated item (e.g., *parrot*). Two hundred msec after word onset, eye-movements were equally likely to the target and cohort, suggesting that both were being considered, but shortly thereafter, fixations to the cohort were suppressed, and there was brief consideration of the rhyme before the participant ultimately selected the target. This provides a clear picture of the timecourse of processing, and the fact that these eye-movements are directed to pictures of the referents indicates that during this competition lexical/semantic representations (not just phonological ones) are engaged (see also, Apfelbaum, Blumstein, & McMurray, 2011; Yee & Sedivy, 2006).

From a developmental perspective, an important question is whether the *situation-time* dynamics of competition change as children acquire language, over developmental time. This question is clearly related to broader work on perceptual and lexical development, but these research programs have often focused on the acquisition of words and categories, not real-time lexical processing. For example, the development of speech sound categorization (clearly a prerequisite to lexical access) appears to develop over the first two to three years (Galle & McMurray, in press; McMurray & Benders, 2014; Werker & Curtin, 2005; but see, Hazan & Barrett, 2000). However, these studies do not address how these categories are used to access the lexicon during word recognition. Similarly, much of the work on lexical development concerns the acquisition of new words (c.f., Golinkoff & Hirsh-Pasek, 2006; Markman, 1990; Mervis & Bertrand, 1994; Storkel, 2009; Storkel, Maekawa, & Hoover, 2010), not the dynamics of their processing.

In contrast, recent studies have examined the development of online processing of known words in young children (Fernald et al., 2006; Fernald, Pinto, Swingley, Weinberg, & McRoberts, 1998; Sekerina & Brooks, 2007). As we describe, they document that *young* children look similar to adults in the broad profile of real-time word recognition. Nonetheless, relatively little is understood about the potential development of the finer grained aspects of these situation-time processes (e.g., their efficiency, the manner in which competitors are suppressed); and it is not yet clear whether development at this level is complete during early childhood, or changes throughout adolescence. Moreover, the existing work on young children does not offer a precise profile of how real-time lexical processing changes over development. Such a description is necessary for developing mechanistic models of development. Moreover, the need for it is intensified by evidence that children with language impairment exhibit differences in online lexical competition even during adolescence (Dollaghan, 1998; McMurray, Munson, & Tomblin, 2014; McMurray, Samelson, Lee, & Tomblin, 2010). Consequently, a precise understanding of which aspects of lexical competition are developing in typical individuals during adolescence may help identify the potential developmental nature of language impairment.

Spoken Word Recognition in Young Children

Virtually all of these studies on the timecourse of word recognition in very young children use a simplified version of the VWP (Fernald et al., 1998), the “looking-while-listening” paradigm. In this paradigm, infants or young children hear a spoken word and see pictures of two objects; accuracy and timing of fixations to the correct picture are used to index the efficiency of word recognition. Using this, Swingley, Pinto and Fernald (1999) showed that 24-month-old children were delayed in recognizing a word if an onset (cohort) competitor (e.g., *doll* when the target was *dog*) was present on the screen, suggests that both words are active at syllable onset (as in adults). Similarly, Fernald, Swingley and Pinto (2001) showed that 18- and 21- month-olds can fixate a word’s referent given only the first 300 msec, suggesting that, infants exhibit immediate lexical access from the earliest portions of the signal (also like adults). There is also evidence for incremental updating: Swingley (2009) showed that in 14 to 22-month-olds, mismatching phonemes (e.g., *tog* instead of *dog*) affect the timecourse of fixations differently when they occur at word onset and offset. Finally, just as in adults, similar sounding words inhibit the recognition of a target word in 24 month olds (Mani & Plunkett, 2011). Thus, the basic principles of word recognition are in place by 24 months.

While this suggests qualitative continuity with adult lexical processing, there is also quantitative change. Fernald and colleagues (Fernald et al., 2006; Fernald et al., 1998; Marchman & Fernald, 2008; Zangl, Klarman, Thal, Fernald, & Bates, 2005) document that the speed to fixate the correct referent (a measure of the efficiency of lexical competition) decreases dramatically over the first 31 months of life. Moreover, Fernald, Perfors, and Marchman (2006) found that at 25 months, recognition speed was related to the speed of vocabulary growth. Such effects are also seen prospectively: word recognition speed at 2 years predicts language and cognitive outcomes as far out as 8 years of age (Marchman & Fernald, 2008) and in late-talking 18 month olds (Fernald & Marchman, 2012). Thus, gains in processing efficiency are not epiphenomenal for development. Their correlations with language outcomes suggests either that efficiency gains either enable or reflect better language development (or both).

What is not clear is how the observed gains in efficiency are achieved with respect to the underlying competition processes. There are multiple ways to tune lexical competition to become more efficient over development. For example, older children could activate the target word more quickly; they could initially activate competitors less (thus yielding less competition); or they could more quickly suppress them (resolving competition faster). The variety of routes to achieve greater efficiency cannot be addressed by existing studies that use only two items on the screen, and thus cannot assess the full range of lexical competitors. It is also not yet clear when this system stops developing –most research stops at around three years of age, and there are good reasons to investigate much older children.

Sekerina and Brooks (2007) examined older children (5 year-olds and adults) with a relatively standard (four-referent) version of the VWP to assess fixations to target and cohort competitors. This showed clear development between five and adulthood. With respect to the target, their findings match the Fernald et al studies—faster fixations to the target in adults than children—and they extend the developmental period by several years. With respect to the competitors, children initially fixated cohort competitors similarly to adults; however, competitor fixations lingered longer than in adults before being suppressed to baseline looking levels. Sekerina and Brooks did not attempt a fine-grained characterization of the timecourse of fixations, nor did they directly compare this to adults, making it difficult to be certain of this characterization.

The present study had two goals: 1) To conduct a more precise investigation of exactly which facets of lexical competition change over development; and 2) To examine even later points in development (adolescence). Addressing these questions may have an ancillary benefit in helping us understand recently described lexical deficits in children with language impairment.

Word Recognition in Language Impairment

Broadly speaking, language impairment (LI) is identified when children score poorly (usually lower than −1 SD from the mean) on standardized measures of language despite the lack of an obvious cause (hearing impairment, speech production difficulties, or neurological or developmental disorders). Specific Language Impairment (SLI) is diagnosed when LI children have normal (> −1 SD) non-verbal IQ as well. Generally, the focus of work on LI is on measures of language knowledge (e.g., the grammar, the size of the vocabulary) or on outcome measures (e.g., standardized assessments), but a number of studies have begun to look at real-time lexical processing (Dollaghan, 1998; Montgomery, 2002; Mainela-Arnold, Evans, & Coady, 2008), as such difficulties could cascade to affect downstream processes like sentence comprehension (Borovsky, Burns, Elman and Evans, 2013).

Perhaps the clearest picture of the dynamics of lexical processing in LI is offered by McMurray, Samelson, Lee, and Tomblin (2010) who used the four-referent version of the VWP to examine adolescents (M=17 years, 1.75 months) with a range of verbal and nonverbal abilities, including a large number with LI. All adolescents showed the same broad pattern of immediate, incremental competition between words. Moreover, during early processing, LI and typically developing (TD) listeners did not differ in fixations to cohort and rhyme competitors. However, later in the timecourse of processing, adolescents with LI showed fewer looks to target pictures (Figure 1A) and more looks to cohorts and rhymes (Figure 1B,C). These results could not be accounted for by a higher error rate. Moreover, as these are asymptotic differences, it is unlikely that they derive from simple changes in processing speed. Even as listeners with LI were clicking on the target object, around 10% of the time they were still fixating a competitor. Follow-up work (McMurray et al., 2014) used a similar paradigm but manipulated phonological/perceptual factors. LI listeners did not differ in their sensitivity to perceptual variation, even as they showed heightened competitor fixations overall, suggesting that their impairments derive from differences in lexical dynamics, not perceptual ones.

Together with earlier studies (Dollaghan, 1998; Mainela-Arnold et al., 2008), these studies suggest a distinct profile of the deficit in lexical competition associated with LI (see, Nation, 2014, for a review). It can be characterized fairly precisely in terms of the timecourse of processing (Figure 1): LI adolescents are unable to commit fully to the target or fully suppress competitors by the end of processing, even as early activation is quite similar to TD adolescents. Much like the longitudinal work by Fernald and colleagues, this finding underscores the importance of real-time spoken word recognition processes for understanding the development of language ability as a whole.

It is hard to evaluate these deficits without a clear picture of the development of real-time word recognition during adolescence. One possibility is that adolescents with LI are simply delayed developmentally and that the specific changes in real-time lexical processing are what would be seen in younger typically developing children. This could be due to their smaller vocabularies (Munson, Kurtz, & Windsor, 2005; Tomblin, Records, & Zhang, 1996), reduced knowledge about words (McGregor, Oleson, Bahnsen, & Duff, 2013), or differences in speed of processing (Kail, 1991, 1994; Miller, Kail, Leonard, & Tomblin, 2001). In contrast, there may be a qualitative difference in how children with LI process spoken words. If so, then the real-time processing changes observed over development may not match the differences observed as a function of LI. A clearer picture of the timecourse of typical development may help evaluate these potential sources of differences associated with LI.

Current Study

There have not been any investigations of developmental changes in spoken word recognition in older ages. While the canonical view (evidenced by the ages commonly studied) is that abilities like familiar word recognition should have stabilized well before adolescence, the lack of any studies of this age leaves open the possibility that there is development during this period. The potential links to LI underscore the importance of such an investigation.

The primary goal of this study was theoretical: to precisely characterize the profile of lexical competition in adolescence and the way in which it changes over development. This could challenge the assumption that word recognition abilities are largely in place by adolescence, and suggest a life-span approach to even basic language skills. By properly characterizing the developmental changes in online processing, we may be able to determine what components of the lexical processing system change over development, and this can be mapped to models of word recognition and learning to identify possible mechanisms of developmental change.

While not our primary goal, an understanding of how real-time processing changes over development may also help us understand whether the differences in LI adolescents observed by McMurray et al., (2010) derive from a developmental delay. We could not conduct a direct comparison with the present data on LI: the items used in the McMurray et al (2010) study were not all appropriate for the younger listeners studied here, precluding a direct comparison, and we did not have a suitable population of younger children with LI. Thus, we cannot make strong claims about LI. Nonetheless, if we observe a similar profile of differences as a function of age, this would present converging evidence for a developmental delay in word recognition. Such a profile would be characterized by largely asymptotic differences in looking as a function of age (analogous to what was seen with LI) and few changes in early aspects of lexical competition.

The present study employed a four-referent version of the VWP examining competition between target words, cohorts and rhymes. This richer competitor set allowed us to document a more complete profile of lexical competition and is similar to prior work on LI. We examined 9 and 16 year-olds. These ages were chosen for two reasons. First, children’s abilities to categorize speech sounds is still developing between 3 and 7 (e.g., Nittrouer, 2002) and possibly as old as 12 (Hazan & Barrett, 2000). Consequently, downstream word recognition processes may also be developing during late childhood. Second, cognitive processes like executive function and inhibitory control continue to develop into puberty and beyond (e.g., Welsh & Pennington, 1988). While it is unclear whether these functions are related to word recognition (though there may be evidence for this in bilinguals: Bartolotti, Marian, Schroeder, & Shook, 2011; Blumenfeld & Marian, 2011), they offer a plausible locus for concurrent development in speech and language perception. Third, 16 year-olds are close to the age of the adolescents in McMurray et al. (2010), and the 9 year-olds were sufficiently younger as to offer reasonable power for detecting any developmental differences.

Methods

Participants

Forty-two children, 24 nine-year-olds (7 male, 17 female) and 18 sixteen-year-olds (10 male, 8 female) participated in this study. Subjects were recruited either through a database of birth records maintained by the University of Iowa Department of Psychology, by a newspaper advertisement, or by word of mouth. Thirty four participants identified as Caucasian, 3 as Caucasian and Asian, 1 as Biracial (without specification), and 4 did not indicate a racial affiliation. 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 $20. Parents provided signed consent for their children, and the participants underwent a verbal assent procedure in accordance with a university approved IRB protocol.

Language Assessments

We assessed overall language ability to ensure that the two age groups were balanced (otherwise findings that appear to be a developmental difference could derive from individual differences in ability). Language ability for each participant was assessed using the *Peabody Picture Vocabulary Test (PPVT-IV;* Dunn & Dunn, 2007) and the Recalling Sentences subtest of the *Clinical Evaluation of Language Fundamentals (CELF-4;* Semel, Wiig & Secord 2003). These assessments were selected from the full assessment battery used for the epiSLI study of language impairment (Tomblin et al., 1996) and both were included in the McMurray et al. (2010) VWP study of LI.

For all participants, standard scores on both assessments were greater than the clinical threshold for LI (i.e., 1 SD below mean), indicating clinically normal language ability. For the PPVT-IV, 9-year-olds averaged 118 (SD=16.6) and 16-year-olds averaged 115 (SD=9.9; t (40) = 0.521, p=0.65). On the CELF-4, 9-year-olds averaged 108 (SD=11.1) while 16-year-olds averaged 106 (SD=9.7; t (40) = 0.465, p=0.644). Thus, the two age groups were matched in terms of relative language ability.

In contrast, the two groups differed considerably in *absolute* language ability: on the PPVT-IV, nine-year-olds' mean raw score was 166.8 (SD=17.7) and 16-year-olds scored 205.2 (SD=8.1; t (40) = 8.6, $p < 0.01$). For the *CELF-4*, 9-year-olds' raw scores averaged 70.1 (SD=10.4) while the older group scored 87.1 (SD=6.6; t (40) = 6.1, $p < 0.01$). Thus, significant development in language, as a whole, is occurring across these ages.

Design

Twenty-five sets of four words were used in this study. Each set consisted of a base word (e.g., *bees*), a competitor that overlapped at onset (a cohort: e.g., *bean*), a competitor that overlapped at offset (a rhyme: e.g., *peas*), and a phonologically unrelated word (e.g., *cap*). The four words within a set always appeared together on a given trial (in a random spatial arrangement), and each word in the set was heard as the target three times. Given 25 sets, this yielded 300 total trials. Because each word could be the auditory stimulus, this led to a number of different competitor configurations on any given trial. For example, on TCRU (target, cohort, rhyme, unrelated) trials, the base word (e.g., *bees*) was heard, and as a result that there were cohort (*bean*) and rhyme (*peas*) competitors on the screen (Table 1). However, on TC trials, when *bean* was the target, there was only another cohort (*bees*) and two unrelated words (*peas* and *cap*). On TR trials, *peas* was the target with only a rhyme competitor (*bees*); and on TU trials, *cap* was the target and all competitors were unrelated.

Our primary comparison was between-subject (age), and we examined multiple dependent variables that characterize the precise timecourse of processing as a function of age.

Stimuli

Auditory stimuli were recorded by a female native English speaker with a standard Midwest dialect. Recordings were made in a sound attenuated room using a Kay CSL 4300B A/D board at 44.1 kHz. Each stimulus was excised from a recording of the word spoken in a carrier phrase (e.g., “He said *bees*”). The average duration of words was 645 milliseconds.

One hundred msec. of silence were added to the beginning of each stimulus and were normalized to the same intensity.

Visual stimuli were selected using a standard procedure designed to ensure that they were clear, free of distracting elements, and representative of the word they were intended to depict (Apfelbaum et al., 2011; McMurray et al., 2010). We started by downloading 8–10 images of each word from a commercial clipart repository. These images were viewed by a focus group of undergraduate and graduate students who arrived at a consensus about which picture was the most representative. Finally, most pictures were edited slightly to be visually consistent, free of distractions, and to have prototypical orientations and colors. All images were approved by a member of the laboratory with extensive experience in the VWP.

Procedure

After informed consent, participants were given the PPVT-IV and the CELF-4 by a researcher trained to administer standardized language tests. Participant responses were recorded online and scored offline.

After the assessments, subjects were seated in front of the computer monitor to begin the VWP study. A padded chin and forehead rest was used for the eye-tracker and its height was adjusted to a comfortable position for each participant. Researchers then calibrated the desktop mounted eye-tracker. Prior to the experimental task, participants were given both written and verbal instructions as well as an opportunity to ask questions.

On each trial, participants first saw the four pictures for that trial (one item-set) randomly assigned to the four locations on the screen and a red dot in the center. After 500 ms, the red dot turned blue, and participants clicked on it with an ordinary computer mouse to start the trial. This pre-scan, coupled with a click on the dot, oriented subjects' eyes to the center of the screen at trial onset and familiarized them with the objects and their locations (minimizing subsequent eye-movements due to visual search). After clicking the dot, subjects heard the target word through high-quality headphones and clicked on the matching picture. Subjects were encouraged to take their time and to strive for accuracy rather than speed.

Eye-movement Recording and Analysis

Eye movements were recorded with a desktop mounted SR Research Eyelink 1000 eye-tracker. A standard 9-point calibration was used. Every twenty trials, a drift correct procedure was performed to maintain calibration. If the participant failed a drift correct, the eye tracker was immediately recalibrated. Both pupil and corneal reflections were used to determine the position of an eye gaze. Eye-movements were processed using a similar procedure to McMurray et al, (2010). Point of gaze was sampled at every 4 msec starting at the onset of each trial and continuing until the subject clicked on a picture. These data were automatically classified into saccades, fixations, and blinks using the default parameter set. These were combined into a "look" for analysis, which starts at the beginning of a saccade and ends at the end of a subsequent fixation. In mapping looks onto specific objects, the boundaries of the objects were extended by 100 pixels to account for any noise in the eye-track. This did not result in any overlap among the regions of interest.

Results

We analyzed the data in three steps. First, we analyzed mouse click responses and reaction time to determine the overall ability of participants to successfully complete the task. Next, we conducted several analyses of basic fixation parameters to understand if there were differences in oculomotor dynamics across age. Finally, we present our primary analysis of participants' fixations over time during word recognition as a function of age.

Mouse click analysis

Across all trials, nine-year-olds selected the target at an average of 98.5% correct (SD = 1.1%; range: 95.3%-99.7%); 16 year olds averaged 99.0% correct (SD = 0.73%; range: 96.7%-100%; *t* (40) = 1.69, p = 0.099). Thus, both groups were highly accurate. With respect to reaction time (computed on correct trials only), 9-year-old participants had significantly slower RTs (M= 1824 msec, SD = 171, range: 1592–2279) than 16-year-olds (M=1421 msec, SD = 140, range: 1202–1679; *t* (40) = 8.159, p < 0.001). This difference was expected, given developmental changes in speed of processing (Kail, 1991), though the large magnitude (400 ms) was not.

Fixation Rate analysis

Before analyzing the fixation data, we wanted to investigate developmental changes in basic eye-movement function that could potentially mask or confound differences in lexical processing. While there were no experimental tasks with only visual stimuli, each trial started with a short pre-scanning period (which ended when the subject clicked the blue dot). Thus, we examined fixations during this pre-scanning period to assess oculomotor behavior that was not driven by lexical dynamics. The duration of the pre-scan period was variable across trials (since subjects it was ended by the subject), although it did not differ between groups (M_9 = 1761 msec, SD_9 = 569; M_{16} = 1650, SD_{16} = 1173; *t*(40) = 0.40, p = 0.69).

To account for this variability, we computed the number of fixations/sec as a dependent measure. When we consider only looks directed to objects on the screen, the younger group made slightly but significantly more fixations to objects (per second) during pre-scanning than 16 year olds (M_9 = 5.0 fixations/sec, SD_9 = .96; M_{16} = 4.4, SD_{16} = .89; *t*(40)=2.1, p = 0.04). In contrast, 16 year olds made significantly more fixations to non-object locations (e.g., the center) (M_9 = 2.7 fixations/sec, SD_9 = .87; M_{16} = 3.2 SD_{16} = .48; *t*(40)=2.15, p=0.038). When we consider the combined rate of fixations, there was no significant difference (t(40)=.20, p=.83). Thus, while the two groups make roughly equal numbers of fixations per second, they differ on where they are directed. This suggests the need to account for basic oculomotor differences in our analysis of lexical competition.

Eye-movement analysis

Our primary analysis examined the proportion of fixations to each class of competitors over time. Such measures are commonly used to estimate how strongly listeners are considering different lexical competitors (cohorts, rhymes) as the decision unfolds. We start with a more descriptive look at the data and describe the assumptions that went into the analysis. Next, we analyze looking to individual classes of lexical competitors as a function of age. Finally, we present a series of analyses examining cohort and rhyme fixations, taking into account the fixations to the unrelated objects.

Consistent with prior studies, we eliminated the small number of trials in which subjects did not click the correct target. This focused our analyses on whether the 9- and 16-year olds differed in the degree and timing of competitor fixations, given that they successfully recognized the word. We also were concerned that the previously described differences in basic fixation behavior could influence the timecourse of fixations in the lexical task. For example, if a listener happened to already be fixating the correct object when the word was heard, they could remain there and would subsequently appear as though they committed to the target very rapidly. In contrast, if they were fixating a competitor, they may be slower to "switch" back to the target than if they were fixating nothing. Given that 9 year olds were more likely to fixate objects in general, it was possible that such effects could mask any age-related effects on lexical processes.

We dealt with this in three ways. First, we only included trials in which subjects were not looking at one of the pictures at 300 milliseconds. This is first time at which we would expect to see signal-driven eye-movements as there was the 100 ms of silence prior to the beginning of the word, and it takes 200 ms to plan and launch an eye-movement (Viviani, 1990). This excluded trials on which whichever object the participant was (randomly) fixating at the onset of the auditory stimulus may have biased subsequent eye movements. An average of 175 trials per subject contributed to this analysis (range: 54–286 across subjects), which corresponded to an average of 58 percent of all trials (range: 18% to 95%). The results of these analyses were highly similar to analyses using all of the trials (see Supplement S2). Second, many of the analyses were also conducted with pre-scan fixation rates as covariates (see Supplement S3). Third, in addition to the standard analyses of the fixations to each competitor individually, we conducted an extensive analysis of the difference between fixations to cohort competitors (cohort / rhyme) and unrelated objects (a baseline).

Figure 2 shows the proportion of trials on which participants fixated each type of competitor (for TCRU trials) as a function of time. Again, we excluded trials in which the participant was fixating anything at stimulus onset. Fixations to the target and cohort first separate from the other objects at around 300 ms. These target and cohort fixations are driven by their similarity to the input at word onset. As the word unfolds, the proportion of fixations to rhyme objects rose slightly, reflecting the later phonological overlap between rhyme and target. By the end of processing, cohort, rhyme, and unrelated words received few looks--subjects almost exclusively fixated the target. Comparing Figure 2A and 2B suggests that, at the broadest levels, 9 year olds and 16 year olds both show the same overall pattern.

Figure 3 plots looks to each competitor separately as a function of age. Nine-year-olds appear to have shallower slopes of target fixations (Figure 3A) than 16-year-olds, suggesting that younger listeners take longer to fixate target objects. However, unlike the LI vs. TD difference of McMurray et al., (2010), the groups do not differ in the maximum level of target fixation; instead they differ in *when* they reach this peak (see Figure 1).

A similar pattern was also observed with cohort and rhyme fixations. Here, the largest differences between the age groups appear early in processing, with 9 year olds initially fixating competitor objects more than 16 year olds, though competitor fixations in both groups appeared to end up at similar asymptotic levels of looking. These overall differences in the timecourse were also observed in an analysis of individual fixation parameters (Supplement S4).

Analysis of Individual Classes of Competitors—To examine these differences statistically, we needed to precisely characterize the differences in each curve (e.g., target, cohort, etc.) as a function of age. To do this, we identified nonlinear functions that describe the shape of the target and competitor fixations over time. We then estimated the parameters of these functions (e.g., the asymptote of target fixations, the peak of cohort fixations) for each subject, and used the parameters of these functions as descriptors of the timecourse of processing. We employed a nonlinear curve-fitting approach (Farris-Trimble & McMurray, 2013; McMurray et al., 2010), fitting separate functions to the timecourse of fixations to target, cohort, rhyme, and unrelated referents separately for each participant. We then compared the estimated parameters across the two ages. For a given subject, data were averaged across all of the relevant trial-types for a given object (e.g., cohort looks were averaged across TC and TCRU trials).

The proportion of looks to the target was fit with a logistic function of time (*t*) with four parameters (Equation 1). The minimum asymptote, or baseline (*b*), is the point at which the function starts. The maximum asymptote, or peak (*p*), is the asymptotic degree of looking at the end of the timecourse of fixations. The crossover point (*c*) is *the* point in time the function crosses the midway point between peak and baseline. The slope (*s*) represents the rate of change in the function measured at the crossover.

$$P(target)=\frac{p-b}{1+\exp\left(4\cdot\frac{s}{p-b}\cdot(c-t)\right)}+b \quad (1)$$

This function was fit to each participant's data using a constrained gradient descent method that minimized the least-squared error between the data and the function while constraining the parameters such that *p* and *b* were between 0 and 1, *p* was always greater than *b, c* remained within the time range of that participant, and *s* was always positive (rising). Baseline (*b*) was generally 0 since the eye-movements prior to the stimulus were ignored, and is not discussed further. Inspections of individual data suggested that all participants demonstrated a general looking pattern that conformed to the logistic function.

Fits using the logistic function were very good with an average R^2 of 0.996 (SD = 0.008, Max = 0.999, Min = 0.955). We compared the estimated parameters of these functions across the two age-groups using T tests (Table 2). The 9 year olds had significantly shallower slopes than the 16 year olds and significantly later crossover points, but the two groups did not differ in their maximum asymptotic level of fixations. In contrast, the LI listeners in McMurray et al., (2010) were characterized by a small change in slope, but a large change in maximum. To account for oculomotor differences, we also analyzed these parameters with ANCOVA, using fixation rate estimated from the pre-scanning period as a covariate (Supplement S3). This showed very similar results.

Fixations to cohort, rhyme, and unrelated competitors were analyzed by fitting an asymmetrical Gaussian function to the data (Equation 2).

$$\mathrm{P(competitor)} = \begin{cases} \exp\left(\frac{(t-\mu)^2}{-2{\sigma_1}^2}\right)(p-b_1)+b_1 & \text{if } t \leq \mu \\ \exp\left(\frac{(t-\mu)^2}{-2{\sigma_2}^2}\right)(p-b_2)+b_2 & \text{if } t > \mu \end{cases} \quad (2)$$

This function has six free parameters. The onset baseline (b_1) and offset baseline (b_2) reflect the asymptotes in the proportion of fixations at the beginning and end of the timecourse. The highest proportion of fixations is described by the peak height (p). The time that this peak occurred at (in msec) is described by the parameter μ (the peak location). Finally, the onset slope (σ_1) and offset slope (σ_2) control how quickly the function transitions from either baseline to peak. These are similar to σ in a Gaussian function —they are expressed in msec, and higher values reflect shallower slopes. Functions were fit using a similar constrained curve fit method, and again we do not discuss b_1 which was almost always 0.

Fits using the asymmetrical Gaussian function were good, with an average R^2 of 0.978 (SD = 0.014, Max = 0.993, Min = 0.929) for cohort competitors, 0.985 (SD = 0.024, Max = 0.985, Min = 0.884) for rhyme competitors, and 0.963 (SD = 0.019, Max = 0.990, Min = 0.914) for unrelated competitors. One subject (a 9 y.o.) did not have good fits for the rhyme or unrelated objects (his data did not conform to the function) and was excluded from the analysis.

Results are shown in Table 3. Nine year olds had significantly shallower cohort offset slopes than the older group as well as significantly higher cohort peak heights. That is, 9 year olds fixated cohorts more initially and took longer to suppress cohort looking. No other parameters showed a significant effect of age. For rhymes, the 9 year olds had significantly steeper onset slopes, earlier midpoints, higher peak heights, and shallower offset slopes as compared to 16 year olds. The offset baseline parameter was not significant. Similarly to cohorts, 9 year olds fixated rhymes more and took longer to suppress them.

Thus, like the targets, both cohorts and rhymes are largely characterized by differences in the peak height, and in the timing of this peak as a function of age. No asymptotic effects were seen. In contrast to these results, competitor fixations among LI listeners in McMurray et al., (2010) were largely characterized by differences in offset baseline, which were only [marginally] observed with rhymes in the present study (more on this later).

In addition to these effects on competitor fixations, there were also differences in the level of looking to the unrelated objects. Here, in general, the younger group made more fixations than the older group to the unrelated objects across the timecourse of processing. They showed significantly higher peak heights, shallower offset slopes, and higher offset baselines for unrelated objects (Table 2) than the older participants. Such differences may reflect both general oculomotor and visual-cognitive factors (e.g., visual search, decision making), but could also indicate a more general lexical uncertainty.

Analysis of Competitor Fixations Over and Above Unrelated Looking—Finally, given these differences, we asked if there were still age related changes in cohort and rhyme fixations over and above these more general differences in looking. To address this, we subtracted looks to unrelated objects from looks to cohorts and rhymes. These are shown in Figure 4 and suggest that across the two ages, both cohorts and rhymes may have had similar peaks of activation (after accounting for unrelated fixations), but remain under consideration for longer. With the unrelated included in the measure, individual subject curves were either too noisy or did not show the right shape to obtain clean fits using the asymmetric Gaussian[1]. Thus, we extracted key variables directly from the data using an approach similar to Farris-Trimble, McMurray, Cigrand, and Tomblin (2014).

We assessed the peak level of activation of these functions by computing the maximum *cohort – unrelated and rhyme – unrelated* value for each subject. We found a significant difference in peak cohort fixations (t (40) = 2.1, p=0.040) over and above unrelated objects; and a marginal effect for rhymes (t (40) = 1.85, p=0.072). Even accounting for unrelated looking, 9 year olds' peak fixations to competitors (particularly rhymes) exceeded that of the 16 year olds.

We next examined how long cohorts and rhymes were under consideration by computing the amount of time for which the cohort (or rhyme) was greater than .03 above the unrelated for each subject[2]. This analysis found that 9 year olds looked to both cohorts and rhymes for more time than 16 year olds (Cohorts: t (40) = 2.70, p=0.005; Rhymes: t (40) = 2.37, p=0.023).

Finally, we investigated the end of processing by computing the proportion of cohort (or rhyme) fixations minus unrelated fixations in a 100 msec window surrounding each participant's own mean reaction time. We found no difference as a function of age for both cohorts (t<1) and rhymes (t<1). We also compared this value to 0 for each group and found that by the end of the trial, both groups had fully suppressed both cohort (16 year olds: t(17) = 1.0, p=.32; 9 year olds: t(23)=1.11, p=.28), though the rhymes were marginally significant for both (16 year olds: t(17)=1.83, p=.085; 9 year olds: t(23)=1.89, p=.072), relative to the unrelated objects.

Thus, these analyses suggest that even accounting for differences in unrelated looking, we find effects of age on both peak fixations to lexical competitors, and on the extent to which cohorts or rhymes are under consideration. However, there was no difference between ages in the final amount of looking, little evidence to suggest that either age group was maintaining substantial looking to competitors at this point.

General Discussion

This study showed significant differences in the situational timecourse of spoken word recognition over development between 9 and 16 years of age: spoken word recognition is still developing during adolescence. Treating the timecourse of fixations as an estimate of

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[1] Indeed the proper function would be the *difference* of two asymmetric Gaussians, a 12 parameter function.

[2] A similar analysis was conducted with a range of different threshold and found significant differences at all thresholds.

real-time lexical activation, we see that nine-year-olds take more time to activate the target word, even though both ages reach the same asymptotic level of activation. Nine-year-olds also had heightened cohort and rhyme activation during the initial period of temporary ambiguity, and maintained consideration of these competitors for longer. However, by the end of the trial, 9 and 16 year olds did differ in their levels of activation and both groups had fully suppressed both types of competitors (relative to unrelated looking).

There are a few limitations of this study that bear mentioning. First, non-verbal cognitive measures were not given to these participants, so we cannot determine if the age-related differences presented here are attributed to more mature language knowledge in the older group or gains in other more general cognitive processes. However, given the strong correlation between non-verbal IQ and language (which was matched between the age-groups), our participants likely had normal non-verbal IQ. Moreover, our previous study with LI (McMurray et al., 2010) did not find a relationship between fixations in this task and nonverbal IQ, suggesting this is unlikely to be an issue. A second limitation is that our participants had language scores in the typical to high-normal range. Developmental effects at the lower end of the language scale may manifest differently from those effects at this range. However, this narrow range is also a strength, enabling us to more precisely pin these changes on development– even in high functioning individuals— not language ability.

The most important caveat is our finding of oculomotor or visual-cognitive differences over age. There were small but significant effects both during the pre-scan period, and in unrelated looking after the stimulus. We dealt with these by excluding trials in which participants were fixating an object prior to the auditory stimulus, and by using pre-scan fixation rate as a covariate (supplement Table S3). Across these analyses we saw consistent evidence for changes in lexical competition with development. Further, while it is not clear that the differences in unrelated fixations after the auditory stimulus represent only visual-cognitive differences (they may also reflect differences in language processing), our conservative analysis of cohort and rhyme minus unrelated fixations continued to show differences as a function of age. Thus, while clearly there is continued development in eye-movement control and visual search, there is considerable evidence for a unique contribution of lexical development.

Beyond these limitations, however, this study makes a number of important contributions. First, and most importantly, we found clear developmental changes in the timecourse of lexical processing. These changes occur at particularly late ages and suggest a more protracted development of these abilities than might be expected. Second, the particular profile of changes in lexical competition is different than the profile of deficits observed in LI, suggesting LI may not be adequately explained by the developmental delay hypothesis. We discuss each of these in turn.

Development of Spoken Word Recognition

Word recognition is usually considered a basic skill that should be in place by school age. In contrast, our findings suggest a protracted period of development continuing through adolescence. So, what accounts for these developmental changes in the dynamics of word recognition? A number of both general cognitive changes and specific developments within the language system may be involved.

The first general possibility is that older children are simply faster and process spoken words more quickly than younger children. Kail (1991) has documented a wealth of evidence of changes in speed of processing over development across an array of tasks. This work has also been extended to language impairment (Kail, 1994; Miller et al., 2001) where linguistic and non-linguistic processing speed may predict language performance separately (Park, Miller & Minaela-Arnold, 2015).

A speed of processing explanation is consistent with our RT findings, as well as the finding that older children fixated the target more quickly than the younger group. These earlier target fixations (in older children) might also reasonably be seen as drawing looks from other objects and thus could also predict reduced competitor fixations. However, under a pure slowing account, there is no obvious reason to expect differential effects of speed/age on cohort and rhyme words over unrelated words (since faster target fixations will also draw fixations from unrelated words). Moreover, McMurray et al (2010) also found differences in reaction times between poorer language users and better language users (also consistent with slowing). However, this study found very different fixations patterns than what was found here, suggesting that slowing may not be able fully account for both sets of findings.

While we cannot be fully ruled out a slowing account, it seems more likely that, rather than the observed lexical changes deriving from changes in speed of processing, children's (lexical) processing speed is improving *because* of these changes in lexical competition. As competition dynamics are likely involved in many verbal and non-verbal processes (Spivey, 2007), it is possible that changes in competition are more global, accounting for processing speed differences in many domains.

The second (perhaps related) possibility is that inhibitory function may play a role in these developmental changes. Children improve inhibitory control throughout development (e.g., Welsh & Pennington, 1988), and adolescence is well-known for large gains in inhibitory control. It is important to note that this top-down inhibition may be quite distinct from the form of inhibition often involved in spoken word recognition. In the latter, inhibition is usually conceptualized as local inhibition between specific words, rather than a controlled top-down effect (Dahan et al., 2001; Luce & Pisoni, 1998; McClelland & Elman, 1986). It is unclear how these two forms of inhibition relate and if top-down inhibitory control is involved in suppressing lexical competitors (though work in speech production suggests it may not be: Shao, Roelofs, Martin, & Meyer, in press). But if they are related, the development of inhibitory control could have an effect on how well children can resolve lexical competition. There may also be development in local (word↔word) forms of inhibition. Indeed, recent work from our lab suggests that such inhibitory processes are plastic and can change with short-term training in adults (Kapnoula & McMurray, submitted). Thus, development in either form of inhibition could give rise to these changes.

Both of these accounts suggest developmental changes in factors that affect situation-time processing dynamics. However, a recent account of word learning (McMurray et al., 2012) raises the possibility that these changes in the efficiency of word recognition derive from changes in the long-term mappings between phonological and semantic representations that are formed over development (word learning). This computational model is built on associative learning which links words to referents over the course of many exposures (developmental time). However, during situation-time recognition of a word, dynamic competition between possible referents plays out over these learned associations. This model accounts for a range of word learning phenomena (e.g., fast-mapping). However, it also offers a unique account of results like these and the looking-while-listening studies of Fernald and colleagues (Fernald et al., 1998; Zangl et al., 2005). In the model, lexical competition resolves much faster over development, but without any change in the parameters that control competition dynamics. Rather, changes in speed of processing derive from the quality of the *learned* mappings between words and objects.

In particular, over learning, the model both builds associations between word/object pairs, and prunes irrelevant associations between a word and irrelevant objects. McMurray et al found processing speed was not related to the strength of the correct associations, but strongly correlated with the weakness of irrelevant associations: smaller (better pruned) irrelevant connections supported faster processing. This is because these irrelevant associations cause activation for a word to spread to many different referents (both correct and incorrect), and these incorrect interpretations must then be suppressed (via competition). Critically, word/referent mappings can be sufficiently robust to support accurate word recognition in many contexts, even as there is still room for significant refinement (pruning) that may take substantial time and may only appear in measures of efficiency. This suggests that the developmental improvements in real-time processing seen here may derive in part from the same processes of building and pruning associations that we normally think of as underlying word learning (see also, McMurray, Kapnoula, & Gaskell, submitted). Moreover, the protracted process of pruning or cleaning up of the irrelevant connections may be the most important basis of the developmental changes we observed.

Beyond the causes of these developmental differences in lexical processing, it is also important to consider their consequences. Recent work suggests that the process of resolving this lexical competition is not encapsulated from other language processes. Ongoing competition between word forms affects how the semantic network is accessed (Apfelbaum et al., 2011), which word forms are linked to referents during learning (Apfelbaum & McMurray, submitted), and influences ongoing sentence processing (Levy, Bicknell, Slattery, & Rayner, 2009; Borovsky et al., 2013). As semantics, word learning and sentence processing are clearly developing during this period, our work suggests differences in spoken word recognition could be part of the story. Moreover, written word recognition is thought to be served by similar sorts of competition processes as spoken word recognition (Norris, 2013). If spoken word recognition continues to gain automaticity during early adolescence, it seems likely that visual word recognition may as well, despite the widespread belief among educators that visual word recognition is largely in place during elementary school for most students (Biancorosa & Snow, 2006).

Implications for Language Impairment

While our primary goal was to examine typical development, our results show a striking contrast to what was observed in LI by McMurray et al (2010). McMurray et al found that adolescents with LI did not reach the same level of target fixations as TD adolescents; in contrast, both the 9 and 16 year olds here did. Additionally, there were no differences in the peak height of competitor activation (during the early portion of processing) as a function of LI, while we found that 9 year olds fixate cohorts and rhymes more than 16 year olds during this window. Finally, well after word offset, 16 year olds with LI maintained activation for cohorts and rhymes more than TD adolescents, whereas here both groups reached the same level of competitor fixations by the end of the word. These studies used slightly different designs and lists of items, so they should be compared cautiously. However, if we compare the profile of real-time word recognition over typical development, with the profile shown by LI, it appears that the word recognition deficits associated with LI cannot be clearly described as a developmental delay, but may represent a different sort of issue. This is underscored by an analysis of the raw language scores (see Supplement S5).

If it is not developmental delay, what might account for the distinct deficits shown by children with LI? The various studies on lexical processing in children with LI (Dollaghan, 1998; Montgomery, 2002; Mainela-Arnold et al., 2008; McMurray et al., 2014; McMurray et al., 2010) all point to some deficit in the nature of competition between words; and they appear to pinpoint this difference at late points in processing. This perhaps suggests some difference in the unfolding of inhibition between words. McMurray et al. (2010) conducted simulations using the TRACE model (McClelland & Elman, 1986) which suggest that, for individuals with LI, target words decay quicker in memory. Since the suppression of cohort and rhyme competitors is driven by inhibition from these target words, less active targets exert less inhibition on the competitors. Whether it is inhibition or decay, all of this work suggests a deficit specifically in the internal dynamics of activation among lexical competitors. This contrasts with differences in the efficiency of learned mappings that we propose to underlie changes associated with typical development.

Conclusion

This study showed clear developmental differences in the way that competition—induced by temporary ambiguity among words—is resolved. Whether this development ultimately derives from changes in real-time processing or it can be pinned on learning, the changes between 9 and 16 years of age are occurring much later in development than what was expected. It suggests that even the most basic language skills may undergo a rather protracted period of development, when examined with the dynamics of underlying processing.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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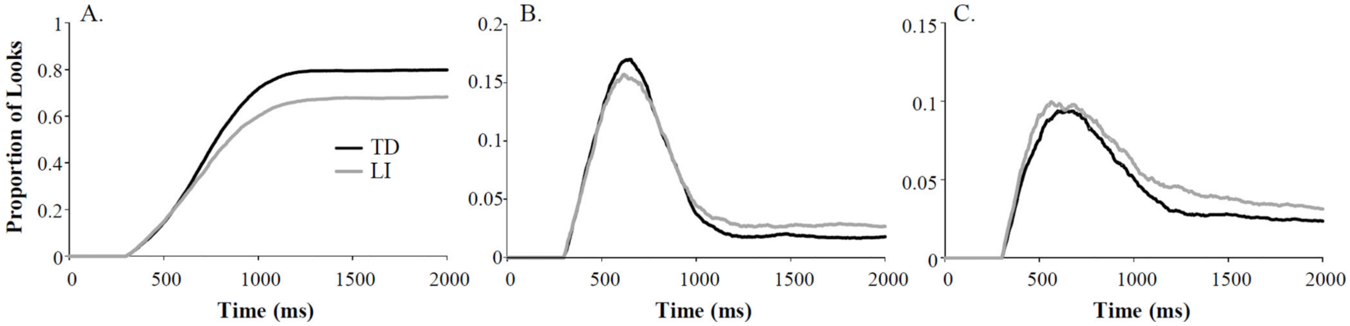

Figure 1.

Proportion of fixations as a function of time and LI status in McMurray et al., (2010). A) Fixations to target object; B) Fixations to cohort competitor; C) Fixations to rhyme competitor.

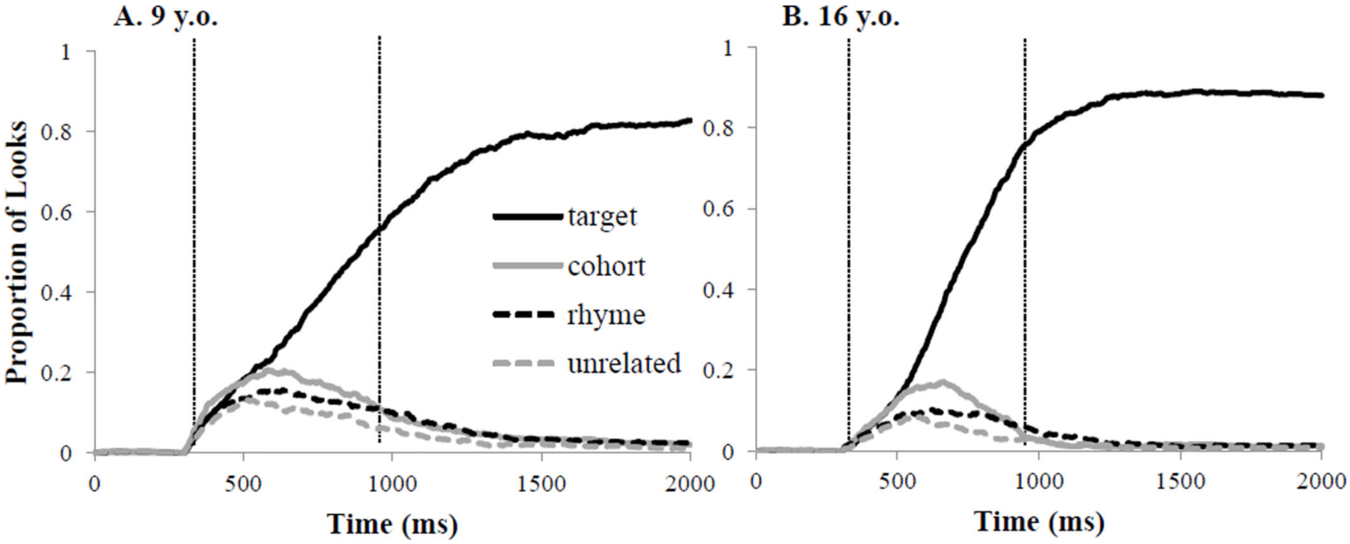

Figure 2.

Proportion of fixations to each word type by participant group on TCRU trials (correct trials only). A) Nine-year-olds. B) Sixteen-year-olds. Vertical lines mark the earliest time we would expect signal driven looks to objects (i.e. 200 ms to plan and launch eye movement and the 100 ms of silence at the beginning of the trial) and the average offset time of our auditory stimuli

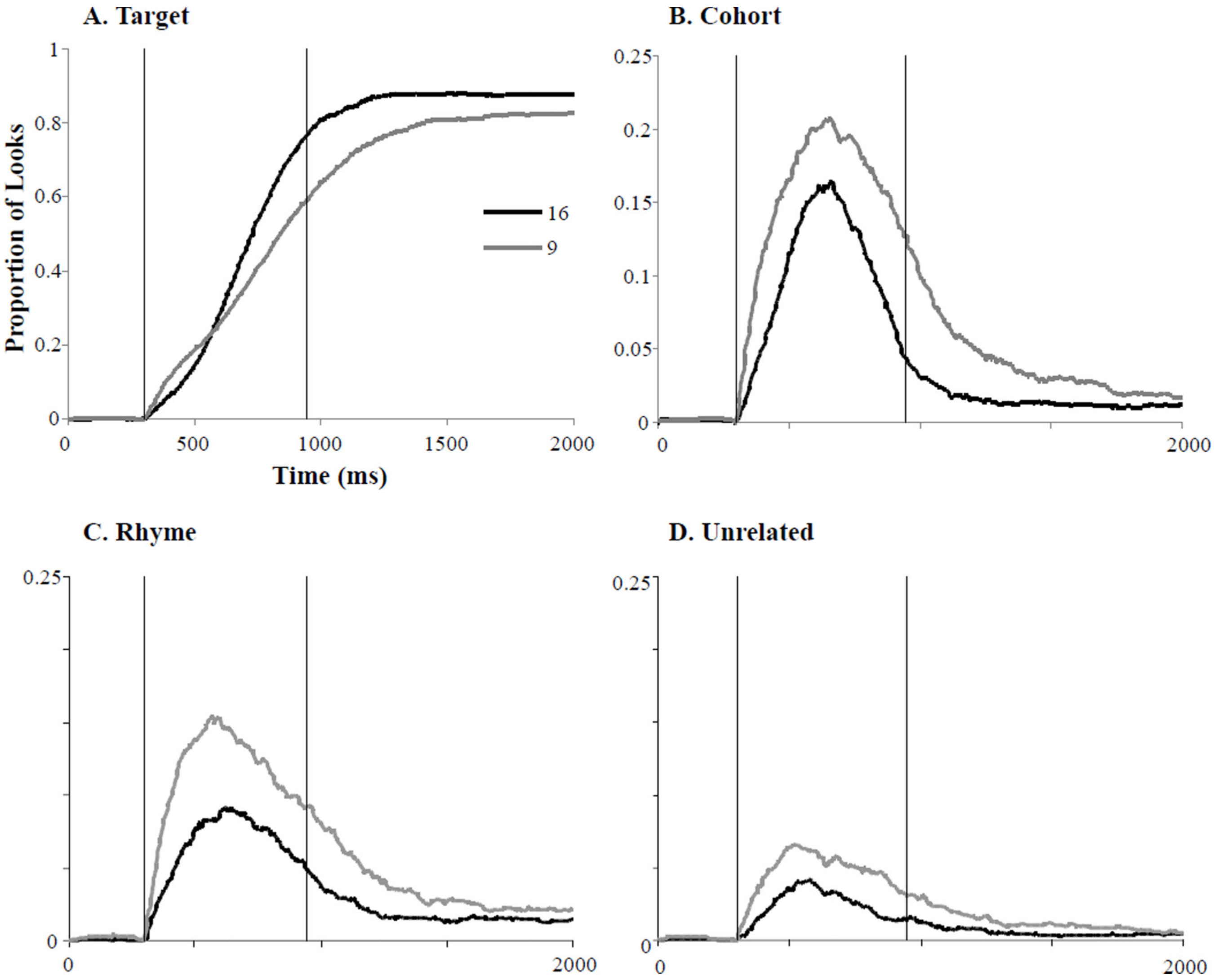

Figure 3.

Proportion of fixations to each word type on TCRU trials, as a function of time by age group. A) Fixations to target. B) Fixations to Cohort. C) Fixations to rhyme. D) Fixations to unrelated. Vertical lines mark the earliest time we would expect signal driven looks to objects (i.e. 200 ms to plan and launch eye movement and the 100 ms of silence at the beginning of the trial) and the average offset of the auditory stimuli

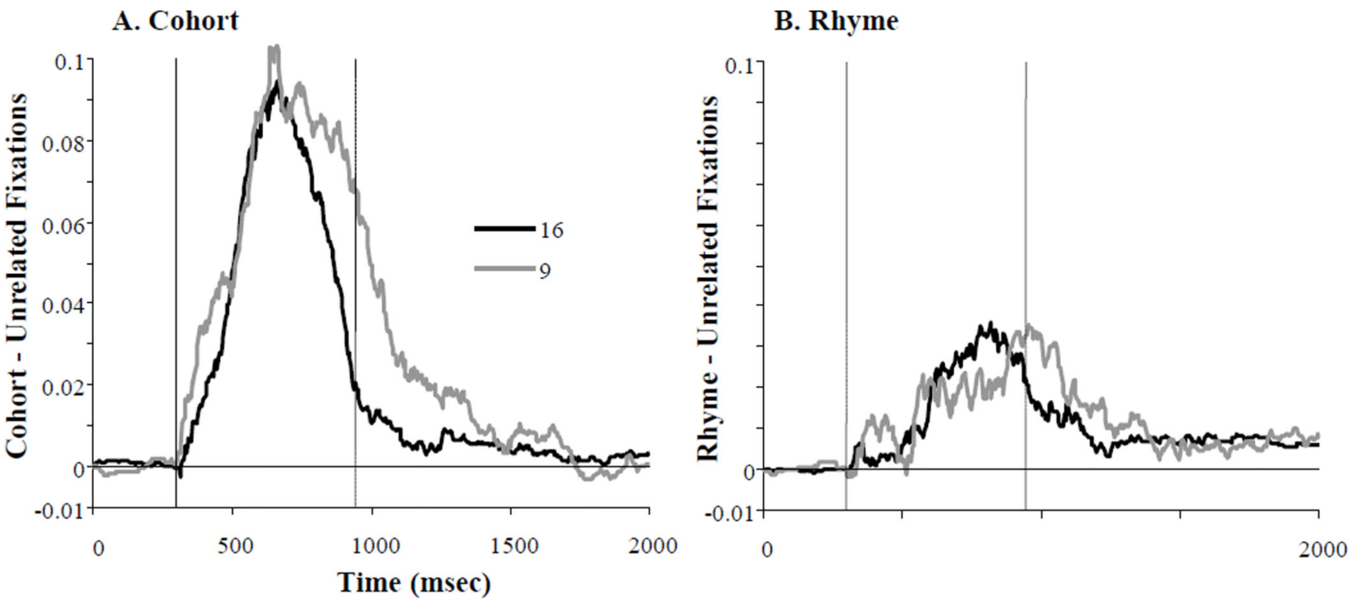

Figure 4.

A) The difference between the proportion of fixations to cohort and unrelated competitors as a function of time and age. B) Difference between roportion of fixations to rhyme competitors and unrelated competitors.

Table 1

The role of each word in a set as a function of which word was the auditory stimulus (target word indicated in italics).

Trial Type			
TCRU	**TC**	**TR**	**TU**
Bees (target)	*Bean (target)*	*Peas (target)*	*Cap (target)*
Bean (cohort)	Bees (cohort)	Bees (rhyme)	Bees (unrelated)
Peas (rhme)	Peas (unrelated)	Bean (unrelated)	Peas (unrelated)
Cap (unrelated)	Cap (unrelated)	Cap (unrelated)	Bean (unrelated)

Table 2

Results of curve fitting analysis examining the timecourse of fixations to the target. For each subject, the logistic function was fit to target fixations (separately). Mean parameter values for each of the analyses are shown for 9 and 16 year olds, as well as the results of T-tests (assuming unequal variance) comparing the parameter estimates between the two ages. D is Cohen's D (effect size).

	M (SD)				
	9 year olds	**16 year olds**	**T(40)**	**p**	**D**
N	24	18			
Maximum (p, proportion)	0.843 (0.135)	0.877(0.082)	0.951	0.347	0.302
Crossover (c, msec)	759 (87)	694 (42)	2.877	0.006	0.840
Slope (s, Δprop / msec)	0.001 (0.0002)	0.002 (0.0002)	2.635	0.012	2.078

Table 3

Results of curve fitting analysis examining the timecourse of fixations to cohort, rhyme and unrelated objects. Shown are the mean parameter values for the asymmetric Gaussian for each competitor type for 9 and 16 year olds, as well as the results of T-tests (assuming unequal variance) comparing the parameter estimates between the two ages. D is Cohen's D (effect size).

	M (SD)				
Cohort	**9 year olds**	**16 year olds**	**T (40)**	**p**	**D**
n	24	18			
onset slope (σ_1, msec)	162 (61)	140 (44)	1.3	0.201	0.406
Midpoint (μ, msec)	620 (111)	630 (59)	<1	0.751	0.100
peak height (p, proportion)	0.229 (0.055)	0.172 (0.043)	3.6	<0.001	1.122
offset slope (σ_2, msec)	290 (98)	204 (70)	3.2	0.003	0.987
offset baseline (b_2, proportion)	0.020 (0.024)	0.014 (0.011)	1.1	0.281	0.340

	M (SD)				
Rhyme	**9 year olds**	**16 year olds**	**T (39)**	**p**	**D**
n	23	18			
onset slope (σ_1, msec)	101 (33)	142 (66)	2.610	0.013	0.83
Midpoint (μ, msec)	518 (65)	611 (134)	2.940	0.005	0.93
peak height (p, proportion)	0.172 (0.068)	0.107 (0.045)	3.461	0.001	1.1
offset slope (σ_2, msec)	408 (232)	253 (95)	2.654	0.011	0.83
offset baseline (b_2, proportion)	0.032 (0.030)	0.018 (0.012)	1.827	0.075	0.57

	M (SD)				
Unrelated	**9 year olds**	**16 year olds**	**T (39)**	**p**	**D**
n	23	18			
onset slope (σ_1, msec)	116 (59)	112 (57)	0.19	0.85	0.06
Midpoint (μ, msec)	541 (114)	558 (118)	0.47	0.64	0.15
peak height (p, proportion)	0.111 (0.027)	0.066 (0.028)	5.2	<0.001	1.6
offset slope (σ_2, msec)	272 (109)	201 (104)	2.1	0.042	0.66
offset baseline (b_2, proportion)	0.015 (0.010)	0.007 (0.006)	3.0	0.005	0.94