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Journal
Proceedings of the Annual Meeting of the Cognitive Science Society, 40(0)

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Publication Date
2018

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Abstract

We examined how phonological competition effects in spoken word recognition change with word length. *Cohort* effects (competition between words that overlap at onset) are strong and easily replicated. *Rhyme* effects (competition between words that mismatch at onset) are weaker, emerge later in the time course of spoken word recognition, and are more difficult to replicate. We conducted a simple experiment to examine cohort and rhyme competition using monosyllabic vs. bisyllabic words. Degree of competition was predicted by *proportion* of phonological overlap. Longer rhymes, with greater overlap in both number and proportion of shared phonemes, compete more strongly (e.g., *kettle-medal* [0.8 overlap] vs. *cat-mat* [0.67 overlap]). In contrast, long and short cohort pairs constrained to have constant (2-phoneme) overlap vary in *proportion* of overlap. Longer cohort pairs (e.g., *camera-candle*) have lower proportion of overlap (in this example, 0.33) than shorter cohorts (e.g., *cat-can*, with 0.67 overlap) and compete more weakly. This finding has methodological implications (rhyme effects are less likely to be observed with shorter words, while cohort effects are diminished for longer words), but also theoretical implications: degree of competition is not a simple function of overlapping phonemes; degree of competition is conditioned on proportion of overlap. Simulations with TRACE help explicate how this result might emerge.

Keywords: spoken word recognition; language processing; phonology; phonological competition

Introduction: The time course of phonological competition

Many models of adult spoken word recognition (SWR) highlight the importance of temporal order of phonetic information (Marslen-Wilson, 1987; McClelland & Elman, 1986) for recognizing words from the lexicon. In general, theories of SWR agree that as a word is heard, multiple words are activated and compete for recognition. Degree of competition depends on factors such as phonetic similarity between words and the frequency of occurrence of each word (Luce & Pisoni, 1998; Kuperman & Van Dyle, 2013), though other factors may come into play, such as semantic relatedness (Rodd, Gaskell, & Marslen-Wilson, 2002).

While some approaches are only sensitive to global (overall) similarity between words (e.g., the *Neighborhood Activation Model [NAM],* Luce & Pisoni, 1998; *Merge* Norris, McQueen, & Cutler, 2000), the temporal, serial nature of the speech signal must be a critical consideration. Many models of spoken word perception suggest that as an individual hears a word, similar words in memory are activated incrementally as the word is heard and compete for recognition (Marslen-Wilson, 1987; McClelland & Elman, 1986). For example, words that start with the phoneme /b/ will activate all words that start with that sound (e.g., *beach*, *big*, *bulge*, *baste*). As additional information from the speech stream is processed, some potential candidates are strengthened while others are attenuated. For example, if the next phoneme is /i/, then *beach*, *beam*, *bee*, and *believe* all become strengthened while *big*, *bulge* and *baste* are attenuated. According to the Cohort Model, this process continues until a single candidate word remains, or until the "current" phoneme cannot be added to a previous series, revealing a word boundary (Cutler, 1995; Marslen-Wilson & Welch, 1978). On this view, word onsets have strong primacy; the detection of an initial /b/, for example, should be taken as evidence *against* other phonemes (though the strength of the negative evidence should be related to phonetic similarity on this account, such that /b/ is greater evidence that /l/ did not occur than that /p/ -- highly similar to /b/ -- did not occur).

Evidence supporting the Cohort Model's prediction that the "recognition *cohort*" should consist only of words overlapping in the first ~2 phonemes has come from several paradigms, including *gating* studies (Marslen-Wilson & Welsh, 1978), and perhaps most notably from *cross-modal semantic priming* (e.g., Zwitserlood & Marslen-Wilson, 1989). In gating, increasingly longer snippets of a word, starting always at word onset, are presented, and participants guess the identity of the word. Responses are clearly guided by phonetic detail and word frequency. Rhymes, for example, are never guessed. In cross-modal semantic priming, participants hear a stream of auditory words and occasionally make a lexical decision to a letter string presented visually. Responses are significantly faster when the letter string is semantically related to a phonological relative of an auditory stimulus. For example, after hearing *beaker*, a participant would be faster to decide that INSECT is a word, presumably because hearing *beaker* activated *beetle*, a semantic relative of INSECT. However, such priming is not observed for rhyme relations (e.g., hearing *beaker* would not prime STEREO, a relative of *speaker*). Onset competitors are now commonly called "cohorts", since they are the items the Cohort Model predicts form the recognition cohort.

While the Cohort Model posits that only words that are very similar at onset are activated, the Neighborhood Activation Model (NAM; Luce, 1986; Luce & Pisoni, 1998) proposes that words that are sufficiently similar *globally* (overall) are activated. Specifically, on NAM's "DAS" rule, words differing by no more than a single phoneme deletion, addition, or substitution are neighbors and compete for recognition. A word's neighborhood includes cohorts only if they differ by no more than one phoneme (*beach*'s neighbors include *bee* and *beam,* but not *beaker*), but also words that mismatch at onset that would be excluded from the Cohort model competitor set (*beach*'s neighbors also include *reach* and *leech*). How can NAM justify including rhymes (and other non-cohort items)? Its *frequency-weighted neighborhood probability rule* (the ease-of-recognition for a word is proportional to the ratio of its log frequency to the summed log frequencies of all its neighbors) accounts for significant variance in predicting item-level response times for lexical decision or auditory naming (Luce & Pisoni, 1998).

Allopenna, Magnuson and Tanenhaus (1998) observed that the TRACE model (McClelland & Elman, 1986) makes an intermediate prediction: words that overlap at onset are strongly activated because of their early overlap; because activated words inhibit other words, words that mismatch at onset but are highly similar to the target word later (e.g., rhymes) are activated more strongly than unrelated words, but less strongly than words overlapping at onset. Allopenna et al. adapted the then-new *visual world paradigm* (VWP; Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy, 1995) to this question. Subjects saw displays of four pictures, and followed simple spoken instructions to interact with items (e.g., "Click on the beaker"). They found strong support for the TRACE predictions in adults: onset competitors ("cohorts") competed early and strongly, while rhymes competed weakly and later. In a second experiment, Allopenna et al. merged the paradigm with gating; subjects were instructed to click on the picture they thought was being named in gated presentation (progressively longer snippets presented from word onset). There was strong competition between cohorts, but no one selected rhymes.

Allopenna et al. suggested their result could reconcile the conflict between experiments supporting the Cohort Model vs. those supporting NAM. Gating emphasizes word onsets by presenting them clearly and repeatedly; it is unsurprising that subjects would not select rhymes. Their time course experiment also suggested an alternative interpretation of cross-modal semantic priming results: detecting priming in that paradigm would require that a phonological competitor be activated strongly enough to drive a detectable level of semantic activation. While rhymes were fixated significantly more than unrelated items, they were also fixated significantly less than cohort items.

The time course results of Allopenna et al. highlight two primary factors that govern competition in adult spoken word recognition: overall similarity and temporal order. The greater the phonetic similarity between two words, the greater the competition effect. However, temporal distribution of overlap modulates phonological competition, such that early overlap yields greater competition than late overlap (because words with later overlap are disadvantaged by inhibition from words with earlier overlap).

The elusiveness of rhyme competition

Desroches, Newmann and Joanisse (2008) pointed out that cohort competition effects are strong and replicable across studies using varying methodologies, but rhyme competition effects have been much harder to obtain. When rhyme effects are found, they tend to be much weaker than onset competition (even weaker than in the original Allopenna et al. demonstration). In a series of studies utilizing cross-modal priming, Marslen-Wilson and Zwisterlood (1989) did not find rhyme-mediated semantic priming. Marslen-Wilson, Moss and Van Halen (1996) found small rhyme priming effects were observed when participants heard a non-word (e.g., *pomato*) and then were presented with a picture of a *tomato.* These findings appear to support the Allopenna et al. (1998) contention that rhyme effects exist but are just weaker and harder to detect than cohort effects.

However, as Desroches et al. (2008) suggest, it is possible that absent or weak rhyme effects may be related to methodological artifacts and not reflect the true effects words with similar offsets have on spoken word recognition. We utilized a modified version of a VWP task and manipulated length of spoken words to evaluate competition effects based on the location and degree of phonetic overlap. While we expected that stronger rhyme effects might be observed with longer words, we also included shorter and longer cohort pairs for comparison, although we did not predict differences in degree of competition since pairs at both word lengths were selected to have similar amount of phonological overlap (~2 first phonemes).

Methods

Participants

Twenty-two college-aged adults (16 women; mean age 19 years) were recruited from the UConn Psychological Sciences participant pool. All were native English speakers with no reported history of speech or language delay, hearing impairment or special education services.

Materials

Auditory stimuli were 108 mono and bisyllabic words following the carrier phase "*find the*" spoken by a native English speaking male. Auditory stimuli were divided into three conditions based on their phonological properties. Each condition had 18 word pairs for a total of 54 pairs. The Unrelated baseline condition contained word pairs that were phonologically unrelated (e.g., *bird-sock*). The Cohort and Rhyme conditions contained phonologically related word pairs. Cohort pairs had the same onset (e.g., same initial consonant-vowel (CV) combination for monosyllable pairs or same initial syllable for bisyllabic words) while Rhyme pairs had the same offset (e.g., same final CV or VC for both mono and bisyllabic words). (We intentionally use *rhyme* rather than *rime*; in longer words, overlap in rhyme pairs is greater than a single rime [e.g., *candle-sandal*]).

We selected target words from the MacArthur-Bates Communicative Development Inventories (MB-CDI; Fenson et al., 2007) and other studies of preschool language (Bryant et al., 1990; De Cara & Goswami, 2003) since this experiment was part of a larger study examining spoken word recognition in toddlers through adults. Mean log word frequency was balanced between condition and list using data derived from the SUBTLEX database (Brysbaert & New, 2009). Mean biphone probability was calculated as outlined by Vitevitch and Luce (1998) and also balanced between each condition and list using the Kucera and Francis (1967) database. For each word, a prototypical photograph appropriate for young children was chosen.

Experimental Task

Each participant completed an adapted version of the visual world paradigm task reported by Allopenna et al. (1998). Two (instead of four) photographs appeared on a computer screen and a target word embedded in a simple auditory instruction (*"Find the coat"*) was presented via headphones.

On each trial, participants were presented with a 500 ms preview of two images, corresponding to target and the potential competitor. After the preview, participants were presented with the auditory instruction (e.g., "*find the comb*") and used the computer mouse to click on the target image. The trial ended once the participant clicked on an image (see Figure 1). Each participant completed 54 trials, consisting of 18 Cohort trials, 18 Rhyme trials and 18 Unrelated trials, with 9 monosyllabic trials and 9 bisyllabic trials in each condition. Trial order was pseudorandomized as described in the materials sections. Target and competitor image locations were balanced so half the target images appeared on the left side of the screen.

Eye movements

Participants' eye movements were measured using an EyeLink 1000 remote eye tracker (SR-Research Ltd.). Eye position was sampled at 500 Hz. Gaze recording began upon image presentation and continued until the participant clicked either image with the computer mouse. We preprocessed gaze data with Data Viewer (SR-Research Ltd.). Fixation locations were coded as fixations to the target, the distractor/competitor, or "other" (any other position, including the central fixation point). We calculated mean fixation proportions for targets, competitors and the "other" category for the duration of the trial.

Results

We used growth curve analysis (GCA; Magnuson, Dixon, Tanenhaus, & Aslin, 2007; Mirman, 2014; Mirman, Dixon, & Magnuson, 2008) to evaluate effects of Phonological condition and Syllable condition on the mean proportion of fixations to the target object utilizing a 1000 ms analysis window from 0 ms to 1000 ms after word onset. We selected an analysis window of 1000 ms based on previous reports (e.g., Mirman et al., 2008) and visual inspection of global patterns.

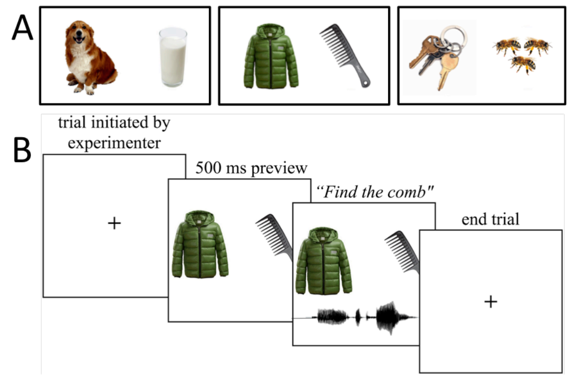

Figure 1. Panel A: example pairs (unrelated: dog, milk; cohort: coat, comb; rhyme: keys, bees). Panel B: trial structure.

We used a fully-crossed model. Mean fixation time course was modeled using 3^{rd}-order orthogonal polynomials and fixed effects of Phonological (Cohort, Rhyme, Unrelated; within-participant) and Syllable conditions (Monosyllabic, Bisyllabic; within-participant) on all time terms. Participant was the random effect (in GCA, one must aggregate over items or participants to derive time course estimates). We included 3 polynomial terms given the shape of fixation proportions over time observed in previous eye tracking studies of phonological competition (Magnuson et al., 2007). The baseline was the Unrelated x Monosyllabic condition. Effects of competitor type (Cohort, Rhyme) were evaluated as difference from baseline (e.g., the Cohort effect describes changes required in GCA parameters to model the Cohort x Monosyllabic condition relative to the Unrelated x Monosyllabic baseline). The effect of syllable was evaluated as changes from baseline (Unrelated x Monosyllabic) needed to model the Unrelated x Bisyllabic condition. Interactions evaluate how growth curve parameters must additionally change to fit the Cohort x Bisyllabic and Rhyme x Bisyllabic combinations. Participant was included as a random variable, including random intercepts.

Contra prescriptions to "keep [random effects structure] maximal" (Barr, Levy, Scheepers, & Tily, 2013), we did not include by-participant random quadratic or cubic terms because we do not have sufficient degrees of freedom with the current enrollment (only ~5 participants per cell due to the constraints on counterbalancing) to support the maximal structure (more participants will be enrolled). Similarly, we did not compare Cohort x Rhyme due to small sample size. All analyses were completed in RStudio (Version 1.0.143) using the lme4 package (1.1-10) for multilevel modeling.

Accuracy and Reaction Times

Trials in which the participants failed to click on the correct target image were excluded from eyetracking and reaction time analyses. Errors rates were 1% or less for all phonological by syllable conditions with the exception of

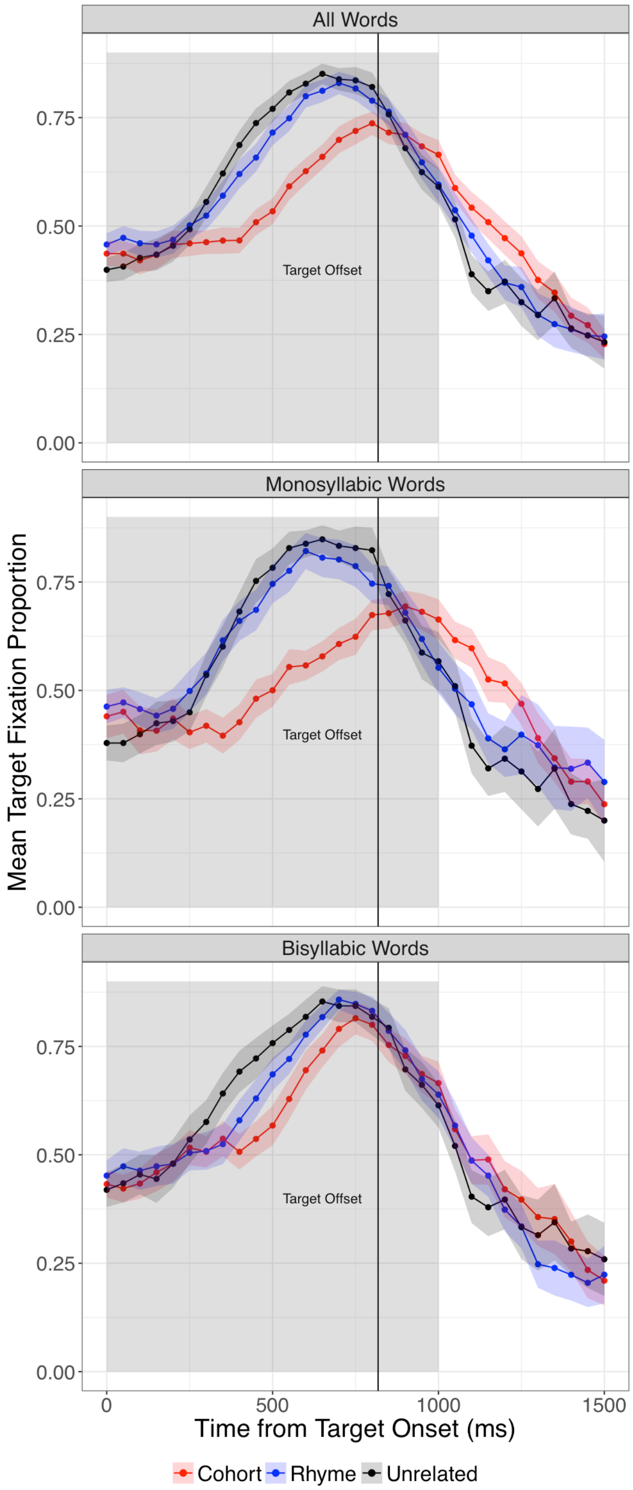

Figure 2: Target fixation proportions over time by phonological condition and syllable level.

the monosyllabic cohort trials which had an error rate of approximately 8%. Due to space constraints, we do not present the error analysis here, but there is a clear interaction between trial type and syllable length on accuracy. Errors on monosyllabic cohort trials were likely due to our use of child-directed speech. Reaction times are

Table 1:Growth curve analysis results.

	Estimate	Std. Err.	*t*	*p*
Intercept	0.636	0.025	25.47	**<.001**
Linear (slope)	0.524	0.037	14.32	**<.001**
Quadratic	-0.488	0.037	-13.30	**<.001**
Cubic	-0.279	0.037	-7.62	**<.001**
Cohort (intercept)	-0.108	0.011	-9.71	**<.001**
Cohort (slope)	-0.068	0.051	-1.31	0.189
Cohort (quad.)	0.590	0.051	11.47	**<.001**
Cohort (cubic)	0.145	0.051	2.83	**0.005**
Rhyme (int.)	0.001	0.011	0.06	0.954
Rhyme (slope)	-0.117	0.051	-2.28	**0.023**
Rhyme (quad.)	0.138	0.051	2.68	**0.007**
Rhyme (cubic)	0.014	0.051	0.28	0.779
Bisyllabic (int.)	0.026	0.011	2.29	**0.022**
Bisyllabic (slope)	-0.019	0.052	-0.37	0.710
Bisyllabic (quad.)	0.103	0.052	1.98	**0.047**
Bisyllabic (cubic)	0.053	0.052	1.02	0.308
Cohort x Bisyl. (int.)	0.052	0.016	3.28	**0.001**
Cohort x Bisyl. (slope)	0.094	0.073	1.30	0.195
Cohort x Bisyl. (quad.)	-0.304	0.073	-4.18	**<.001**
Cohort x Bisyl. (cubic)	-0.124	0.073	-1.70	0.088
Rhyme x Bisyl. (int.)	-0.021	0.016	-1.31	0.190
Rhyme x Bisyl. (slope)	0.142	0.073	1.95	0.051
Rhyme x Bisyl. (quad.)	0.039	0.073	0.53	0.594
Rhyme x Bisyl. (cubic)	-0.083	0.073	-1.14	0.255

not reported due to their lack of sensitivity and post-perceptual influence.

Eye Tracking

Descriptive overview Visual examination of the timecourse plots (Figure 2) revealed differences between types of phonological competitors, and potential interactions of phonological competitor type with mono- vs. bisyllabic words. Collapsed across syllables, our participants demonstrated strong cohort effects with a trend toward rhyme effects. However, potential differences emerged for mono- vs. bisyllabic items. For monosyllabic words, cohort effects were strong and rhyme effects were weak. For bisyllabic words, cohort effects appeared faster than for monosyllabic words and rhyme effects seemed robust. (Note that we plot mean target proportions for each condition, whereas GCA assesses model parameter changes required to fit differences relative to baselines, as described above.)

Growth Curve Analysis All orthogonal polynomial terms included in the model (e.g., linear, quadratic, cubic), significantly contributed to modeling the Unrelated, Monosyllabic target baseline. We now turn to how the timecourse for targets differed from this baseline in other conditions. See Table 1 for a summary of GCA results.

There was a clear phonological competition effect of the monosyllabic Cohort trials compared to the Unrelated monosyllabic trials as evidenced by significantly lower intercept (lower mean fixation proportion) and significantly more positive quadratic (less bowing as seen in Figure 2) and cubic components. We also observe a similar pattern of competition between the monosyllabic Rhyme and monosyllabic Unrelated conditions. The monosyllabic Rhyme trials had a significantly lower slope (slower to get to target) and significantly more positive quadratic component (less bowing, also reflecting a slower and more extended trajectory to the target, as seen in Figure 2). Examining the effect of Syllable, there was a significant effect of syllable length on the Bisyllabic Unrelated trials compared to Monosyllabic Unrelated trials as indicated by a significantly higher intercept (higher mean fixation proportion) and significantly more positive quadratic component (again less bowing, reflecting a slower timecourse; see Figure 2).

Finally, our examination of the relationship between Syllable and Condition revealed a significant interaction between Cohort Condition and Bisyllabic trials. The significant intercept interaction of Cohort and syllable is consistent with the smaller cohort effect observed for bisyllables in Figure 2 (formally, the intercept for Bisyllabic Cohort trials was significantly lower than predicted from the effects of Cohort and Syllable alone). The significant quadratic interaction indicates more upward bowing of the Cohort Bisyllabic target curve than would be predicted from the addition of quadratic terms for Cohort and Bisyllabic effects, again reflecting a weaker Cohort effect for bisyllabic than monosyllabic targets.

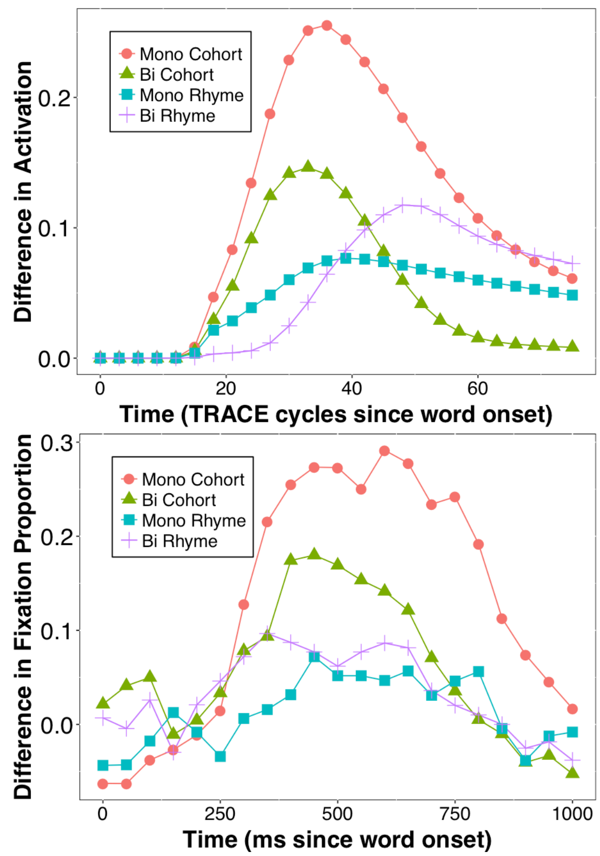

Figure 3. Top: TRACE simulation results. Lines represent competitor-unrelated differences over time. Bottom: comparable differences in fixation proportions to competitors for human Ss.

Discussion and Simulation

Our aim was to examine how phonological competition might be affected by word length and amount of phonological overlap. As expected, rhyme effects were stronger for longer words. Given our definition of rhymes – words that overlap from at least the nucleus of the first syllable through the end of the word – longer rhyme pairs must have greater phonological overlap. However, there was also an effect of word length on cohort competition, but apparently in the opposite direction: cohort effects were smaller for longer words.

However, both results are explainable by the same principle if we instead consider *proportion* of overlap. Again, the length of the rhyming portion of word pairs increases, simple amount of overlap increases, but so does proportion of overlap (e.g., proportion of overlap is 0.67 for *cat-mat*, but 0.8 for *kettle-medal*). For cohorts, defined here as words overlapping in (at least) the first 2 phonemes, the opposite relationship holds. As word length increases, the proportion of overlap will decrease (on average; there are of course longer cohort pairs that have greater proportion of overlap, such as *friend-french* [0.8] vs. *castle-cabin* [0.2]). Thus, where proportion of overlap is lower (on average), competition is weaker (for shorter pairs for rhymes, but longer pairs for cohorts).

The rhyme-length interaction (stronger effects for longer words) is not surprising, and we expect it would be easily accounted for by computational models of spoken word recognition, such as TRACE (McClelland & Elman, 1986). However, whether the cohort-length interaction (weaker effects for longer words) would emerge from TRACE is less apparent. To test this, we conducted some simple simulations using jTRACE (Strauss, Harris, & Magnuson, 2007). We compared a short target word (/bit/) to a short cohort (/bid/) and a short rhyme (/pit/), as well as to an unrelated baseline word (/lak/). We also compared a long target (/targ^t/) to a long cohort (/tasilu/, added to the TRACE lexicon for this simulation) and a long rhyme (/darg^t/, also added for this simulation). To quantify degree of cohort and rhyme competition, we plot difference scores for competitors versus unrelated baseline items in the top panel of Figure 3 (e.g., the line for *Mono Rhyme* is the activation of /pit/ minus the activation of /lak/ at each processing cycle). As can be seen in the figure, TRACE predicts the phonological overlap effects observed in our experiment: the cohort effect was larger for shorter words while the rhyme effect was larger for longer words. In the bottom panel, we have plotted comparable differences in competitor fixations for human subjects. The rank ordering is the same, though we do not observe the saliently later rhyme effect predicted for bisyllabic items.

These effects emerge in TRACE largely due to lateral inhibition at the word level. Word nodes in TRACE have specific temporal positions, and width in memory proportional to their length in phonemes. Words receive lateral inhibition from word nodes with which they overlap in "time" in the TRACE memory. Longer words overlap with more word nodes than shorter words, and therefore receive more inhibition. This causes TRACE to exhibit an early short word bias (short words can activate more quickly because they receive less inhibition) and a late long-word bias (longer words receive more bottom-up input). The difference in cohorts TRACE predicts emerges directly from the early short-word bias; shorter targets activate more quickly. The difference in onset of competition for rhymes also follows from faster activation for shorter words, though the larger rhyme effect in the late time course emerges from the late long-word bias.

Although the full pattern predicted by TRACE is not observed, it provides an interesting hypothesis as to the basis for the proportion-of-overlap effects observed in Figure 2. We intend to test these predictions more thoroughly in future work.

Acknowledgments

Funding for this project was provided by NSF IGERT grant number DGE-1144399 (J. Magnuson, PI). We thank Dan Mirman for helpful advice about GCA.

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