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CHAPTER 11

Phonological Instability in Young Adult Poor Readers

Time Course Measures and Computational Modeling

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INTRODUCTION

A fundamental principle shared by nearly all theories of reading is that phonology plays a key role in mediating the mapping from print to meaning (Harm & Seidenberg, 2004; Shankweiler, Liberman, Mark, Fowler, & Fischer, 1979; Snowling & Hulme, 2005; Ziegler & Goswami, 2005). For virtually all individuals, acquiring reading skill—a cultural innovation that builds directly on extant linguistic abilities—is more difficult than spoken language acquisition (Liberman, Shankweiler, & Liberman, 1989). Moreover, many findings link specific reading disability (dyslexia) to impairments in phonological abilities (e.g., Snowling, 1981), or sensory impairments likely to reduce phonological abilities (Tallal, 1980). Although these theories vary in important ways, they share the key postulation of a *phonological deficit hypothesis*. However, phonological deficits have primarily been observed in children, given that most research on reading development and reading disability has focused on this population. Much less attention has been devoted to the adult endpoint of atypical reading development.

In this chapter, we briefly review our recent work with a community-based sample of young adults with a high proportion of poor readers. There are two crucial reasons why this population merits attention. First, though other chapters in this volume make a compelling case for the importance of early detection and intervention for reading disability, thousands reach adulthood each year without achieving a functional level of reading competence. Some may have been genetically predisposed to dyslexia. Others may represent failures of instruction; for example, individuals with the potential to become competent, fluent readers had they been given appropriate experience. Understanding the distribution of these cases will provide the necessary foundation for addressing urgent public health questions: How might reading interventions be best designed for adults? Are there subgroups of adult poor readers for whom different interventions may be most appropriate? Second, examining the endpoint of atypical development may provide new insight into neurobiological and cognitive bases for typical reading and provide constraints on theories of reading development and disability. To that end, we have been carefully characterizing the linguistic and nonlinguistic abilities of our community sample and examining both the functional neural architecture underlying spoken and written language ability and how individual differences in reading relate to other abilities. We briefly review our progress in the project so far.

We then report preliminary results from new experiments with this population, examining the time course of spoken-word recognition and learning. These experiments are motivated by the goal of better understanding potential differences in phonological ability in poor and good readers. They are also pertinent to recent work by Ramus and Szenkovits (2008), who revived and extended a specific sort of phonological deficit hypothesis. Ramus and Szenkovits reviewed three primary dimensions to phonological deficits in dyslexia: reduced phonological awareness, reduced verbal short-term memory, and slowed lexical retrieval. They pointed out that the tasks used to assess these dimensions impose time pressure demands (in the case of rapid naming tasks used to assess lexical access) or require storage or manipulation of phonological representations. They then reviewed unpublished evidence suggesting that adults with dyslexia may have intact phonological representations (e.g., their sample of adult dyslexics showed a phonological similarity effect comparable to that of typical readers in a nonword discrimination task, contra Shankweiler et al., 1979). Ramus and Szenkovits propose therefore that dyslexics may not have degraded phonological representations; rather, the basis for their phonological deficits may be an impairment of phonological access (compare the processing limitation hypothesis of Shankweiler & Crain, 1986), which manifests only (or most prominently) under particularly challenging task demands.

However, the data motivating this phonological access hypothesis come from tasks in which the response reflects a late, possibly post-perceptual stage of processing. Measures of the time course of phonological processing could provide greater insight into whether and how phonology might be different in low-ability readers.

In the rest of this chapter, we briefly review our work with our community sample, then report two new experiments that impose minimal task demands and employ fine-grained measures that have been used previously to investigate the time course of language processing and learning in typical adults. We also report simulations using a computational model and then discuss the implications of the experiments and simulations for phonological deficit hypotheses.

THE PROJECT SO FAR

The overarching goal of this project is to examine the linguistic and nonlinguistic abilities and the underlying functional neural architecture supporting linguistic abilities of a broad community sample of young adults. We recruit from high-school equivalency (General Educational

Development, or GED) programs and community colleges in the greater New Haven, Connecticut, region. Participants tend to be from relatively low socioeconomic strata and ethnic minorities. They exhibit a wide range of performance abilities, although a greater proportion of low-ability individuals are found in comparison with more typical (in reading research) samples of college students at research universities.

By sampling from these settings, we achieve important goals. First, though we are able to oversample at the low end of ability ranges in comparison with a university sample, we obtain a wide range of abilities suitable for assessing individual differences. Second, because of the relative socioeconomic homogeneity of this sample, our high- and low-ability participants tend to be well matched demographically. Third, we are able to extend reading research to two strata of the population that have historically been underrepresented: adults with low reading ability and low-socioeconomic-status adults from ethnic minorities. Finally, we note that because our participants are nearly all enrolled in some form of continuing education, we assume that they are generally motivated; indeed, they tend to be diligent, compliant research participants.

Braze, Tabor, Shankweiler, and Mencl (2007) conducted comprehensive linguistic, cognitive, and neuropsychological assessments of a sample of 44 young adults from this community sample. The results were assessed from the perspective of the simple view of reading (Gough & Tunmer, 1986), which states that reading ability is the product of decoding skill and general language comprehension capacity. To oversimplify slightly, the idea is that ability to read text should be predicted by print decoding (pseudoword naming) and listening comprehension abilities. In other words, the chief additional complexity imposed by reading in comparison with listening is the ability to map print to phonology. The simple view failed to fully explain individual differences in the assessments of Braze et al.: Measures of oral vocabulary knowledge explained significant variance above and beyond that explained by decoding and auditory comprehension.

Braze et al. (2007) suggested that this finding, when considered within the framework of the *triangle model* of visual word recognition (Harm & Seidenberg, 2004; Seidenberg & McClelland, 1989; see Figure 11.1), is consistent with the lexical quality hypothesis (Perfetti, 2007; Perfetti & Hart, 2002). The logic is that poor performance on vocabulary measures does not reflect the mere presence or absence of a form or concept in memory. Rather, poor performance reflects relatively slow and noisy activation of representations as a function of less detailed or refined knowledge associated with lexical items in memory. In the triangle model, the representation of a lexical item is distributed in weighted connections linking orthographic and phonological forms and semantic knowledge. When input arrives on any of those banks of interface nodes, activation flows in every direction through the entire system in a gradual fashion. In a well-trained system, coherent covariation in orthography, phonology, and semantics allows the system to settle into distinct states despite similarities between items in any of those dimensions. The system can settle quickly onto a correct phonological form, given the orthographic form of an English word with regular, high-frequency orthographic–phonological mappings based on oft-used orthography–phonology connections. However, given an irregular pattern, it will take the system longer to settle, and connections along the orthography-semantics-phonology sides of the triangle will play a larger role in arriving at the correct stable state. Braze et al. therefore suggested that lexical quality suffers when readers do not have the opportunity to sufficiently tune connections along the orthography–phonology, orthography–semantics, and semantics–phonology pathways (including orthographically conditioned changes in the semantics–phonology pathways observed in well-tuned models) in response to print. Absent such tuning, the system may take longer to settle (analogous to retrieval time in a more conventional memory model), and lexical representations may be less stable or distinctive than in a highly practiced, fluent reader. Phonology–semantics pathways are presumed to be well practiced and therefore well tuned in poor readers who are competent speakers; in contrast, orthographic pathways and orthographic contingencies are presumed to be relatively weak in poor readers. This set of assumptions leads to a prediction that vocabulary should differentially

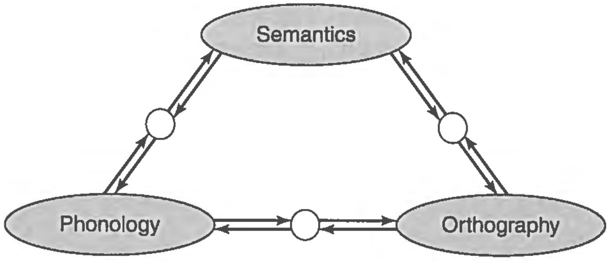

Figure 11.1. Schematic of the triangle model. Each interface level (phonology, orthography, semantics) is a bank of a large number of nodes (which could represent, for example, specific phonological or semantic features, though more abstract, distributed codes are possible as well). Small, empty ovals indicate banks of hidden nodes that do not themselves correspond to a discrete level of representation but afford a larger number of weighted connections between interfaces. Arrows indicate full connectivity (a connection from every node at the origin to every node at the destination). The model is trained to settle to a stable state where a pattern on one interface level (e.g., phonology) leads to correct patterns at the other levels (i.e., orthography and semantics) by adjusting the connection weights in small increments based on how far the model state is from the desired state. (*Sources:* Harm & Seidenberg, 2004; Seidenberg & McClelland, 1989.)

explain variance in poor readers for speech and print. This result is exactly what they found: Vocabulary accounted for significant variance in print comprehension but not in speech comprehension.

Van Dyke, Johns, and Kukona (2010) found additional support for the lexical quality hypothesis in our sample. They examined susceptibility to proactive interference during sentence processing (see also Van Dyke & McElree, 2006). Challenging object-cleft sentences in which a direct object is displaced from its verb (e.g., *It was the boat that the man who lived by the sea fixed*) were presented in a self-paced reading paradigm. Immediately prior to reading these sentences, participants were asked to remember a list of words that included items that were all plausible objects of the verb *fixed* (e.g., table, sink, truck). These researchers looked for individual differences in sensitivity to interference from the memory words by comparing this condition with a noninterference condition identical to the interference condition, except that the memory words could not serve as the direct object of the verb (e.g., the verb *fixed* was substituted for *sailed*, as in *It was the boat that the man who lived by the sea sailed*). The performance of individuals from our community sample on this task was compared with performance on a battery of 25 measures of various cognitive abilities (both linguistic and nonlinguistic). The only factor that explained significant variance in participants' sensitivity to interference was receptive vocabulary (and crucially, not working memory span). Van Dyke et al. (2010) interpreted this result as consistent with the lexical quality hypothesis, assuming that poor-quality lexical representations result in faulty retrieval of the direct object when the direct object must be integrated with its verb.

The functional magnetic resonance imaging (fMRI) results of Shankweiler et al. (2008) further imply that phonology is an important locus of difference between good and poor readers. They used anomalous written and spoken sentences to localize brain regions selectively activated for print and speech in 36 individuals from our community sample. Individuals varied in the degree to which the areas recruited for the two modalities overlapped. Regressions with reading skill measures revealed that the amount of overlap increased with reading skill, suggesting that overlap in the neural substrates of speech and reading is a hallmark of the endpoint of a successful reading development trajectory.

Collectively, these studies are highly consistent with the view that reading difficulties have specific phonological bases. However, these results do not reveal the way(s) in which good and poor readers' phonological processes differ, suggesting that further direct examination of phonological abilities in our community sample is warranted. The experimental results we present here are in a preliminary report on new tasks that we are using to assess the time course of phonological processing and learning in our sample, with the goal of arriving at a better understanding of how phonological skills differ in naturalistic tasks as a function of reading skill.

EXPERIMENT 1

In Experiment 1, we used the paradigm of Dahan, Magnuson, Tanenhaus, and Hogan (2001) because it provides a test of the time course for processing fine-grained phonological detail, but in a task that minimizes cognitive demands. Dahan et al. investigated the impact of misleading coarticulation (subphonemic/subcategorical mismatches). They achieved misleading coarticulation by cross-splicing recordings of words. For example, they took the initial consonant-vowel (CV) from *neck*, cut as late as possible before the final stop consonant, and spliced it together with the final consonant of *net*. The result sounds like *net*, but the vowel includes coarticulation consistent with /k/. They labeled this sort of item *w2w1* (word 2 spliced to word 1). They also had cases in which the initial CV came from a nonword (*nep* + *net* → n3w1). Finally, they included cross-spliced items without misleading coarticulation by splicing together two recordings of a target word such as *net* (w1w1). Dahan et al. presented these items with displays similar to the one shown in Figure 11.2, using the visual world paradigm (VWP; Tanenhaus, Spivey-Knowlton, Eberhard, & Sedivy, 1995). Eye movements were recorded as participants followed spoken instructions such as "point to the net."

The motivation for their study was the apparent deficiency in the TRACE model (McClelland & Elman, 1986) identified by Marslen-Wilson and Warren (1994). Specifically, human lexical decision reaction times appeared inconsistent with the time course of activation in TRACE. However, the time course measure provided by the VWP (Figure 11.2, right) showed that the TRACE predictions (Figure 11.2, center) were remarkably accurate. Crucially, participants fixated the competitor, *neck*, most when there was misleading coarticulation consistent with that

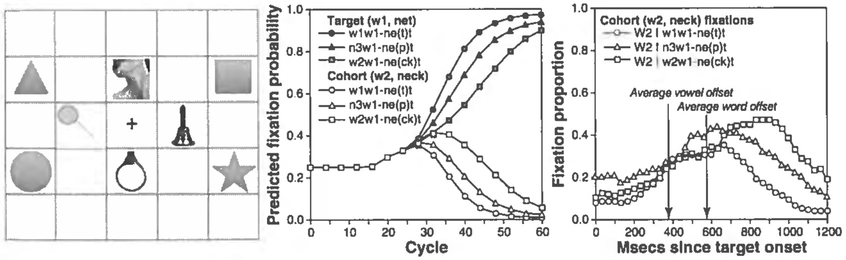

Figure 11.2. Sample display (left). TRACE predictions (center). Each pair of shapes (e.g., closed and open circles) represent the activations of the target word (closed symbols) and the competitor word (open symbols) when each cross-spliced stimulus is presented to the model. The key predictions are greater competitor activation given coarticulation consistent with the competitor (w2w1) and least given coarticulation consistent with the target (w1w1) due to bottom-up fit to lexical items. Given coarticulation consistent with a nonword (n3w1), an intermediate level of competitor activation is predicted because neither the target nor the competitor has an advantage based on the bottom-up stimulus. Competitor fixations over time (right) from Dahan et al. (2001).

word (w2w1) and least when the coarticulation was fully consistent with the target (w1w1). Fixation proportions were intermediate when misleading coarticulation did not map onto a word (n3w1). TRACE predicts the w1w1 and w2w1 patterns transparently; the word with best bottom-up match is initially activated most strongly. The n3w1 results follow because neither *net* nor *neck* has an advantage as the nonword coarticulation is heard; thus, both reach a relatively high level of activation before the disambiguating final consonant.

What might we predict for our sample? If linguistic difficulties arise from sensory or phonological impairments, such that research participants have "fuzzy" (e.g., under the phonological quality hypothesis of Joanisse, 2004) or slow-to-activate phonological representations (compare the generalized slowing hypothesis of Kail, 1994), we might expect them to be less affected by misleading coarticulation and to show weaker competition effects. On the phonological access hypothesis (Ramus & Szenkovits, 2008), if the task minimizes processing demands, our sample ought to look no different from a typical college sample. Although one might argue that demands remain substantial in this task, note that there is no time pressure, and the task is extremely naturalistic (for a laboratory task); participants simply follow spoken instructions to interact with items in a display. Thus, differences in our (on average) lower ability readers may reveal more details about the ways in which their phonology may differ from that of typical readers.

Methods

Participants The participants were 32 college-age adults (mean age of 21) recruited from community colleges and GED programs in the New Haven area. A subset of the 25-test assessment battery is summarized in Table 11.1, which makes it apparent that this population tends to lag in language and other cognitive domains. Our approach with samples from this population is to employ a continuum method of analysis, including nonlinguistic abilities in regression models rather than partitioning the sample based on ability and/or excluding participants based on thresholds. For the current report, because we have a fairly small sample, we will compare our sample with typical college students. The results we report do not differ if we remove, for example, participants with low approximated intelligence quotients (IQs) (< 75), so the full sample is included.

Materials The auditory materials were those used by Dahan et al. (2001) and consisted of 15 *word 1, word 2, nonword 3* triplets (w1,w2,n3), such as *net, neck,* and *nep* (for the full set, see Appendix B of Dahan et al., 2001). The visual materials were similar to those used by Dahan et al., except that we used photographs instead of line drawings.

Procedure The procedure was identical to that of Dahan et al. except that we used color photographs of real objects rather than line drawings. There were three lists, with five items assigned to each condition (w1w1 [consistent coarticulation], w2w1 [misleading cohort coarticulation], and n3w1 [misleading nonword coarticulation]) in each list. Participants were randomly assigned to lists. On each trial, four pictures of objects and four simple geometrical shapes appeared when the participant clicked on a central fixation cross (see Figure 11.2). On critical trials, these included the target (e.g., *net*) and a cohort competitor (e.g., *neck*). A spoken instruction was presented over speakers, such as "Point to the net; now click on it and put it below the circle." We tracked eye movements using an SR Research EyeLink II head-mounted eye tracker. The measure of interest was the probability of fixating each item over time from the onset of the target word. (See Dahan et al., 2001, for full details on the makeup of critical and filler trials.)

Table 11.1. Sample characteristics

Standardized (M = 100, SD = 15)		Age-equivalent scores	
Assessment	Mean (*SD*)	Assessment	Mean (*SD*)
WASI general IQ approximation	89 (15)	Chronological age	21 (2)
PPVT picture vocabulary	89 (13)	WJ3 word identification	14 (3)
CTOPP phonological awareness	79 (16)	WJ3 word attack	12 (4)
CTOPP phonological memory	91 (10)		

Key: M, mean; *SD,* standard deviation; WASI, Wechsler Abbreviated Scale of Intelligence (Wechsler, 1999); PPVT, Peabody Picture Vocabulary Test–Third Edition (Dunn & Dunn, 1997); CTOPP, Comprehensive Test of Phonological Processing (Wagner, Torgesen, & Rashotte, 1999; WJ3, Woodcock-Johnson III Test of Achievement (Woodcock, McGrew, & Mather, 2000).

Results

Eye movements were parsed into saccades and fixations. Saccade time was attributed to the following fixation because the initiation of a saccade is the earliest indicator of the choice to fixate the next gaze position. Figure 11.3 shows competitor fixations (target fixations are essentially complementary) from our sample, with competitor fixations from Dahan and colleagues' *presumed typical* sample for qualitative comparison. There is a striking difference between the groups: The fixation proportions to competitors are relatively elevated in each condition in the community sample. The typical sample had cohort peaks of approximately 0.5 for w2w1, 0.45 for n3w1, and 0.3 for w1w1. Our sample had peaks of 0.6, 0.4, and 0.4, respectively. Competitor proportions also remain elevated for a more extended time. There is also a striking similarity with the typical college sample: There is no apparent delay in the response to the bottom-up signal.

An analysis of variance comparing mean fixation proportion in the window from 200 to 1200 milliseconds (ms) suffices to quantify the obvious pattern in the figure for our sample. (We are currently collecting data from a new sample of college students along with formal language ability assessments to afford more direct investigation of individual differences.)

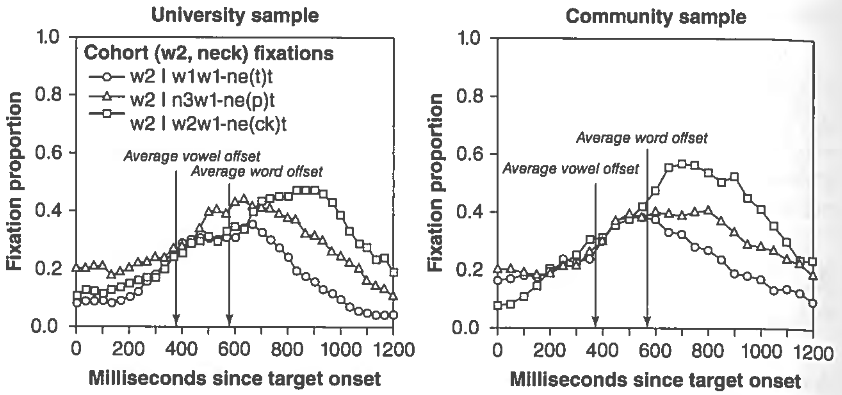

Figure 11.3. Competitor effects in Dahan and colleagues' presumed typical sample (left) and our community sample that included many poor readers (right). The arrows indicate mean vowel offset and word offset. There is notably greater and more sustained competition in the community sample.

The main effect of condition was significant ($F[2, 62] = 12.3, p < .001$). Planned comparisons revealed that mean fixation proportions were reliably higher in the w2w1 condition (0.53) than in the n3w1 condition (0.42; $F[1, 31] = 8.0, p = .008$) and marginally higher in the n3w1 condition than in the w1w1 condition (0.33; $F[1, 31] = 3.8, p = .06$).

Together, these patterns rule out all of the predictions discussed previously. Generalized slowing does not apply because there is no apparent delay in bottom-up response. Delayed, weak, or absent competitor effects that might be predicted on phonological quality hypotheses were not observed. Instead, our sample appeared to be *more* sensitive to subtle phonetic detail than typical participants, showing greater lexical competition effects. This may be compatible with the phonological access hypothesis of Ramus and Szenkovits (2008) in that initial lexical contact appears to proceed with similar timing in lower ability readers, but differences emerge in subtle details of lexical activation and competition.

Computational Modeling

To help make sense of this unexpected result, we turned to the jTRACE reimplementation of TRACE (Strauss, Harris, & Magnuson, 2007), which includes several additional features, such as a graphical user interface and plotting and scripting utilities. TRACE is an interactive network (i.e., a neural network with recurrent [feed-forward, feed-back, and inhibitory] connections with fixed parameter settings rather than connection weights changeable via online learning; see Figure 11.4). Although TRACE has well-known limitations (as discussed in McClelland & Elman, 1986), it still has the deepest and broadest empirical coverage of any model of spoken-word recognition, while compactly embodying the core principles shared by most current theories (see Magnuson, Mirman, & Harris, in press).

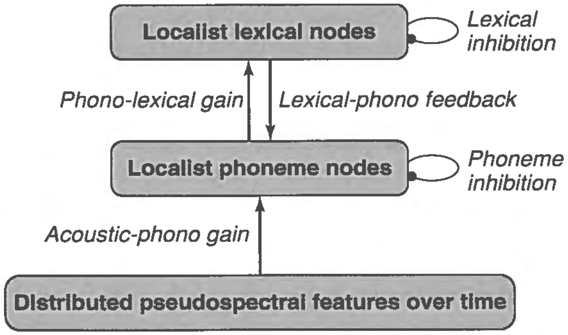

Figure 11.4. Schematic of the TRACE interactive-activation model of speech perception and spoken word recognition. Each level represents a bank of many nodes. At the phoneme and lexical levels, a localist representation is used (i.e., with one node per phoneme and one node per word). Arrows stand for partial connectivity between levels; phonemes have feed-forward connections to each word containing them, with reciprocal feedback connections. The loops with round connectors on the phoneme and lexical levels indicate lateral inhibition within levels, such that active nodes send inhibitory signals to other nodes within the same layer. Lateral inhibition governs activation, allowing a single node to tend to dominate within each level at the time scale of phonemes and words. Each of these connection types has associated gain parameters. Changing these parameters changes the behavior of the entire system but tends to have the largest impact at the level where the parameter is changed (e.g., Changing phoneme inhibition changes phonological stability but also has repercussions at the lexical level). (In the full model, phoneme and lexical nodes are temporal-spatial templates reduplicated many times so that there are many copies of each phoneme node aligned with long stretches of the potential input window, which is what allows the model to handle over-time input. See McClelland & Elman, 1986, for details.)

Our strategy was simple. Starting with the default parameters used by Dahan et al. (2001) to obtain the simulations shown in the middle panel of Figure 11.2, we explored a wide range of changes to several parameters in TRACE, changing them one at a time. The goal was to determine whether any parameter could be changed to produce the observed pattern: increased competition effects without any slowing of initial lexical access. Although we tried many parameters, only reducing lateral inhibition at the phoneme or lexical level could produce this pattern. We will summarize the results with a few theoretically motivated parameter explorations.

Generalized slowing (turning down feedforward gain at any level of the model) does not work; it slows initial activations and damps competition effects. "Fuzzing" phonology by adding noise to the input or to any level within the model does not work; it also damps competition effects. Lexical decay—the parameter that McMurray, Samelson, Lee, and Tomblin (2010) claim best fits individual differences in a lexical competition in a group of adolescents with a range of language and cognitive abilities—influences activations too late and weakly. Reducing lateral inhibition works, at both the phoneme and lexical levels, when lateral inhibition is reduced by approximately 50% from default levels. Reducing inhibition does not affect initial activation rates, but it allows larger competition effects because it delays the impact of late-arriving bottom-up disambiguation.

Summary

In Experiment 1 we found that a sample with a high proportion of poor readers exhibited larger competition effects in response to misleading coarticulation than do typical college students, without any evidence that processing is generally slowed or delayed (because they respond equally quickly to word-initial information). Simulations with TRACE suggest that the only way to achieve larger competition effects in this paradigm without slowing initial processing is by reducing lateral inhibition at the phoneme or lexical level. There is a potentially interesting connection to the notion that poor readers have difficulties in suppression of irrelevant details or representations at multiple levels (Gernsbacher, 1993).

EXPERIMENT 2

In Experiment 2, we continued our exploration of our sample's phonological abilities by examining lexical competition in the context of an artificial lexicon learning task, modeled after a study by Magnuson, Tanenhaus, Aslin, and Dahan (2003). This examination allowed us to simultaneously study phonological competition effects in word recognition (How strongly do "cohorts" such as /pibo/ and /pibu/ compete? How strongly do rhymes such as /pibo/ and /dibo/ compete?) and word learning ability in this population. Magnuson et al. (2003) were motivated in part by the goal of precisely controlling lexical characteristics such as phonological similarity, frequency, and neighborhood density. This approach has an added advantage for our sample. To the degree that our sample diverges from the performance of typical participants using real words, it is difficult to determine the locus of the difference. There may be deep reasons, such as differential organization of processing mechanisms, or shallow ones, such as simple differences in vocabulary size. An artificial lexicon paradigm allows us to put participants on maximally similar footing. Although they arrive with individual differences in linguistic and cognitive abilities, the items are equally unfamiliar to all.

On a sensory, phonological, or cognitive theory of the etiology of reading disability, one might expect our sample to perform worse than one of typical college students. There are two precedents using familiar, real words in the visual world eye tracking paradigm that suggest possible outcomes. Desroches, Joanisse, and Robertson (2006) examined cohort and rhyme competition effects in children with dyslexia and found that—unlike typically developing peers—these children did not exhibit rhyme competition effects. In contrast, McMurray et al. (2010) reported that adolescents meeting criteria for specific language impairment (SLI) showed stronger cohort *and* rhyme effects, though only in the late time course (a result that is potentially consistent with the elevated and persistent onset competition effects we observed in Experiment 1).

Methods

Participants There were two groups of participants. One group, the community sample (CS) group, was a subset of 22 participants from our community sample in Experiment 1. The other was a group of unassessed but presumed typically developing (TD) college students from the University of Connecticut (the TD group, $n = 14$).

Materials The auditory materials were eight artificial words constructed such that each item had one cohort (onset) competitor in the artificial lexicon and one rhyme. The words were /pibo/, /pibu/, /dibo/, /dibu/, /tupa/, /tupi/, /bupa/, and /bupi/. The visual materials were photos of eight unusual animals from other continents unlikely to be familiar to Americans. Names were mapped randomly to pictures for each participant.

Procedure Each trial had identical structure. A fixation cross appeared in the center of the screen. When the participant clicked the cross, the trial began. Two pictures appeared, at left and right; 500 ms later, an instruction was played, such as "Find the pibo." At first, participants could only guess. If they clicked on the incorrect object, they heard, "Try again." When they clicked on the correct object, they heard feedback, such as, "That's right, that's the pibo!" The experiment consisted of 8 blocks of 24 trials. Each item appeared as the target 3 times per block, paired with its cohort, its rhyme, and an unrelated item. Thus, each block had eight cohort, rhyme, and unrelated trials. There was no formal test; instead, we measured behavior continuously over learning.

Results and Discussion

Accuracy and response time (for accurate trials) are shown in Figure 11.5 for the two groups. Growth-curve analysis was used to assess change over time for the two groups, using orthogonal power polynomials, following the methods described by Mirman, Dixon, and Magnuson (2008). In this

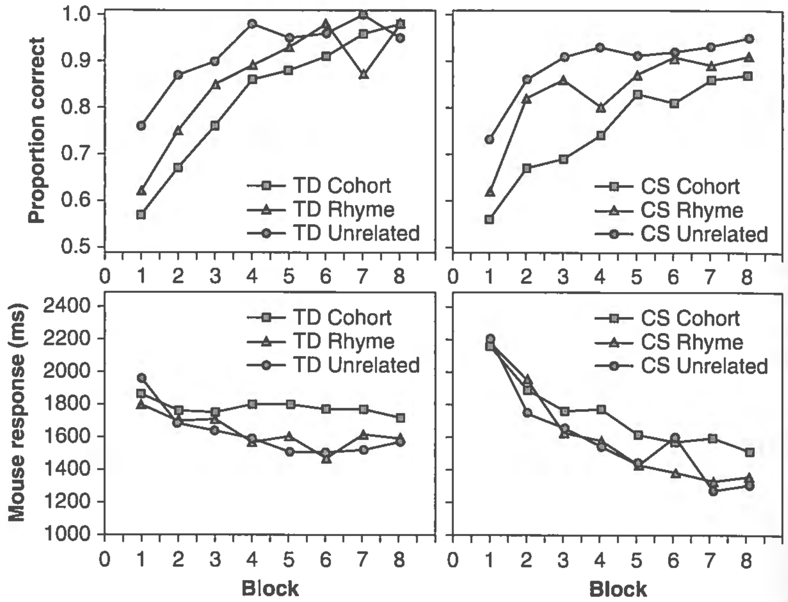

Figure 11.5. Mean accuracy (top row) and mouse-click response time (bottom row) in Experiment 2 for the assumed typically developing (TD) group (left column) and the community sample (CS) group with many poor readers (right).

approach, polynomial curves are fit to individual data and analyses are conducted on curve parameters. A conceptual benefit of this approach is that the intercept is recentered such that it is analogous to mean fixation proportion. In accuracy, collapsing over groups, the intercept was reliably lower for cohort than rhyme trials, and for rhyme versus unrelated trials. In reaction time, cohort trials had higher intercept than the other two trial types, which did not differ from each other. Notably, the TD and CS groups did not differ in intercept for accuracy or RT. But they did differ in slope, as is clear from Figure 11.5. Interestingly, both groups show strong effects of competitor type in accuracy.

Fixation proportions over time are presented compactly in Figure 11.6 by showing target fixations (competitor fixations are essentially complementary) averaged over all correct trials (as the patterns did not change substantially with training). Qualitatively, there is a striking result. There are clear effects of both cohort and rhyme for the TD group sample. The cohort effect is stronger and earlier, as with real words (Allopenna, Magnuson, & Tanenhaus, 1998; Desroches et al., 2006), and the rhyme effect emerges later. Growth curve analysis reveals reliable intercept differences for the TD group (unrelated > rhyme > cohort) analogous to differences in mean proportion over the analysis window. In contrast, the CS group shows a strong cohort effect, but not even a hint of a rhyme effect. This pattern is confirmed by assessing intercepts (unrelated ≈

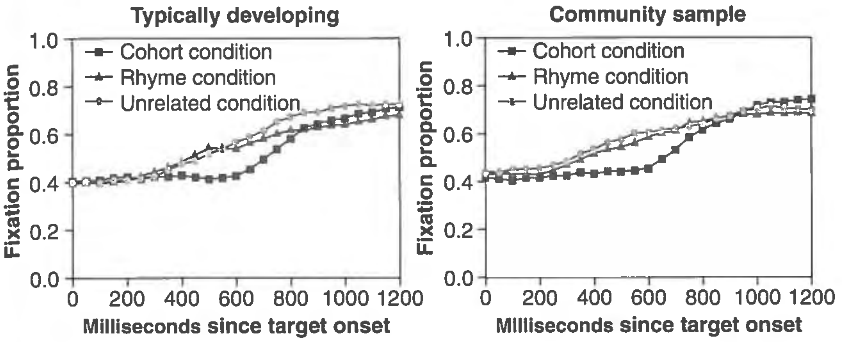

Figure 11.6. Target fixation proportions over time in Experiment 2, collapsed across block and only including correct trials, averaged over all 8 blocks. (Left) Typically developing (TD) group; (right) community sample (CS) group. These patterns of results were apparent from the first training/testing block.

Our results are consistent with those of Desroches et al. (2006), who reported an absence of rhyme effects in children with dyslexia using a similar eye tracking paradigm with familiar, real words. They are not consistent with the recent report of McMurray et al. (2010) that indicates that adolescents with SLI show larger but later competition effects than typically developing peers. We again turned to the model in order to explore possible bases for such a pattern.

Computational Modeling

As with Experiment 1, we explored the pattern of results using the jTRACE model. Because TRACE is not a learning model (although see the Hebbian version of TRACE developed by Mirman, McClelland, & Holt, 2006), we treated TRACE as a model of the stabilized system at the end of learning. Again, we changed one parameter at a time, looking for a change that would leave the magnitude and timing of the cohort effect intact, ideally while wiping out the rhyme effect. We again tried several parameters. Here we summarize the most theoretically interesting ones.

Generalized slowing (feed-forward gain) does not work; it changes timing but does not wipe out rhyme effects. Fuzzing phonology by adding input or internal noise tends to boost both competition effects. Lexical decay does not selectively affect rhyme effects. Reducing lexical lateral inhibition does not work; it actually boosts rhyme effects. *Reducing phoneme lateral inhibition does work* and is the only parameter that can induce the correct change in model performance. It does not completely wipe out rhyme effects, but comes close, while leaving the cohort time course intact. This is a counterintuitive outcome, but it follows from what happens to phonemes other than the initial phoneme of the target word. In general, with inhibition reduced, similar phonemes get much more active because they receive less inhibition from though the phoneme inhibition parameter is lower, there is actually greater inhibitory flow at the phoneme level—because so many more phonemes remain active, the total inhibition in the system increases. This greater total inhibition puts rhymes at even greater disadvantage than under the standard phoneme inhibition parameter setting.

Interestingly, lateral inhibition at the phoneme level was one of two parameters that could achieve the correct pattern to fit the CS group behavior in Experiment 1. The other was lexical inhibition, but this cannot capture the pattern of Experiment 2. We return to this in the general discussion section following the summary of this experiment.

Summary

In Experiment 2, we found that a sample with a high proportion of poor readers achieved final accuracy levels similar to a TD comparison group. However, the time course of learning was substantially different, with slower learning in early trials. A comparison of phonological competition effects using fixation proportions over time revealed that the poor readers showed similar onset (cohort) competition effects to the TD comparison group, but failed to exhibit an effect of rhyme competition. This result replicates a report that children with dyslexia did not exhibit rhyme effects in a similar study (Desroches et al., 2006). In computational modeling with TRACE, the only way to substantially reduce rhyme effects without perturbing cohort (onset) effects was to reduce lateral inhibition at the phoneme level, which was one of the parameter manipulations that allowed the model to capture the enhanced subcategorical mismatch effects observed in Experiment 1.

GENERAL DISCUSSION

We found clear evidence that low-ability adult readers continue to differ from typical peers in phonological processing. Our sample with a high proportion of poor readers showed substantially *larger* sensitivity to misleading coarticulation than typical peers in Experiment 1. The sample learned new words with a different trajectory than typical peers in Experiment 2 and failed to exhibit rhyme competition effects. At the same time, they did not appear to differ in the timing of initial lexical access (e.g., signal driven differences in fixation proportions emerge for university and community samples at virtually identical lags relative to target onsets in Figures 11.3 and 11.6).

The two primary patterns of differences—enhanced competition due to misleading coarticulation and absence of rhyme effects—can be modeled in TRACE in only one way: reduced lateral inhibition at the phoneme level. What conclusions can be drawn from this convergence of modeling results? First, we do not wish to imply that we believe that discrete representations of phonemes in the brain necessarily exist, let alone that there is a discrete parameter controlling lateral inhibition at that level. The ability of TRACE to simulate differences based on reduced phoneme inhibition instead points to the level of phonological organization in the dynamical system it is meant to simulate; that is, the mechanisms underlying human word recognition.

It is crucial to note that although adding noise (for example) to TRACE did not succeed in simulating the correct patterns, this result does not mean that adding noise would not succeed in another modeling framework. Instead, our simulations identify the organizational level of the system—sublexical phonological organization—that appears to be crucially different in poor readers. It is also important to note that our results are potentially consistent with any form of the phonological deficit hypothesis, although they somewhat favor accounts that assume typical phonetic resolution (that is, their phonological representations allow at least equal sensitivity to subphonemic phonetic detail, given the results of Experiment 1) and differences in the stability of phonological representations.

In particular, our results may be compatible with the phonological access hypothesis proposed by Ramus and Szenkovits (2008). Direct manipulations of representational quality in the TRACE model (e.g., adding noise) did not capture the subtle differences in the (millisecond-scale) time course of lexical activation and competition we observed in our lower ability readers in both experiments. Instead, we were able to simulate the patterns observed in Experiments 1 and 2 by changing the dynamics and stability of the phoneme level in TRACE (via reduced inhibition). The convergence on phoneme inhibition in the simulations of Experiments 1 and 2 increases our confidence that we may be on the right track. One next step will be to use the reparameterized model to generate predictions for the community sample in other tasks.

One could easily construe reduction of phoneme inhibition as a change in the dynamics of phonological access and therefore as consistent with the phonological access hypothesis. However, our results also suggest that differences in phonological access may be more subtle than suggested by Ramus and Szenkovits (2008), who emphasize the (specifically verbal) executive demands implied by difficulties in tasks tapping into phonological awareness, verbal short-term memory, and speed of lexical access. The fact that we observed differences in the time course of lexical activation, competition, and learning in poor adult readers in minimally demanding, naturalistic tasks suggests that the locus of the phonological deficit may be a low-level property of the system that requires either difficult or sensitive tasks to be detected. This possibility requires further testing. Our next step will be to use an individual-differences approach to examine these issues in both a larger community sample and samples of university students, both in conventional statistical modeling of individual differences and computational modeling (finding specific model parameterizations for each participant and then generating individual-specific predictions for other tasks. Compare the participant-based modeling approach of Ziegler et al., 2008).

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