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The time course of phonological coding during reading

A dissertation submitted in partial satisfaction of the requirements for the degree

Doctor of Philosophy

in

Psychology

by

Mallorie Leinenger

Committee in charge:

Professor Victor Ferreira, Chair
Professor David Barner
Professor Sarah Creel
Professor Rachel Mayberry
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2016

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Chair

University of California, San Diego

2016

DEDICATION

I dedicate my dissertation work to my parents for giving me the support and encouragement I needed to get to where I am today, to Jeremy for sharing in this adventure with me, and to Keith for inspiring my future pursuits.

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Chapter 2, in full is currently being prepared for submission for publication of the material. The dissertation author was the sole investigator of this paper.

Chapter 3, in full is currently being prepared for submission for publication of the material. The dissertation author was the sole investigator of this paper.

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- Leinenger, M.** (2014). Phonological coding during reading. *Psychological Bulletin*, 140, 1534-1555.
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ABSTRACT OF THE DISSERTATION

The time course of phonological coding during reading

by

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Doctor of Philosophy in Psychology

University of California, San Diego, 2016

Professor Victor Ferreira, Chair

There are two potential routes to identifying written words; meanings can be “looked up” directly based on written forms, or written forms can be recoded into phonological (sound-based) codes and used to access the meanings of words. The direct route is assumed to be faster, yet skilled readers still generate phonological codes. In this dissertation I investigated how rapidly skilled readers generate phonological codes and whether they use them to identify the meanings of words. Measuring the time course is important because only rapidly generated codes could actually be used to identify words.

In Study 1, I conducted survival analyses of eye movement data to determine how early skilled readers generate phonological codes. Results suggest that readers

rapidly generate phonological codes, and that earlier code generation is associated with faster word identification—suggesting that skilled readers use phonological codes to identify the meanings of words.

In Study 2, I investigated which underlying language skills were predictive of early phonological code use. The rapidity with which readers generated phonological codes was not related to general reading skill, but instead to phonemic decoding ability specifically. Furthermore, the rapidity with which a given reader generated phonological codes was more predictive of word identification speed among highly skilled phonemic decoders and readers with lower general reading skill, suggesting that readers with different language skills might adjust their reliance on the different routes to meaning as their skills allow.

Finally, in Study 3, I investigated phonological coding in profoundly deaf readers. Results suggest that skilled deaf readers can generate phonological codes and may use them to identify the meanings of words. As with hearing readers, there was a high degree of subject variability in the time course, yet all of the subjects were very efficient readers, suggesting that readers may adopt different strategies for or rely more heavily on different routes to meaning.

Together, these studies demonstrate that the cognitive system is flexible and adaptive, and the processes associated with word identification can be adjusted to a given reader's individual set of language skills to maximize the efficiency of word recognition during reading.

CHAPTER 1:
INTRODUCTION

When a child approaches the task of learning to read, he or she is generally already a skilled user of a spoken language, with a vocabulary of at least a couple thousand words (individual estimates for 5-7 year old children range from 2,500 words to more than 10,000 words, see Anglin, Miller, & Wakefield, 1993 for a review). Luckily, written languages, particularly alphabetic languages, are designed to recreate the speech stream that they represent. Instead of facing the daunting task of memorizing associations between seemingly arbitrary strings of letters and the spoken words that they already know, the task becomes much easier if the child is able to discover and use the alphabetic principle—the understanding that words are made up of letters and that these letters map onto specific sounds (for a discussion see Rayner, Pollatsek, Ashby, & Clifton, 2012). Although most alphabetic languages only roughly approximate the alphabet principle, it nonetheless provides the beginning reader with a valuable tool. If they can learn the relatively small number of grapheme-to-phoneme (i.e., letter-to-sound) correspondences that their written language is built on, they can use that knowledge to decode any novel word into its spoken form (e.g., Jorm & Share, 1983; Share, 1995; 2008). Termed the *sine qua non* of reading acquisition, the ability to phonologically decode a novel written string (i.e., recode the written word into a sound-based code), allows a developing reader to identify any unknown written word by translating into its spoken counterpart (i.e., sounding it out; Share, 1995). Furthermore, through repeated encounters with the same written words, the child is thought to acquire word-specific orthographic knowledge, eventually developing direct connections between a

word's meaning and its written form (de Jong, Bitter, van Setten, & Marinus, 2009; Jorm & Share, 1983; Share, 1995; 2008).

Once these direct connections are established between orthography and meaning, and the reader becomes more skilled, what is the continued role for phonological coding? Clearly even a skilled reader might fall back on their decoding abilities when they encounter very rare (i.e., low frequency) words or novel words (e.g., Waters, Seidenberg, & Bruck, 1984), but do they still rely on phonological coding to help them identify the meanings of more common, higher frequency words as well? Answers to this question are still debated despite over a century of research (for reviews see Leinenger, 2014; McCusker, Hillinger, & Bias, 1981). Indeed, over two decades ago, Seidenberg and McClelland speculated that this was, “probably the single most widely studied question in reading research (1989, p. 559). Although there appear to be clear roles for phonological coding for the purposes of maintaining word order in short term memory, connecting meanings across sentences, and comprehending discourse (e.g., Baddeley, Eldridge, & Lewis, 1981; Daneman & Newson, 1992; Levy, 1978; Slowiaczek & Clifton, 1980), whether or not phonological codes also aid word identification in skilled readers is unclear. Answering this question requires determining whether phonological codes are generated rapidly using grapheme-to-phoneme correspondence rules (i.e., *assembled* codes) or instead if they only come online after a word is identified directly (i.e., on the basis of its orthography) and its associated phonology is made available (i.e., *addressed* codes). In other words, a parallel question is: do skilled

readers assemble phonological codes (via grapheme-to-phoneme correspondences) to help them identify words or instead rely on direct associations between orthography and meaning?

Models of word identification during reading.

Extant models of word identification implement these two routes to meaning, however because of differing architectures, they vary in the extent to which they predict skilled adult readers should rely on each route. In the dual-route cascaded model (DRC; e.g., Coltheart, 1978; Coltheart, Curtis, Atkins, & Haller, 1993; Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; see Coltheart, 2000 for a discussion of the distinction between the more well-known dual-route model of reading aloud and the dual-route model of reading for meaning), the direct and indirect routes to meaning perform their computations somewhat independently, and (once built up) the direct route is generally thought to be more efficient. Therefore, it is the primary route used by skilled readers to access the meanings of most words. On the other hand, in the parallel-distributed processing model (PDP; Harm & Seidenberg, 2004; Seidenberg & McClelland, 1989) both routes accrue activation in parallel to mutually inform the activation of semantic representations for most words. Under this model, the meanings of most words are computed by combined activation from both routes, however the relative contributions from each route can vary. Therefore, when considering word identification in skilled readers, the PDP model assumes that the indirect route (and therefore assembled phonology) is contributing to the identification of most words, whereas the DRC

model assumes only a limited role for the indirect route. Said another way, the PDP model assumes that assembled phonology is often contributing to the identification of most words (e.g., Harm & Seidenberg, 2004), whereas the DRC model assumes that most words are identified on the basis of orthography alone (e.g., Coltheart, 1980), therefore paralleling the larger debate surrounding the role of phonology in skilled reading.

Methods for studying phonological coding.

For phonological codes to be implicated in word identification, they must necessarily be generated rapidly. Therefore, answering the question, *do readers use phonological codes to identify the meaning of words*, requires a dependent measure sensitive enough to reveal fine-grained time course information. Unfortunately, many of the methods that have been used to study phonological coding are not sensitive enough to provide fine-grained time course information. Tasks such as semantic categorization, naming, lexical decision, and word identification, all rely on recording downstream responses, so while these tasks can reveal an influence of phonological coding, it is impossible to determine how early the phonological codes that gave rise to the effect were generated (for a discussion see Leinenger, 2014).

More sensitive measures, such as eye tracking and neurophysiological recording have provided stronger evidence for the early generation of phonological codes. Readers are less likely to notice (at least initially) or be disrupted by homophonic errors embedded in text than orthographic control errors (e.g., Inhoff & Topolski, 1994; Jared, Levy, & Rayner, 1999; Rayner, Pollatsek, & Binder, 1998), and

there is even evidence that readers can begin to generate phonological codes for an upcoming word before they directly fixate it (e.g., Miellet & Sparrow, 2004; Pollatsek, Lesch, Morris, & Rayner, 1992). Results from neurophysiological recording (e.g., event-related potentials (ERP) and magnetoencephalography (MEG)) suggest a very early time course for phonological coding, with differential processing emerging within 80-125 ms in the ERP and MEG record (e.g., Ashby, 2010; Ashby, Sanders, & Kingston, 2009; Cornelissen, Kringelbach, Ellis, Whitney, Holliday, & Hansen, 2009; Wheat, Cornelissen, Frost, & Hansen, 2010). These results were obtained measuring the processing of single-word stimuli rather than connected text, but it suggests that the time course of phonological coding during normal reading might be similar.

In this dissertation, I investigate the time course of phonological coding during normal, silent reading, addressing the following questions: How early are phonological codes generated during normal silent reading (Study 1)? What reading skills are (and are not) associated with early phonological code generation (Study 2)? Are phonological codes generated rapidly among skilled deaf readers who do not have full access to the phonology of the language in which they read (Study 3)?

Eye movements as an index of cognitive processing during reading.

When someone is reading, where they look and how long they spend looking there are good indexes of what word they are currently attending to and how easy or difficult it is to process, respectively (see Rayner, 1998, 2009). Furthermore, the duration of a given fixation reflects not only how difficult the visual stimulus is to

process (e.g., if it is degraded in some way or printed in a strange font), but also the cognitive processes underlying language processing. Indeed, fixation durations increase when reading words that are less common (i.e., lower frequency), less predictable, more ambiguous, etc. Because eye movements reflect online processing without requiring any overt response from subjects, all studies reported here use eye movement behavior as the dependent measure to assess the influence of phonological processing during reading.

Survival Analyses to estimate the earliest observable effect of a manipulation.

Although eyetracking during the silent reading of sentences and discourse provides a sensitive, on-line measure of cognitive processing, fixation durations include not only the time it takes for lexical processing, but also the time it takes to program and execute an eye movement (a minimum of 100-150 ms). Therefore, for an average fixation of 250 ms, lexical variables that affect when the eyes move (and therefore the duration of a given fixation) must actually be exerting their influences within the first 100-150 ms, even though these effects aren't observed behaviorally until the eyes move (Sereno & Rayner, 2000). Therefore, analyses of mean fixation durations alone cannot reveal the earliest influences of phonological coding on the eye movement record.

Even though the majority of eye movement research relies on analyses of means, distributional analyses of eye movement measures have also been used to characterize patterns of fixation data (e.g., ex-Gaussian analyses; Balota & Yap, 2011; Staub, White, Drieghe, Hollway, & Rayner, 2010). One type of distributional

analysis, a survival analysis, has recently been adapted to eye movement measures as well, and has the advantage of being able to reveal the earliest discernible influence of a manipulation on eye movement behavior (Reingold, Reichle, Glaholt, & Sheridan, 2012; Reingold & Sheridan, 2014). Because determining whether phonological codes are implicated in word identification requires determining how early they are generated, all studies reported here conduct survival analyses of eye movement data to reveal the earliest observable effect of phonological coding. Furthermore, survival analyses were conducted on individual subject data to provide an estimate of the time course of phonological code generation for each subject.

Study 1

In study 1, I investigated how early readers generate phonological codes during silent reading. In Experiment 1, I recorded eye movements while subjects read target words (e.g., *beach*), phonologically related words (e.g., *beech*), and orthographic control words (e.g., *bench*) embedded in sentences. I used survival analyses to compare the processing of the phonologically related and orthographic control words to determine the earliest observable influence of phonological coding. An early time course would suggest that readers generate phonological codes prior to word identification (i.e., via grapheme-to-phoneme correspondences) and that phonological codes could be used to aid word identification.

The lexical nature of the stimuli used in Experiment 1 left open the possibility that readers could have identify words via the direct route, and effects of

phonology might have actually reflected addressed phonology that was retrieved after successful word identification. To avoid this confound, in Experiment 2, phonologically related and orthographic control words were replaced with pseudohomophones (e.g., *sleap*) and orthographic non-word controls (e.g., *slerp*) of different targets (e.g., *sleep*). Because non-words are novel, readers should not be able to identify such words via the direct route. Instead, differences in processing should reflect the use of assembled phonological codes, and easier processing of the pseudohomophone relative to the orthographic control would suggest that readers are using assembled phonological codes to identify the meaning of words.

Experiments 3 and 4 investigated how early purely parafoveally acquired phonological codes exert an influence on eye movement behavior using the gaze-contingent boundary paradigm (Rayner, 1975). In the boundary paradigm, an invisible boundary is inserted to the left of the target word, which is used to trigger a display change when a reader saccades past the boundary to fixate the target location. In these studies, the phonologically related and orthographic control (non-) words were presented as parafoveal *previews* for the correct target words. Differences in fixation durations on the correct target across different preview conditions are thought to reflect processing that occurred prior to fixation (i.e., when the preview word was still in the parafovea). Prior research has demonstrated that readers can begin to extract phonology from the parafovea (e.g., Mielliet & Sparrow, 2004; Pollatsek et al., 1992), but the specific question addressed in Experiments 3 and 4 is how early can purely parafoveally extracted phonological

codes influence behavior, and whether this time course is different than the estimate from Experiments 1 and 2. Similar time courses across all experiments would suggest that the locus of the effect was always parafoveal in nature.

Study 2

Prior research has suggested that the early generation of assembled phonological codes might be related to general reading skill, although the direction of the relationship is debated. Some evidence suggests that the rapid generation of phonological codes is associated with lower reading skill (e.g., Jared et al., 1999), other research suggests that it is associated with higher reading skill (e.g., Binder & Borecki, 2008; Chace, Rayner, & Well, 2005; Majeres, 2005), and still other research suggests that there is no relationship between reading skill and the early use of phonological codes (e.g., Daneman & Stainton, 1991; Jared, Ashby, Aquas, and Levy, 2016). These different results suggest that the relationship between reading skill and the time course of phonological code generation might be more nuanced. Potentially, the early generation of phonological codes is not related to reading skill in general, but instead related specifically to phonemic decoding ability (i.e., the ability to rapidly decode letter strings).

To explore this possibility, in Study 2 I measured readers' general reading skill (reading comprehension ability and vocabulary) as well as their specific phonemic decoding ability. I also recorded readers' eye movements as they read a subset of the materials used in Experiments 1 and 2 of Study 1, so that the values obtained from the individual subject survival analyses could be related to the

measures of general reading skill and phonemic decoding ability. Positive correlations between either skill measure and individual estimates of phonological coding would suggest that more skilled readers generated phonological codes later, whereas negative correlations would suggest that the early generation of phonological codes was associated with higher reading skill. Finally, I related the time course of phonological coding to eye movement measures thought to index word identification speed (i.e., gaze duration), to determine the degree to which different groups of subjects rely on phonological codes to help them identify words.

Study 3

There has been considerable debate as to whether or not deaf readers, who do not have full access to the phonology of the language in which they read, generate phonological codes during reading. In Study 3, I investigated whether deaf native signers, who are skilled readers of English, rapidly generate phonological codes during reading. In Experiment 1, subjects read the same materials used in Experiment 1 of Study 1, and survival analyses were used to determine how rapidly they generated phonological codes. In Experiment 2, subjects read the same materials used in Experiment 2 of Study 1 (i.e., the non-word stimuli), so that any effects of phonology could be attributed to assembled phonological codes. An early time course would suggest that deaf readers do generate phonological codes prior to word identification (i.e., via grapheme-to-phoneme correspondences) and that phonological codes may be used to aid word identification even in this population. A late time course, or no difference between processing of the phonologically related

and orthographic control (non-) words would suggest that deaf readers do not rely on phonological codes for word identification.

Summary

Together, the following studies address the questions of how early phonological codes are generated during reading, whether skilled readers use phonological codes to help them identify the meanings of words, and if the time course of phonological coding varies as a function of reading skill or language background and experience. In Study 1 I investigate how early phonological codes are generated during normal silent reading. In study 2 I investigate which reading skills influence the time course with which readers generate phonological codes or the degree to which they use phonological codes to help them identify words. In study 3 I investigate how early deaf readers generate phonological codes during reading and whether they use phonological codes to help them identify the meaning of words.

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CHAPTER 2:
SURVIVAL ANALYSES OF EYE MOVEMENT DATA REVEAL THE TIME COURSE OF
PHONOLOGICAL CODING DURING READING

Abstract

Numerous studies have provided evidence that readers generate phonological codes while reading. However, a central question in much of this research has been how early these codes are generated—more specifically, whether the codes are generated pre-lexically or if they instead only come online after lexical access. Answering this question has implications for the roles that phonological coding might play, especially whether it is implicated in the process of lexical access, which can only be the case if these codes are generated rapidly and pre-lexically. To investigate the time course of phonological coding during silent reading, the present series of experiments examined survival analyses of first-fixation durations on phonologically related (homophones, pseudohomophones) and orthographic control (orthographically matched words and non-words) stimuli embedded in sentences in place of correct targets. Experiments 1 and 2 measured reading times when the phonologically related and control stimuli were embedded in sentences and Experiments 3 and 4 used the boundary paradigm to present the phonologically related and orthographic control stimuli as parafoveal previews for correct target words. Survival analyses revealed a significant influence of the homophone versus orthographic control word manipulation as early as 173 ms from the start of fixation (170 ms in the display change experiment) and a significant influence of the pseudohomophone versus orthographic control non-word manipulation as early as 161 ms from the start of fixation (160 ms in the display change experiment). The fact that the time course for phonological coding was similar regardless of lexical

status suggests that the early effects are due to the generation of pre-lexical, assembled phonological codes.

The exact role that phonological coding (the recoding of written, orthographic information into a sound based code) plays during silent reading has been extensively studied for more than a century. Despite the large body of research surrounding the topic, varying theories as to the time course and function of this recoding still exist (for reviews see Leinenger, 2014; McCusker, Hillinger, & Bias, 1981). A wealth of research on the topic has been concerned with whether or not phonological coding precedes lexical access and can in fact be implicated in the process of lexical access. In other words, there has been considerable interest in determining whether phonological codes are rapidly generated from grapheme-to-phoneme mapping rules (*assembled phonology*) or instead retrieved from the lexicon through the orthographic representation of the printed word (*addressed phonology*). The former route is one in which phonological codes are generated pre-lexically and can in fact aid lexical access, whereas the latter route is a direct mapping from orthography to the lexical entry and phonological codes can only come online once the correct lexical entry has been accessed and the associated phonological representation retrieved.

For phonology to be implicated in the process of lexical access, phonological codes must necessarily be generated rapidly, prior to lexical access. As such, measuring the time course of phonological code generation could help illuminate the roles that phonological coding might serve—that is, if codes are generated early, they may in fact be implicated in lexical access, whereas if codes come online more slowly, they likely only support post-lexical processes (e.g., short term memory,

comprehension). Unfortunately, much of the research regarding phonological coding has used tasks that are not well suited to producing fine-grained time course information (for a discussion see Leinenger, 2014). Tasks such as semantic categorization, naming, lexical decision, and word identification all rely on recording later response time measures, so while these tasks can reveal an influence of phonological coding, it is impossible to tell how early phonological codes are generated and even if the codes are generated pre- or post-lexically.

Stronger evidence for the early (pre-lexical) generation of phonological codes has come from research using eye tracking and electrophysiological recording to measure online processing during reading. First, data from normal reading studies revealed that readers are less likely to notice (at least initially) or be disrupted by homophonic errors—words that are pronounced the same, but differ in spelling and meaning—embedded in texts than by orthographically matched control errors. Furthermore, this is the case both for both real word homophone errors (e.g., *beech* in place of *beach*—*They went swimming at the beech.*), and non-word pseudohomophone errors (e.g., *sleap* in place of *sleep*—*The insomniac couldn't get to sleap.*) compared to orthographically matched controls (e.g., *bench* and *slerp*, respectively—e.g., Inhoff & Topolski, 1994; Jared, Levy, & Rayner, 1999; Jared & O'Donnell, under review; Rayner, Pollatsek, & Binder, 1998). Indeed, the fact that this effect holds not only for homophone errors but also for pseudohomophone errors further suggests a pre-lexical influence. Homophone errors could be missed due to either the assembling of phonological codes pre-lexically or the retrieval of

addressed phonological codes post-lexically, but pseudohomophone errors should only be missed if codes are assembled pre-lexically, since they have no representations in the lexicon from which to retrieve their phonological codes.

Further evidence for early, pre-lexical codes comes from studies using the invisible boundary paradigm (Rayner, 1975) to manipulate the types of information that readers get either before directly fixating a word (e.g., parafoveal preview studies), or immediately after fixating a word (e.g., fast-priming studies). In both paradigms, an invisible boundary is inserted to the left of the target word, which is used to trigger a display change when a reader saccades past the boundary to fixate the target location. In fast-priming studies (Sereno & Rayner, 1992), crossing the invisible boundary triggers the brief presentation of a prime word (e.g., for 30-60 ms), which is then replaced with the target word. Evidence from fast priming with phonologically related primes suggests that phonological code generation can begin within 30-40 ms of fixating a word. That is, phonologically related primes presented for as little as 30-40 ms provide significant target facilitation, measured as shorter gaze durations on the subsequently presented target word (e.g., H.-W. Lee, Kambe, Pollatsek, & Rayner, 2005; H.-W. Lee, Rayner, & Pollatsek, 1999; Y.-A. Lee, Binder, Kim, Pollatsek, & Rayner, 1999; Rayner, Sereno, Lesch, & Pollatsek, 1995). Because the locus of this effect is so early (i.e., differences in processing of the prime must begin to emerge within 30-40 ms), it seems likely that this effect is due to the early assembly of phonological codes. However, pseudohomophone primes presented for similar durations do not consistently facilitate processing of the target, leading some

to conclude that the fast-priming effect is in fact lexical in nature (i.e., dependent on addressed phonological codes), and that assembled phonological codes come online slightly more slowly than addressed phonological codes (H.-W. Lee et al., 2005; Y.-A. Lee et al., 1999). However, in parafoveal preview studies, both homophones and pseudohomophones result in significant *preview benefit*—faster processing of a target word following a phonologically related preview than an orthographic control preview—providing evidence that readers can begin to generate phonological codes (presumably whether assembled or addressed) prior to actually fixating a word (i.e., when it is still in the parafovea—e.g., Miellet & Sparrow, 2004; Pollatsek, Lesch, Morris, & Rayner, 1992). Furthermore, the results of Henderson, Dixon, Petersen, Twilley, and Ferreira (1995) suggest that the nature of this parafoveal preview benefit effect is due to the assembly of phonological codes, as effects are greater for words with regular initial trigrams (for which phonological codes can be assembled) than for words with irregular initial trigrams (for which assembled codes might prove to be incorrect). Finally, results from eye tracking and neurophysiological recording (e.g., event-related potentials (ERP) and magnetoencephalography (MEG)) converge in support of an early time course for phonological processing during silent reading, with differential processing emerging between 80-125 ms in the ERP and MEG record during the reading of single words (Ashby, 2010; Ashby, Sanders, & Kingston, 2009; Cornelissen, Kringelbach, Ellis, Whitney, Holliday, & Hansen, 2009; Wheat, Cornelissen, Frost, & Hansen, 2010) and

as early as the first fixation on a word during normal, silent reading (e.g. Slattery, Pollatsek, & Rayner, 2006).

While these later results provide evidence for an early locus of phonological effects during reading, the exact time course remains somewhat unclear. Results of fast-priming studies suggest that codes can begin to be generated quite rapidly for word stimuli, but that code generation for non-word stimuli (which require the assembly of phonological codes) might be somewhat delayed. On the other hand, it is clear that codes for both words and non-words can begin to be generated parafoveally (i.e., quite early and before direct fixation), but unfortunately using traditional means analyses, even these early effects cannot actually be measured in the eye movement record until a subject terminates his or her fixation on the target word. In other words, although the phonological coding for word n begins when the reader is still fixating word $n-1$ (i.e., through parafoveal preview), we cannot actually measure the influence of this coding until a reader makes a saccade off of word n , at which point we can measure the duration of their fixation on word n . In other words, any difference in fixation duration on word n as a function of the preview a reader had when they were fixating word $n-1$, doesn't actually manifest until 2 saccades later (unless there is also a difference in the rate of skipping word n as a function of preview). Compounding the matter further, fixation durations on a word include not only the time it takes for lexical processing of that word, but also the time it takes to program and execute an eye movement off of that word (a minimum of 100-150 ms). Therefore, for an average fixation of 250 ms, lexical

variables that affect when the eyes move (and therefore the duration of a given fixation) must actually exert their influences within the first 100-150 ms, even though these effects aren't observed behaviorally until the eyes move (for a discussion see Sereno & Rayner, 2000). This makes it somewhat challenging to draw firm conclusions about the time course of code generation in general, and differences in the time course of necessarily assembled versus potentially addressed code generation more specifically, from traditional means analyses alone.

Furthermore, differences that emerge in mean fixation durations across two conditions could be generated in a number of different ways. Distributions of fixation durations, like other reaction time data, tend to be roughly normal, but with some degree of right skew (since extremely short fixations are rare and limited by oculomotor constraints). These data can be fit well by the ex-Gaussian distribution (Ratcliff, 1979), which results from the convolution of a Gaussian and an exponential distribution, with two parameters corresponding to the normal component (μ and σ , which describe the mean and standard deviation, respectively), and one exponential parameter (τ). Changes to μ represent shifts in the normal component of the distribution, whereas changes in τ reflect the degree of skew. If readers have longer fixation durations on a control word than a phonologically related word, this could reflect a shift in the entire distribution of fixations on the control word (i.e., an increase in the μ parameter—a shift in the normal component of the ex-Gaussian distribution, see Figure 2.1, left hand panel) or it could reflect a small population of longer fixations in the tail of the orthographic control condition (i.e., an increase in

the τ parameter—the skew of the distribution, see Figure 2.1, right hand panel). The former case represents an earlier influence since both short and long fixations are influenced by the manipulation of frequency, whereas the latter case represents a relatively late effect, driven by a subset of trials in which the reader experienced processing difficulty in the orthographic control condition. Distributional analyses of fixation durations (e.g., ex-Gaussian fitting, survival analyses) have proven useful for distinguishing between these different possibilities and have allowed for investigations into the time course of lexical variables during reading (e.g., Reingold, Reichle, Glaholt, & Sheridan, 2012; Sheridan & Reingold, 2012a,b; Staub, 2011; Staub, White, Drieghe, Holloway, & Rayner, 2010).

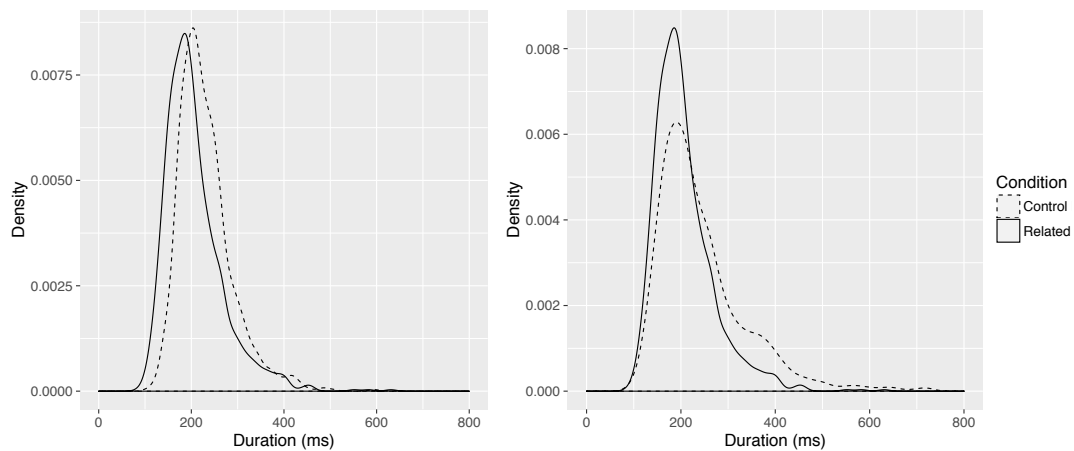


Figure 2.1. Examples of different potential effects on the ex-Gaussian distribution of fixations. In both panels, the solid line represents a sample of 1000 data points from a distribution with ($\mu=150$, $\sigma=25$, $\tau=55$). The dashed line in each panel represents the data obtained from two different hypothetical control conditions. Both panels represent significant effects of the relatedness manipulation on mean fixation duration ($M_{\text{related}} = 206$, $M_{\text{control left}} = 231$, $M_{\text{control right}} = 244$; both $ps < .001$). The manipulation in the left hand panel produces only a change in the μ parameter (1000 samples from a distribution with $\mu=175$, $\sigma=25$, $\tau=55$) and the manipulation in the right hand panel produces only a change in the τ parameter (1000 samples from a distribution with $\mu=150$, $\sigma=25$, $\tau=100$).

While ex-Gaussian fitting can reveal information about which parameters are affected by a given manipulation, survival analyses are able to provide an estimate of the earliest observable influence of a manipulation on behavior (e.g., Reingold et al., 2012, Reingold & Sheridan, 2014). Survival analyses compare the percentage of fixations on a target word still “surviving” at any time point t across two conditions. Adapted from the medical literature, a “surviving” fixation is one that has not yet been terminated (i.e., it has not been ended by a reader making a saccade off of the target word). Specifically, for a given time t , the survival percentage is calculated as the percentage of fixations with a duration greater than t . Thus, at $t=0$, the survival percentage is 100 (since all fixation duration are greater than zero), and as t increases the percent survival decreases, eventually approaching zero as t approaches the duration of the longest fixation in a given condition. Comparison between the survival curves of two conditions allows for computation of the *divergence point*—the earliest point in time at which the curves for the two conditions begin to significantly diverge (see Figure 2.2). The divergence point then provides an estimate of the earliest observable influence of a manipulation on the eye movement record.

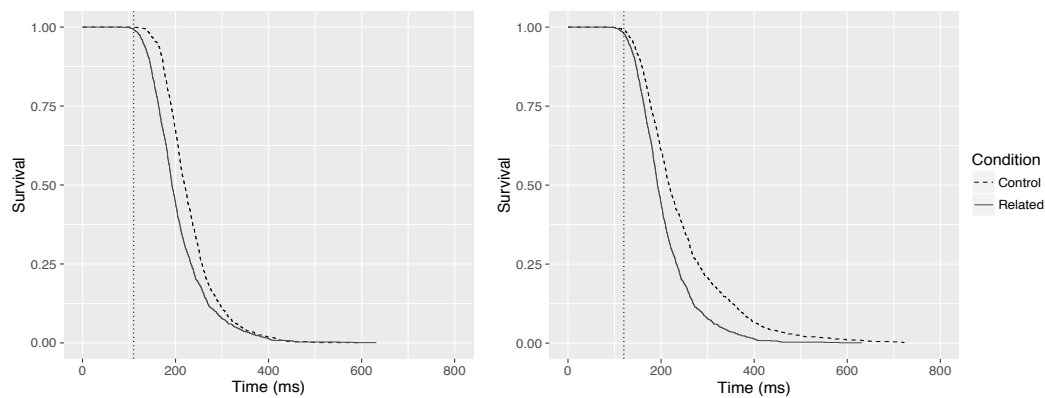


Figure 2.2. Examples of survival curves for the same data presented in Figure 2.1. In both panels, the solid line represents a sample of 1000 data points from a distribution with ($\mu=150$, $\sigma=25$, $\tau=55$). The dashed line in each panel represents the effect of two hypothetical control conditions. The dashed line in the left hand panel represents 1000 data points sampled from a distribution with $\mu=175$, $\sigma=25$, $\tau=55$, and the dashed line in the right hand panel represents 1000 data points sampled from a distribution with $\mu=150$, $\sigma=25$, $\tau=100$. The vertical dotted line in each panel represents the divergence point, which is shifted slightly later in the right hand panel.

Using an earlier method for computing divergence point estimates, Feng, Miller, Shu, and Zhang (2001) had subjects read correct targets, homophone errors, or orthographic control errors embedded in short passages. They compared the survival curves of homophones and orthographic control words and found an effect of phonology that became significant by 168 ms—supporting an early locus of phonological effects. However, there are two aspects of their design that may have influenced their results beyond the manipulation of phonological overlap. First, their homophones and orthographic controls were not actually matched on degree of orthographic overlap with the target. Rather, they used a metric to split their items into orthographically similar and orthographically dissimilar target-homophone pairs, and then created either orthographically similar or dissimilar

control words to use as baselines, however the actual degree of similarity was not considered, leading to many cases where the homophone not only had a higher degree of phonological overlap than the orthographic control, but also a higher degree of orthographic overlap (e.g., *cereal-serial-injure*, *hire-higher-mood*, also note that the stimuli sometimes differed in length). Second, they used a limited number of subjects and items, potentially reducing their power to detect the true earliest influence of phonology. This suggests that further research is needed to ensure that their divergence point estimates are accurate. It could be that their divergence point estimates were artificially early, reflecting not only the effect of phonological coding, but also the differences in the degree of orthographic overlap between the homophones and control words (i.e., capturing the generally earlier emerging effect of orthography—e.g., Grainger, Kiyonaga, & Holcomb, 2006). Alternatively, it could be that their divergence point estimates were actually somewhat delayed from the true earliest observable difference due to their relatively low power (indeed their survival curves visually diverge before a true divergence point is detected statistically).

To more precisely characterize the time course of phonological coding in the eye movement record, the current series of experiments conducted survival analyses of first fixation durations following the method outlined in Reingold and Sheridan (2014). This survival analysis technique was selected because of its ability to provide an estimate of the earliest observable effect of a manipulation on behavior and because it has been used successfully to investigate the time course of

other lexical variables during reading such as lexical ambiguity (Sheridan & Reingold, 2012a), word frequency (Reingold et al., 2012), word predictability (Sheridan & Reingold, 2012b), and indeed phonology (Feng et al., 2001, but using a different survival analysis technique). The current series of experiments has three main aims. First, Experiment 1 was designed to determine how early phonological codes are generated during normal silent reading by conducting survival analyses of first fixation durations on a larger sample of phonologically related words and orthographic control words embedded in sentences. Second, by also conducting survival analyses of first fixation durations on pseudohomophones and orthographic control non-words embedded in sentences, Experiment 2 was designed to determine if the generation of necessarily assembled codes is in fact delayed relative to potentially lexically-derived addressed codes as the results of fast-priming studies have suggested. Finally, Experiments 3 and 4 were designed to compare the time course of phonological code generation obtained in Experiments 1 and 2 with the time course of purely parafoveally derived code generation, by conducting survival analyses of first fixation durations on target words preceded by phonologically related and orthographic control word (and non-word) previews.

Experiment 1

Method

Participants. Forty-eight undergraduates from the University of California, San Diego, participated in this experiment for course credit or monetary

compensation. All were native English speakers, had normal vision, and were naïve to the purpose of the experiment.

Apparatus. Eye movements were recorded with an SR Research Ltd. Eyelink 1000 eye tracker (sampling rate of 1000 Hz) in a tower setup that restrained head movements with forehead and chin rests. Viewing was binocular, but only the eye movements of the right eye were recorded. Subjects were seated approximately 60 cm away from a 19-inch View-Sonic LCD monitor with a screen resolution of 1280 x 1024 pixels. Text was displayed in black, 14-point, fixed-width Consolas font on a white background. Sentences were always displayed in the center of the screen in one line of text, and approximately 4 characters subtended 1° of visual angle.

Materials. 56 heterographic homophone pairs that always shared at least the same initial letter were selected. One member of each pair was designated as the correct target word and the other was designated as the homophone. Additionally, for each homophone pair, an orthographic control word was selected that was as orthographically similar to the correct target as the homophone, but did not fully share phonology. Correct targets, homophones, and orthographic control words were roughly matched on lexical frequency, length, mean bigram frequency (the average bigram count for a particular word), and bigram frequency by position (the sum of the bigram count (by position) for a particular word). Additionally, the homophone and orthographic control were also matched on their degree of orthographic overlap with the correct target. Lexical frequencies (per 400 million) for all stimuli were computed via log-transformed HAL frequency norms (Lund &

Burgess, 1996) using the English Lexicon Project (Balota et al., 2007). Correct targets had an average log frequency of 8.91 (range 3.99 to 13.8), homophones had an average log frequency of 9.01 (range 5.73 to 13.27), and orthographic controls had an average log frequency of 9.21 (range 5.57 to 13.16). All critical words were on average 4.45 letters long (range 3 to 9). Summary statistics for the target words appear in Table 2.1.

Table 2.1. Experiment 1 summary statistics for target words.

	Correct Target		Homophone		Orthographic Control	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Log HAL Frequency (per 400 mil)	8.91	1.94	9.01	1.86	9.21	1.75
Length	4.45	1.08	4.45	1.08	4.45	1.08
Mean Bigram Frequency	1857	869	1979	910	1922	928
Bigram Frequency by Position	1223	636	1291	592	1190	568
Orthographic Overlap			0.6	0.15	0.63	0.14
Cloze Predictability	0.39	0.33				
Sentence Acceptability	6.04	0.58	3.09	0.69	2.85	0.83
Fragment Acceptability	6.03	0.76	2.94	0.74	2.7	0.86

Note. Orthographic overlap refers to the percentage of position specific letters that the homophones or orthographic controls shared with the correct target words (e.g., *made* and *maid* share the first two, or 50%, of their letters in the same positions).

For each set of critical words, three sentences were created that rendered the correct target word somewhat predictable (assessed via the norms described below), resulting in a total of 168 experimental sentences. In this way, for each set of critical words, each subject could read the correct target, homophone, and orthographic control word each in a different sentence and contribute data to all three conditions. The type of critical word presented in each sentence was counterbalanced across participants, such that across experimental lists, for every

item, each type of critical word appeared in each of the three sentence frames an equal number of times. The 168 experimental sentences were presented along with 50 filler sentences. Simple comprehension questions appeared after 20 of the filler items, and comprehension accuracy was high (92.9%). Word type (correct target, homophone, orthographic control) was tested within participants, and, because there were three experimental sentences for each target triplet, each participant contributed data to all three conditions for each set of critical words. An example stimulus is shown in (1), with the correct target/homophone/orthographic control word italicized (the full set of stimuli is listed in the Appendix).

(1) The surfers traveled to the word famous *beach/beechn/bench* where the waves were very large.

Normative data. Three types of normative data were collected.

Cloze Task. 30 subjects from the United States, who did not participate in the reading experiment, were recruited through Amazon’s Mechanical Turk service to participate in a cloze norming task (Taylor, 1953) for monetary compensation. This task was used to evaluate the predictability of the target words, and each subject provided data for 1/3 of the items, such that 10 subjects completed each item. This norming task revealed that the sentences were moderately predictable, with (on average) the target word being produced 39% of the time.

Sentence Acceptability. An additional set of 18 subjects from the United States, who did not participate the reading experiment or other norming tasks, were recruited through Amazon’s Mechanical Turk service to participate in a sentence

acceptability rating task for monetary compensation. This task was administered to ensure that the correct target word fit into each sentence frame better than either the homophone or orthographic control words. Each subject rated one version of each of the 168 sentences with the correct target, homophone, or orthographic control word, such that 6 subjects rated each version of a given sentence. The average acceptability scores (on a 1-7 scale) for sentences with the correct target, homophone or orthographic control were 6.04, 3.09, and 2.85 respectively, demonstrating that the correct targets fit better into the sentences than either the homophones ($p < .001$) or orthographic controls ($p < .001$). These norms also revealed that the homophone was rated as more acceptable than the orthographic control ($p = .004$), which was likely due to the fact that homophonic errors are more likely to be mistaken for their homophone counterpart than are matched orthographic control errors (e.g., Daneman & Stainton, 1991; Jared et al., 1999; Jared, Ashby, Agauas, & Levy, 2016; Rayner et al., 1998)

Fragment Acceptability. An additional set of 18 Native English speakers from the United States, who did not participate in other norming tasks or the reading experiment, were recruited through Amazon's Mechanical Turk service to participate in a sentence fragment acceptability rating task for monetary compensation. Although the sentence acceptability-rating task demonstrated that the correct targets fit into the sentences better overall, this task was administered to ensure that the correct target word also fit into each sentence better than either the homophone or orthographic control words at the point it was first read. Each

subject rated one version of each of the 168 sentence fragments up to and including either the correct target, homophone, or orthographic control word, such that 6 subjects rated each version of a given sentence fragment. The average acceptability scores (on a 1-7 scale) for sentence fragments with the correct target, homophone, or orthographic control were 6.03, 2.94, and 2.7 respectively, demonstrating that the correct targets were more acceptable continuations of the sentences than either the homophone ($p < .001$) or orthographic control ($p < .001$) at the point at which they were first read. As with the sentence acceptability norms, these norms also revealed that the homophone was rated as more acceptable than the orthographic control ($p = .006$), which was likely due to the same reason outlined above.

Procedure. Subjects were instructed to read the sentences for comprehension and to respond to occasional comprehension questions using a gamepad to indicate “yes” or “no” responses. At the start of the experiment, the eye-tracker was calibrated with a 3-point calibration scheme. At the beginning of the experiment, subjects received nine practice trials (five of which were followed by a comprehension question) to allow them to become comfortable with the experimental procedure.

Each trial began with a fixation point in the center of the screen (that served as a drift correction), which the subject was required to fixate until the experimenter initiated the trial. Then a fixation box appeared on the left side of the screen, which was located where the beginning of the sentence would appear. Once a stable fixation was detected within the box, the box disappeared and was replaced

by the sentence, which remained on the screen until the subject pressed a button signaling that they understood the sentence and were ready to move on. Order of sentence presentation was randomized for each participant, and the experimental session lasted approximately fifty minutes.

Results

Prior to analysis, fixations under 81 ms were pooled if they were within 1 character of another fixation, as these fixations likely preceded corrective saccades. Consistent with other studies that have examined distributions of fixation durations (e.g., Reingold et al., 2012; Schotter & Leininger, in press; Sheridan & Reingold, 2012), fixations shorter than 81 ms that were further from an adjacent fixation remained in the dataset. All fixations over 800 ms were deleted, as were any trials in which subjects blinked during first-pass reading of the target word, resulting in 4.5% data loss. Additionally, gaze durations longer than 2,000 ms and total times longer than 4,000 ms were excluded. After all exclusions, 95% of the original data was retained for analysis.

Standard reading time measures (Rayner, 1998, 2009) used to investigate the time-course of word processing in reading are reported, including *first fixation duration* (the duration of the first fixation on a word), *single fixation duration* (the duration of the first fixation on a word when a reader makes only one fixation during first-pass reading), *gaze duration* (the sum of all first-pass fixation durations on a word before leaving it), *go-past time* (the sum of all first-pass fixation durations on a word and any fixations on preceding words before going past it to the right),

and *total time* (the sum of all fixation durations on a word including any time spent re-reading it following a regression). In addition, three probability measures are also reported: *fixation probability* (the probability that a word was fixated at least once during first-pass reading), *regression-out probability* (the probability of making a regression out of a word to re-read prior words in the sentence) and *regression-in probability* (the probability of making a regression into a word—i.e., from subsequent words in the sentence).

Table 2.2. Means and standard errors for reading time measures in Experiment 1.

	Identical	Homophone	Orthographic control
Fixation Probability	0.66 (0.009)	0.67 (0.009)	0.67 (0.009)
Single Fixation Duration	226 (1.9)	244 (2.4)	249 (2.5)
First Fixation Duration	225 (1.9)	241 (2.1)	245 (2.3)
Gaze Duration	239 (2.2)	266 (2.8)	276 (3.2)
Go-Past Time	280 (4.2)	325 (5.2)	361 (6.6)
Total Time	272 (3.5)	372 (5.6)	436 (6.6)
Regressions Out	0.07 (.005)	0.1 (.006)	0.12 (.006)
Regressions In	0.12 (.006)	0.26 (.009)	0.36 (.01)

Linear mixed-effects models were fitted using the `lmer` function from the `lme4` package (version 3.2.3; Bates, Maechler, Bolker, & Walker, 2015) within the R Environment for Statistical Computing (R Development Core Team, 2015). Models were fit using the maximal random effects structure justified by the design of the experiment (Barr, Levy, Scheepers & Tily, 2013), which included subjects and items

as crossed random effects.¹ The comparisons between different levels of the fixed effect were specified using the default treatment coding in R, with the mean of the homophone condition represented by the intercept. Regression coefficients (which estimate the effect size (in milliseconds) of the reported comparisons), the standard errors, and the (absolute) *t* values of the coefficients are all reported.

For binary dependent variables (fixation probability data), generalized mixed-effects regression models (GLMMs) were used with a logit link function, and regression coefficients (*b*—which represent effect size in log-odds space), and the (absolute) *z* value and *p* value of the effect coefficient are all reported. Absolute values of the *t* and *z* statistics greater than or equal to 1.96 indicate an effect that is significant at approximately the .05 alpha level. Reading measures on the target word are shown in Table 2.2, results of the LMMs on fixation duration measures are reported in Table 2.3 and results of the GLMMs on fixation probability measures are reported in Table 2.4.

Fixation duration measures. For all reading time measures the correct target was fixated for significantly less time than the homophone (all *ts* > 4.91). Critically, subjects had significantly shorter gaze durations, go-past times, and total times on the homophone than on the orthographic control word (all *ts* > 1.98), suggesting that the homophone was easier to process than the orthographic control

¹ Some models showed convergence failures, in which case random slopes were removed and the results of the first model to converge are reported. In Experiment 1, the random slopes for items in the FFD and GZD models were removed, and the random slopes for subjects and items in the TVT model were removed.

² The divergence point estimates for 7 subjects were deemed unreliable because a divergence point

and was processed more similarly to the correct target than the orthographic control was. Group means for all fixation duration measures appear in Figure 2.3.

Fixation probability measures. There were no differences between either the correct target and homophone or the homophone and orthographic control in the probability of fixation (all $ps > .35$). There was a significant difference in the likelihood of making a regression-out of the critical words, such that subjects were more likely to make a regression out of the homophone than the correct target ($p = .002$), however the rate of regressions out of the homophone and orthographic control did not differ ($p = .3$), suggesting that the correct target was easier to process than either the homophone or orthographic control. Finally, there were also significant differences in the likelihood of making regressions in to reread the critical words, such that subjects were significantly more likely to make a regression into the homophone than the correct target and also more likely to regress into the orthographic control than the homophone (all $ps < .001$), suggesting graded processing, whereby the homophone was easier to process than the orthographic control, but not as easy to process as the correct target.

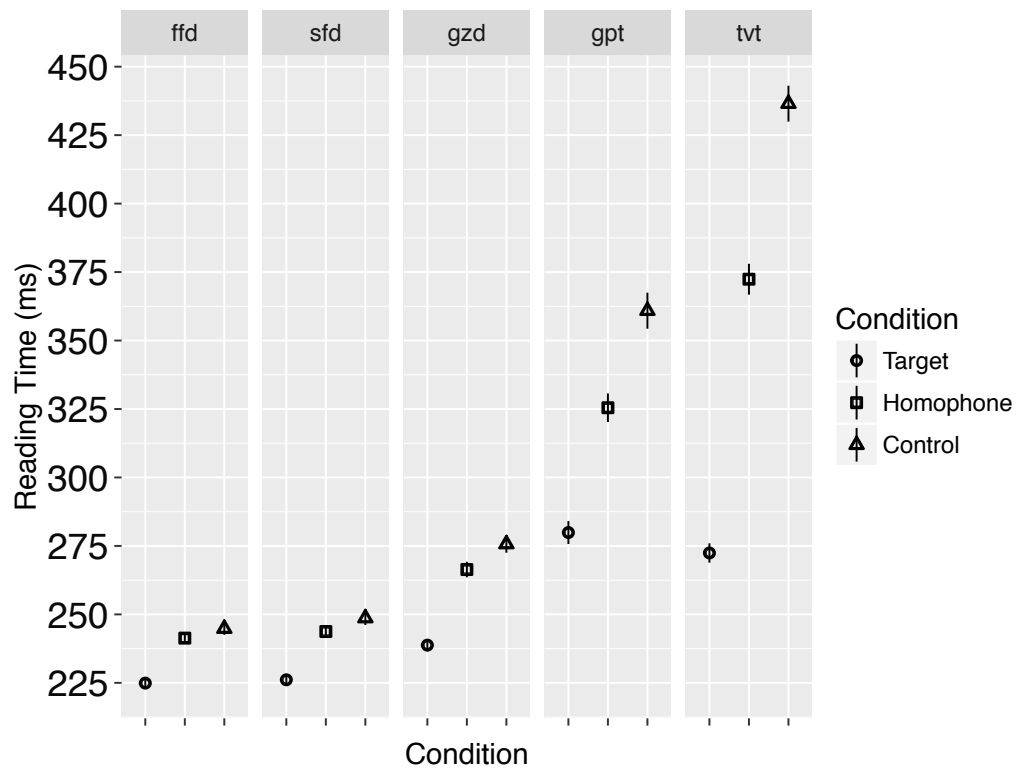


Figure 2.3. Reading time on the target word in Experiment 1 as a function of condition (correct target, homophone, or orthographic control), across 5 reading time measures (ffd = first fixation duration, sfd = single fixation duration, gzd = gaze duration, gpt = go-past time, tvt = total time). Error bars represent +/- 1 standard error of the mean.

Table 2.3. Results of linear mixed effects models for reading time measures on the critical word in Experiment 1. The intercept represents the mean duration for the homophone condition. Significant effects are indicated by boldface.

Measure	Contrast	Model		
		b	SE	t
First Fixation Duration	Intercept	239.44	4.27	56.14
	Correct Target	-16.22	3.30	4.92
	Orthographic control	2.54	2.95	0.86
Single Fixation Duration	Intercept	241.93	4.88	49.62
	Correct Target	-17.56	3.57	4.93
	Orthographic control	4.85	3.50	1.38
Gaze Duration	Intercept	262.17	6.45	40.66
	Correct Target	-26.18	4.72	5.55
	Orthographic control	7.75	3.90	1.99
Go-Past Time	Intercept	320.29	10.07	31.81
	Correct Target	-43.44	8.41	5.16
	Orthographic control	31.48	11.79	2.67
Total Time	Intercept	361.01	15.47	23.34
	Correct Target	-99.57	7.16	13.90
	Orthographic control	66.10	6.94	9.52

Table 2.4. Results of the logistic regression models for fixation probability measures across conditions in Experiment 1. The intercept represents the mean probability for the homophone condition. Significant effects are indicated by boldface.

Measure	Contrast	Model		
		b	z	p
Fixation Probability	Intercept	0.83	6.93	< .001
	Correct Target	-0.03	0.37	0.71
	Orthographic control	0.07	0.91	0.36
Regression-out Probability	Intercept	-2.43	20.18	< .001
	Correct Target	-0.4	3.0	.002
	Orthographic control	0.13	1.03	0.3
Regression-in Probability	Intercept	-1.19	9.15	< .001
	Correct Target	-1.01	8.69	< .001
	Orthographic control	0.52	5.65	< .001

Survival Analyses. Means analyses revealed a difference between the processing of the homophone and orthographic control word as early as the gaze duration on the critical word. While this difference is suggestive of an early locus of phonological influence during lexical access (since gaze duration is thought to roughly index lexical access), it is also possible that the difference was driven by a small subset of long fixations in the orthographic control condition. Therefore survival analyses were conducted to determine the earliest observable effect of phonology on the eye movement record.

Survival Analyses were conducted on first fixation duration data following the Individual Participant Divergence Point Analysis (IP-DPA) procedure outlined in Reingold and Sheridan (2014) and using the Matlab script supplied in their supplementary materials. The IP-DPA procedure uses a bootstrap resampling

procedure to compare survival curves of first fixation duration data in two conditions (here, the homophone and orthographic control conditions) to determine the divergence point estimate for each subject individually. The procedure, outlined in Reingold and Sheridan (2014), is repeated for 1,000 iterations per subject, and the median divergence point estimate obtained across all iterations is used as the divergence point for that individual subject. Using this procedure to compare the survival curves for the homophone and orthographic control conditions results in the generation of divergence point estimates that correspond to the earliest observable effect of phonology. Furthermore, using the IP-DPA procedure provides divergence point estimates for each individual subject, which allows for an investigation into the degree of variability of phonological code generation across subjects. The survival curves for the homophone and orthographic control condition are displayed in Figure 2.4 as well as the mean divergence point obtained by taking the mean of the individual subject divergence points. The homophone and orthographic control curves significantly diverged at 173 ms on average across all subjects ($M = 173$ ms, range = 74-360 ms, $SE = 10.57$, $N=41$)², and 61% of individual subjects had divergence point estimates that were earlier than this group mean. Finally, across all subjects, only 21.3% of first fixations had durations shorter than this divergence point estimate, suggesting that the majority of fixations were influenced by phonology.

² The divergence point estimates for 7 subjects were deemed unreliable because a divergence point estimate was obtained in less than 50% of the iterations. Following Reingold and Sheridan (2014) these subjects were excluded from computation of the group divergence point estimate, however their raw fixation duration data is included in the survival figure.

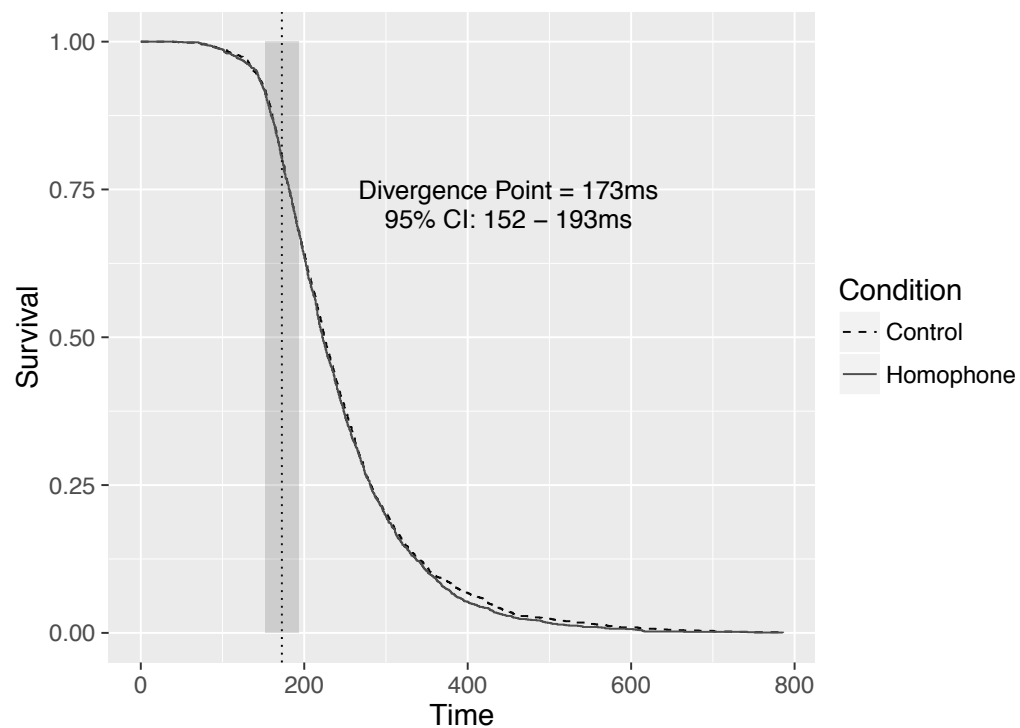


Figure 2.4. Proportion of fixations surviving as a function of time for Experiment 1. Line type represents the condition (homophone, control) and the dotted vertical line denotes the divergence point. The grey band surrounding the divergence point line represents the 95% confidence interval.

Discussion

Consistent with prior research (e.g., Jared et al., 1999; Rayner, 1998), by as early as gaze duration on the critical words, mean fixation durations were significantly shorter for a word phonologically related to a contextually appropriate target than for a control word matched on orthographic overlap. These findings are consistent with an early locus of phonological effects, but alone are not conclusive. However, taken together with the results of the survival analysis, it becomes clear that phonology is indeed exerting an early effect on processing and the eye

movement record. The survival curve for the phonologically related word significantly diverged from that of the orthographic control word 173 ms after fixation (and therefore foveal processing) began, confirming an early influence of phonological coding.

While these results clearly demonstrate that phonological codes can be generated quite early, it is not clear whether these codes are generated pre-lexically (i.e., assembled codes) or if they are simply retrieved rapidly from the lexicon following lexical access (i.e., addressed codes). While the early time course is suggestive of a pre-lexical code, the lexical nature of the stimuli makes it impossible to definitively determine. Therefore Experiment 2 measured the processing of phonologically related non-words (i.e., pseudohomophones) and orthographically matched non-word controls. In this way, it could be ensured that any observed effects of phonology were due to the generation of assembled phonological codes; since non-words do not have entries in the lexicon from which addressed phonological codes could be retrieved.

Experiment 2

Method

Participants. An additional set of forty-eight undergraduates from the University of California, San Diego, who did not participate in Experiment 1, participated in this experiment for course credit or monetary compensation. All

were native English speakers, had normal vision, and were naïve to the purpose of the experiment.

Apparatus. The apparatus was identical to Experiment 1.

Materials. Material design was similar to Experiment 1 except that the homophone and orthographic control word conditions were replaced with pseudohomophone and orthographic control non-word conditions. For this experiment, the correct target words consisted of 60 words for which pseudohomophones (homophonic non-words) could be created. Each pseudohomophone constituted a pronounceable, orthographically legal letter string, which shared at least the same initial letter with, and would be pronounced the same as, its corresponding correct target word (assessed via the norms described below). For each correct target word/pseudohomophone pair, an orthographic control non-word was created that was orthographically legal, pronounceable, and as orthographically similar to the correct target as the pseudohomophone, but did not fully share phonology. Correct targets, pseudohomophones, and orthographic control non-words were roughly matched on length, mean bigram frequency, and bigram frequency by position. Additionally, the pseudohomophones and orthographic control non-words were also matched on lexical frequency (i.e., all had a lexical frequency of zero, since they are not real words) and their degree of orthographic overlap with the correct target. Correct targets had an average log frequency of 9.7 (range 6.22 to 12.42). All critical words were on average 4.58

letters long (range 4 to 8). Summary statistics for the target words appear in Table 2.5.

Table 2.5. Experiment 2 summary statistics for target words.

	Correct Target		Pseudohomophone		Orthographic Control	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Log HAL Frequency (per 400 mil)	9.7	1.53	0	0	0	0
Length	4.58	0.74	4.58	0.74	4.58	0.74
Mean Bigram Frequency	1748	769	1666	687	1651	691
Bigram Frequency by Position	1214	513	1112	503	1182	480
Orthographic Overlap			0.63	0.13	0.66	0.13
Cloze Predictability	0.65	0.32				
Sentence Acceptability	6.12	0.49	2.95	0.73	2.65	0.65
Fragment Acceptability	5.97	0.69	2.95	0.50	2.44	0.34
Pronunciation			4.38	0.4		

Note. Orthographic overlap refers to the percentage of position specific letters that the homophones or orthographic controls shared with the correct target words (e.g., *wheel* and *whele* share the first three, or 60%, of their letters in the same positions).

For each set of critical words, three sentences were created that rendered the correct target word somewhat predictable, resulting in a total of 180 experimental sentences. In this way, for each set of critical words, each subject could read the correct target, pseudohomophone, and orthographic control non-word each in a different sentence and contribute data to all three conditions. The type of critical word presented in each sentence was counterbalanced across participants, such that across experimental lists, for every item, each type of critical word appeared in each of the three sentence frames an equal number of times. The 180 experimental sentences were presented along with 50 filler sentences. Simple comprehension questions appeared after 20 of the filler items, and comprehension accuracy was

high (91.7%). Word type (correct target, pseudohomophone, orthographic control non-word) was tested within participants, and, because there were three experimental sentences for each target triplet, each participant contributed data to all three conditions for each set of critical words. An example stimulus is shown in (2), with the correct target/pseudohomophone/orthographic control non-word italicized (the full set of stimuli is listed in the Appendix).

(2) Because of his insomnia, Caleb couldn't sleep/sleap/slerp even though he was tired.

Normative data. Four types of normative data were collected.

Cloze Task. The same 30 subjects from the United States, who participate in the cloze norming study for Experiment 1, also provided cloze norming for the Experiment 2 stimuli. This norming task revealed that the sentences were moderately predictable, with (on average) the target word being produced 65% of the time.

Sentence Acceptability. An additional set of 18 subjects from the United States, who did not participate in other norming tasks or the reading experiments, were recruited through Amazon's Mechanical Turk service to participate in a sentence acceptability rating task for monetary compensation. Each subject rated one version of each of the 180 sentences with the correct target, pseudohomophone, or orthographic control non-word, such that 6 subjects rated each version of a given sentence. The average acceptability scores (on a 1-7 scale) for sentences with the correct target, pseudohomophone or orthographic control non-word were 6.12,

2.95, and 2.65 respectively, demonstrating that the correct targets fit better into the sentences than either the pseudohomophones ($p < .001$) or orthographic controls ($p < .001$). As with Experiment 1, the sentences with the pseudohomophones were again rated as more acceptable than the sentences with the orthographic control non-words ($p < .001$), which can again likely be attributed to the fact that readers are less likely to notice errors that sound the same as an acceptable word.

Fragment Acceptability. An additional set of 18 subjects from the United States, who did not participate in other norming tasks or the reading experiment, were recruited through Amazon's Mechanical Turk service to participate in a sentence fragment acceptability rating task for monetary compensation. Each subject rated one version of each of the 180 sentence fragments up to and including either the correct target, pseudohomophone, or orthographic control non-word, such that 6 subjects rated each version of a given sentence fragment. The average acceptability scores (on a 1-7 scale) for sentence fragments with the correct target, pseudohomophone, or orthographic control non-word were 5.97, 2.95, and 2.44 respectively, demonstrating that the correct targets were more acceptable continuations of the sentences than either the pseudohomophones ($p < .001$) or orthographic controls ($p < .001$) at the point at which they were first read. Again, fragments ending with the pseudohomophones were rated as more acceptable than those ending with the orthographic control non-words ($p < .001$), likely for the reasons mentioned above.

Pronunciation Verification. An additional set of 10 participants from the University of California San Diego, who did not participate in the reading experiment or any other norming, participated in a pronunciation verification task where they were shown a non-word followed by a word (e.g., *sleep* – *sleep*) and asked to judge how similar the pronunciation of the word was to that of the preceding non-word string. The non-word string always preceded the word to reduce the chance of biasing subjects toward pronouncing them similarly. The average similarity rating across all items (on a 1-5 scale) was 4.38 (range 3.1 to 5).³

Procedure. The procedure was identical to Experiment 1.

Results

Data exclusion criteria were identical to Experiment 1 and resulted in 97% of data being retained for analysis.

The same standard reading time measures as Experiment 1 are reported and all reading measures on the target word are summarized in Table 2.6. Results of the linear mixed-effects models (with the intercept representing the mean of the pseudohomophone condition) are summarized in Table 2.7, and results of the general linear mixed-effects regression models in Table 2.8.⁴

³ Pronunciation norming was missing for one pseudohomophone *brane*, however this item has been used as a pseudohomophone for *brain* in previous studies (e.g., Inhoff & Topolski, 1994; Rayner et al., 1998).

⁴ In Experiment 2, due to convergence issues the random slopes for items in the GPT and TVT models were removed, and the random slopes for subjects and items in the GZD model were removed.

Table 2.6. Means and standard errors for reading time measures in Experiment 2.

	Identical	Pseudohomophone	Orthographic control
Fixation Probability	0.68 (0.009)	0.75 (0.008)	0.74 (0.008)
Single Fixation			
Duration	220 (1.9)	251 (2.4)	263 (2.6)
First Fixation			
Duration	218 (1.8)	248 (2.2)	260 (2.4)
Gaze Duration	232 (2.2)	275 (2.9)	300 (3.5)
Go-Past Time	254 (3.2)	309 (4.1)	343 (4.9)
Total Time	250 (2.7)	325 (4)	410 (5.8)
Regressions Out	0.05 (.004)	0.06 (.005)	0.07 (.005)
Regressions In	0.08 (.005)	0.17 (.007)	0.27 (.009)

Fixation duration measures. The correct target was fixated for significantly less time than the pseudohomophone across all fixation duration measures (all t s > 8.42). Critically, the pseudohomophone was fixated for significantly less time than the orthographic control across all fixation duration measures as well (all t s > 2.88), suggesting that readers had an easier time processing phonologically related stimuli relative to control stimuli matched on level of orthographic overlap. Group means for all fixation duration measures appear in Figure 2.5.

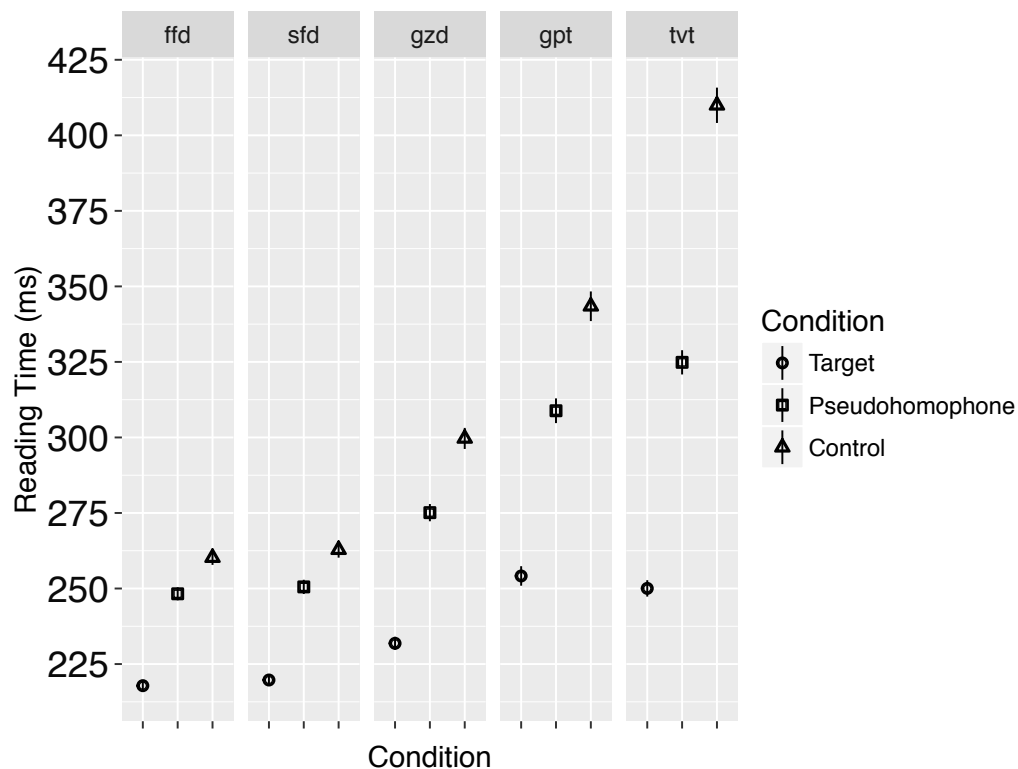


Figure 2.5. Reading time on the target word in Experiment 2 as a function of condition (correct target, pseudohomophone, or orthographic control), across 5 reading time measures (ffd = first fixation duration, sfd = single fixation duration, gzd = gaze duration, gpt = go-past time, tvf = total time). Error bars represent ± 1 standard error of the mean

Fixation probability measures. The correct target was skipped at a significantly higher rate (i.e., the probability of fixation was lower) than the pseudohomophone ($p < .001$), whereas skipping rates between the pseudohomophone and orthographic control did not significantly differ ($p = .81$). There was a significantly lower rate of regressions out of the correct target than the pseudohomophone ($p = .02$), however the rate of regressions out of the pseudohomophone and orthographic control did not significantly differ ($p = .27$).

The probability of making a regression in to the orthographic control was significantly higher than for the pseudohomophone ($p < .001$), which had a significantly higher regression-in rate than the correct target ($p < .001$).

Table 2.7. Results of linear mixed effects models for reading time measures on the critical word in Experiment 2. The intercept represents the mean duration for the pseudohomophone condition. Significant effects are indicated by boldface.

Measure	Contrast	Model		
		b	SE	t
First Fixation Duration	Intercept	246.53	5.40	45.64
	Target	-30.58	3.09	9.90
	Orthographic control	12.02	4.05	2.97
Single Fixation Duration	Intercept	250.22	5.65	44.26
	Target	-32.05	3.31	9.68
	Orthographic control	13.25	4.58	2.89
Gaze Duration	Intercept	272.14	6.96	39.13
	Target	-44.69	3.87	11.56
	Orthographic control	25.22	3.79	6.65
Go-Past Time	Intercept	305.57	9.47	32.37
	Target	-54.97	6.28	8.75
	Orthographic control	35.38	7.09	4.99
Total Time	Intercept	320.81	11.67	27.49
	Target	-74.61	8.85	8.43
	Orthographic control	84.94	8.32	10.21

Table 2.8. Results of the logistic regression models for fixation probability measures across condition in Experiment 2. The intercept represents the mean probability for the pseudohomophone condition. Significant effects are indicated by boldface.

Measure	Contrast	Model		
		b	z	p
Fixation Probability	Intercept	1.23	11.03	< .001
	Target	-0.39	5.45	< .001
	Orthographic control	-0.02	0.25	0.81
Regression-out Probability	Intercept	-2.97	22.02	< .001
	Target	-0.42	2.25	0.02
	Orthographic control	0.18	1.11	0.27
Regression-in Probability	Intercept	-1.75	15.54	< .001
	Target	-0.89	6.62	< .001
	Orthographic control	0.66	7.16	< .001

Survival Analysis. As with Experiment 1, survival analyses were again computed to determine the earliest observable effect of assembled phonology on the eye movement record. The survival curves for the pseudohomophone and orthographic control condition are displayed in Figure 2.6 as well as the mean divergence point obtained by taking the mean of the individual subject divergence points. The pseudohomophone and orthographic control curves significantly diverged at 161 ms on average across all subjects ($M = 161$ ms, range = 49-282 ms, $SE = 7.67$, $N = 43$)⁵, and 46.5% of individual subjects had divergence point estimates that were earlier than this group mean. Finally, across all subjects, only 16.2% of

⁵ The divergence point estimates for four subjects were unreliable and the divergence point estimate for one additional subject could not be computed (i.e., their curves never significantly diverged); therefore the data of all five subjects were excluded from the group divergence point estimate, however their raw fixation duration data are included in the survival figure.

first fixations had durations shorter than this divergence point estimate, suggesting that the majority of fixations were influenced by phonology.

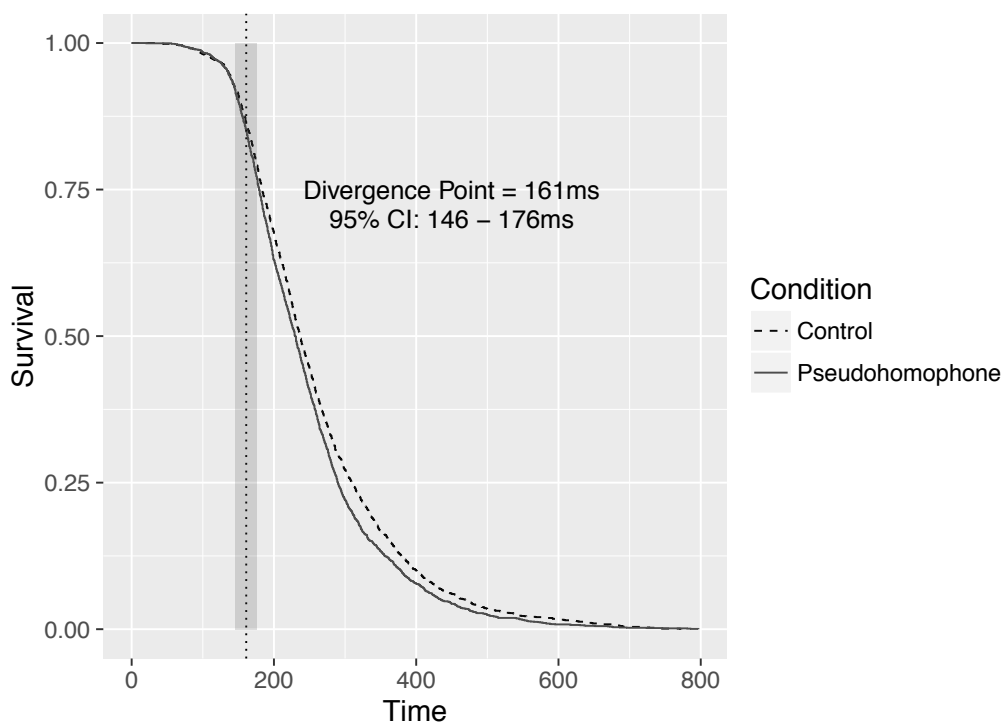


Figure 2.6. Proportion of fixations surviving as a function of time for Experiment 2. Line type represents the condition (pseudohomophone, control) and the dotted vertical line denotes the divergence point. The grey band surrounding the divergence point line represents the 95% confidence interval.

Discussion

Again, there was an advantage for phonologically related stimuli compared to matched orthographic controls, but the advantage emerged even earlier than in Experiment 1. Mean fixation durations were significantly shorter by as early as the first fixation duration for a non-word that was phonologically related to a contextually appropriate target than for a control non-word matched on orthographic overlap. These findings suggest that assembled phonological codes can

indeed be generated quite rapidly, and indeed, survival analyses confirm that the effect of assembled phonology has an early locus. The survival curve for the phonologically related non-word significantly diverged from that of the orthographic control non-word 161 ms after fixation (and therefore foveal processing) began, confirming an early, influence of pre-lexical, assembled phonological coding. Comparing these results to those of Experiment 1 suggests that the assembled phonological codes measured in Experiment 2 are exerting an influence that is as early as the codes that were generated in Experiment 1 (whether assembled or addressed)—statistically, the divergence point estimate for Experiments 1 and 2 did not differ, $F(1, 82) = 0.79, p = .38$. This is somewhat surprising given the conclusions from fast-priming studies that assembled phonological codes are delayed relative to addressed phonological codes (e.g., H.-W. Lee et al., 2005; H.-W. Lee et al., 1999; Y.-A. Lee et al., 1999, but see Rayner et al., 1995).

There are notable differences between the present studies and prior studies using the fast-priming paradigm, which may account for the different findings. First, facilitation from fast-priming is limited to a narrow “window of opportunity’ ...when the prime is on long enough for phonological coding to develop sufficiently but not long enough for the reader to be consciously aware of the prime” (Y.-A. Lee et al., 1999, p. 956). Failure to find significant facilitation from pseudohomophone primes suggests that the associated assembled phonological codes are not sufficiently developed within the first ~40 ms of processing, after which point the reader would

become consciously aware of the prime therefore obliterating any facilitation that might have occurred and leading to increased fixation durations. Because the present study does not rely on priming, readers are able to consciously process the phonologically related stimuli, meaning that effects of phonology that might emerge later could still affect fixation durations. Second, significant prime facilitation in fast-priming is not only limited to words, but is also limited to high-frequency words, suggesting that the rapidity with which phonological code generation can begin might be tied tightly to how frequent (and therefore easy to process) a word is. Under this explanation, the lack of significant priming from pseudoword primes does not necessarily reflect a dichotomy whereby assembled phonological codes are delayed relative to addressed phonological codes, rather it suggests a continuum where the speed with which phonological coding can begin is a function of how easy the word is to process. The directionality of this effect in fast priming is not clear; it could be that, as a function of higher frequency words being easier to process, phonology can be extracted more readily. Alternatively, if phonological codes aid lexical access, part of what might make a high frequency word easier to process is the rapidity with which its phonological codes can be generated. Regardless, as previously mentioned, because during normal reading we are not limited to a narrow window of opportunity for observing effects, we could have the opportunity to observe graded processing as a function of ease of processing (i.e., frequency). Instead of graded processing, the survival analyses suggest a similar time course for the influence of phonological coding on the processing of words and necessarily

lower- (i.e., zero) frequency non-words, suggesting that even if there are differences in the speed with which these codes begin to be generated (as fast priming suggests), these differences disappear by the point at which code activation affects decisions regarding when to move the eyes, therefore not showing up in behavioral measures during normal reading.

There is however one criticism of Experiments 1 and 2 that may make drawing conclusions about normal reading potentially problematic. In both experiments, eye movement measures are recorded as subjects actually read words that do not make sense in the context (Experiment 1) or non-words that on their own have no lexical entry or semantic representation (Experiment 2). Despite this fact, a significant, early difference between the processing of phonologically related and orthographic control stimuli still emerged. To ensure that this effect was not a by-product of the somewhat strange reading situation (or driven by differences in acceptability—recall that the phonologically related words were rated as more acceptable continuations of the sentences in both experiments), two additional experiments were designed. Experiments 3 and 4 closely paralleled the first two experiments with one notable exception; rather than being directly fixated, the phonologically related and orthographic control stimuli were presented as parafoveal previews using the boundary paradigm. In this way, processing of a semantically coherent word could be analyzed as a function of the type of preview that was available prior to direct fixation.

Experiment 3

To ensure that the early effect of phonology that was observed in Experiment 1 was not due to the somewhat strange situation of reading semantically incongruent words, Experiment 3 was designed using the invisible boundary paradigm to manipulate the information available in the parafovea prior to direct fixation. The results of Pollatsek et al. (1992) and Miellet and Sparrow (2004) clearly demonstrate that phonological codes can begin to be generated before a word is directly fixated, as homophones and pseudohomophones typically provide greater preview benefit than orthographic controls. The specific question addressed in Experiments 3 (and 4) is how early these purely parafoveally acquired codes exert an influence on eye movement behavior.

Methods

Participants. An additional set of forty-eight undergraduates from the University of California, San Diego, who did not participate in Experiments 1 or 2, participated in this experiment for course credit or monetary compensation. All were native English speakers, had normal vision, and were naïve to the purpose of the experiment.

Apparatus. Eye movements were recorded with an SR Research Ltd. Eyelink 1000 eye tracker (sampling rate of 1000 Hz) in a tower setup that restrained head movements with forehead and chin rests. Viewing was binocular, but only the eye movements of the right eye were recorded. Subjects were seated approximately 60 cm away from an HP p1230 CRT monitor with a screen resolution of 1024 x 768

pixels and a refresh rate of 150 Hz. Text was displayed in black, 12-point, fixed-width Consolas font on a white background. Sentences were always displayed in the center of the screen in one line of text, and 4.4 characters subtended 1° of visual angle. Display changes were completed, on average, within 4 ms of the tracker detecting a saccade crossing the invisible boundary, which was located between the last two letters of the pre-target word.

Materials. Materials were identical to Experiment 1, except that the homophone and orthographic control words were presented as parafoveal previews using the invisible boundary paradigm (Rayner, 1975), such that all subjects only ever directly fixated the correct target words. Comprehension accuracy was high (94%). Preview type (identical, homophone, orthographic control) was tested within participants, and, because there were three experimental sentences for each target triplet, each participant contributed data to all three conditions for each set of critical preview words.

Procedure. The procedure was identical to Experiment 1 except that on critical trials, an invisible boundary was located between the last two letters of the pre-target word. While a subject's eyes were to the left of the boundary, the preview word was the correct target (identical preview), the homophone preview, or the orthographic control word preview. When the eyes crossed the boundary, the preview was replaced with the correct target word, which remained on the screen for the rest of the trial. The experimental session lasted approximately fifty minutes.

Results

Prior to analysis, fixations under 81 ms were pooled if they were within 1 character of another fixation, and fixations over 800 ms were deleted, also any trials in which subjects blinked during first-pass reading of the target word (6.2% of data), trials in which the display change was triggered by a saccade that landed to the left of the boundary, or trials in which the display change was completed late were deleted as well (13.6% of data). Additionally, gaze durations longer than 2,000 ms and total times longer than 4,000 ms were excluded. Finally, because the invisible boundary was located between the last two letters of the pre-target word, any trials in which a reader's saccade into the target came from the last letter of the pre-target word (i.e., the letter after the invisible boundary) were also excluded (1.2% of data) because these represent cases in which the subject could parafoveally process the target rather than the preview. After all exclusions, 79% of the original data were retained for analysis.

The same standard reading time measures as Experiments 1 and 2 are reported. Reading measures on the target word (as a function of preview type) are summarized in Table 2.9. Results of the linear mixed-effects models (with the intercept representing the mean of the homophone preview condition) are summarized in Table 2.10, and results of the general linear mixed-effects regression models in Table 2.11.⁶

⁶ In Experiment 3, the models for GPT, TVT, and RGO failed to converge so random slopes for items were removed.

Table 2.9. Means and standard errors for reading time measures in Experiment 3.

Preview Type	Identical	Homophone	Orthographic Control
Fixation Probability	0.65 (0.01)	0.66 (0.01)	0.66 (0.01)
Single Fixation Duration	221 (2)	237 (2.2)	244 (2.3)
First Fixation Duration	220 (1.9)	235 (2.1)	241 (2.2)
Gaze Duration	231 (2.3)	253 (2.6)	260 (2.7)
Go-Past Time	265 (4.4)	296 (4.9)	307 (4.9)
Total Time	257 (3.3)	286 (3.5)	290 (3.6)
Regressions Out	.06 (.005)	.07 (.006)	.08 (.006)
Regressions In	.11 (.007)	.16 (.008)	.15 (.008)

Fixation duration measures. Following an identical preview, the target was fixated for significantly less time than following the homophone preview across all fixation duration measures (all t s > 4.14). Unlike the first two experiments, reading times on the target following a homophone preview never significantly differed from times following the orthographic control preview (all t s < 1.94). Alone, these data would seem to suggest that there was no significant advantage to readers having a phonologically related preview over an orthographically related preview. Group means for all fixation duration measures appear in Figure 2.7.

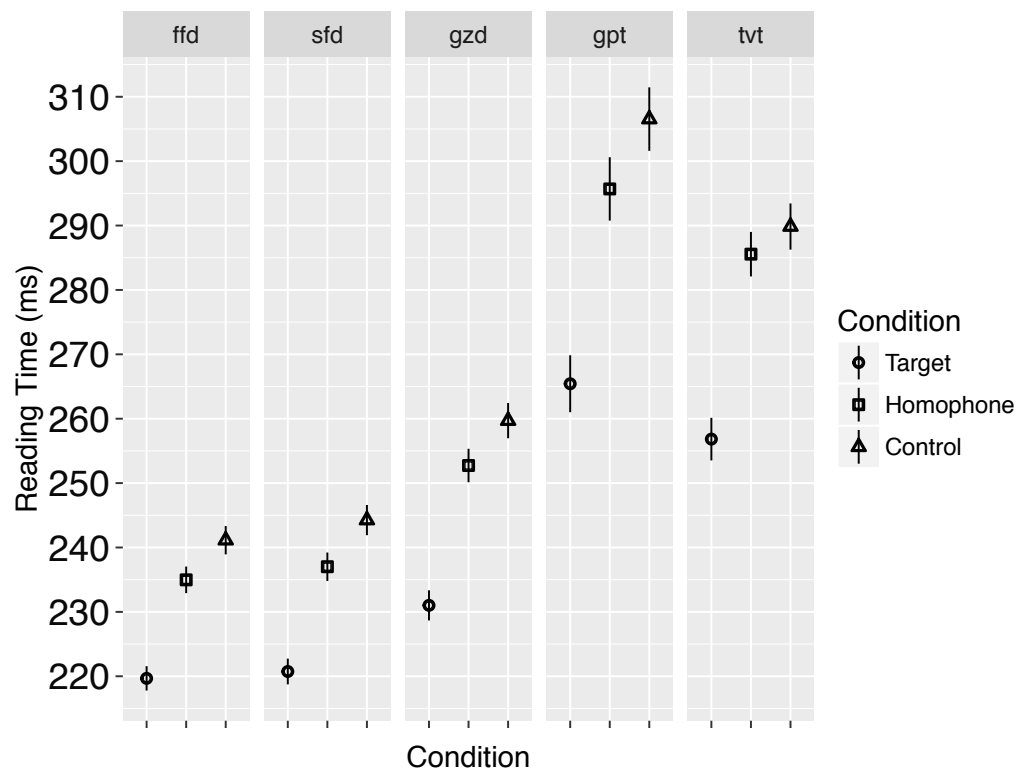


Figure 2.7. Reading time on the target word in Experiment 3 as a function of preview condition (target (identical) preview, homophone preview, or orthographic control preview), across 5 reading time measures (ffd = first fixation duration, sfd = single fixation duration, gzd = gaze duration, gpt = go-past time, tvt = total time). Error bars represent ± 1 standard error of the mean.

Table 2.10. Results of linear mixed effects models for reading time measures on the target word in Experiment 3. The intercept represents the mean duration for the homophone preview condition. Significant effects are indicated by boldface.

Measure	Contrast	b	Model SE	t
First Fixation Duration	Intercept	234.96	3.92	59.94
	Target	-14.96	2.98	5.03
	Orthographic control	5.28	2.92	1.81
Single Fixation Duration	Intercept	237.38	4.39	54.06
	Target	-15.57	2.99	5.21
	Orthographic control	6.37	3.31	1.93
Gaze Duration	Intercept	251.77	4.99	50.43
	Target	-21.29	4.14	5.15
	Orthographic control	5.53	3.92	1.41
Go-Past Time	Intercept	293.4	9.22	31.8
	Target	-27.44	6.62	4.15
	Orthographic control	9.42	7.34	1.28
Total Time	Intercept	281.87	7.31	38.58
	Target	-27.63	5.68	4.87
	Orthographic control	4.11	4.73	0.87

Table 2.11. Results of the logistic regression models for fixation probability measures across condition in Experiment 3. The intercept represents the mean probability for the homophone preview condition. Significant effects are indicated by boldface.

Measure	Contrast	Model		
		b	z	p
Fixation Probability	Intercept	0.80	7.46	< .001
	Target	-0.05	0.65	0.52
	Orthographic control	< -0.01	0.01	0.99
Regression-out Probability	Intercept	-2.97	17.37	< .001
	Target	-0.07	0.48	0.63
	Orthographic control	0.11	0.76	0.45
Regression-in Probability	Intercept	-2.0	13.1	< .001
	Target	-0.32	2.33	0.02
	Orthographic control	0.08	0.66	0.51

Fixation probability measures. There were no significant differences in the likelihood of fixating the target as a function of preview (both $ps > .51$), nor were there any differences in the likelihood of making a regression-out of the target as a function of preview (both $ps > .44$). Subjects were significantly less likely to make a regression into the correct target following the identical preview than the homophone preview ($p = .02$), but there was no difference in the probability of making a regression into the target following the homophone or orthographic control previews ($p = .51$).

Survival Analyses. Survival analyses were again computed to determine the earliest observable effect of parafoveally-generated phonology on the eye movement record. The survival curves for the homophone and orthographic control

preview conditions are displayed in Figure 2.8 as well as the mean divergence point obtained by taking the mean of the individual subject divergence points. The homophone and orthographic control curves significantly diverged at 170 ms on average across all subjects ($M = 170$ ms, range = 86-375 ms, $SE = 7.76$, $N = 46$)⁷, and 52.2% of individual subjects had divergence point estimates that were earlier than this group mean. Finally, across all subjects, only 19.6% of first fixations had durations shorter than this divergence point estimate, suggesting that the majority of fixations were influenced by phonology.

⁷ The divergence point estimates for two subjects were unreliable and therefore their divergence point estimates were excluded from the group divergence point estimate, however their raw fixation duration data are included in the survival figure.

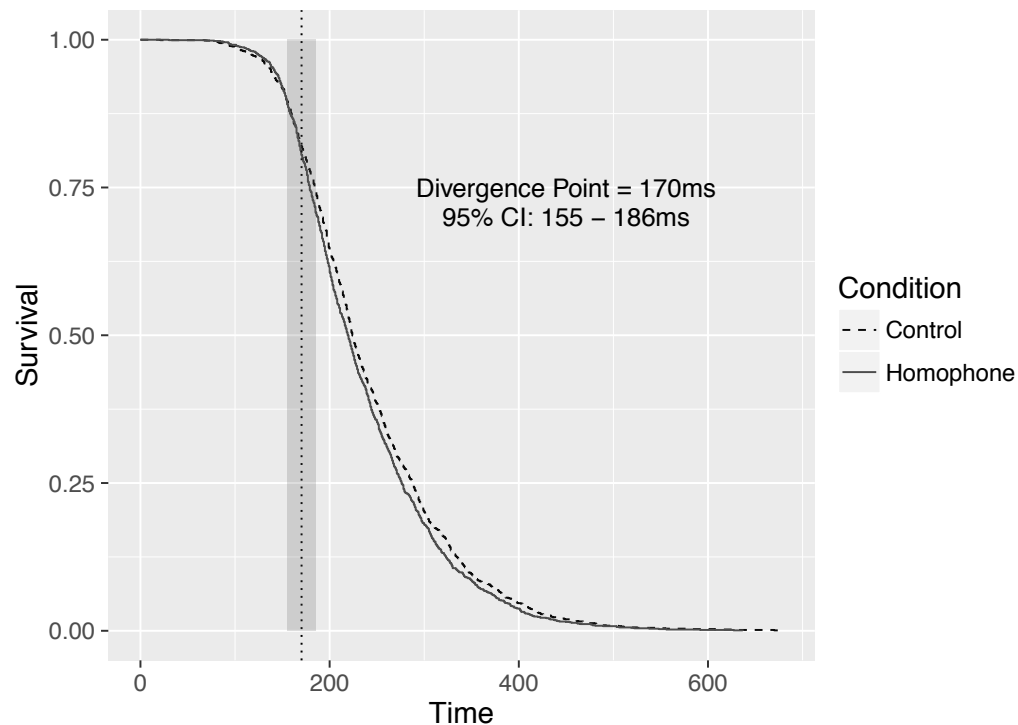


Figure 2.8. Proportion of fixations surviving as a function of time for Experiment 3. Line type represents the condition (homophone preview, control preview) and the dotted vertical line denotes the divergence point. The grey band surrounding the divergence point line represents the 95% confidence interval.

Discussion

Results of the survival analyses clearly demonstrate that the early effect of phonology observed in Experiments 1 and 2 was not simply due to the somewhat strange situation of reading words and non-words that did not make sense in the sentences. Even when the phonologically related homophone was only presented as a parafoveal preview for the correct target word, effects of phonological coding emerged 170 ms after target fixation—very similar to the 173 ms estimate that was obtained in Experiment 1 using the same stimuli (without a parafoveal preview

manipulation), but an entirely different set of subjects. This seems to suggest that the locus of the phonological effect in both experiments is parafoveal—subjects begin generating codes parafoveally that go on to influence their eye movement planning behaviors regardless of whether or not the target information is completely consistent with the information they extracted parafoveally.

This is not to say that there were no differences between the results of Experiments 1 and 3. Although divergence point estimates were almost identical, means analyses were not. In Experiment 1, where subjects actually fixated the homophone and orthographic control words, there was an advantage from processing the homophone in several measures (gaze duration, go-past time, total time, and regression-in probability). Here, where the manipulation was more subtle (i.e., the homophone and orthographic controls were only presented as previews), no significant mean differences emerged between processing the homophone preview and orthographic control preview. Inspection of the means reveals that they pattern numerically like the means for Experiment 1, such that there is a numerical advantage in most measures for the homophone preview compared to the orthographic control preview, but that advantage never reached significance. Furthermore, comparison of the regression coefficients across experiments reveals that the size of the homophone advantage (relative to the orthographic control) gets larger in later measures for Experiment 1 (first fixation duration = 2.54, gaze duration = 7.75, go-past time = 31.48, total time = 66.1), but not for Experiment 3 (first fixation duration = 5.28, gaze duration = 5.53, go-past time = 9.42, total time =

4.11), suggesting that in later measures for Experiment 3, processing differences originating from the different preview conditions were obscured by processing of the now identical foveal target. That is, by the point at which phonology would begin exerting a significant effect on mean processing time in Experiment 3 (presumably gaze duration since that is the earliest measure showing a significant difference in Experiment 1), the foveal stimulus available for continued processing was identical across conditions, therefore obscuring any continued effect of the preview.

Experiment 4

The results of Experiment 3 suggest that the phonological effects observed in both Experiments 1 and 3 were likely generated parafoveally, as the divergence point estimates were nearly identical for phonologically related words which were able to be processed across both parafoveal and foveal vision and those which were only ever processed as parafoveal previews. Experiment 4 then sought to determine if the same were true for necessarily assembled codes, by comparing processing of contextually appropriate targets preceded by phonologically related (pseudohomophone) and orthographic control non-word previews.

Participants. An additional set of forty-eight undergraduates from the University of California, San Diego, who did not participate in Experiments 1, 2, or 3, participated in this experiment for course credit or monetary compensation. All were native English speakers, had normal vision, and were naïve to the purpose of the experiment.

Apparatus. The apparatus was identical to Experiment 3.

Materials. Materials were identical to Experiment 2, except that the pseudohomophone and orthographic control non-words were presented as parafoveal previews using the invisible boundary paradigm (Rayner, 1975). Comprehension accuracy was high (92.9%). Preview type (identical, pseudohomophone, orthographic control non-word) was tested within participants, and, because there were three experimental sentences for each target triplet, each participant contributed data to all three conditions for each set of critical words.

Procedure. The procedure was identical to Experiment 3, except that the preview word was the correct target (identical preview), pseudohomophone, or orthographic control non-word.

Results

Data exclusions were identical to Experiment 3 and resulted in, 78% of the original data being retained for analysis.

The same standard reading measures as the previous three experiments are reported. Reading measures on the target word (as a function of preview type) are summarized in Table 2.12. Results of the linear mixed-effects models (with the intercept representing the mean of the pseudohomophone preview condition) are summarized in Table 2.13, and results of the general linear mixed-effects regression models in Table 2.14.⁸

⁸ In Experiment 4, the models for SFD and TVT failed to converge, so random slopes for items were removed.

Table 2.12. Means and standard errors for reading time measures in Experiment 4.

Preview Type	Identical	Pseudohomophone	Orthographic Control
Fixation Probability	0.69 (0.01)	0.73 (0.01)	0.72 (0.01)
Single Fixation Duration	214 (1.8)	235 (1.9)	243 (2.1)
First Fixation Duration	215 (1.8)	232 (1.8)	238 (1.9)
Gaze Duration	229 (2.3)	249 (2.2)	257 (2.3)
Go-Past Time	256 (3.7)	287 (5.4)	291 (4)
Total Time	250 (3.2)	271 (3.2)	276 (3.1)
Regressions Out	.06 (.005)	.07 (.006)	.07 (.006)
Regressions In	.09 (.006)	.1 (.006)	.11 (.007)

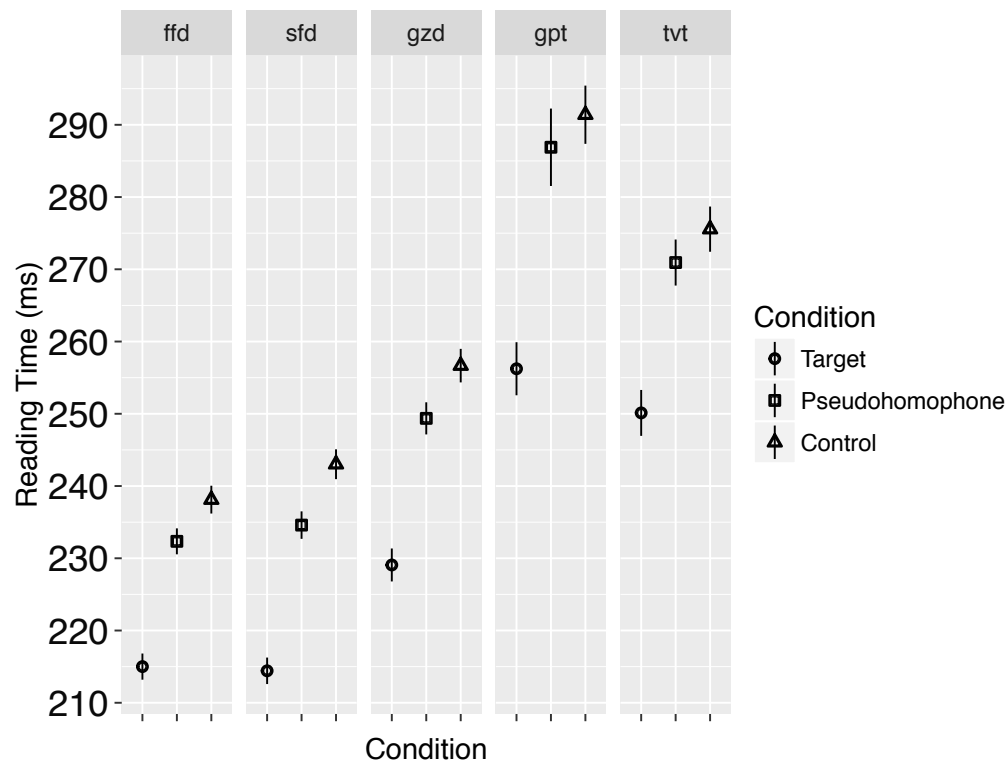


Figure 2.9. Reading time on the target word in Experiment 4 as a function of preview condition (target (identical) preview, pseudohomophone preview, or orthographic control preview), across 5 reading time measures (ffd = first fixation duration, sfd = single fixation duration, gzd = gaze duration, gpt = go-past time, tvf = total time). Error bars represent ± 1 standard error of the mean.

Fixation duration measures. Following an identical preview, the target was fixated for significantly less time than following the pseudohomophone preview across all fixation duration measures (all t s > 3.69). Unlike Experiment 3, reading times on the target following a pseudohomophone preview did significantly differ from reading times following an orthographic control preview, but only in single fixation duration ($t = 2.96$, all other t s < 1.92). These data would seem to suggest that there was only a brief advantage to readers having a phonologically related preview over an orthographically related preview, which appeared in the first

fixation on the target word, when subjects needed only one first pass fixation to identify the word, but did not carry over into any refixations or later measures.

Group means for all fixation duration measures appear in Figure 2.9.

Table 2.13. Results of linear mixed effects models for reading time measures on the target word in Experiment 4. The intercept represents the mean duration for the pseudohomophone preview condition. Significant effects are indicated by boldface.

Measure	Contrast	b	Model SE	t
First Fixation Duration				
	Intercept	230.9	4.37	52.83
	Target	-17.66	2.5	7.06
	Orthographic control	4.81	2.76	1.74
Single Fixation Duration				
	Intercept	233.97	5.03	46.56
	Target	-20.9	2.8	7.47
	Orthographic control	7.26	2.46	2.96
Gaze Duration				
	Intercept	245.49	5.71	42.99
	Target	-20.01	3.07	6.53
	Orthographic control	6.68	3.49	1.91
Go-Past Time				
	Intercept	281.21	11.1	25.34
	Target	-28.55	7.73	3.7
	Orthographic control	7.02	8.92	0.79
Total Time				
	Intercept	264.34	8.34	31.7
	Target	-19.25	4.87	3.95
	Orthographic control	6.65	4.38	1.52

Table 2.14. Results of the logistic regression models for fixation probability measures across condition in Experiment 4. The intercept represents the mean probability for the pseudohomophone preview condition. Significant effects are indicated by boldface.

Measure	Contrast	b	Model z	p
Fixation Probability	Intercept	1.27	7.8	< .001
	Target	-0.3	3.29	.001
	Orthographic control	-0.12	1.27	0.21
Regression-out Probability	Intercept	-2.92	17.91	<.001
	Target	-0.22	1.31	0.19
	Orthographic control	0.07	0.42	0.68
Regression-in Probability	Intercept	-2.57	16.93	< .001
	Target	-0.15	0.95	0.34
	Orthographic control	0.11	0.82	0.41

Fixation probability measures. Subjects were significantly less likely to fixate the target following an identical preview than the pseudohomophone preview ($p = .001$), but there was not a significant difference in the likelihood of fixating the target following either the pseudohomophone or orthographic control preview ($p = .21$). There were no significant differences in the likelihood of making a regression out of the target word as a function of preview condition (both $ps > .18$), nor were there any significant differences in the likelihood of making a regression into the target as a function of preview condition (both $ps > .33$).

Survival Analyses. Survival analyses were again computed to determine the earliest observable effect of parafoveally generated assembled phonology on the eye movement record. The survival curves for the pseudohomophone and orthographic

control condition are displayed in Figure 2.10 as well as the mean divergence point obtained by taking the mean of the individual subject divergence points. The pseudohomophone and orthographic control curves significantly diverged at 160 ms on average across all subjects ($M = 160$ ms, range = 91-260.5 ms, $SE = 6.46$, $N = 39$)⁹, and 53.8% of individual subjects had divergence point estimates that were earlier than this group mean. Finally, across all subjects, only 15.4% of first fixations had durations shorter than this divergence point estimate, suggesting that the majority of fixations were influenced by phonology.

⁹ The divergence point estimates for seven subjects were unreliable and the divergence point estimates for two additional subjects could not be computed (i.e., their curves never significantly diverged); therefore their individual divergence point estimates were excluded from the calculation of the group divergence point estimate, however their raw fixation duration data are included in the survival figure.

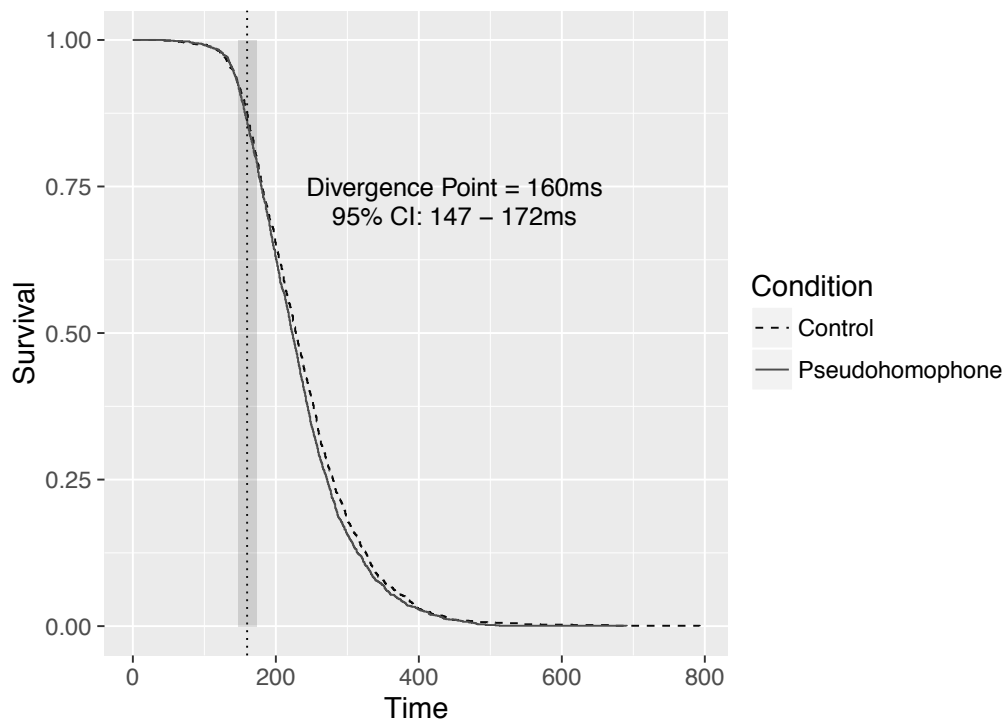


Figure 2.10. Proportion of fixations surviving as a function of time for Experiment 4. Line type represents the condition (pseudohomophone preview, control preview) and the dotted vertical line denotes the divergence point. The grey band surrounding the divergence point line represents the 95% confidence interval.

Discussion

Consistent with Experiment 3, there was again an early effect of phonological coding that emerged even though the phonologically related non-word (and orthographic control non-word) was only ever presented as a parafoveal preview for the correct target word. Indeed, as was the case for Experiments 1 and 3, the divergence point estimate obtained from the survival analyses for Experiment 4 (160 ms) was almost identical to that obtained in Experiment 2 (161 ms). This again seems to suggest that the locus of the phonological effect observed in each

experiment is parafoveal—subjects begin generating codes parafoveally that go on to influence their eye movement planning behaviors regardless of whether or not the target information is completely consistent with the information they extracted parafoveally and regardless of the lexical status of the phonologically related word.

General Discussion

Across four studies, survival analyses provided evidence for the rapid generation of phonological codes during normal reading. These data support earlier findings suggesting the early generation of phonological codes during skilled reading (e.g., Inhoff & Topolsky, 1994; Rayner et al., 1998), and further demonstrate that the locus of these effects is quite early and that phonological coding affects the majority of fixations, rather than only a small subset of long fixations. Furthermore, the similarity between the divergence point estimates obtained here and the estimate reported by Feng et al. (2001) is striking. They reported a divergence point estimate of 168 ms in their experiment, the stimuli and design of which were most similar to the current Experiment 1, where the obtained divergence point estimate was 173 ms.

Although these divergence point estimates support an early role for phonology, the estimates are not as early as one might expect given the results of neurophysiological recording, which have found evidence for differential processing of phonologically related words relative to controls (or differential processing of words following phonologically related primes relative to control primes) within

80-125 ms during single word reading (e.g., Ashby, 2010; Ashby et al., 2009; Cornelissen et al., 2009; Wheat et al., 2010). This discrepancy between the time course inferred from neurophysiological recording and survival analyses does not always emerge, for example the earliest effects of word frequency emerge at approximately the same time in the ERP record (e.g., 132 ms—Sereno, Rayner, & Posner, 1998) and survival analyses (e.g., 138-145 ms—Reingold et al., 2012; Reingold & Sheridan, 2014; see Reichle & Reingold, 2013 for a cross-methodology review of the time course of lexical processing). Perhaps the difference for phonological coding reflects the generation of these codes over time. In other words, whereas effects of word frequency likely reflect a rapid assessment of something like word familiarity or ease of processing (e.g., Balota & Chumbley, 1984), which, at least according the E-Z Reader model of eye movement control, has a direct influence on the first stage of word identification and eye movement programming (e.g., the *familiarity check*, Reichle, Pollatsek, Fisher, & Rayner, 1998), phonological codes take some time to assemble. Although ERP and MEG recording can pick up on the early stages of this generation process, the codes might not actually exert an effect on behavior (the point at which survival analyses can first detect an effect), until they are more developed. Indeed, many of the earliest effects observed in the ERP record (within 80-100 ms), arose from differential processing of subphonemic (Ashby et al., 2009) and syllabic (Ashby, 2010; Ashby & Martin, 2008) information, aspects of phonology that may come online before a complete phonological

representation is formed. Even so, the fact that these codes are influencing behavior within ~160 ms, suggests that the generation process is quite rapid.

Although the survival analyses provided support consistent with the early generation of phonological codes across all four experiments, the means analyses were not always as clear. The earliest eye movement measure to show a significant difference between the phonologically related and control stimuli in each experiment was gaze duration in Experiment 1, first fixation duration in Experiment 2, there were no significant differences between the homophone and control in Experiment 3, and single fixation duration in Experiment 4. These differences across experiments are perhaps not all that surprising given the differing results of previous experiments—some studies report effects emerging as early as first fixation duration (e.g., Miellet & Sparrow, 2004; Pollatsek et al., 1992; Rayner et al., 1998), and others report that differences do not emerge until later measures like total time (e.g., Feng et al., 2001; Daneman & Reingold, 1993, 2000; Daneman, Reingold, & Davidson, 1995). One explanation for these differences across studies has concerned the influence of contextual constraint, but here too the findings have been inconsistent. Some research has suggested that significant differences between phonologically related words and orthographic control words only emerge (or emerge sooner) in high-constraint contexts (e.g., Rayner et al., 1998, Daneman & Reingold, 2000), but others have still found significant differences even when constraint was low (e.g., Jared et al., 1999). In the current series of experiments, effects tended to emerge slightly earlier in Experiments 2 and 4, where average

cloze predictability was also higher, than in Experiments 1 and 3, so the possibility is worth exploring. Post-hoc analyses of the current data did not reveal a significant correlation between the predictability rating for a given item and the size of the shared phonology advantage (calculated as gaze duration on the orthographic control condition-gaze duration on the phonologically related condition, averaged across subjects, following Daneman & Reingold, 2000— $r(694) = .04, p = .29$)¹⁰. This suggests, that at least in the current data, differences in predictability cannot account for the differences in the means analyses across experiments. In any case, differences emerged during first pass reading in all but Experiment 3, and in general, there was a pattern for effects to emerge slightly sooner when comparing the processing of pseudohomophones and non-word controls (Experiments 2 & 4) than when comparing the processing of homophones and real word controls (Experiments 1 & 3). This could reflect an earlier effect for phonology when other variables like lexical frequency cannot exert an effect.

A remarkable aspect of the current data is the consistency of the mean divergence point estimates across experiments (range = 160-173 ms), especially when one considers that there were four groups of subjects, reading two sets of stimuli, in two different experimental paradigms. Indeed a post-hoc analysis of the divergence point estimates across experiments revealed no significant differences as a function of experiment, $F(3, 165) = 0.6, p = .62$. Despite the relative consistency across experiments, there was considerable subject variability within each

¹⁰ The effect was the same for first fixation duration as well $r(694) = .03, p = .41$.

experiment—across all four experiments, individual subject divergence point estimates ranged from 48.5 ms to 374.5 ms (excluding the subjects for whom no divergence point could be determined, i.e., whose survival curves never significantly diverged, as well as those for whom the divergence point estimates were unreliable). Considering these subjects are all skilled, college-aged readers who scored high on reading comprehension questions, it is interesting to consider whether there are any measurable differences in other aspects of the reading process as a function of how early a given subject activates phonological codes.

Because rapidly generated phonological codes might support lexical access, an interesting question is whether there is any relationship between a subject's divergence point estimate (i.e., the rapidity with which they generate phonological codes) and the speed with which they identify words. Since gaze duration is thought to roughly index speed of lexical access, subjects' divergence point estimates were used to predict their average gaze durations for only the correct target words (and identical preview condition for Experiments 3 and 4) for all four experiments (i.e., 1/3 of the items from each experiment, and only the condition in each experiment that did not contribute to calculation of the divergence point). Doing so revealed a significant relationship, whereby a subject's divergence point estimate significantly predicted their average gaze duration, $b = 0.14$, $t(167) = 3.13$, $p = .002$, and explained a small, but significant proportion of variance in gaze duration, $R^2 = 0.06$, $F(1, 167) = 9.79$, $p = .002$. These effects are small, but they do point to a relationship

whereby subjects who generate phonological codes more rapidly, are also faster to identify words (Figure 2.11).¹¹

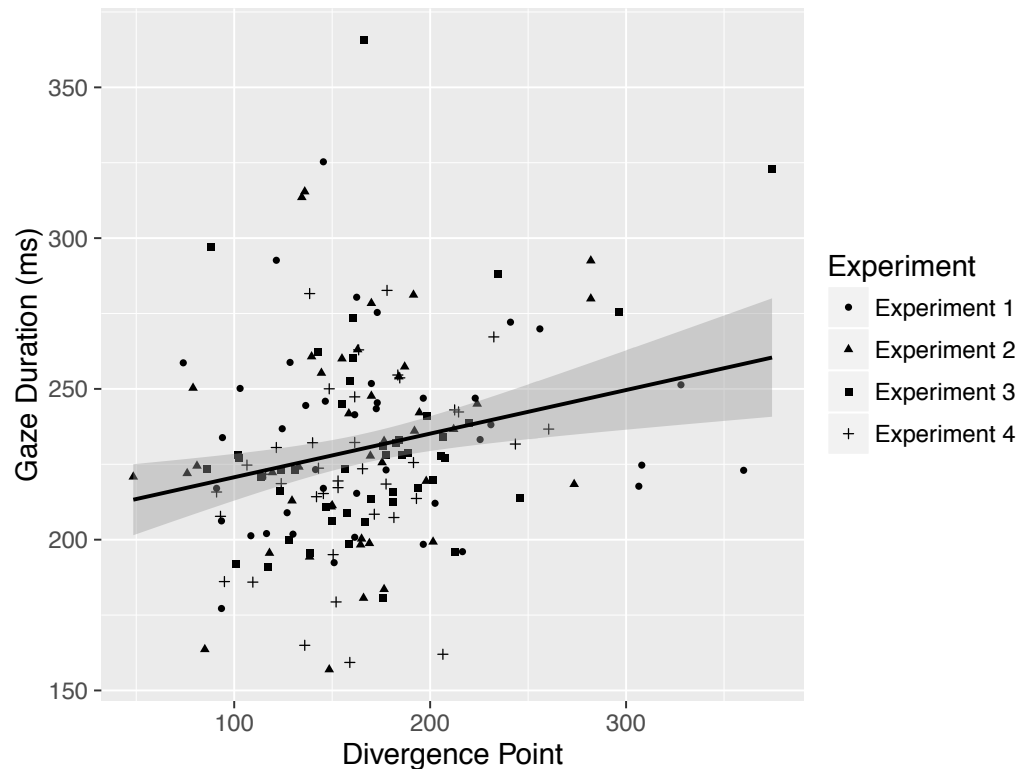


Figure 2.11. Relationship between mean gaze duration for the correct target condition (i.e., identical preview condition for Experiments 3 & 4) and divergence point estimate for each subject. Each point represents an individual subject and the shape of the point represents the experiment that subject participated in. The regression line and 95% confidence interval are represented by the black line and surrounding grey band respectively.

The directionality of this relationship is less clear. It could be that subjects who generate phonological codes earlier (i.e., assembled codes) are able to use those codes to help them identify words—leading to shorter gaze durations.

¹¹ The pattern held for total time as well, $b = 0.17$, $t(167) = 2.73$, $p = .007$, $R^2 = 0.04$, $F(1, 167) = 7.43$, $p = .007$, demonstrating that the effect in gaze duration was not due to different reading strategies where shorter first pass times resulted in compensatory regressions and longer second pass times (e.g., “risky” reading strategies, O’Regan, 1990; Rayner, Reichle, Stroud, Williams, & Pollatsek, 2006).

Alternatively, it could be that subjects who are able to more rapidly identify the meaning of words, are able to retrieve the associated phonological code more rapidly (i.e., addressed codes). The fact that the pattern remains the same for studies using pseudohomophones (i.e., Experiments 2 and 4, see Figure 2.12) suggests that the locus of the effect is pre-lexical—that subjects who are able to rapidly assemble phonological codes, are able to use those codes to help them identify words more quickly.

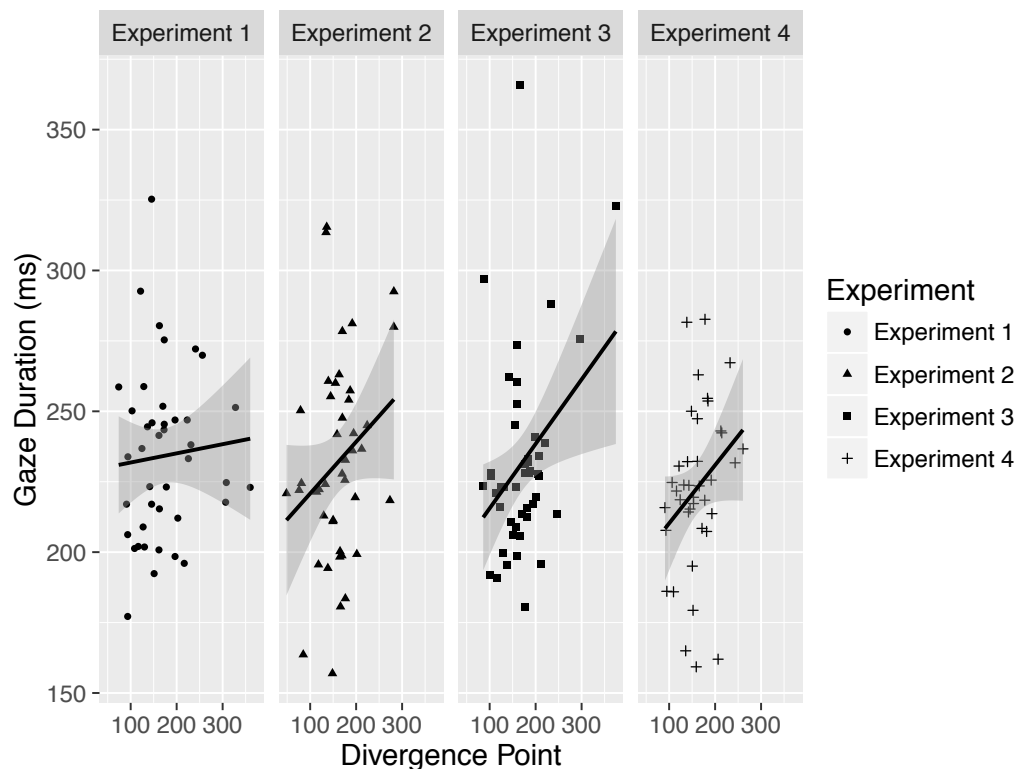


Figure 2.12. Relationship between mean gaze duration and divergence point estimate for each subject, split by experiment. Each point represents an individual subject and the shape of the point represents the experiment that subject participated in. The regression lines and 95% confidence intervals are represented by the black lines and surrounding grey bands respectively. Due to reduced power in each individual analysis, the divergence point only significantly predicted mean gaze duration in Experiment 3 ($b = 0.23$, $t(44) = 2.43$, $p = .02$, $R^2 = 0.12$, $F(1, 44) = 5.91$, $p = .02$), all other $ps > .07$.

Conclusion

Across four experiments, survival analyses revealed that effects of phonological coding emerge within 160-173 ms during normal silent reading. Furthermore, the time course was the same for the processing of phonologically related words (or phonologically related word previews) and phonologically related non-words (or phonologically related non-word previews), providing no evidence for the idea that necessarily assembled codes (i.e., codes for non-words without lexical entries) come online later than codes for real words. Indeed, the similar time course for both types of codes and the fact that across studies, earlier code generation was associated with more rapid word identification, suggests that the early effects observed are due to the generation of pre-lexical assembled phonological codes, which may in turn be used to help readers identify words.

Acknowledgements

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Chapter 2, in full is currently being prepared for submission for publication of the material. The dissertation author was the sole investigator of this paper.

Appendix

Complete set of stimuli including the three sentence versions (a,b,c) for each set of critical words. Each sentence is shown with all possible targets (previews for Experiments 2 and 4) separated by forward slashes (correct target/phonologically related/orthographic control). In Experiments 1 and 3 the phonologically related and orthographic controls were real words (homophones and orthographic control words) and in Experiments 2 and 4 the phonologically related and orthographic controls were non-words (pseudohomophones and orthographic control non-words). In Experiments 3 and 4, the pseudohomophones and orthographic control non-words were presented as parafoveal previews for the correct target.

Exp.	Item	Sentence
1 & 3	1a	After dropping her toy, the baby began to loudly bawl/ball/bail and throw a tantrum.
1 & 3	1b	After skinning his knee, the boy started to uncontrollably bawl/ball/bail and make quite the scene.
1 & 3	1c	After her boyfriend broke up with her, the girl began to hysterically bawl/ball/bail in the middle of the hallway.
1 & 3	2a	People who live inland never get to see the beautiful beach/beechn/bench unless they travel far.
1 & 3	2b	The cove hid a sheltered, sandy beach/beechn/bench without very many waves.
1 & 3	2c	The surfers traveled to the world famous beach/beechn/bench where the waves were very large.
1 & 3	3a	In the cool breeze, she pulled on a sweater to cover her completely bare/bear/beat shoulders and keep her warm.
1 & 3	3b	Since he didn't wear shoes, he had mud all over his dirty bare/bear/beat feet after playing by the pond.
1 & 3	3c	Everything echoed in the large room since the walls were totally bare/bear/beat and there wasn't any furniture.
1 & 3	4a	The veggie garden had only one purple beet/beat/belt and three carrots.
1 & 3	4b	The deep red vegetable smoothie contained fresh beet/beat/belt juice and other veggies.
1 & 3	4c	He learned that the sliced purple vegetable was an unusual beet/beat/belt that only grew in a few places.
1 & 3	5a	As the scuba diver dove deeper, the water became a darker blue/blew/bled and it became difficult to see.
1 & 3	5b	The gorgeous lake was shade of bright blue/blew/bled shining in the sun.
1 & 3	5c	In the afternoon, the sky was a shade of light blue/blew/bled with white fluffy clouds.
1 & 3	6a	Because Daniela had nothing to do, she would get extremely bored/board/bound during summer session.

- 1 & 3 6b Despite having many toys, the children were complaining that they were really bored/board/bound and that there was nothing to do.
- 1 & 3 6c Airplanes have televisions on each seat to keep people from getting bored/board/bound during really long flights.
- 1 & 3 7a Because the task was really exhausting, it was necessary to take several breaks/brakes/breath in order to avoid fatigue.
- 1 & 3 7b In addition to an hour long lunch, Jared could also take two short breaks/brakes/breath anytime during his shift.
- 1 & 3 7c When solving difficult problems, it helps to take frequent breaks/brakes/breath to clear your mind and refocus.
- 1 & 3 8a He woke up in a complete daze/days/dare and forgot about his meeting.
- 1 & 3 8b The hard hit to the head left Tim in a strange daze/days/dare for a couple of minutes.
- 1 & 3 8c When he missed his turn, he realized that he was driving in a total daze/days/dare and needed to pay better attention.
- 1 & 3 9a The watch he inherited from his grandfather was extremely dear/deer/deep to him, so he always kept it in his safe.
- 1 & 3 9b Since her grandmother gave her the ring, it was really dear/deer/deep to her as a treasured heirloom.
- 1 & 3 9c The letters her husband sent while he was deployed were especially dear/deer/deep to her, and she didn't share them with anyone.
- 1 & 3 10a The only two republican committee members always dissent/descent/disrupt from the democratic majority.
- 1 & 3 10b The company's controversial new policy led to strong dissent/descent/disrupt among the employees.
- 1 & 3 10c The politician's unpopular decisions evoked fierce dissent/descent/disrupt from members of the community.
- 1 & 3 11a According to the lease, their rent check was always due/dew/den on the first day of the month.
- 1 & 3 11b The final assignment for one class was unfortunately due/dew/den the same day as all of her exams.
- 1 & 3 11c Tracy went into labor even though her baby wasn't due/dew/den for another two weeks.
- 1 & 3 12a To cover her gray hairs, she bought the darkest permanent dye/die/due that the store sold.
- 1 & 3 12b Kristen decided to become a red-head, but the cheap dye/die/due she bought wasn't bright enough to cover her natural color.
- 1 & 3 12c Food coloring is a variety of edible dye/die/due that can be used in baking.
- 1 & 3 13a Instead of traveling all the way around the lake, they decided to take the quick ferry/fairy/fiery directly across it instead.

- 1 & 3 13b In Seattle, both people and cars can travel across the water in a large ferry/fairy/fiery that runs every hour.
- 1 & 3 13c To get to Catalina Island you can take a small ferry/fairy/fiery from the mainland.
- 1 & 3 14a War sometimes forces people to quickly flee/flea/flew their native countries.
- 1 & 3 14b The loud gunshot made many people hastily flee/flea/flew the dangerous scene.
- 1 & 3 14c The doors locked behind the thief so he couldn't flee/flea/flew the scene of the crime.
- 1 & 3 15a The basketball player was ejected after receiving his fifth foul/fowl/foal of the championship game.
- 1 & 3 15b Even though the cheese had a strong, foul/fowl/foal odor, it was not spoiled.
- 1 & 3 15c They warned the teens to not use offensive, foul/fowl/foal language around the kids.
- 1 & 3 16a The northern forest had the tallest fir/fur/fin trees she had ever seen.
- 1 & 3 16b The ground outside Alana's window was covered in needles from the short fir/fur/fin tree in her backyard.
- 1 & 3 16c The family's Christmas tree was the greenest fir/fur/fin that they found on the lot.
- 1 & 3 17a Her strained Achilles tendon resulted in a swollen heel/heal/hell and made it hard to walk.
- 1 & 3 17b Because she had to wear dress shoes, Kali had a sore and tired heel/heal/hell by the end of the day.
- 1 & 3 17c While dancing, Sara broke her shoe's heel/heal/hell and had to leave.
- 1 & 3 18a Since they were whispering, Emma could barely hear/here/head what her friend was saying.
- 1 & 3 18b Speak loud and clearly so people can easily hear/here/head you even in the back.
- 1 & 3 18c With the megaphone, everyone could clearly hear/here/head the instructions being given.
- 1 & 3 19a The pirates found the hidden loot/lute/lull in the bottom of the cove.
- 1 & 3 19b The Vikings plundered the city and took the prized loot/lute/lull back to their village.
- 1 & 3 19c The prisoners of war took the precious loot/lute/lull back to their country as revenge.
- 1 & 3 20a Because his house was a mess after the party, he had to hire a professional maid/made/make to help clean it up.
- 1 & 3 20b They had to wait for their hotel room to be cleaned by the elderly maid/made/make before they could check in.

- 1 & 3 20c Since she loved cleaning houses, Rachel thought she would make a wonderful maid/made/make and quit her other job.
- 1 & 3 21a The boy's job was to deliver mail/male/mate every morning in his neighborhood.
- 1 & 3 21b She was surprised when a package arrived in the daily mail/male/mate with her name on it.
- 1 & 3 21c She received coupons and letters in yesterday's mail/male/mate but only catalogues today.
- 1 & 3 22a After making four burger patties, Charlie put the rest of the unused meat/meet/melt back in the fridge.
- 1 & 3 22b The steakhouse was known for the quality of their fresh meat/meet/melt and won many awards.
- 1 & 3 22c The new restaurant used only locally sourced vegetables and hormone-free, organic meat/meet/melt in all of their dishes.
- 1 & 3 23a Since she enjoyed many subjects, Annie majored in human biology and got a double minor/miner/mixer in psychology and sociology.
- 1 & 3 23b The spooky song was composed in an eerie minor/miner/mixer key for greater effect.
- 1 & 3 23c Although there were no major oversights, the investigation revealed several minor/miner/mixer errors in procedure.
- 1 & 3 24a Walking by the pier, Jamie cut her foot on the shell of a small mussel/muscle/muster hidden in the water.
- 1 & 3 24b The sailors checked their boat to see if an invasive, black zebra mussel/muscle/muster had attached itself.
- 1 & 3 24c The fisherman had a hard time prying open the stubborn mussel/muscle/muster with just his knife.
- 1 & 3 25a Since she avoids the sun, her complexion is really pale/pail/pair and she burns easily.
- 1 & 3 25b Right before fainting, the girl's face became extremely pale/pail/pair and she got really dizzy.
- 1 & 3 25c The red-head's freckles were easy to spot against her pretty pale/pail/pair skin and clear complexion.
- 1 & 3 26a The bird flew right into the window pane/pain/paid since it was so clean.
- 1 & 3 26b The beautiful glass door had a thick pane/pain/paid of glass so that no one could break in.
- 1 & 3 26c The baseball shattered the window's glass pane/pain/paid costing the family a lot of money.
- 1 & 3 27a To stick the pictures to her poster, she used a tacky paste/paced/packs that was guaranteed to hold.
- 1 & 3 27b To thicken the sauce, the chef grabbed a tube of tomato paste/paced/packs and squeezed it into the pot.
- 1 & 3 27c They mixed the water and powder together to form a thick, sticky paste/paced/packs to use for their art project.

- 1 & 3 28a The hippie movement in the 1960's wanted world peace/piece/place to become a reality.
- 1 & 3 28b Olive branches and white doves are the classic peace/piece/place symbols around the world.
- 1 & 3 28c After the surrender, the commanders met to sign the famous peace/piece/place treaty to end the war.
- 1 & 3 29a The shoe rack was designed to fit several pairs/pears/pours without any trouble.
- 1 & 3 29b After washing his socks, there were so many mismatched pairs/pears/pours in the drawer.
- 1 & 3 29c After she got her ears pierced, Kylee's mom bought her several pairs/pears/pours of new earrings.
- 1 & 3 30a The lighthouse was on the end of the wooden pier/peer/pies at their favorite lake.
- 1 & 3 30b The Santa Monica beach has a famous pier/peer/pies with shops and attractions.
- 1 & 3 30c Fishermen often fish from the edge of the sturdy pier/peer/pies and sell their catch at the farmer's market.
- 1 & 3 31a The picky child insisted on eating her hamburger completely plain/plane/plant with no toppings on it.
- 1 & 3 31b The animals were grazing on the grassy plain/plane/plant when a predator approached.
- 1 & 3 31c Without decorations, the dorm was really plain/plane/plant and boring looking.
- 1 & 3 32a Santa clause lives in the north pole/poll/poke where it's really cold.
- 1 & 3 32b At the sporting goods store, Dan bought a new fishing pole/poll/poke and some bait for his weekend trip.
- 1 & 3 32c Instead of stairs, firefighters use a metal pole/poll/poke to get down quicker.
- 1 & 3 33a Carrie knew that most of the people at the shelter were unemployed and extremely poor/pore/poem so she brought them all small gifts.
- 1 & 3 33b The family couldn't afford to buy many presents because they were really poor/pore/poem and had many other expenses.
- 1 & 3 33c Because they are not well-paid, many teachers are quite poor/pore/poem even though they work so hard.
- 1 & 3 34a The misbehaving student was sent to the strict principal/principle/primarily as his punishment.
- 1 & 3 34b The student scored so high in testing that the proud principal/principle/primarily presented her with an award.
- 1 & 3 34c All the teachers had a meeting with the upset principal/principle/primarily to talk about changes.

- 1 & 3 35a Yesterday's wet weather consisted of heavy rain/rein/ruin and hail, so we stayed inside.
- 1 & 3 35b He needed to pack an umbrella since the forecast called for consistent rain/rein/ruin over the weekend of his trip.
- 1 & 3 35c There was a terrible drought because there had been very little rain/rein/ruin for the past few months.
- 1 & 3 36a Since it was his first time on his bike without training wheels, the boy slowly rode/road/rude around his neighborhood.
- 1 & 3 36b Since he was too little to sit in the front seat, he always rode/road/rude in the back seat of the car.
- 1 & 3 36c The shinning knight mounted his horse and quickly rode/road/rude off into the distance toward the castle.
- 1 & 3 37a The actress got the leading role/roll/rule for the play.
- 1 & 3 37b During the first day of his new job, his boss explained his important role/roll/rule in the corporation.
- 1 & 3 37c The famous actor won an Oscar for best actor in a supporting role/roll/rule for his part in the popular movie.
- 1 & 3 38a The farmer's corn grew in long straight rows/rose/room that stretched across his field.
- 1 & 3 38b The houses in the new development were built in neat little rows/rose/room with very small yards.
- 1 & 3 38c Prior to the ceremony, the wedding planner set up the chairs in short rows/rose/room and placed flowers along the edge of each one.
- 1 & 3 39a On holiday weekends, car dealerships often have amazing sales/sails/salts and special offers.
- 1 & 3 39b On Black Friday there are tons of great sales/sails/salts on most items.
- 1 & 3 39c He waited for the store to have one of its famous sales/sails/salts before buying the expensive television he wanted.
- 1 & 3 40a Fishermen have to sail far into the great sea/see/set to catch large fish.
- 1 & 3 40b The couple sat in their beach chairs, enjoying the gentle sea/see/set breeze on their faces.
- 1 & 3 40c The salty water revealed that the body of water was actually an inland sea/see/set rather than a lake.
- 1 & 3 41a Reincarnation is the belief that all people's souls/soles/sorts are reborn in an endless cycle.
- 1 & 3 41b Christians believe that after death, believers' souls/soles/sorts go to heaven for eternity.
- 1 & 3 41c Followers of some religions believe that their dead relatives' souls/soles/sorts can visit the living.
- 1 & 3 42a They needed to install a wheelchair ramp since there was a single stair/stare/state up to the front door.

- 1 & 3 42b Climbing up to the second floor, Tyler tripped on the final stair/stare/state and fell on his face.
- 1 & 3 42c The first step up was a doozy since the bottom stair/stare/state was broken and unsafe.
- 1 & 3 43a The vampire hunter used a wooden stake/steak/stale to kill Count Dracula.
- 1 & 3 43b The witch was burned at the central stake/steak/stale for everyone else to see.
- 1 & 3 43c To help support the delicate young tree, the gardener tied it to a sturdy stake/steak/stale so that it wouldn't get damaged.
- 1 & 3 44a The baseball player stepped off first base to try and sneakily steal/steel/steam second base before the pitcher noticed.
- 1 & 3 44b In capture the flag, you have to try to quickly steal/steel/steam the flag from the other team.
- 1 & 3 44c The thief managed to sneak in to the house and quietly steal/steel/steam all of the jewelry and other valuables.
- 1 & 3 45a They were surprised when they were upgraded from a standard room to a fancy suite/sweet/spite with a great view of the skyline.
- 1 & 3 45b When staying in hotels, celebrities are known to book the most expensive suite/sweet/spite that is available.
- 1 & 3 45c Because they needed multiple rooms, the family decided to book a large suite/sweet/spite so they could all sleep comfortably.
- 1 & 3 46a Compared to their well-behaved daughter, their rambunctious son/sun/sin was completely out of control.
- 1 & 3 46b The father always took his athletic son/sun/sin to hockey practice.
- 1 & 3 46c For his sixteenth birthday, Todd bought his youngest son/sun/sin a brand new car.
- 1 & 3 47a The really big alligator had the longest tail/tale/talk that the guide had ever seen.
- 1 & 3 47b Many monkeys have a prehensile tail/tale/talk so that they can grip tree branches.
- 1 & 3 47c Before the competition, the rider decided to braid her horse's tail/tale/talk and put ribbons in its mane.
- 1 & 3 48a Jim assessed the direction of the wind as he placed his ball on the first tee/tea/ten and got ready to swing.
- 1 & 3 48b When golfing, it is a good idea to carry an extra tee/tea/ten in your pocket in case the first gets lost.
- 1 & 3 48c The golfer placed his ball on the small, white tee/tea/ten and stepped back to plan his stroke.
- 1 & 3 49a To secure objects in the back of his truck during the move, Andrew tightly tied/tide/tire them to the sides of his truck.
- 1 & 3 49b When she was done sewing, she grabbed the end of the thread and carefully tied/tide/tire a knot to secure it.

- 1 & 3 49c During the race, his shoelaces came undone, so he quickly tied/tide/tire them and kept running.
- 1 & 3 50a If you park on a red curb, the city will definitely tow/toe/toy your car away.
- 1 & 3 50b When her car broke down, she had to call a company to quickly tow/toe/toy her car to the shop.
- 1 & 3 50c Even though she was parked illegally, Dory didn't believe that the cops would actually tow/toe/toy her car to impound.
- 1 & 3 51a Far from being humble, the girl was extremely vain/vein/veil and very shallow.
- 1 & 3 51b Mark was always boasting about his accomplishments and making other vain/vein/veil remarks about himself.
- 1 & 3 51c Although she knew that she was very pretty, she was never vain/vein/veil nor boastful about her appearance.
- 1 & 3 52a Jenny wore a belt to emphasize her narrow waist/waste/worst at the party.
- 1 & 3 52b She had an hourglass body shape with a small waist/waste/worst and long legs.
- 1 & 3 52c The fancy dress had a high empire waist/waste/worst to make one look skinnier.
- 1 & 3 53a They decided to stay on vacation for an extra week/weak/weed because the weather was so perfect.
- 1 & 3 53b For spring break, they were only off for one short week/weak/weed before heading back to school.
- 1 & 3 53c Freshmen generally have orientation during the first week/weak/weed of their college career.
- 1 & 3 54a The glass blower was happy to sell his expensive wares/wears/waves to patrons in the marketplace.
- 1 & 3 54b The group of artists set up a table to display their various wares/wears/waves at the large public market.
- 1 & 3 54c The pottery collector had an impressive collection of ancient wares/wears/waves from Central America.
- 1 & 3 55a Since she wasn't really excited about the party, she couldn't decide whether/weather/whereas or not she should go.
- 1 & 3 55b It was the jury's job to determine whether/weather/whereas or not he was guilty.
- 1 & 3 55c She liked the computer, but it was really expensive, so she couldn't choose whether/weather/whereas or not to buy it.
- 1 & 3 56a There were so many flavors that Tony couldn't decide which/witch/watch one to try first.
- 1 & 3 56b Because all of the dogs were so cute, Amy couldn't choose which/witch/watch one she wanted to take home.
- 1 & 3 56c The boy didn't study because he thought he could guess which/witch/watch answers were correct.

- 2 & 4 1a Janet sometimes forgets to use a timer and lets her cookies bake/baik/balt for too long in the oven.
- 2 & 4 1b Melissa owns a bakery and will often bake/baik/balt bread for her neighbors.
- 2 & 4 1c Kim's oven is sparkling clean because she doesn't bake/baik/balt in it at all.
- 2 & 4 2a After he cut his arm, he quickly wrapped it so that he wouldn't bleed/blead/blerd on any of his clothes.
- 2 & 4 2b Although he boy scraped his knee falling off his bike, it didn't bleed/blead/blerd and he only cried a little.
- 2 & 4 2c Paper cuts hurt a lot even though they barely bleed/blead/blerd and heal quite quickly.
- 2 & 4 3a The man put on his life jacket when the waves began to wash over his small boat/bote/bofe filling it with water.
- 2 & 4 3b The man stored his poles and bait in his fishing boat/bote/bofe so he wouldn't forget them.
- 2 & 4 3c All the oars disappeared from their boat/bote/bofe when they weren't paying attention.
- 2 & 4 4a The anatomy class had to identify different skeletal bones/boans/borvs for the final test.
- 2 & 4 4b They knew they'd uncovered an ancient graveyard when they found human bones/boans/borvs buried in the field.
- 2 & 4 4c The archaeologists found huge dinosaur bones/boans/borvs in the previously unexplored area.
- 2 & 4 5a Milk sprayed everywhere when the dog knocked the cereal bowl/bole/boke off the coffee table.
- 2 & 4 5b She tossed lettuce in the salad bowl/bole/boke to make her signature dish.
- 2 & 4 5c To make brownies, Jamie poured the ingredients into a mixing bowl/bole/bokel and began to stir.
- 2 & 4 6a Lisa put her hair into a thick braid/brade/bralk for her graduation party.
- 2 & 4 6b Now that her hair is long, Kelly's little sister wants to learn how to French braid/brade/bralk her hair by herself.
- 2 & 4 6c Her layered hair was so difficult to style into an orderly braid/brade/bralk that she gave up.
- 2 & 4 7a The psychology class was studying the human brain/brane/broin and the nervous system.
- 2 & 4 7b The new neurosurgeon has never performed such a complicated brain/brane/broin surgery on a real person before.
- 2 & 4 7c Einstein was known for his large brain/brane/broin and clever theories.
- 2 & 4 8a The witch rode on a wooden broom/brume/brame across the moon in the sky.

- 2 & 4 8b To sweep up the dog hair, Jen used an ancient broom/brume/brame she found in the garage.
- 2 & 4 8c While sweeping, Karen screamed and hit a mouse with the heavy broom/brume/brame when it ran over her foot.
- 2 & 4 9a The boxes fell off the truck because the rusty chain/chayn/charn finally broke apart.
- 2 & 4 9b The ships anchor is attached with a heavy chain/chayn/charn so it won't drift away.
- 2 & 4 9c Adam wore several rings and a thick golden chain/chayn/charn around his neck.
- 2 & 4 10a Because he couldn't win honestly, the boy decided that he would cheat/cheet/chelt during the game and win the prize.
- 2 & 4 10b To do well without studying, Rachel would often cheat/cheet/chelt off of other students on exams.
- 2 & 4 10c The paranoid man was worried that his girlfriend might cheat/cheet/chelt on him with her coworker.
- 2 & 4 11a The miners shoveled the heavy coal/cole/cobe out of the path.
- 2 & 4 11b For Christmas, Kyle was worried that he would get a lump of black coal/cole/cobe in his stocking.
- 2 & 4 11c The old locomotive burned coal/cole/cobe to power its engine.
- 2 & 4 12a The little boy asked for extra whipped cream/creem/crelm on his apple pie.
- 2 & 4 12b When making icing, Mary likes to use heavy cream/creem/crelm for its consistency.
- 2 & 4 12c The baker filled the donuts with pastry cream/creem/crelm and the kids loved them.
- 2 & 4 13a Using the coupons, Mary got a great deal/deel/derl on the outfit she wanted.
- 2 & 4 13b Tom looked through ads to find a better deal/deel/derl for a lawnmower.
- 2 & 4 13c On black Friday, the store offered their biggest deal/deel/derl of the entire year.
- 2 & 4 14a Their team usually won, so it was hard for him to accept defeat/defeet/defert in today's game.
- 2 & 4 14b Napoleon's army suffered a horrible defeat/defeet/defert at the Battle of Waterloo.
- 2 & 4 14c The soccer game ended with a crippling defeat/defeet/defert for the home team.
- 2 & 4 15a The class examined the painting to see the intricate detail/detale/detarg on the woman's clothing.
- 2 & 4 15b She was yelled at for overlooking a minor detail/detale/detarg in the experimental protocol.
- 2 & 4 15c Her mother demanded to know every little detail/detale/detarg about the wedding plans.

- 2 & 4 16a Maddie woke up terrified because she had a scary dream/dreem/dreilm in which she was being chased.
- 2 & 4 16b Becoming a star on Broadway was Katherine's biggest dream/dreem/dreilm ever since she was a little girl.
- 2 & 4 16c Pat woke up from an extremely weird dream/dreem/dreilm in which he was a fish.
- 2 & 4 17a The top of the volcano exploded in a fiery eruption/erupshun/erpluion as everyone nearby was evacuated.
- 2 & 4 17b The island formed as a result of a volcanic eruption/erupshun/erpluion hundreds of years ago.
- 2 & 4 17c The molten lava was from the recent eruption/erupshun/erpluion that damaged their town.
- 2 & 4 18a She always studies hard so she will never fail/fale/falm a test in that class.
- 2 & 4 18b After getting a terrible grade on her final, Cam was worried she would fail/fale/falm the entire course.
- 2 & 4 18c Even though the test was hard, he was confident that he wouldn't fail/fale/falm and might even get an A.
- 2 & 4 19a The blind person would use her fingers to carefully feel/feal/ferl the Braille on her book.
- 2 & 4 19b After getting food poisoning, Ray was worried that he would never feel/feal/ferl like eating food again.
- 2 & 4 19c Crystal took the medicine and hoped that she would feel/feal/ferl better in the morning.
- 2 & 4 20a Jeff's poor dog came home covered with pesky fleas/fleze/flern after running through the field.
- 2 & 4 20b Their new apartment was infested with small fleas/fleze/flern from the previous owner's cat.
- 2 & 4 20c The vet explained that the bites were from annoying fleas/fleze/flern that were biting the dog.
- 2 & 4 21a Because the hot tub was dirty, the water was covered with a layer of thick foam/fome/forv that made her not want to get in.
- 2 & 4 21b Shannon's new mattress had a layer of memory foam/fome/forv on the top for extra comfort.
- 2 & 4 21c As she stood in the shoreline, she saw the bubbly foam/fome/forv from the waves touch her feet.
- 2 & 4 22a Mark spent all day watching the football game/gaim/garm with his friends.
- 2 & 4 22b On Friday night, the roommates decided to play a board game/gaim/garm and order pizza.
- 2 & 4 22c Jenny got tickets to the basketball game/gaim/garm for Friday night.
- 2 & 4 23a The fundraisers reached their immense goal/gole/garl of raising five thousand dollars.

- 2 & 4 23b The hockey player scored an impressive goal/gole/garl in the last second of the game
- 2 & 4 23c Messi scored the winning goal/gole/garl needed to advance.
- 2 & 4 24a If she studied hard, Amy knew she could get a better grade/graïd/grald in biology class.
- 2 & 4 24b After he forgot to study, Ben received the worst grade/graïd/grald ever in his lab class.
- 2 & 4 24c The first year of high school is ninth grade/graïd/grald and the last is twelfth.
- 2 & 4 25a He watered the lawn often to keep the grass green/grean/greln even during summer.
- 2 & 4 25b They drove through the intersection when the light turned green/grean/greln and all of the traffic had cleared.
- 2 & 4 25c The young grasshopper was a bright green/grean/greln color and very cute.
- 2 & 4 26a Last summer, Amy fainted after running outside in the oppressive heat/heet/hept and humid weather.
- 2 & 4 26b The bonfire flames were so high that we could feel the fire's heat/heet/hept from twenty feet away.
- 2 & 4 26c The ice cream rapidly melted in the summer heat/heet/hept and dripped all over his hands.
- 2 & 4 27a Calvin tripped and fell into a large hole/hoal/hofe in the ground.
- 2 & 4 27b The nature guide told them that a gopher lived in the small hole/hoal/hofe by the edge of the trail.
- 2 & 4 27c Alice fell down the rabbit hole/hoal/hofe and into Wonderland.
- 2 & 4 28a The children were glad to return home/hoam/horv after the baseball game.
- 2 & 4 28b When their grandma got old, they put her in a nursing home/hoam/horv so she could be taken care of.
- 2 & 4 28c Because of his curfew, John had to drive home/hoam/horv before midnight or he'd get in trouble.
- 2 & 4 29a During the earthquake, many inmates escaped from the county jail/jale/jaln when a wall fell.
- 2 & 4 29b The prisoner was relocated to a distant jail/jale/jaln on an island.
- 2 & 4 29c The burglar was arrested and taken to a nearby jail/jale/jaln to serve out his sentence.
- 2 & 4 30a He tried to make her laugh by telling a funny joke/joak/jonk about some of their friends.
- 2 & 4 30b The whole audience was laughing after the comedian told a hilarious joke/joak/jonk to end his routine.
- 2 & 4 30c Henry was fired for telling a dirty joke/joak/jonk to a female coworker.
- 2 & 4 31a Even though they failed many times, the kids decided they would keep/keap/kerp trying until they succeeded.

- 2 & 4 31b Since they found the dog's rightful owner, Mary couldn't keep/keap/kerp him as she had been hoping.
- 2 & 4 31c When the boy found the stray kitten, he asked his mother if he could keep/keap/kerp it as a new pet.
- 2 & 4 32a They took their old fishing boat out on the large lake/laik/lask near their vacation home.
- 2 & 4 32b Their family cottage sat on the edge of a serene lake/laik/lask where the kids spent time swimming and fishing.
- 2 & 4 32c While camping, Sheryl drank water from a sparkling lake/laik/lask and ended up getting sick.
- 2 & 4 33a Since Tom was almost done with school, he only signed a one-year lease/leese/lerse on his rental house.
- 2 & 4 33b The apartment manager hoped he could get her to sign the landlord's lease/leese/lerse without having to lower the price.
- 2 & 4 33c After seeing the amazing unit, the couple sat down to sign the apartment lease/leese/lerse as quickly as possible.
- 2 & 4 34a Because their dog was in training, they kept him on a tight leash/leesh/lemsh so he would learn not to pull.
- 2 & 4 34b Jenna's dog gets really excited to go for a walk whenever she grabs his bright leash/leesh/lemsh from the hall closet.
- 2 & 4 34c Because their dog pulled a lot on walks, they had to buy a thick leash/leesh/lemsh so it wouldn't break.
- 2 & 4 35a The class bully was know for being extremely mean/mene/marn to the younger kids.
- 2 & 4 35b Cinderella's evil stepmother was always mean/mene/marn to her and made her clean.
- 2 & 4 35c The strict principal was unfair and really mean/mene/marn to all of the students.
- 2 & 4 36a Patricia broke her freshly manicured finger nail/nale/noil trying to open a jar of peanut butter.
- 2 & 4 36b She stepped on a sharp nail/nale/noil while cleaning the garage.
- 2 & 4 36c He was careful not to step on the rusty nail/nale/noil on the floor of the shack.
- 2 & 4 37a Morgan's brother was audited by the IRS because he hadn't paid/pade/pawd his taxes for years.
- 2 & 4 37b The family went out for dinner and a generous stranger paid/pade/pawd their entire bill.
- 2 & 4 37c After struggling all season, the team's dedication and hard work finally paid/pade/pawd off when they won the championship.
- 2 & 4 38a Stephanie realized she left her cellular phone/phoan/phand at the office.
- 2 & 4 38b Jeff didn't want to answer the ringing phone/phoan/phand because he was worried it would be his boss.

- 2 & 4 38c The lost child managed to call her parents on a public phone/phoan/phand by the side of the road.
- 2 & 4 39a The boy was so hungry he ate a whole plate/playt/plard of chicken wings.
- 2 & 4 39b To avoid doing dishes after dinner, Mark decided to use a paper plate/playt/plard that he could just throw away.
- 2 & 4 39c She arranged the appetizers on a large plate/playt/plard and placed them on the buffet.
- 2 & 4 40a Because Jane forgot her umbrella, she had to run through heavy rain/rane/ranz to get back to her apartment.
- 2 & 4 40b During monsoon season, there was torrential rain/rane/ranz almost every day.
- 2 & 4 40c The couple was drenched after running through the pouring rain/rane/ranz to catch a cab.
- 2 & 4 41a While diving, Stacey saw many fish around a coral reef/refe/relf in the clear water.
- 2 & 4 41b The island is surrounded by a barrier reef/refe/relf in the warm water.
- 2 & 4 41c Robert couldn't wait to snorkel the island's hidden reef/refe/relf and see the rare coral.
- 2 & 4 42a Billy's car got really dirty after driving on the muddy road/roed/rond that ran through the woods.
- 2 & 4 42b The child felt carsick as they drove along the windy road/roed/rond on their way home.
- 2 & 4 42c She spilled hot coffee on her lap driving along the bumpy road/roed/rond on her way to work.
- 2 & 4 43a On Mother's Day, he brought his mother a beautiful rose/roze/rofe and some chocolates.
- 2 & 4 43b Karen's boyfriend bought her a crimson rose/roze/rofe for Valentine's day.
- 2 & 4 43c At the burial, the members of his family each laid a single rose/roze/rofe on his grave.
- 2 & 4 44a Someone broke into the bank and robbed the locked safe/saif/salf without getting caught.
- 2 & 4 44b The money was stashed away in a heavy safe/saif/salf in her basement.
- 2 & 4 44c Built into the wall of Cindy's home was a hidden safe/saif/salf for her to put her valuables.
- 2 & 4 45a They did everything they could, but the doctors couldn't save/saiv/sarv him after the terrible accident.
- 2 & 4 45b Jeff lost all his work on the essay because he didn't save/saiv/sarv before the power went out.
- 2 & 4 45c While playing beach volleyball, she dove to gracefully save/saiv/sarv the ball before it hit the sand.

- 2 & 4 46a At the movie theater it is sometimes hard to find the perfect seat/seet/sest , but Sally finally succeeded.
- 2 & 4 46b When flying, Jen always picks the window seat/seet/sest on the airplane.
- 2 & 4 46c Before driving, she always adjusts the driver's seat/seet/sest to accommodate her height.
- 2 & 4 47a Because of his insomnia, Caleb couldn't sleep/sleap/slerp even though he was tired.
- 2 & 4 47b Because of her loud neighbors, Amy couldn't get enough sleep/sleap/slerp to stay awake the next day.
- 2 & 4 47c Monica was tired because she got very little sleep/sleap/slerp and didn't drink any coffee.
- 2 & 4 48a The fire filled the air with thick, black smoke/smoak/smold that could be seen for miles.
- 2 & 4 48b The old truck expelled a lot of thick smoke/smoak/smold from its exhaust pipe.
- 2 & 4 48c After the fire was extinguished, the air was still filled with heavy smoke/smoak/smold rising from the embers.
- 2 & 4 49a The shirt was so dirty that even the toughest soap/sope/sorp could not get all of the stains out.
- 2 & 4 49b The bathroom smells nice because of the fragrant soap/sope/sorp by the sink.
- 2 & 4 49c After handling the garbage, John always washes his hands with antibacterial soap/sope/sorp and scrubs extra hard.
- 2 & 4 50a James burned his finger on the kitchen stove/stoav/stoze and had to put it in ice.
- 2 & 4 50b Her new apartment had a four-burner electric stove/stoav/stoze that would make cooking very easy.
- 2 & 4 50c Tiffany left the soup boiling on the small stove/stoav/stoze for too long.
- 2 & 4 51a After the game, they congratulated the winning team/teme/telm on their unexpected victory.
- 2 & 4 51b Ron is wearing the jersey with the colors of his favorite sports team/teme/telm on the logo.
- 2 & 4 51c Alexa made it on the varsity soccer team/teme/telm after her first tryout.
- 2 & 4 52a Gary and his friends hiked up the mountain trail/trale/tralb early yesterday morning.
- 2 & 4 52b They went for a long walk on the winding trail/trale/tralb by the river.
- 2 & 4 52c Sally and Pete walked along the hiking trail/trale/tralb in the national park.
- 2 & 4 53a During her trip to Japan, Angelina got to ride a bullet train/trane/trawp for the very first time.

- 2 & 4 53b To cut a few hours off of her trip, Janice booked a ticket on the express train/trane/trawp that made fewer stops.
- 2 & 4 53c They got stopped at the railroad crossing while a long freight train/trane/trawp passed through town.
- 2 & 4 54a Because it was his birthday, the boy got to eat a special treat/treet/trept with his lunch.
- 2 & 4 54b The dog knows that it will get a delicious treat/treet/trept after performing its tricks.
- 2 & 4 54c On really hot days, ice cream is her favorite summer treat/treet/trept to share with her kids.
- 2 & 4 55a The travelers waited by the side of the road for the supply wagons/waguns/warons to catch up.
- 2 & 4 55b The settlers discovered that fording the river in wooden wagons/waguns/warons was actually very difficult.
- 2 & 4 55c Before cars, people made long journeys in covered wagons/waguns/warons that were pulled by horses.
- 2 & 4 56a Since the line looked long, she was surprised at the short wait/wate/wapt to get to the front.
- 2 & 4 56b The theme park was so crowded that there was a lengthy wait/wate/wapt for each ride they wanted to go on.
- 2 & 4 56c When they got in line, the ride operator told them that the estimated wait/wate/wapt time was over an hour.
- 2 & 4 57a She was hoping to buy rye bread, but the baker only had cracked wheat/wheet/whect left by the time she got to the store.
- 2 & 4 57b Her favorite kind of toast is whole wheat/wheet/whect because she loves its health benefits.
- 2 & 4 57c Paul likes white bread, but his mom makes him use nutritious wheat/wheet/whect bread for his sandwiches instead.
- 2 & 4 58a The driving instructor told him to try to keep both hands on the steering wheel/whele/whert at all times.
- 2 & 4 58b They gave her a chance to spin the giant wheel/whele/whert at the county fair.
- 2 & 4 58c Her favorite ride at the fair was the tall ferris wheel/whele/whert because there were great views from the top.
- 2 & 4 59a The tablecloth had to be bleached until it became white/whyte/whute again after her guest spilled red wine.
- 2 & 4 59b The wedding dress was a bright shade of beautiful white/whyte/whute that sparkled in the sun.
- 2 & 4 59c They decided to paint their picket fence bright white/whyte/whute like the old country homes they loved.
- 2 & 4 60a The family goes to Disneyland every year/yeer/yeel with their four children.
- 2 & 4 60b Tim decided to live on campus for another year/yeer/yeel because it was very convenient.

2 & 4 60c She studied hard for the entire school year/yeer/yeel and got an A
in every class.

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CHAPTER 3:
EFFECTS OF PHONEMIC DECODING ABILITY AND READING SKILL ON THE TIME
COURSE OF PHONOLOGICAL CODING DURING READING

Abstract

There is considerable evidence that readers generate phonological codes during silent reading. However, the extent to which this code generation varies as a function of reading skill has been debated. Some research suggests that phonological codes are only used by less skilled readers, while other research suggests that either there is no difference as a function of reading skill or that skilled readers may in fact be more effective at generating phonological codes. The current study collected language assessment data and recorded eye movements of subjects reading sentences containing correct target words, phonologically related words (and non-words), or orthographically matched control words (and non-words). Survival analyses of first fixation durations on the phonologically related and orthographic control words were conducted to determine how early each individual subject generated phonological codes during reading (i.e., individual *divergence point estimates*). Language assessment scores were used to predict divergence point estimates and mean fixation durations. Results revealed that there was not a significant relationship between general reading ability (i.e., comprehension, vocabulary) and the rapidity with which a given subject generated phonological codes during reading. Instead, results suggested that early phonological code generation was specifically related to phonemic decoding efficiency, such that readers who were more skilled at phonemic decoding (i.e., rapidly pronouncing novel pseudo-word strings, assessed via the TOWRE phonemic decoding efficiency subtest) tended to also generate phonological codes earlier during normal, silent

reading. Results suggest that readers with strengths in different language skills might adopt different strategies for or rely more heavily on different routes to word identification.

In alphabetic languages like English, a word's written form encodes its spoken counterpart, such that knowledge of letter-sound correspondence allows a reader to transform a written word into its spoken form. Even though the letter-sound mappings are not one-to-one in deeper orthographies such as English, in many cases, recoding in this way will be accurate or at least result in a very close approximation. As such, it is perhaps unsurprising that phonological coding—the recoding of written words into their sound-based codes—is often implicated in the process of word identification (for reviews, see Leinenger, 2014; McCusker, Hillinger, & Bias, 1981).¹²

Certainly, phonological coding seems to serve an important role in word identification during reading development—numerous studies have found evidence suggesting a crucial link between a child's phonological awareness (i.e., their knowledge of the internal sound structure of words), phonological coding ability, and their success learning to read (for reviews, see Ashby & Rayner, 2006; Rayner, Foorman, Perfetti, Pesetsky, & Seidenberg, 2001). This is perhaps unsurprising given that a child approaches the task of learning to read with a substantial spoken vocabulary (individual estimates for 5-7 year old children range from 2,500 words to more than 10,000 words, see Anglin, Miller, & Wakefield, 1993 for a review), and phonological coding provides a child with an invaluable tool—a tool which allows them to identify a novel written word by translating it into its known spoken counterpart (i.e., sounding it out). Ultimately, through repeated encounters, this

¹² Phonological coding is not however only limited to alphabetic languages, as evidence for phonological coding has also been found in Chinese, a logographic language (e.g., Pollatsek, Tan, & Rayner, 2000; Tan & Perfetti, 1998; Tsai, Lee, Tzeng, Hung, & Yen, 2004)

translation process is thought to result in the development of direct connections between written words and their meanings (e.g., de Jong, Bitter, van Setten, & Marinus, 2009; Jorm & Share, 1983; Share, 1995, 2008). The question then becomes, once these direct connections between the written forms and meanings of words are established, and a reader becomes more skilled, is phonological coding still important for word identification, and if so, are phonological codes used to the same extent by all readers?

Phonological coding is certainly not the only route by which a skilled reader could retrieve the meaning of a word during reading. It is also possible for them to use a word's orthographic form to retrieve its meaning directly, potentially bypassing the phonological recoding stage altogether. Indeed, some models of word identification during reading, in particular Coltheart's dual-route model, support word identification via these two routes: the indirect route where phonological codes are assembled to access a word's meaning and the direct route where a word's meaning is accessed directly on the basis of its orthographic form (at which point phonological codes can be retrieved as a bi-product of identification; e.g., Coltheart, 1978, 1980, 2000; Coltheart, Curtis, Atkins, & Haller, 1993; Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001). Inherent to this model is the assumption that, once built up, the direct route is more efficient, and therefore should be the primary route by which skilled readers access the meaning of most words (e.g., Coltheart, 1980). On the other hand, the parallel distributed processing (PDP) model introduced by Seidenberg and McClelland (1989) and revised by Harm and

Seidenberg (2004), which also proposes dual routes to meaning, assumes that both routes work in parallel to mutually inform the activation of semantic representations (though the degree to which each route accrues activation and contributes to identification can vary). Indeed, comparisons between simulations of the PDP model and simulations of disabled versions of the model in which only the direct or only the indirect pathway remained intact demonstrated the continued importance of both routes; the intact model computed the correct semantic representation more often than either of the disabled single-route models.

In support of the idea that phonological coding remains an important aspect of the word identification process, many studies find evidence of phonological coding in adult readers. Adult readers are less likely to notice (at least initially) or be disrupted by phonologically related errors embedded in text than orthographically matched control errors (e.g., Inhoff & Topolski, 1994; Jared, Levy, & Rayner, 1999; Rayner, Pollatsek, & Binder, 1998). They also receive a significant phonological preview benefit—faster processing of a target word when a phonologically related preview word was available in the parafovea compared to an orthographically matched control preview (e.g., Miellet & Sparrow, 2004; Pollatsek, Lesch, Morris, & Rayner, 1992). Furthermore, these phonological codes seem to be activated quite early—there is evidence for phonological processing that emerges in the ERP and MEG record within 80-125 ms during single word reading (e.g., Ashby, 2010; Ashby, Sanders, & Kingston, 2009; Cornelissen, Kringelbach, Ellis, Whitney, Holliday, & Hansen, 2009; Wheat, Cornelissen, Frost, & Hansen, 2010), and survival analyses of

eye movement data reveal an effect of phonological coding within 160 ms of fixation during sentence reading (Chapter 2, see also Feng, Miller, Shu, & Zhang, 2001). This early time course is suggestive of pre-lexical code generation in adult readers, and together, these results suggest that phonological codes are indeed being used to help adult readers identify words.

Despite clear effects of phonology among adult readers, researchers have still questioned whether the extent to which an individual reader relies on these codes for word identification might vary as a function of their reading skill (e.g., Waters, Seidenberg, & Bruck, 1984). If the developmental trajectory for word identification moves from a complete reliance on phonology initially to a shared reliance on both routes later on (or an almost complete reliance on the direct route as proponents of the dual-route model would suggest), then variation as a function of skill could be expected. Unfortunately, investigations into the effect of reading skill on the use of phonological coding during reading have produced mixed results. Some studies have indeed found evidence that less skilled readers seem to rely more heavily on phonological coding than more skilled readers—for example, less skilled readers are more likely to miss homophone errors embedded in texts during proofreading tasks, suggesting that they might rely more heavily on phonological codes during reading than their higher-skilled counterparts (Jared et al., 1999). However, higher skilled readers show evidence for phonological preview benefit whereas less skilled readers do not (Chace, Rayner, & Well, 2005). One way to reconcile the results of Jared et al. (1999) and Chace et al. (2005) is to assume that less skilled readers do

indeed rely more heavily on phonological codes, but as a result of their lower reading skill, their attention is limited to processing only the foveal word during reading—leading to reduced preview benefit of any kind. However, other research has actually found the opposite, a greater reliance on and more efficient use of phonological codes in skilled readers than less skilled readers. For example, Binder and Borecki (2008) found that less skilled readers were more likely than skilled readers to notice homophone errors during reading, suggesting that they were less efficient at generating phonological codes (see also Majeres, 2005). Finally, some research has found no differences in phonological coding as a function of reading skill—for example, Jared, Ashby, Aqauas, and Levy (2016), measured skilled and less skilled 5th grade readers' detection of phonologically related and orthographic control errors embedded in texts and found that both groups showed evidence of phonological coding to the same degree (see Daneman & Stainton, 1991 for similar effects in skilled and less-skilled adult readers reading familiar texts). Although these were 5th grade readers rather than adults, they had multiple years of reading instruction and practice, so shifts in their reliance on phonological coding could be expected, especially a reduced reliance on phonological coding for the identification of high frequency words (for which the direct route should have been more established; e.g., Waters & Seidenberg, 1985; Waters et al., 1984), however phonological coding for high frequency words was still observed. Taken together, no clear relationship between reading skill and phonological coding emerges from the prior body of research.

Rather than simply separating readers into skilled and less skilled categories, it might instead prove informative to ask which specific reading skills might influence the use of phonological codes during reading. In many of the previous studies (e.g., Chace et al., 2005; Daneman & Stainton, 1991; Jared et al., 2016, Jared et al., 1999) reading comprehension ability has served as a proxy for reading skill. Although comprehension ability is clearly a central skill to the reading process, it is by no means the only skill that might affect overall reading ability or the use of phonological coding more specifically. The primary aim of the current experiment was to determine what specific skills are associated with the early use of phonological codes and which are not.

Current Experiment

The current experiment recorded eye movements while subjects read sentences containing target words that were sometimes replaced with either phonologically related stimuli or orthographically matched controls. To quantify how early an individual subject used phonological codes, survival analyses of first fixation durations were conducted following the method outlined in Reingold and Sheridan (2014; see also Reingold, Reichle, Glaholt, & Sheridan, 2012). These analyses provide an estimate of the earliest observable influence of a manipulation on behavior by comparing the percent of fixations on a critical word still “surviving” across two conditions. A surviving fixation is one that has not yet been terminated by a reader making a saccade off of the critical word. Specifically, for a given time t , the percent survival is calculated as the percentage of fixations with a duration

greater than t . Thus at time $t = 0$, the percent survival is 100 (since all fixations have a duration greater than zero), and as t increase the survival percentage decreases, eventually approaching zero as t approaches the duration of the longest fixation in a given condition. By comparing survival curves across two conditions (here the phonologically related condition and the control condition), this analysis allows for computation of the *divergence point*—the earliest point in time at which the curves for the two conditions begin to significantly diverge. The divergence point then provides an estimate of the earliest observable influence of a manipulation—here shared phonology and the activation of phonological codes—on the eye movement record of a given subject. Using the divergence point estimate as an index of phonological code use, we can explore which language skills might be related to the early versus late use of phonological codes. Within this framework, there are a number of hypotheses that fall out from the results of previous research.

General reading ability. If, as proponents of the dual-route mode suggest, there truly is a shift from relying on phonological coding to relying on a more direct route to meaning as reading skill increases, then readers who have higher general reading ability (e.g., comprehension, vocabulary) should rely less on phonological codes to identify words. Under this hypothesis, general reading ability should be positively correlated with divergence point estimates, as lower (earlier) divergence point estimates are indicative of early phonological code use. On the other hand if the early use of phonological codes is predictive of better general reading ability in adults (as it is for developing readers; e.g., Binder & Borecki, 2008; Majeres, 2005),

there should be a negative correlation between divergence point estimates and reading skill, such that readers who rapidly generate phonological codes (i.e., have early divergence point estimates) tend to be more skilled readers in general. Finally, if there is no difference in the use of phonological coding as a function of reading skill (e.g., Daneman & Stainton, 1991; Jared et al., 2016), then the two should not be correlated.

Decoding ability. If phonological codes are generated pre-lexically (i.e., before word identification), then they must necessarily be assembled (e.g., via grapheme-to-phoneme correspondence) before a word is identified, rather than coming online as a bi-product of identification. Therefore, the early use of pre-lexical assembled phonology might be related to phonological decoding ability. In other words, readers who more successfully decode orthographic strings into their phonological components might be more likely to rapidly generate phonological codes from print during reading (i.e., have earlier divergence point estimates), irrespective of more general reading ability. In this case, there should be a negative correlation between a reader's decoding ability and their divergence point estimate, such that better decoders generate phonological codes earlier during reading.

Method

Participants

Sixty undergraduates from the University of California, San Diego, participated in this experiment for course credit. All were native English speakers, had normal vision, and were naïve to the purpose of the experiment.

Apparatus

Eye movements were recorded with an SR Research Ltd. Eyelink 1000 eye tracker (sampling rate of 1000 Hz) in a tower setup that restrained head movements with forehead and chin rests. Viewing was binocular, but only the eye movements of the right eye were recorded. Subjects were seated approximately 60 cm away from a 19-inch View-Sonic LCD monitor with a screen resolution of 1280 x 1024 pixels. Text was displayed in black, 14- point, fixed-width Consolas font on a white background. Sentences were always displayed in the center of the screen in one line of text, and approximately 4 characters subtended 1° of visual angle.

Materials

Stimuli were taken from Experiments 1 and 2 of Chapter 2. 30 *real-word* triplets (target, homophone, orthographic control) were selected from Experiment 1 and 30 *non-word* triplets (target, pseudohomophone, orthographic control non-word) were selected from Experiment 2. In both sets of stimuli, the phonologically related stimulus and orthographic control always shared at least the first letter with the target.

For the real-word stimuli, correct targets, homophones, and orthographic control words were roughly matched on lexical frequency, length, mean bigram frequency (the average bigram count for a particular word), and bigram frequency by position (the sum of the bigram count (by position) for a particular word). Additionally, the homophone and orthographic control were also matched on their degree of orthographic overlap with the correct target. Lexical frequencies (per 400

million) for all stimuli were computed via log-transformed HAL frequency norms (Lund & Burgess, 1996) using the English Lexicon Project (Balota et al., 2007). Correct targets had an average log frequency of 9.45 (range 6.88 to 12.47), homophones had an average log frequency of 9.0 (range 5.73 to 13.08), and orthographic controls had an average log frequency of 9.26 (range 6.23 to 13.16). All critical real-word stimuli were on average 4.27 letters long (range 3 to 6). Summary statistics for the real-word stimuli appear in Table 3.1.

For the non-word stimuli, correct targets, pseudohomophones, and orthographic control non-words were roughly matched on length, mean bigram frequency, and bigram frequency by position. Additionally, the pseudohomophones and orthographic control non-words were also matched on lexical frequency (i.e., all had a lexical frequency of zero) and their degree of orthographic overlap with the correct target. Correct targets had an average log frequency of 9.76 (range 6.4 to 12.19). All critical words were on average 4.6 letters long (range 4 to 6). Summary statistics for the non-word stimuli appear in Table 3.2.

For each set of critical words, three sentence frames were taken from Chapter 2 that rendered the correct target word predictable (assessed via cloze norming)¹³, resulting in a total of 180 experimental sentences. In this way, for each set of critical words, each subject could read the correct target, phonologically related (non-) word, and orthographic control (non-) word each in a different sentence and contribute data to all three conditions. The type of critical word

¹³ For details regarding this and other norming procedures (e.g., sentence acceptability, fragment acceptability, pronunciation), see Chapter 2.

presented in each sentence was counterbalanced across participants, such that across experimental lists, for every item, each type of critical word appeared in each of the three sentence frames an equal number of times. The 180 experimental sentences were presented along with 50 filler sentences. Simple comprehension questions appeared after 20 of the filler items, and comprehension accuracy was high (92.3%). Word type (correct target, phonologically related, orthographic control) was tested within participants, and, because there were three experimental sentences for each target triplet, each participant contributed data to all three conditions for each set of critical words. Example stimuli are shown in (1) and (2), with the correct target/phonologically related/orthographic control (non-) word italicized.

(1) The surfers traveled to the word famous *beach*/*beech*/*bench* where the waves were very large.

(2) Because of his insomnia, Caleb couldn't *sleep*/*sleap*/*slerp* even though he was tired.

Table 3.1. Summary statistics for the real-word stimulus set.

	Correct Target		Homophone		Orthographic Control	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Log HAL Frequency (per 400 mil)	9.45	1.49	9.0	1.97	9.26	1.69
Length	4.27	0.73	4.27	0.73	4.27	0.73
Mean Bigram Frequency	1883	894	1983	902	1903	974
Bigram Frequency by Position	1164	522	1255	427	1057	427
Orthographic Overlap			0.58	0.15	0.63	0.13
Cloze Predictability	0.58	0.3				
Sentence Acceptability	6.09	0.59	2.99	0.61	2.76	0.79
Fragment Acceptability	6.16	0.74	2.8	0.64	2.57	0.80

Note. Orthographic overlap refers to the percentage of position specific letters that the homophones or orthographic controls shared with the correct target words (e.g., *maid* and *made* share the first two, or 50%, of their letters in the same positions).

Table 3.2. Summary statistics for the non-word stimulus set.

	Correct Target		Pseudohomophone		Orthographic Control	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Log HAL Frequency (per 400 mil)	9.76	1.36	0	0	0	0
Length	4.6	0.55	4.6	0.55	4.6	0.55
Mean Bigram Frequency	1770	742	1772	715	1672	686
Bigram Frequency by Position	1209	463	1103	511	1144	397
Orthographic Overlap			0.64	0.13	0.66	0.13
Cloze Predictability	0.84	0.19				
Sentence Acceptability	6.08	0.51	2.96	0.74	2.68	0.66
Fragment Acceptability	6.15	0.5	3.03	0.5	2.45	0.33
Pronunciation			4.45	0.33		

Note. Orthographic overlap refers to the percentage of position specific letters that the homophones or orthographic controls shared with the correct target words (e.g., *wheel* and *wehle* share the first three, or 60%, of their letters in the same positions).

Procedure

Eyetracking procedure. Subjects were instructed to read the sentences for comprehension and to respond to occasional comprehension questions using a gamepad to indicate “yes” or “no” responses. At the start of the experiment, the eyetracker was calibrated with a 3-point calibration scheme. At the beginning of the experiment, subjects received nine practice trials (five of which were followed by a comprehension question) to allow them to become comfortable with the experimental procedure.

Each trial began with a fixation point in the center of the screen (that served as a drift correction), which the subject was required to fixate until the experimenter initiated the trial. Then a fixation box appeared on the left side of the screen, which was located where the beginning of the sentence would appear. Once a stable fixation was detected within the box, the box disappeared and was replaced by the sentence, which remained on the screen until the subject pressed a button signaling that they understood the sentence and were ready to move on. Order of sentence presentation was randomized for each participant, and the eyetracking session lasted approximately fifty minutes.

Language Assessment procedure. In addition to completing the eyetracking portion of the experiment, a battery of language assessments was administered. Subjects were tested individually in a small room where they sat across a desk from the experimenter. Subjects were administered an entire battery of general language assessments, a subset of which was of specific interest to the

current study.¹⁴ In advance of analysis, four assessments were selected because they tested various components of the reading process—some directly tested phonological coding while others tested other components. The language assessment session lasted approximately forty-five minutes.

Word identification and non-word decoding measures. Two subtests of the Test of Word Reading Efficiency (TOWRE; Rashotte, Torgesen, & Wagner, 1999) were administered. The Sight Word Efficiency (T-SWE) subtest measures the number of real words (out of a list of 104) that an individual can accurately identify (by reading aloud) within 45 seconds. The Phonemic Decoding Efficiency (T-PDE) subtest, measures the number of pronounceable non-words (out of a list of 63) that an individual can accurately decode (again by reading aloud) in 45 seconds. For both tests, an *items per second* score was computed for each subject, which captured their efficiency at performing the task (e.g. a subject who correctly produced 98 words in 45 seconds on the T-SWE test would receive a score of 2.18 (98/45) and a subject who correctly produced all 104 words in only 40 seconds would receive a score of 2.6 (104/40)).

Reading comprehension and vocabulary measures. Two tests of general reading ability, thought not to directly relate to the speed with which words are identified, were administered.

¹⁴ Every subject in this experiment was run through the entire battery of assessments used in the lab. Although only a subset of these assessments was relevant to the present study, others were related to additional studies being run in the lab. By testing subjects on the entire battery at once, they were then eligible to come back in to complete additional eye tracking studies for further compensation. The measures examined in the current study were planned in advance of data analysis.

WASI-II vocabulary test. The Wechsler Abbreviated Scale of Intelligence—Second Edition (WASI-II; Wechsler, 2011) Vocabulary subset was used as a measure of verbal knowledge. In this test, the experimenter read aloud words, one at a time, and subjects were instructed to verbally provide a definition for each word. If a subject's response was similar to a correct response, but not fully correct, the experimenter prompted the subject to elaborate. Raw scores were transformed into T scores following the standard scoring procedure.

PIAT-R reading comprehension. The Peabody Individual Achievement Test—Revised (PIAT-R; Markwardt, 1998) reading comprehension subtest was used to assess reading comprehension ability. In this test, subjects silently read a series of sentences, each printed on a separate page of the testing booklet held by the experimenter. When the subject is confident that they understand a sentence, they indicate that they are ready to move on and the experimenter turns the page, removing the sentence and presenting an array of 4 black and white illustrations. The subject chooses the illustration that best depicts the meaning of the sentence they just read, at which point the experimenter turns the page and presents the next sentence. Over the course of the test, the sentences get progressively more difficult. The standard stopping criteria were followed (i.e., if a subject made 5 errors in a run of 7 consecutive items before the end of the test, testing was stopped), and the standard scoring procedure was used to determine a subject's raw score.

To capture a singular measure of general reading skills not directly related to the speed with which words are identified, a composite measure of reading

comprehension and vocabulary (C & V) was created. To create the composite measure, the WASI-II and PIAT-R scores were transformed to be on the same scale and an average of the two scores was taken. As would be expected, the composite scores were highly correlated with both the PIAT-R scores ($r(57) = .78, p < .001$) and the WASI-II scores ($r(57) = .86, p < .001$). Summary statistics for all language assessments appear in Table 3.3.

Table 3.3. Summary of tests of language skills. Raw scores and standardized z-scores are included.

Domain	Test	Raw scores				Z-score
		Mean	SD	Min	Max	Range
Reading comprehension	PIAT-R	88.02	6.64	66	98	-3.32 - 1.5
Vocabulary	WASI	52.57	5.48	43	65	-1.75 - 2.27
Composite Reading + Vocabulary Measure	PIAT-R & WASI	83.37	6.16	71.75	95.25	-1.89 - 1.93
Rapid word naming	TOWRE-SWE	2.21	0.28	1.44	2.81	-2.75 - 2.14
Rapid non-word decoding	TOWRE-PDE	1.36	0.18	0.91	1.75	-2.5 - 2.17

Results

Prior to analysis, fixations under 81 ms were pooled if they were within 1 character of another fixation, as these fixations likely preceded corrective saccades. Consistent with other studies that have examined distributions of fixation durations (e.g., Chapter 2; Reingold et al., 2012; Sheridan & Reingold, 2012), fixations shorter than 81 ms that were further from an adjacent fixation remained in the dataset. All fixations over 800 ms were deleted, as were any trials in which subjects blinked during first-pass reading of the target word, resulting in 4.9% data loss. Additionally, gaze durations longer than 2,000 ms and total times longer than 4,000

ms were excluded. After all exclusions, 93.8% of the original data were retained for analysis (94.2% of data for real-word stimuli and 93.5% of the data for non-word stimuli).

Standard reading time measures (Rayner, 1998, 2009) used to investigate the time-course of word processing in reading are reported, including *first fixation duration* (the duration of the first fixation on a word), *single fixation duration* (the duration of the first fixation on a word when a reader makes only one fixation during first-pass reading), *gaze duration* (the sum of all first-pass fixation durations on a word before leaving it), *go-past time* (the sum of all first-pass fixation durations on a word and any fixations on preceding words before going past it to the right), and *total time* (the sum of all fixation durations on a word including any time spent re-reading it following a regression). In addition, three probability measures are also reported: *fixation probability* (the probability that a word was fixated at least once during first-pass reading), *regression-out probability* (the probability of making a regression out of a word to re-read prior words in the sentence) and *regression-in probability* (the probability of making a regression into a word—i.e., from subsequent words in the sentence).

Table. 3.4 Means and standard errors for reading time measures across all items.

	Identical	Related	Orthographic control
Fixation Probability	0.60 (.008)	0.68 (.008)	0.70 (.008)
Single Fixation Duration	225 (1.7)	261 (2.3)	276 (2.7)
First Fixation Duration	225 (1.7)	256 (2.1)	272 (2.4)
Gaze Duration	233 (1.9)	282 (2.6)	313 (3.5)
Go-Past Time	276 (4.6)	342 (4.8)	403 (6.3)
Total Time	264 (2.9)	370 (4.5)	491 (6.5)
Regressions Out	0.06 (.004)	0.09 (.005)	0.11 (.006)
Regressions In	0.1 (.005)	0.23 (.007)	0.36 (.008)

Linear mixed-effects models were fitted using the lmer function from the lme4 package (version 3.2.3; Bates, Maechler, Bolker, & Walker, 2015) within the R Environment for Statistical Computing (R Development Core Team, 2015). Models were fit using the maximal random effects structure justified by the design of the experiment (Barr, Levy, Scheepers & Tily, 2013), which included subjects and items as crossed random effects.¹⁵ The comparisons between different levels of the fixed effect were specified using the default treatment coding in R, with the mean of the homophone condition represented by the intercept. Regression coefficients (which estimate the effect size (in milliseconds) of the reported comparisons), the standard errors, and the (absolute) t values of the coefficients are all reported.

¹⁵ Some models showed convergence failures, in which case random slopes were removed and the results of the first model to converge are reported. The random slopes for items in the GZD and GPT models were removed.

For binary dependent variables (fixation probability data), generalized mixed-effects regression models (GLMMs) were used with a logit link function, and regression coefficients (b —which represent effect size in log-odds space), and the (absolute) z value and p value of the effect coefficient are all reported. Absolute values of the t and z statistics greater than or equal to 1.96 indicate an effect that is significant at approximately the .05 alpha level. Reading measures on the target words are reported in Table 3.4, results of the LMMs on fixation duration measures are reported in Table 3.5, and results of the GLMMs on fixation probability measures are reported in Table 3.6.

Fixation duration measures

For all reading time measures, the correct target was fixated for significantly less time than the phonologically related (non-) word (all $ts > 8.02$), which was fixated for significantly less time than the orthographic control (all $ts > 4.38$). This pattern of results is suggestive of graded processing whereby the phonologically related (non-) word was easier to process than the orthographic control word, but not as easy to process as the correct target. Group means for all fixation duration measures as a function of stimulus set appear in Figure 3.1.

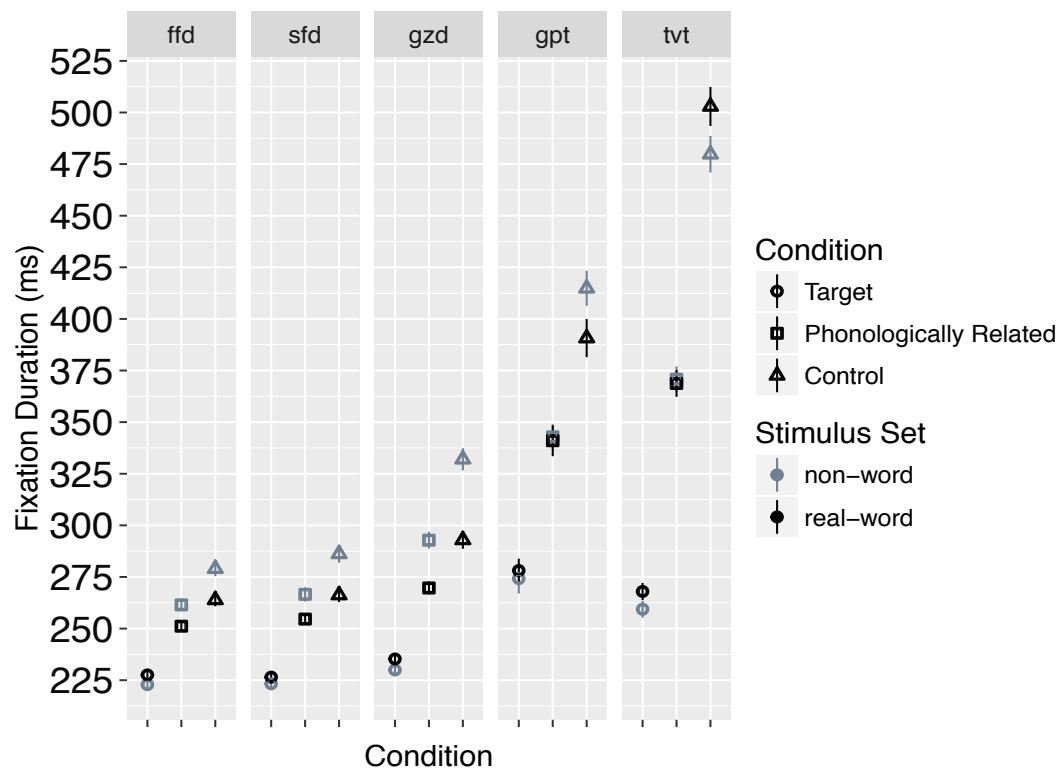


Figure 3.1. Reading time on the critical word as a function of condition (correct target, phonologically related, or orthographic control) and stimulus set (real-word, non-word) across 5 reading time measures (ffd = first fixation duration, sfd = single fixation duration, gzd = gaze duration, gpt = go-past time, tvf = total time). Shape represents condition and color represents the stimulus set. Error bars represent ± 1 standard error of the mean

Fixation probability measures

The correct target was skipped at a significantly higher rate (i.e., the probability of fixation was lower) than the phonologically related (non-) word ($p < .001$), whereas skipping rates between the phonologically related (non-) word and the orthographic control did not significantly differ ($p = .51$). Subjects were significantly less likely to make a regression out of the correct target word than out of the phonologically related (non-) word ($p < .001$), which subjects were less likely to regress out of than the orthographic control ($p = .01$). The probability of making a

regression into the orthographic control was significantly higher than the probability of making a regression into the phonologically related (non-) word ($p < .001$), which had a significantly higher regression-in rate than the correct target ($p < .001$). Together, the regression-out and regression-in data suggest that the correct target was easier to process than the phonologically related (non-) word, which was in turn easier to process than the orthographic control.

Table 3.5. Results of linear mixed effects models for reading time measures on the critical words. The intercept represents the mean duration for the phonologically related condition. Significant effects are indicated by boldface.

Measure	Contrast	Model		
		b	SE	t
First Fixation Duration	Intercept	254.31	5.15	49.42
	Target	-29.95	3.71	8.08
	Orthographic control	15.41	3.51	4.39
Single Fixation Duration	Intercept	258.87	5.59	46.32
	Target	-34.77	4.05	8.59
	Orthographic control	17.03	3.43	4.97
Gaze Duration	Intercept	277.07	6.13	45.17
	Target	-47.03	4.9	9.6
	Orthographic control	31.51	4.68	6.74
Go-Past Time	Intercept	337.64	9.57	35.27
	Target	-64.98	8.09	8.03
	Orthographic control	61.02	7.96	7.67
Total Time	Intercept	361.36	12.71	28.43
	Target	-101.08	10.78	9.38
	Orthographic control	119.85	11.8	10.16

Table 3.6. Results of the logistic regression models for fixation probability measures across condition. The intercept represents the mean probability for the phonologically related condition. Significant effects are indicated by boldface.

Measure	Contrast	Model		
		b	z	p
Fixation Probability	Intercept	0.94	7.19	< .001
	Target	-0.43	6.42	< .001
	Orthographic control	-0.04	0.66	0.51
Regression-out Probability	Intercept	-2.54	21.58	< .001
	Target	-0.48	3.69	< .001
	Orthographic control	0.27	2.55	.01
Regression-in Probability	Intercept	-1.39	12.05	< .001
	Target	-1.01	8.83	< .001
	Orthographic control	0.76	9.6	< .001

Survival Analyses

Survival Analyses were conducted on first fixation duration data following the Individual Participant Divergence Point Analysis (IP-DPA) procedure outlined in Reingold and Sheridan (2014) and using the Matlab script supplied in their supplementary materials. The IP-DPA procedure uses a bootstrap resampling procedure to compare survival curves of first fixation duration data in two conditions (here, the phonologically related and orthographic control conditions) to determine the divergence point estimate for each subject individually. The procedure, outlined in Reingold and Sheridan (2014), is repeated for 1,000 iterations per subject, and the median divergence point estimate obtained across all iterations is used as the divergence point for that individual subject. Using this procedure to compare the survival curves for the phonologically related and orthographic control conditions results in the generation of divergence point

estimates that correspond to the earliest observable effect of phonology. Furthermore, using the IP-DPA procedure provides divergence point estimates for each individual subject, which allows for an investigation into the degree of variability of phonological code generation across subjects. The survival curves for the phonologically related and orthographic control condition are displayed in Figure 3.2 as well as the mean divergence point estimate obtained by taking the mean of the individual subject divergence point estimates. The phonologically related and orthographic control curves significantly diverged at 187 ms on average across all subjects ($M = 187$ ms, range = 55-397.5 ms, $SE = 8.16$, $N = 58$)¹⁶, and 63.8% of individual subjects had divergence point estimates that were earlier than this group mean. Finally, across all subjects, only 27.6% of first fixations had durations shorter than this divergence point estimate, suggesting that the majority of fixations were influenced by phonology.

¹⁶ The divergence point estimate for 1 subject could not be determined (i.e., their survival curves never significantly diverged). The divergence point estimates for 1 additional subject was deemed unreliable because a divergence point estimate was obtained in less than 50% of the iterations. Following Reingold and Sheridan (2014) these subjects were excluded from computation of the group divergence point estimate, however their raw fixation duration data is included in the survival figure.

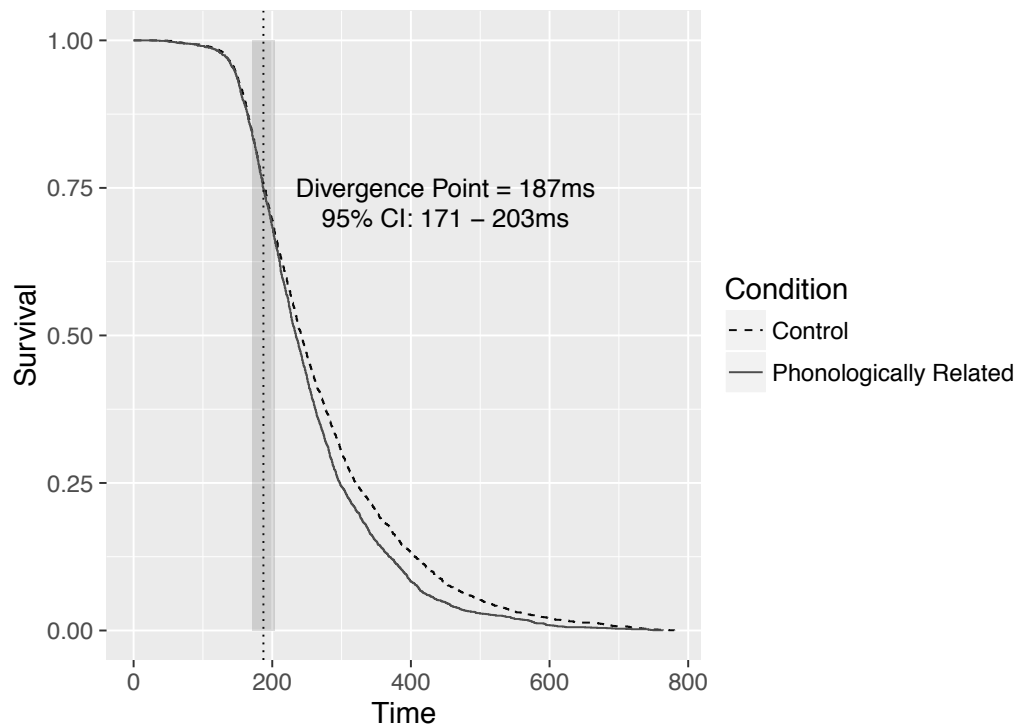


Figure 3.2. Survival percentage as a function of time for all stimuli. Line type represents the condition (phonologically related, control) and the dotted vertical line denotes the divergence point. The grey band surrounding the divergence point line represents the 95% confidence interval.

To determine whether individual subjects differed in how early they generated phonological codes for the real-word and non-word stimuli, separate divergence point estimates were also calculated for each set of items (real-word, non-word). In the real-word stimuli, the homophone and orthographic control curves significantly diverged at 199 ms on average across all subjects ($M = 199$ ms, range = 106.5-413.5 ms, $SE = 9.73$, $N = 58$)¹⁷, and 65.5% of individual subjects had divergence point estimates that were earlier than this group mean. In the non-word

¹⁷ The divergence point estimate for 1 subject could not be determined (i.e., their survival curves never significantly diverged) and the divergence point estimates for 1 additional subject was deemed unreliable and excluded from computation of the group divergence point estimate.

stimuli, the homophone and orthographic control curves significantly diverged at 188 ms on average across all subjects ($M = 188$ ms, range = 49-427 ms, $SE = 10.18$, $N = 55$)¹⁸, and 61.8% of individual subjects had divergence point estimates that were earlier than this group mean. Consistent with the findings of Chapter 2, the average divergence point estimate for non-word stimuli was numerically earlier than for real-word stimuli, but again estimates for real-word and non-word stimuli did not significantly differ ($t(111) = 0.79$, $p = .43$).

Table 3.7. Correlation Matrix for language measures and relevant reading measures (DPE = divergence point estimate, RW-DPE = real-word divergence point estimate, NW-DPE = non-word divergence point estimate, GZD = gaze duration (for correct targets only), C & V = composite comprehension & vocabulary measure, T-SWE = TOWRE sight word efficiency, T-PDE = TOWRE phonemic decoding efficiency.)

	DPE	RW-DPE	NW-DPE	GZD	C&V	T-SWE
DPE	—					
RW-DPE	0.44	—				
NW-DPE	0.63	< .01	—			
GZD	0.18	0.23	0.30	—		
C&V	-0.08	-0.11	-0.19	-0.32	—	
T-SWE	-0.15	-0.30	-0.09	-0.49	0.27	—
T-PDE	-0.27	-0.10	-0.22	-0.38	0.23	0.49

Individual Differences

Of particular interest in the current study, was the degree to which different language skills (assessed via offline tests) might be predictive of early phonological code use. To investigate these relationships, a series of planned comparisons were

¹⁸ The divergence point estimates for 2 subjects could not be determined (i.e., their survival curves never significantly diverged), and the divergence point estimates for 3 additional subject was deemed unreliable and excluded from computation of the group divergence point estimate.

conducted. Prior to any of the language assessment analyses, one subject was removed because their divergence point estimate was more than 3 standard deviations above the mean (z -score = 3.38) and more than 1 standard deviation above the next highest subject. For transparency, the entire correlation matrix is included in Table 3.7, but only planned, theoretically motivated analyses were actually carried out (see Table 3.8).

Table 3.8. Results of planned correlations. Significant correlations appear in bold. (DPE = divergence point estimate, RW-DPE = real-word divergence point estimate, NW-DPE = non-word divergence point estimate, GZD = gaze duration (for correct targets only), C & V = composite comprehension & vocabulary measure, T-SWE = TOWRE sight word efficiency, T-PDE = TOWRE phonemic decoding efficiency.)

Factor 1	Factor 2	r	df	95% Confidence Interval		p
				lower	upper	
RW DPE	NW DPE	< .01	50	-0.27	0.28	0.98
DPE	T-DEC	-0.27	55	-0.5	-0.02	0.04
DPE	T-EF	-0.15	55	-0.39	0.12	0.27
DPE	C & V	-0.08	55	-0.33	0.19	0.56
DPE	GZD	0.18	55	-0.8	0.42	0.17
GZD	C & V	-0.32	57	-0.53	-0.06	0.01
GZD	T-DEC	-0.38	57	-0.58	-0.14	0.003
GZD	T-EF	-0.49	57	-0.66	-0.26	< .001

Language skill predictors of reading times. Consistent with prior research (for a review see Rayner, 1998), scores on all language assessments (comprehension & vocabulary, TOWRE-sight word efficiency, TOWRE-phonemic decoding efficiency) were negatively correlated with gaze durations on the correct

target words¹⁹, such that higher-skilled readers (in every assessment) tended to have shorter gaze durations (all $ps < .01$).

Language skill predictors of divergence point estimates. Figure 3.3 shows the relationships between divergence point estimates and all language assessments. There were no significant relationships between subjects overall divergence point estimate and their scores on the composite comprehension and vocabulary measure (Figure 3.3, Panel B) or on the TOWRE sight word efficiency test (Figure 3.3, Panel C; both $ps > .35$). There was however a significant negative correlation between a subject's overall divergence point estimate and their score on the TOWRE phonemic decoding efficiency test, such that subjects who scored higher on the test of phonemic decoding efficiency tended to have earlier divergence point estimates (Figure 3.3, Panel D; $p = .04$)

¹⁹ Because fixation times on the phonologically related and orthographic control (non-) words were used in calculating the divergence point estimates and may reflect somewhat different processing than the reading of real, semantically congruent words, gaze durations exclusively on the correct targets (1/3 of all stimuli) were used for all language assessment analyses.

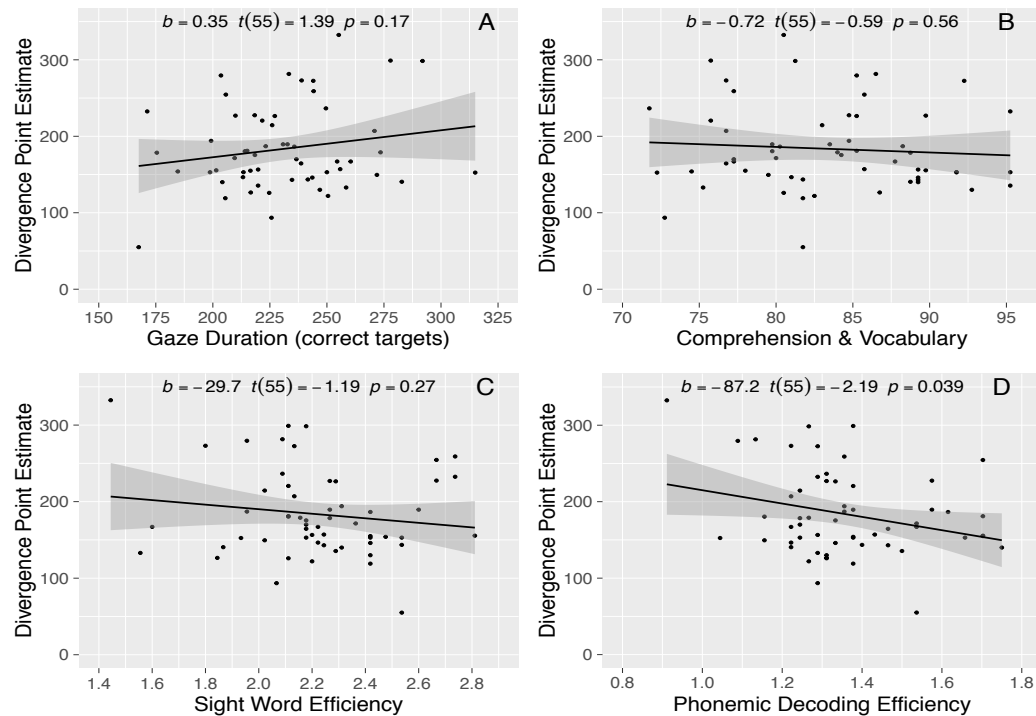


Figure 3.3. Relationships between divergence point estimates and different language assessment and eye movement measures. Panel A shows the correlation between divergence point and gaze duration (on correct targets), Panel B shows the correlation between divergence point and the composite comprehension and vocabulary measure, Panel C shows the correlation between divergence point estimate and the TOWRE-SWE test, and Panel D shows the significant negative correlation between divergence point estimate and the TOWRE-PDE test. In each panel, the regression line and 95% confidence interval are represented by the black line and grey band respectively.

Unlike Chapter 2, there was not a significant relationship between a subject's divergence point estimate and their average gaze duration on correct targets (Figure 3.3, Panel A). The data trended in the same direction, such that earlier divergence points were associated with shorter gaze durations, but the correlation was non-significant ($p = .17$). However, to further explore how reading skill might influence this relationship, post-hoc analyses were carried out to determine how the

relationship between average gaze duration and divergence point estimate might vary as a function of reading skill. Each continuous language assessment measure was transformed into a categorical variable (“high-skill” and “low-skill”) using a median split. When gaze durations (on the correct targets) were regressed on divergence point estimates and general reading skill (comprehension & vocabulary) the main effect of divergence point estimate was non-significant ($p = .24$), the main effect of reading skill was marginal ($b = -49.7$, $t(53) = -1.92$, $p = .06$), and the regression coefficient for the interaction was significant ($b = 0.35$, $t(53) = 2.57$, $p = .01$), suggesting that the effect of phonological coding was different for lower- and higher-skilled readers. Follow-up tests revealed that divergence point estimate predicted gaze durations for lower-skilled ($b = 0.22$, $t(26) = 2.64$, $p = .01$), but not higher-skilled readers ($b = -0.13$, $t(27) = -1.23$, $p = .23$), suggesting that the use of phonological codes among less-skilled readers (i.e., those with smaller vocabularies and lower comprehension) leads to more efficient word identification (i.e., shorter gaze durations) whereas phonological coding does not significantly influence the time it takes higher-skilled readers to identify words (see Figure 3.4, left-hand panel).

When gaze durations (on the correct targets) were regressed on divergence point estimates and phonemic decoding skill (TOWRE-PDE), the regression coefficients for the main effects of divergence ($b = 0.24$, $t(53) = 2.17$, $p = .03$) and skill ($b = 63.13$, $t(53) = 2.43$, $p = .02$) were significant, and the interaction was marginal ($b = -0.26$, $t(53) = -1.86$, $p = .07$). Because the test was marginal and these

analyses are exploratory, follow-up tests were run despite the marginal interaction. Follow-up tests revealed that divergence point estimates predicted gaze durations for higher-skilled decoders ($b = 0.24$, $t(27) = 2.9$, $p = .007$), but not lower-skilled decoders ($b = -0.02$, $t(26) = -0.18$, $p = .86$). This suggests that the use of phonological codes among skilled decoders leads to more efficient word identification (i.e., shorter gaze durations) whereas for less-skilled decoders, phonological coding does not significantly influence the time it takes to identify words (see Figure 3.4, right-hand panel).

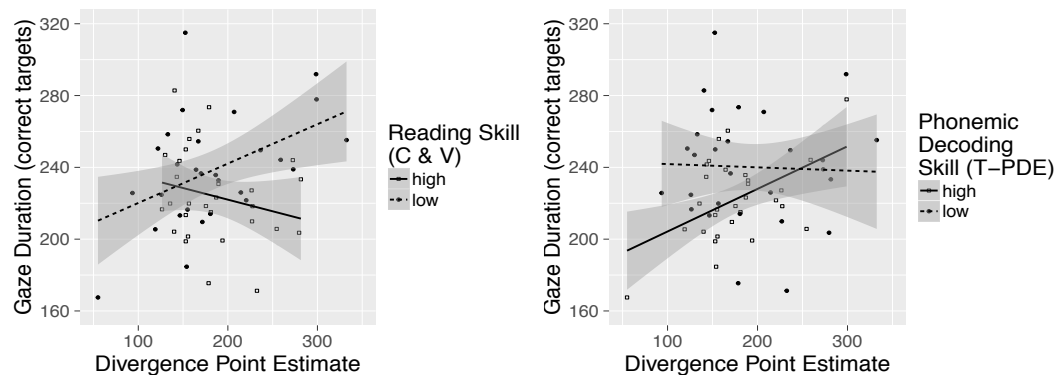


Figure 3.4. Gaze duration (on correct targets) as a function of divergence point estimate and either general reading skill (comprehension & vocabulary; left-hand panel) or phonemic decoding skill (TOWRE-PDE; right-hand panel). Shape and line type denote skill level with solid lines/open squares denoting high-skilled subjects and dashed lines/filled circles denoting lower-skilled subjects in each language assessment. Lines and grey bands represent the regression lines and 95% confidence intervals respectively.

Relationship between real-word and non-word divergence point

estimates. Surprisingly, there was not a statistically significant relationship between a given subject's divergence point estimates for the real-word and non-word stimuli. To further explore this null effect, difference scores were calculated for each subject by subtracting their non-word divergence point estimate from their

real-word divergence point estimate ($M = -1.96$, $SD = 96.28$, range = -298-225). Doing so revealed that most subjects did in fact have divergence point estimates that were similar to one another, only 13 subjects had divergence point estimates that differed by more than 100 ms, and over half (62%) had estimates that were within 50 ms of each other. Therefore, each subject was reclassified based on how extreme his or her difference score was. Subjects whose scores were more than 2 standard deviations above or below the mean were re-classified as “outliers” ($N=5$) and the rest were classified as having “standard” scores ($N=47$). As Figure 3.5 shows, although there was not a significant relationship between divergence point estimates for the group overall (solid regression line; $b = 0.003$, $t(50) = 0.02$, $p = 0.98$), when the outliers were removed, a significant positive relationship emerged (dashed regression line, $b = 0.25$, $t(45) = 2.17$, $p = 0.036$), suggesting that, for the majority of subjects, there was a significant relationship between the time course of phonological code generation for word and non-word stimuli.

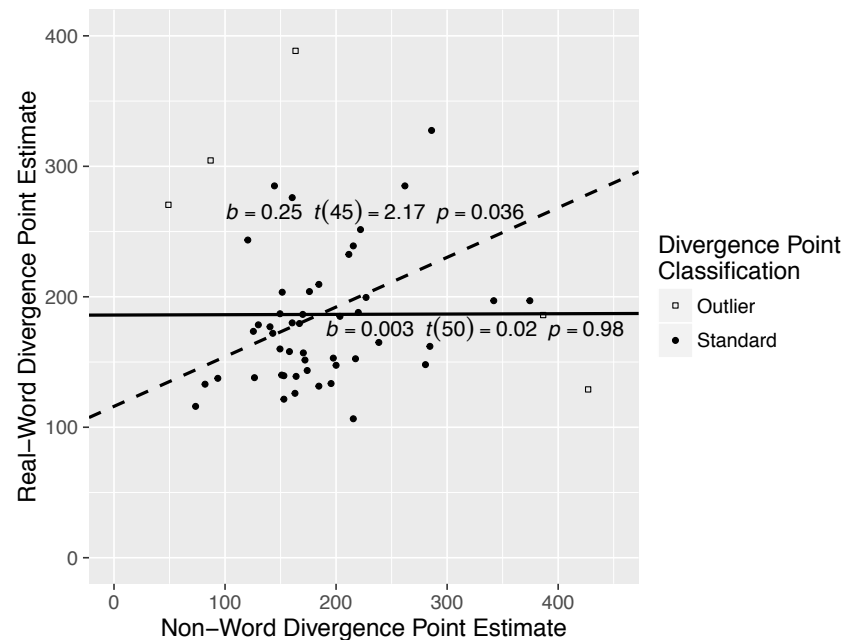


Figure 3.5. Relationship between the real-word divergence point estimate and non-word divergence point estimate for each subject. Each point represents an individual subject and the shape of that point represents whether the difference between their divergence point estimates was in the standard range (“Standard”, $N = 47$) or more than 2 standard deviations beyond the mean (“Outlier”, $N = 5$). Regression lines for the entire data set and only the “standard” data are represented by the solid line and dashed line respectively.

Discussion

The current study confirmed the results of prior research (e.g., Feng, et al., 2001; Leinenger, Chapter 2; Rayner, 1998) in that readers showed a processing advantage for phonologically related words relative to orthographic control words by as early as the first fixation duration on the critical word, and survival analyses revealed that this advantage was the result of rapidly generated phonological codes. Indeed, the survival curve for the phonologically related stimuli significantly diverged from the orthographic control stimuli 187 ms after fixation began.

Although this is evidence that phonological codes exert a relatively early effect on processing and the eye movement record, the estimate is not as early as divergence point estimates obtained in prior studies (i.e., 160-173 ms in Feng et al., 2001 and Chapter 2). This is especially surprising considering the stimuli used here are in fact a subset of the stimuli used in Chapter 2. Furthermore, cloze predictability was higher for the critical words in this subset ($M = .71$) than for the entire stimulus set used in the prior study ($M = .52$). This is interesting considering prior research has suggested that significant differences between the processing of phonologically related words and orthographic control word should emerge sooner in high-constraint contexts (e.g., Rayner et al., 1998, Daneman & Reingold, 2000; but see Jared et al., 1999). Because the effect of phonology emerged later for the subset of high predictability items, it seems unlikely that contextual constraint drives the early generation of phonological codes. Despite the slightly later average divergence point estimate obtained in this study, the range of individual subject divergence point estimates was consistent with prior research (i.e., 55-397.5 ms in the current experiment and 48.5 – 374.5 ms in Chapter 2).

This high degree of subject variability in divergence point estimates allowed for exploration into the underlying language skills that might be predictive of early or late phonological code use. Doing so revealed no significant relationship between general reading skills (reading comprehension and vocabulary) and the rapidity with which subjects generate phonological codes. Instead, the only language measure that was significantly related to the time course of phonological code

generation was phonemic decoding efficiency—suggesting that subjects who were better at rapidly decoding novel non-word stimuli into their phonological codes (i.e., on the TOWRE-PDE test), were those who rapidly generated phonological codes during silent reading. Furthermore, this effect was not simply driven by processing speed or rapid word reading ability because there was not a significant relationship between subjects' divergence point estimates and their scores on the TOWRE sight word efficiency test. The sight word efficiency test has the same task demands as the phonemic decoding test but uses real word stimuli for which phonological codes could either be generated rapidly or come online after identification (i.e., via the direct route from orthography to meaning), such that rapid phonological decoding is not necessarily required to perform well.

Because general reading skills like reading comprehension and vocabulary were not predictive of phonological code use, the early or late use of phonology does not appear to be indicative of being a relatively good or poor reader as some prior research has suggested (e.g., Jared et al., 1999). Instead, the relationship seems to be more nuanced. The data suggest that readers who are more skilled at phonological decoding rapidly generate pre-lexical phonological codes to help them identify words, whereas readers who are less skilled at phonological decoding do not generate phonological codes as rapidly. This could mean either that the less skilled decoders still generate pre-lexical codes, but that the process is less efficient, likely leading to longer word identification times, or that they instead rely more on a direct route to meaning (with phonological codes coming online only after word

identification). Post-hoc analyses suggested that phonological code generation was predictive of word identification speed for skilled decoders, but not less-skilled decoders, suggesting perhaps that less skilled decoders are relying more heavily on other strategies, perhaps the direct route to meaning, to identify words.

These results cast doubt on theories that claim that the developmental trajectory is such that readers move from a complete reliance on phonological coding to a complete reliance on the direct route to meaning, and that reliance on the direct route is the more efficient route to meaning for skilled readers. These data provide clear evidence that a portion of skilled readers do in fact rapidly generate pre-lexical phonological codes, and the positive (though non-significant) correlation between divergence point estimates and mean gaze durations suggests that the early use of phonology was actually associated with more efficient word identification. Interestingly, post-hoc analyses of the current data suggest that phonological coding was predictive of word identification speed for readers with smaller vocabularies and lower reading comprehension ability, but not for readers who scored higher on these skills. While it is clearly not the case that only less-skilled readers generate phonological codes, the data suggest that they may benefit more from the early generation of phonological codes than their higher-skilled counterparts. This does suggest potentially that, as a group, readers with bigger vocabularies and better reading comprehension rely less on phonological coding to identify the meaning of words. Alternatively, it could be that for these readers word identification speed was at ceiling, such that additional benefits from phonological

coding could not be observed. Indeed, in Harm and Seidenberg's (2004) simulations of the PDP model, although the two routes to meaning propagate activation in parallel to mutually inform word identification for skilled readers, activation from the direct route tends rise at a much faster rate than the phonologically mediated route. Thus, if words are recognized quickly, the phonologically mediated route may not yet have contributed substantially to their identification.

Taken together, the results of this study suggest that rather than a universal shift from the indirect route to the direct route across development, it seems that readers may rely more heavily on the input of one route or the other as their language abilities allow, or at least that readers may use different word identification strategies to differing degrees. Readers who are particularly skilled at phonemic decoding rapidly generate high-fidelity phonological codes that contribute substantial activation to semantic representations and help them efficiently identify words, whereas readers with larger vocabularies and better reading comprehension, might already be so efficient at word identification (potentially in some cases via more reliance on the direct route) that the addition of phonological coding does not further improve their word identification speed.

Conclusions

The rapidity with which a given subject generated phonological codes was not related to their general reading ability (i.e., vocabulary, comprehension ability). Instead, the data suggest that early phonological code generation was specifically related to phonemic decoding efficiency, such that readers who were more skilled at

phonemic decoding tended to also generate phonological codes earlier during normal, silent reading. Furthermore, more skilled readers were faster to identify words (i.e., had shorter fixation durations) independent of the speed with which they generated phonological codes, suggesting that readers with strengths in different language skills might adopt different strategies for or rely more heavily on different routes to word identification. In support of this, the rapidity with which a reader generated phonological codes was most predictive of word identification speed among two groups of subjects: highly-skilled phonemic decoders (for whom phonological coding was likely more efficient and resulted in higher fidelity codes) and lower-skilled comprehenders with smaller vocabularies (for whom the addition of phonological coding could significantly aid word identification).

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Chapter 3, in full is currently being prepared for submission for publication of the material. The dissertation author was the sole investigator of this paper.

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CHAPTER 4:
THE TIME COURSE OF PHONOLOGICAL CODING IN DEAF READERS: EVIDENCE
FROM SURVIVAL ANALYSES OF EYE MOVEMENT DATA

Abstract

There is a substantial body of research demonstrating that hearing readers generate phonological codes during reading. Furthermore, the early use of phonological codes in hearing readers is associated with more efficient word identification, suggesting that phonological coding serves a pivotal role in word identification and reading. The illiteracy rates in the deaf population (who do not have full access to the phonology of the language in which they read) are higher than the general population, however it is not clear that difficulties with phonological coding are responsible, and a small percentage of deaf readers do become skilled readers. The current series of experiments recorded eye movements of deaf native signers (who are skilled readers of English) as they read English sentences. These sentences contained correct target words, phonologically related words (and non-words), or orthographically matched controls. Survival analyses of first fixation durations on the phonologically related and orthographic control words were conducted to determine how early skilled deaf readers generate phonological codes during normal reading. Results suggest that some skilled deaf readers, who are native signers of American Sign Language, do generate English phonological codes quite rapidly during reading. Furthermore, there was some suggestion that the early generation of phonological codes might be related to more efficient word identification and higher reading comprehension skill, such that better comprehenders tended to generate phonological codes more rapidly, and

rapidly generated phonological codes were associated with shorter average gaze durations.

There is considerable evidence that hearing readers generate phonological codes (i.e., sound-based codes) during reading (for reviews see Leininger, 2014; McCusker, Hillinger, & Bias, 1981). Readers are less likely to notice (or be disrupted by) words that are phonologically related to semantically appropriate target words than control words that are matched on orthographic overlap (e.g., Chapters 2 & 3, Inhoff & Topolski, 1994; Jared, Levy, & Rayner, 1999; Rayner, Pollatsek, & Binder, 1998), they obtain phonological preview benefit from phonologically related words presented as parafoveal previews for targets (e.g., Miellet & Sparrow, 2004; Pollatsek, Lesch, Morris, & Rayner, 1992), and they use phonological codes after word identification to aid comprehension and help integrate meaning across sentences (e.g., Daneman & Newson, 1992; Slowiaczek & Clifton, 1980). Furthermore, there is evidence that the early generation of phonological codes is associated with more efficient word identification, since readers who generate phonological codes earlier tend to have shorter gaze durations (e.g., Chapter 2).

Together, these data suggest a pivotal role for phonological coding among hearing readers, both in the identification of words and in later comprehension processes during reading. Yet, recoding a written word into its phonological form is not the only way in which a skilled reader can identify the meaning of a written word. Although beginning readers must rely heavily on phonological coding to translate written words back into their known spoken forms (for reviews see Ashby & Rayner, 2006; Rayner, Foorman, Perfetti, Pesetsky, & Seidenberg, 2001), as reading skill increases, frequent encounters with a word's written form establish

direct connections between the orthographic string and the word's meaning (e.g., Jorm & Share, 1983; Share, 1995, 2008). The development of these direct connections makes identification of a word purely on the basis of its visual, orthographic form possible for skilled readers.

Indeed models of word identification during reading generally support word identification both via a direct route (from orthography to meaning) and an indirect route or phonologically mediated route, whereby phonological codes are generated in order to access the meaning of a word. Both the dual-route cascaded model (DRC; Coltheart, 1978, 1980, 2000; Coltheart, Curtis, Atkins, & Haller, 1993; Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001) and the parallel distributed processing model (PDP; e.g., Seidenberg & McClelland, 1989) propose these two routes to meaning in skilled, adult readers, but their assumptions about skilled readers' reliance on the two routes differ. The DRC model assumes that the two routes perform their computations somewhat independently and that the direct route is generally more efficient. Therefore, according to the DRC model, it should be the primary route by which skilled readers access the meanings of most words (e.g., Coltheart, 1980). On the other hand, the PDP model assumes that both routes work in parallel to mutually inform the activation of semantic representations (though the degree to which each route accrues activation and contributes to identification can vary). Under this model, the meanings of most words are accessed by a combination of activation from both routes, though the relative contributions can vary (e.g., Harm & Seidenberg, 2004).

The large body of evidence suggesting that skilled readers generate phonological codes rapidly during reading casts doubt on the DRC model's assumption that the direct route is the primary route by which skilled readers identify the meanings of words. However, the data can be accommodated under the PDP model's assumption that both routes are activated in parallel to inform the identification of most words. Under the PDP model, readers who generate phonological codes more rapidly should be faster to identify words, since this will increase activation from the indirect route. This model can also accommodate the finding that word identification speed is increased in less skilled, but not more skilled readers, by the early generation of phonological codes (Chapter 3). Under the PDP model, as reading skill increases, so does the efficiency of the direct route, such that it will likely be so efficient for highly skilled readers that additional activation from the indirect route will not have time to contribute substantially to word identification, whereas for less efficient readers, it will. Therefore, it may be possible (and the results of Chapter 3 suggest) that the extent to which each route contributes to the activation of semantic representations may vary as a function of an individual reader's skills.

If the relative contribution of each route does vary as a function of reader skill, then we might expect to find the greatest reliance on the direct route in a group of readers without full access to the phonology of the language in which they read. Prelingually, profoundly deaf readers of English (or other languages) represent exactly one such group of readers. Deaf individuals lack the auditory input

necessary for the development of fully specified phonological codes, and although their individual experiences with lip reading and speaking may provide access to articulatory-based phonological codes, these representations are still likely underspecified (for a reviews see Kelly & Barac-Cikoja, 2007; McQuarrie & Parrila, 2014). Therefore, if readers can modulate their relative reliance on the direct and indirect route to meaning based on their own relative language strengths (or if only one route every gets substantially developed as a function of language experience), deaf readers, for whom phonological codes are likely underspecified, might rely more heavily on the direct route to word identification than hearing readers. Indeed, Bélanger & Rayner (2015) suggested exactly that. In their *word-processing efficiency* hypothesis, they claim that deaf readers are more efficient than hearing readers at processing written words because they have developed “tighter connections between orthography and semantics...[and] are extremely attuned to the visual-orthographic makeup of words” (p. 224). Indeed in earlier work, Bélanger and colleagues failed to find any evidence that skilled deaf readers generate phonological codes during word identification—they found no evidence for phonological priming during a masked-priming lexical decision task (Bélanger, Baum, & Mayberry, 2012) and no evidence for phonological preview benefit during silent reading (Bélanger, Mayberry, & Rayner, 2013).

In contrast to the results of Bélanger and colleagues, other research has provided evidence that deaf readers do generate phonological codes during reading. Hanson, Goodell, and Perfetti (1991) had hearing and deaf subjects perform

semantic acceptability judgments for tongue-twisters and control sentences and found that both groups of subjects produced more errors on the semantic acceptability task when reading tongue-twisters than control sentences. Furthermore, error rates increased in both groups when the sentences were phonetically similar to a string of to-be-remembered numbers in a concurrent memory load version of the task. These results suggest that deaf readers may generate phonological codes during reading and also use phonological codes for memory maintenance (see also Engle, Cantor, & Turner, 1989; Hanson, 1982; Hanson & Lichtenstein, 1990). However other research has produced evidence that deaf readers instead generate codes in American Sign Language (ASL) based on the formational properties of signs (i.e., hand shape, location, movement, orientation) for short term memory maintenance (e.g., Bellugi, Klima, & Siple, 1975; Hanson, 1982; Krakow & Hanson, 1985; Shand, 1982) and potentially even for word identification (e.g., Morford, Wilkinson, Villwock, Piñar, & Kroll, 2011; Treiman & Hirsh-Pasek, 1983). Morford et al. (2011) had deaf ASL signers perform semantic relatedness judgments on pairs of English words, and found that subjects were faster to accept pairs of related English words that had phonologically related ASL translations, and were slower to reject pairs of unrelated English words that had phonologically related ASL translations, suggesting that deaf readers automatically generate ASL translations during a purely English task. Similarly, Treiman and Hirsh-Pasek (1983) had second-generation deaf signers and hearing controls perform acceptability judgments on English sentences. They found that hearing

controls made more errors on sentences that contained incorrect homophones (e.g., “he doesn’t like to eat meet”), whereas deaf readers made more errors on hand-twisters—English sentences that if recoded into ASL would contain many formationally similar signs, suggesting that the deaf readers may have recoded into sign during online sentence comprehension.

The results then are mixed, with some research suggesting that deaf readers generate phonological codes for the language in which they are reading (e.g., Hanson et al., 1991), other research suggesting that they do not generate phonological codes (Bélanger et al., 2012; Bélanger et al., 2013), and still other research suggesting that they instead generate ASL phonological codes (e.g., Morford et al., 2011; Treiman & Hirsh-Pasek, 1983). These differences in results could stem in part from the various tasks used across studies. Indeed, very little research has directly examined the early use of phonological codes in deaf readers. Most experiments have relied on downstream judgments or responses (e.g., semantic relatedness, lexical decision, acceptability) rather than measuring online processing. These later judgments are not very sensitive and do not always reflect processing during normal word identification or reading (e.g., for a discussion see Leininger, 2014). One notable exception is Bélanger et al. (2013) that used eye tracking to measure the generation of parafoveally extracted phonological codes during silent reading. This failure to find phonological preview benefit in deaf readers suggests that they may not extract English phonology from the parafovea like skilled hearing readers do. While Bélanger et al. interpreted this as evidence

that deaf readers do not generate English phonological codes during reading, it could instead be that deaf readers' relatively impoverished phonological codes take longer to develop and/or contribute meaningfully to word identification, potentially only exerting an effect once a word is actually fixated. This does not imply that deaf readers should be slower to identify words (indeed skilled deaf readers tend to be more efficient at word identification than skilled hearing readers, e.g., Bélanger & Rayner, 2015), instead if phonological code generation is somewhat delayed, then under the PDP model, deaf readers might identify many words largely via activation from the direct route before the phonologically mediated route has had time to accrue enough activation to contribute meaningfully to identification. Indeed, the results of Chapter 3 suggest that this may in fact be the case among some highly skilled hearing readers (e.g., skilled comprehenders with larger vocabularies)—these highly skilled hearing readers were quick to identify words, but the speed with which they did so did not vary as a function of how rapidly they generated phonological codes, suggesting that they may have relied more heavily on the direct route to meaning. Said another way, although the PDP model assumes that both routes to meaning propagate activation in parallel to mutually inform word identification, if the direct route is well-established, activation through this route will rise at a faster rate than through the phonologically mediated route. Therefore, if words are identified quickly (as is the case for skilled deaf readers), the phonologically mediated route may not accrue enough activation to contribute substantially to their identification.

Indeed, other research has provided evidence that deaf readers with different language backgrounds may in fact rely on different word identification strategies as their language skills allow (e.g., Hirshorn, Dye, Hauser, Supalla, & Bavelier, 2015). For example, in a meta-analysis of reading achievement in deaf readers, Mayberry, del Giudice, and Lieberman (2011) found that English phonological coding and awareness (PCA) accounted for only 11% of the variance in reading ability. Furthermore, because the effect size did not show systematic variation related to reading skill, the authors concluded that their results were consistent with some deaf readers using English phonological coding and awareness and others adopting different strategies, critically with no clear advantage to adopting one strategy over another (see also, Miller & Clark, 2011). Indeed others have found evidence for a positive relationship between ASL phonological awareness and English reading skills (e.g., McQuarrie & Abbott, 2013), suggesting that successful reading outcomes might be achievable through a variety of different strategies.

Current Experiments

The current series of experiments recorded eye movements while deaf ASL signers (who were also skilled readers of English) read English sentences containing target words that were sometimes replaced with either phonologically related stimuli or orthographically matched controls. Survival analyses were conducted (following the method outlined in Reingold & Sheridan, 2014) in order to quantify the earliest observable influence of phonology on the eye movement record, as

means analyses can sometimes obscure different underlying distributions of fixations. These analyses provide an estimate of the earliest observable influence of a manipulation on behavior by comparing the percent of fixations on a critical word that have not yet been terminated by a reader making a saccade off of the critical word (i.e., that are still “surviving”), across two conditions. Specifically, for a given time t , the percent survival is calculated as the percentage of fixations with a duration greater than t . Thus at time $t = 0$, the percent survival is 100 (since all fixations have a duration greater than zero), and as t increase the survival percentage decreases, eventually approaching zero as t approaches the duration of the longest fixation in a given condition. By comparing survival curves across the phonologically related and orthographic control word conditions, this analysis allows for computation of the *divergence point*—the earliest point in time at which the curves for the two conditions begin to significantly diverge. The divergence point then provides an estimate of the earliest observable influence of phonology (i.e., the generation of phonological codes) on the eye movement record of a given subject.

These two experiments were designed with the following aims: (1) To determine whether there is any evidence for the generation of English phonological codes during reading in skilled deaf readers, and if so, to quantify how early phonological codes are exerting an influence on behavior during normal reading. (2) To examine variability in the generation of phonological codes across subjects and to explore which measures of general language skill (e.g., reading comprehension)

or language background (e.g., experience producing and comprehending spoken English) might be predictive of phonological code use during reading.

Experiment 1

Method

Participants. 18 adults from San Diego's Deaf community participated in this experiment for monetary compensation. One subject was removed for scoring too low on an offline test of reading comprehension (see below)²⁰, leaving 17 subjects for analysis. They were aged 20-43 years ($M = 30$ years), profoundly deaf before the age of 2, and used American Sign Language (ASL) as their main communication mode for at least 20 years ($M = 27$ years). Additionally, all began using ASL at an early age ($M = 2$ years, max = 8 years). All had hearing loss of at least 80 dB in their better ear²¹, none had cochlear implants (though 1 subject indicated that they had one in the past), and 4 subjects currently used a hearing aid. Finally, all subjects had normal or corrected to normal vision, and were naïve to the purpose of the experiment.

Background Measures. All participants completed the Reading Comprehension subtest of the Peabody Individual Achievement Test-Revised (PIAT-R; Markwardt, 1989) as well as three subtests (Picture Completion, Picture Arrangement, and Block Design) of the Wechsler Adult Intelligence Scale-Revised

²⁰ This subject scored 3 standard deviations below the group mean on the PIAT-R reading comprehension subtest (equivalent to a 5th grade reading level). Additionally, examination of their comprehension accuracy during the eyetracking experiment revealed that they scored more than 3 standard deviations below the group mean in online comprehension as well.

²¹ Two subjects did not indicate their exact degree of hearing loss, however they did indicate that they could not hear speech unaided.

(WAIS-R; Wechsler, 1981). The PIAT-R test was administered to ensure that all participants were indeed skilled readers of English, as low reading levels and illiteracy are serious problems in the deaf population (e.g., Kelly & Barac-Cikoja, 2007). This test revealed that participants were indeed skilled readers who read at a 10th grade level on average, which aligned well with participants' self-assessments of their own reading ability ($M = 9.29$ on a 1-10 scale). The WAIS-R test was administered to ensure that all participants had normal non-verbal IQ, and indeed that was the case—subjects had an average scaled score of 11.7 across each of the three tests ($M = 11.7$, $SD = 1.76$, range = 8.67-14.33), which translated to an average Non-verbal IQ of 113.²² In addition to these tests, participants also completed a language history questionnaire with information about their language history and self-assessed proficiency with both ASL and English (both written and spoken). The results of several of the relevant questions, as well as the results of the PIAT-R and WAIS-R are presented in Table 4.1.

²² Because subjects only completed 3 of the 5 performance subtests that contribute to computation of non-verbal IQ, each subject's average scaled score (across the three tests) was multiplied by 5 to obtain a projected sum of scaled scores. This value was then used to determine each subject's non-verbal IQ.

Table 4.1. Summary of tests of skills (language and non-verbal IQ) and responses on the language history questionnaire. Raw scores and standardized z-scores are included.

Skill	Language	Raw scores				Z-score
		Mean	SD	Min	Max	Range
WAIS-R non-verbal IQ	NA	113	14.74	92	136	-1.44 – 1.55
PIAT-R reading comprehension	English	88	5.43	81	95	-1.29 – 1.29
Comprehension (spoken)	English	4.41	2.83	0	10	-1.56 – 1.97
Comprehension (written)	English	9.29	0.92	7	10	-2.49 – 0.77
Expression (spoken)	English	3.59	3.55	0	10	-1.01 – 1.80
Daily hours reading	English	4.18	3.40	1	15	-0.94 – 3.19
Age of exposure	English	0.59	1.50	0	5	-0.39 – 2.94
Comprehension	ASL	9.71	0.47	9	10	-1.50 – 0.63
Expression	ASL	9.00	1.37	5	10	-2.92 – 0.73
Age of exposure	ASL	2.18	2.67	0	8	-0.81 – 2.18

Apparatus. Eye movements were recorded with an SR Research Ltd. Eyelink 1000 eye tracker (sampling rate of 1000 Hz) in a tower setup that restrained head movements with forehead and chin rests. Viewing was binocular, but only the eye movements of the right eye were recorded. Subjects were seated approximately 60 cm away from a 19-inch View-Sonic LCD monitor with a screen resolution of 1280 x 1024 pixels. Text was displayed in black, 14- point, fixed-width Consolas font on a white background. Sentences were always displayed in the center of the screen in one line of text, and approximately 4 characters subtended 1° of visual angle.

Materials. Materials were taken from Chapter 2 (Experiment 1). These consisted of 56 triplets (target, homophone, orthographic control) that always shared at least the same first letter. Correct targets, homophones, and orthographic control words were roughly matched on lexical frequency, length, mean bigram frequency (the average bigram count for a particular word), and bigram frequency

by position (the sum of the bigram count (by position) for a particular word).

Additionally, the homophone and orthographic control were also matched on their degree of orthographic overlap with the correct target. Lexical frequencies (per 400 million) for all stimuli were computed via log-transformed HAL frequency norms (Lund & Burgess, 1996) using the English Lexicon Project (Balota et al., 2007). Correct targets had an average log frequency of 8.91 (range 3.99 to 13.8), homophones had an average log frequency of 9.01 (range 5.73 to 13.27), and orthographic controls had an average log frequency of 9.21 (range 5.57 to 13.16). All critical words were on average 4.45 letters long (range 3 to 9). Summary statistics for the critical stimuli appear in Table 4.2.

Table 4.2. Experiment 1 summary statistics for target words.

	Correct Target		Homophone		Orthographic Control	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Log HAL Frequency (per 400 mil)	8.91	1.94	9.01	1.86	9.21	1.75
Length	4.45	1.08	4.45	1.08	4.45	1.08
Mean Bigram Frequency	1857	869	1979	910	1922	928
Bigram Frequency by Position	1223	636	1291	592	1190	568
Orthographic Overlap			0.6	0.15	0.63	0.14
Cloze Predictability	0.39	0.33				
Sentence Acceptability	6.04	0.58	3.09	0.69	2.85	0.83
Fragment Acceptability	6.03	0.76	2.94	0.74	2.7	0.86

Note. Orthographic overlap refers to the percentage of position specific letters that the homophones or orthographic controls shared with the correct target words (e.g., *made* and *maid* share the first two, or 50%, of their letters in the same positions).

For each set of critical words, three sentence frames were also taken from Chapter 2 (Experiment 1) that rendered the correct target word predictable

(assessed via cloze norming)²³, resulting in a total of 168 experimental sentences. In this way, for each set of critical words, each subject could read the correct target, homophone, and orthographic control word each in a different sentence and contribute data to all three conditions. The type of critical word presented in each sentence was counterbalanced across participants, such that across experimental lists, for every item, each type of critical word appeared in each of the three sentence frames an equal number of times. The 168 experimental sentences were presented along with 50 filler sentences. Simple comprehension questions appeared after 20 of the filler items, and comprehension accuracy was high (94.1%). Word type (correct target, homophone, orthographic control) was tested within participants, and, because there were three experimental sentences for each target triplet, each participant contributed data to all three conditions for each set of critical words. An example stimulus is shown in (1), with the correct target/homophone/orthographic control word italicized.

(1) The surfers traveled to the word famous *beach/beechn/bench* where the waves were very large.

Procedure. Subjects were instructed to read the sentences for comprehension and to respond to occasional comprehension questions using a gamepad to indicate “yes” or “no” responses. At the start of the experiment, the eye-tracker was calibrated with a 3-point calibration scheme. At the beginning of the experiment, subjects received nine practice trials (five of which were followed by a

²³ For details regarding this and other norming procedures (e.g., sentence acceptability, fragment acceptability), see Chapter 2.

comprehension question) to allow them to become comfortable with the experimental procedure.

Each trial began with a fixation point in the center of the screen (that served as a drift correction), which the subject was required to fixate until the experimenter initiated the trial. Then a fixation box appeared on the left side of the screen, which was located where the beginning of the sentence would appear. Once a stable fixation was detected within the box, the box disappeared and was replaced by the sentence, which remained on the screen until the subject pressed a button signaling that they understood the sentence and were ready to move on. Order of sentence presentation was randomized for each participant, and the experimental session lasted approximately fifty minutes.

Results

Prior to analysis, fixations under 81 ms were pooled if they were within 1 character of another fixation, as these fixations likely preceded corrective saccades. Consistent with other studies that have examined distributions of fixation durations (e.g., Chapters 2 & 3; Reingold, Reichle, Glaholt, & Sheridan, 2012), fixations shorter than 81 ms that were further from an adjacent fixation remained in the dataset. All fixations over 800 ms were deleted, as were any trials in which subjects blinked during first-pass reading of the target word. Additionally, gaze durations longer than 2,000 ms and total times longer than 4,000 ms were excluded. After all exclusions, 99.5% of the original data were retained for analysis.

Standard reading time measures (Rayner, 1998, 2009) used to investigate the time-course of word processing in reading are reported, including *first fixation duration* (the duration of the first fixation on a word), *single fixation duration* (the duration of the first fixation on a word when a reader makes only one fixation during first-pass reading), *gaze duration* (the sum of all first-pass fixation durations on a word before leaving it), *go-past time* (the sum of all first-pass fixation durations on a word and any fixations on preceding words before going past it to the right), and *total time* (the sum of all fixation durations on a word including any time spent re-reading it following a regression). In addition, three probability measures are also reported: *fixation probability* (the probability that a word was fixated at least once during first-pass reading), *regression-out probability* (the probability of making a regression out of a word to re-read prior words in the sentence) and *regression-in probability* (the probability of making a regression into a word—i.e., from subsequent words in the sentence).

Table 4.3. Means and standard errors for reading time measures in Experiment 1.

	Target	Homophone	Orthographic control
Fixation Probability	0.63 (0.016)	0.62 (0.016)	0.66 (0.015)
Single Fixation Duration	240 (3.6)	255 (3.9)	255 (3.9)
First Fixation Duration	241 (3.5)	255 (3.8)	253 (3.6)
Gaze Duration	260 (4.5)	273 (4.6)	279 (4.9)
Go-Past Time	303 (11)	327 (9.8)	337 (9.9)
Total Time	291 (6.2)	365 (9.8)	413 (12)
Regressions Out	0.05 (.007)	0.07 (.008)	0.08 (.009)
Regressions In	0.09 (.01)	0.22 (.013)	0.25 (.014)

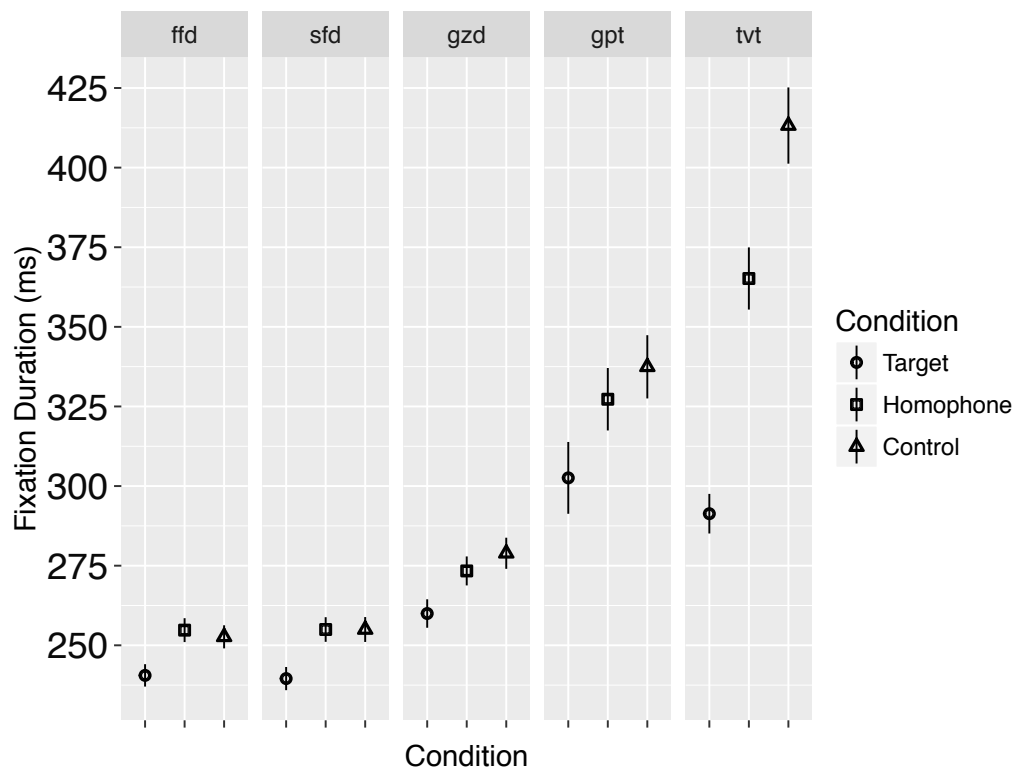


Figure 4.1. Reading time on the critical word as a function of condition (correct target, homophone, or orthographic control) across 5 reading time measures (ffd = first fixation duration, sfd = single fixation duration, gzd = gaze duration, gpt = go-past time, tvt = total time). Shape represents condition and error bars represent ± 1 standard error of the mean.

Linear mixed-effects models were fit using the `lmer` function from the `lme4` package (version 3.2.3; Bates, Maechler, Bolker, & Walker, 2015) within the R Environment for Statistical Computing (R Development Core Team, 2015). Models were fit using the maximal random effects structure justified by the design of the experiment (Barr, Levy, Scheepers & Tily, 2013), which included subjects and items as crossed random effects.²⁴ The comparisons between different levels of the fixed

²⁴ Some models showed convergence failures, in which case random slopes were removed and the results of the first model to converge are reported. The random slope for items in the SFD model and the random slopes for subjects and items in the GZD model were removed.

effect were specified using the default treatment coding in R, with the mean of the homophone condition represented by the intercept. Regression coefficients (which estimate the effect size (in milliseconds) of the reported comparisons), the standard errors, and the (absolute) t values of the coefficients are all reported.

For binary dependent variables (fixation probability data), generalized mixed-effects regression models (GLMMs) were used with a logit link function, and regression coefficients (b —which represent effect size in log-odds space), and the (absolute) z value and p value of the effect coefficient are all reported. Absolute values of the t and z statistics greater than or equal to 1.96 indicate an effect that is significant at approximately the .05 alpha level. Reading measures on the target words are reported in Table 4.3, results of the LMMs on fixation duration measures are reported in Table 4.4, and results of the GLMMs on fixation probability measures are reported in Table 4.5.

Fixation duration measures. With the exception of go-past time ($t = 1.53$), the correct target was fixated for significantly less time than the homophone across all reading time measures (all $ts > 2.17$). Fixation durations on the homophone and orthographic control conditions only significantly differed in total time ($t = 2.08$), where the homophone was fixated for significantly less time than the orthographic control (all other $ts < 0.87$). Group means for all fixation duration measures appear in Figure 4.1.

Fixation probability measures. There was a significant difference in fixation probability, such that readers were more likely to skip (i.e., the fixation

probability was lower for) the homophone than the orthographic control word ($p = .007$), whereas the likelihood of fixating the homophone and the correct target did not differ ($p = .64$). There were no significant differences in the likelihood of making a regression out of the critical word across conditions (both $ps > .11$). Finally, there was a significant difference in the likelihood of making a regression into the critical word, such that readers were less likely to make a regression into the correct target than the homophone ($p < .001$), and the regression-in rate did not differ between the homophone and orthographic control ($p = .34$).

Table 4.4. Results of linear mixed effects models for reading time measures on the critical word in Experiment 1. The intercept represents the mean duration for the homophone condition. Significant effects are indicated by boldface.

Measure	Contrast	b	Model SE	t
First Fixation Duration	Intercept	248.48	10.47	23.74
	Target effect	-13.61	4.95	2.75
	Orthographic control effect	-0.99	6.33	0.16
Single Fixation Duration	Intercept	247.72	11.36	21.81
	Target effect	-13.74	5.02	2.74
	Orthographic control effect	2.76	5.82	0.48
Gaze Duration	Intercept	265.22	11.49	23.09
	Target effect	-13.39	6.14	2.18
	Orthographic control effect	5.19	6.05	0.86
Go-Past Time	Intercept	317.02	18.48	17.15
	Target effect	-24.57	16.03	1.53
	Orthographic control effect	5.94	14.84	0.40
Total Time	Intercept	347.96	28.03	12.42
	Target effect	-64.15	19.55	3.28
	Orthographic control effect	38.29	18.39	2.08

Table 4.5. Results of the logistic regression models for fixation probability measures across condition in Experiment 1. The intercept represents the mean probability for the homophone condition. Significant effects are indicated by boldface.

Measure	Contrast	Model		
		b	z	p
Fixation Probability	Intercept	0.57	2.96	.003
	Target	0.05	0.47	0.64
	Orthographic control	0.33	2.67	.007
Regression-out Probability	Intercept	-3.34	8.47	< .001
	Target	-0.91	1.57	0.12
	Orthographic control	0.37	1.04	0.30
Regression-in Probability	Intercept	-1.60	5.25	< .001
	Target	-0.98	4.52	< .001
	Orthographic control	0.15	0.96	0.34

Survival Analyses. Although means analyses suggested that phonology did not influence early eye movement measures (i.e., there were no differences between mean fixation times on the homophone and orthographic control in early fixation duration measures), it is possible that the nature of the means analyses could obscure earlier effects of phonology. Indeed, analysis of fixation probability revealed that subjects were equally likely to skip the homophone and the correct targets, whereas skipping rates were reduced for the orthographic control. This suggests that already in the parafovea, readers experienced easier processing of the homophone than the orthographic control, potentially driven by the homophone's phonological relationship to the target. As such, the lack of an effect in early fixation duration measures warrants further exploration. Indeed, in previous research (e.g.,

Chapter 2, Experiment 1), survival analyses revealed an effect of phonology that emerged approximately 100 ms earlier than the mean of the first fixation duration measure to show a significant difference between the homophone and orthographic control condition (i.e., the divergence point estimate was 173 ms, whereas mean gaze duration on the homophone was 266 ms compared to 276 ms for the orthographic control). Therefore survival analyses were conducted to determine the earliest observable effect of phonology to emerge after fixation.

Survival Analyses were conducted on first fixation duration data following the Individual Participant Divergence Point Analysis (IP-DPA) procedure outlined in Reingold and Sheridan (2014) and using the Matlab script supplied in their supplementary materials. The IP-DPA procedure uses a bootstrap resampling procedure to compare survival curves of first fixation duration data in two conditions (here, the homophone and orthographic control conditions) to determine the divergence point estimate for each subject individually. The procedure, outlined in Reingold and Sheridan (2014), is repeated for 1,000 iterations per subject, and the median divergence point estimate obtained across all iterations is used as the divergence point for that individual subject. Using this procedure to compare the survival curves for the homophone and orthographic control conditions results in the generation of divergence point estimates that correspond to the earliest observable effect of phonology. Furthermore, using the IP-DPA procedure provides divergence point estimates for each individual subject, which allows for an investigation into the degree of variability of phonological code generation across

subjects. The survival curves for the homophone and orthographic control condition are displayed in Figure 4.2 as well as the mean divergence point obtained by taking the mean of the individual subject divergence points. The homophone and orthographic control curves significantly diverged at 180 ms on average across all subjects ($M = 180$ ms, range = 91-279.5 ms, $SE = 16.8$, $N = 14$)²⁵, and 50% of individual subjects had divergence point estimates that were earlier than this group mean. Finally, across all subjects, only 20.4% of first fixations had durations shorter than this divergence point estimate, suggesting that the majority of fixations were influenced by phonology.

²⁵ The divergence point estimate for 1 subject was deemed unreliable because a divergence point estimate was obtained in less than 50% of the iterations, and the divergence point estimates for 2 additional subjects could not be computed (i.e., their curves never significantly diverged). Following Reingold and Sheridan (2014) the data for all three subjects were excluded from computation of the group divergence point estimate, however their raw fixation duration data are included in the survival figure.

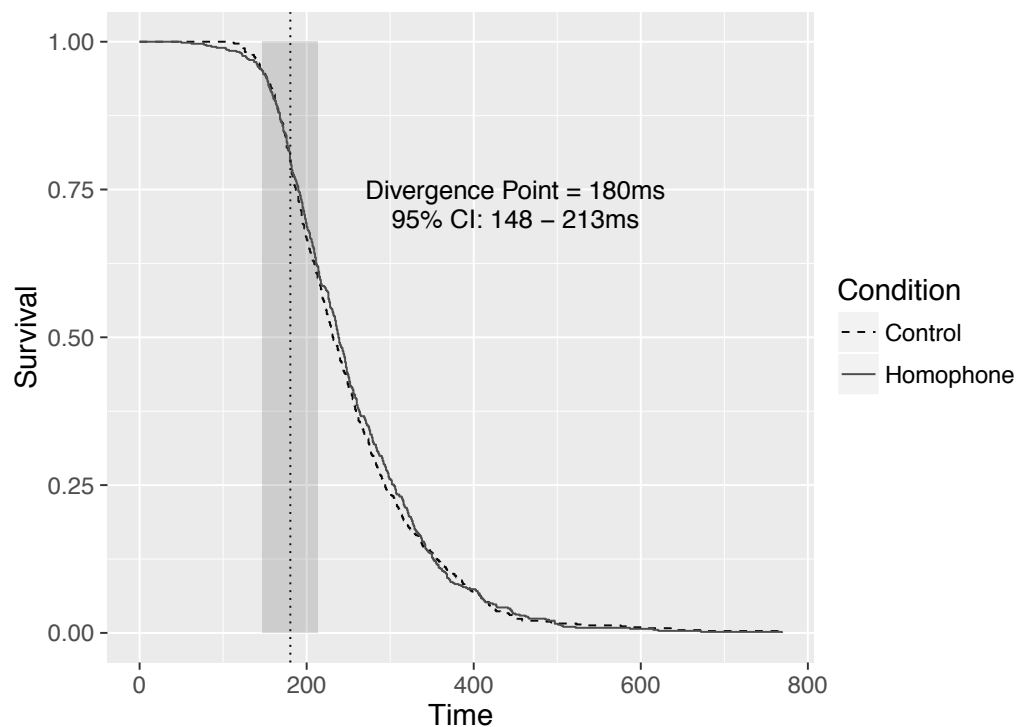


Figure 4.2. Proportion of fixations surviving as a function of time for Experiment 1. Line type represents the condition (homophone, control) and the dotted vertical line denotes the divergence point. The grey band surrounding the divergence point line represents the 95% confidence interval.

Because previous research (e.g., Chapter 3) has suggested a relationship between the speed of phonological coding and word identification time in hearing readers, gaze durations (on the correct targets—i.e., the 1/3 of trials that were not used in computation of the divergence point estimates) were regressed on divergence point estimates to determine if the same were true for deaf readers. Results suggested that the effect for deaf readers was the same as hearing readers (see Figure 4.3, Panel B), subjects who showed an early use of phonological codes tended to be faster to identify words, as a subject's divergence point estimate significantly predicted their average gaze duration ($b = 0.41$, $t(12) = 2.20$, $p = .048$)

and explained a significant proportion of the variance in gaze duration ($R^2 = 0.29$, $F(1, 12) = 4.84$, $p = .048$). Interestingly there was also an effect whereby a subject's reading comprehension score (measured on the PIAT-R test) significantly predicted their use of phonological codes, such that more skilled readers generated phonological codes more rapidly ($b = -6.86$, $t(12) = -2.61$, $p = .02$, $R^2 = 0.36$, $F(1, 12) = 6.83$, $p = .02$; see Figure 4.3, Panel C). This is in contrast to the results of hearing readers, where no differences in the time course of phonological code generation were observed as a function of general reading skill (i.e., reading comprehension and vocabulary; Chapter 3). Surprisingly, there was not a significant relationship between a given subject's reading comprehension score and their average gaze duration ($b = -12.76$, $t(15) = -1.10$, $p = .29$, $R^2 = 0.07$, $F(1, 15) = 1.20$, $p = .29$; see Figure 4.3, Panel A). There was a slight tendency for better comprehenders to have shorter gaze durations, but it was far from significant.

Prior research on hearing readers has suggested that skilled phonemic decoders generate earlier phonological codes than less skilled phonemic decoders, potentially highlighting strategic processing as a function of different reading skills. Although a direct test of phonemic decoding ability was not administered, subjects did provide self-ratings of their own abilities to produce and comprehend spoken English. While not a perfect measure of phonemic decoding ability, these self-assessments provide the closest approximation of a subject's knowledge of the way English phonology is produced and articulated. Analyses revealed no systematic relationship between a subject's divergence point estimate and either their self-

rated spoken English comprehension ability ($p = .85$) or their self-rated spoken English expression ability ($p = .80$), suggesting that a subject's self-assessed knowledge of English articulation did not influence their generation of phonological codes during reading.

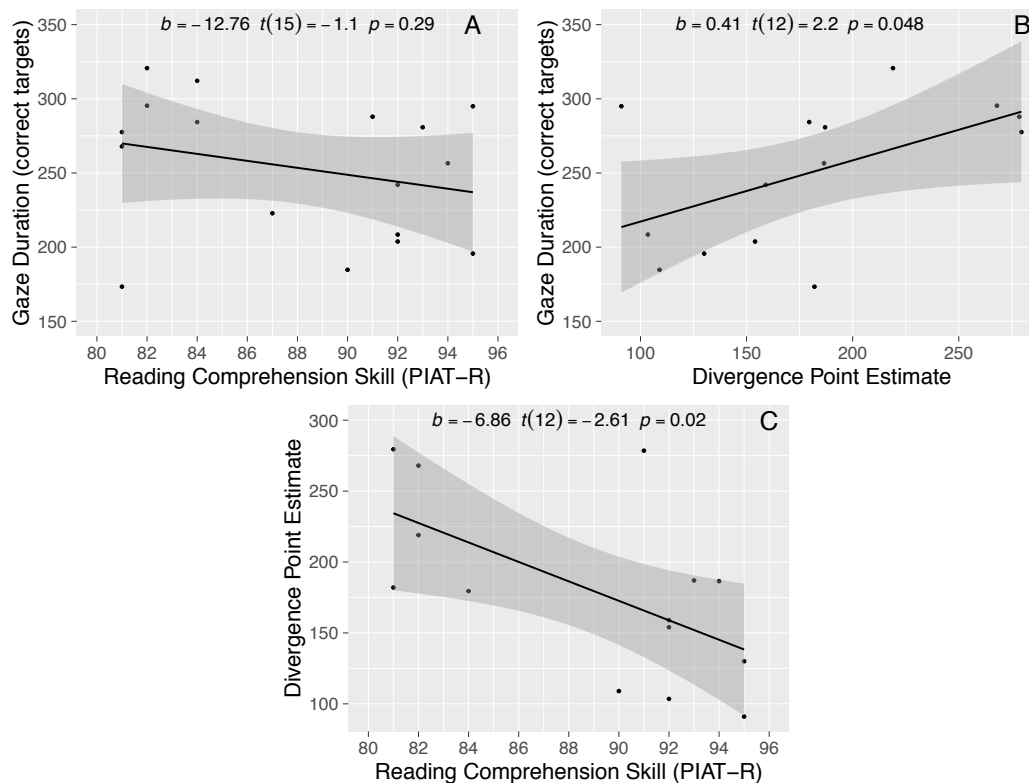


Figure 4.3. Relationships between divergence point estimates and different language assessment and eye movement measures. Panel A shows the correlation between divergence point and gaze duration (on correct targets), Panel B shows the correlation between divergence point and reading comprehension skill measured on the PIAT-R. In each panel, the regression line and 95% confidence interval are represented by the black line and grey band respectively.

Discussion

Taken together, the means analyses and survival analyses seem to suggest somewhat different stories. The means analyses reveal that there was a hint of an early phonological processing advantage in that readers skipped the homophone at

a rate similar to the correct target and significantly higher than the orthographic control, however this advantage disappeared in early fixation duration measures, which reflect early processing and word identification. Examining only these early fixation duration measures (i.e., first fixation duration, single fixation duration, gaze duration) would likely lead one to conclude that deaf readers do not generate phonological codes during reading (indeed, these are the same measures that failed to show an effect of phonological preview benefit in Bélanger et al., 2013). However, the survival analyses indicated that phonological coding affected behavior on average within 180 ms of fixating the target across subjects.

Additionally, earlier divergence point estimates were associated with shorter gaze durations, suggesting that subjects who generated phonological codes more rapidly were also faster to identify words (see Chapter 2 for similar results in hearing readers). Furthermore, the rapidity with which a given subject generated phonological codes was related to their reading comprehension skill—the data suggest that subjects who scored higher on the PIAT-R test of reading comprehension tended to be those who also generated phonological codes earlier during reading. This result is in contrast to the results from hearing readers presented in Chapter 3, which suggested no direct relationship between reading comprehension ability and the time course of phonological code generation in hearing readers.

Finally, there was no significant relationship between reading comprehension ability and average gaze duration. Although the data trended

toward a negative relationship, it was not significant. This is in contrast to prior results from both hearing and deaf subjects—prior research has consistently found a relationship between reading skill and average fixation duration, such the higher-skilled readers tend to have shorter average fixation durations (for reviews see Bélanger & Rayner, 2015; Rayner, 1998; 2009). This lack of an effect may reflect the fact that all of the deaf readers who were tested were highly skilled readers. In other words, because selection was limited to highly skilled readers, the range of reading comprehension ability sampled may have been too limited to detect any significant variation. Indeed, comparison between the range of scores on the PIAT-R in this experiment and the experiment reported in Chapter 3 (where a significant relationship between reading skill level and average gaze duration was found) reveals that the scores in Chapter 3 came from a much larger range (66-98) than the scores obtained here (81-95). Although this limited range of reading comprehension ability can explain the lack of a relationship with gaze duration, it does not explain the presence of a relationship between comprehension ability and phonological code generation, nor between phonological code generation and average gaze duration. It is worth noting that some prior research has suggested that the use of English phonological codes is indicative of skilled reading (e.g., Hanson & Fowler, 1987; Hanson, Liberman, & Shankweiler, 1984), however other research has failed to find a difference in phonological code generation as a function of reading skill (e.g., Bélanger et al., 2012; Bélanger et al., 2013). It could be that there is an additional skill correlated with reading comprehension ability in this group of

subjects that was not directly tested for. One possibility is English phonological awareness and phonemic decoding ability. Although self-assessed abilities to produce and comprehend spoken English were not related to divergence point estimates, it could be that this measure was not sensitive enough to tap into true differences in phonemic awareness and phonological coding ability.

The results of Experiment 1 suggest that more skilled deaf readers (i.e., better comprehenders) are those who generate phonological codes rapidly and in turn are faster to identify words. However, the lexical nature of the homophones and orthographic control words used in this study leaves open the possibility that readers are rapidly identifying these words via the direct route to meaning with phonology potentially coming online later. Although the early time course suggested by the divergence point estimates of some subjects (e.g., as early as 91 ms) seems to suggest that the codes exert an effect prior to word identification, the lexical nature of the stimuli makes it impossible to definitively determine. Therefore, Experiment 2 measured processing of phonologically related and orthographic control non-words. This was done to ensure that any apparent effects of phonology were indeed the result of phonological code generation, since non-words do not have existing entries in the lexicon that can be activated solely via the direct route.

Experiment 2

Method

Participants. The same set of participants from Experiment 1 also participated in Experiment 2. The order of experiment presentation was counterbalanced across participants.

Apparatus. The apparatus was identical to Experiment 1.

Table 4.6. Experiment 2 summary statistics for target words.

	Correct Target		Pseudohomophone		Orthographic Control	
	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>	<i>M</i>	<i>SD</i>
Log HAL Frequency (per 400 mil)	9.7	1.53	0	0	0	0
Length	4.58	0.74	4.58	0.74	4.58	0.74
Mean Bigram Frequency	1748	769	1666	687	1651	691
Bigram Frequency by Position	1214	513	1112	503	1182	480
Orthographic Overlap			0.63	0.13	0.66	0.13
Cloze Predictability	0.65	0.32				
Sentence Acceptability	6.12	0.49	2.95	0.73	2.65	0.65
Fragment Acceptability	5.97	0.69	2.95	0.50	2.44	0.34
Pronunciation			4.38	0.4		

Note. Orthographic overlap refers to the percentage of position specific letters that the homophones or orthographic controls shared with the correct target words (e.g., *wheel* and *whele* share the first three, or 60%, of their letters in the same positions).

Materials. Materials were taken from Chapter 2 (Experiment 2), and were similar to those used in Experiment 1 except that the homophone and orthographic control word conditions were replaced with pseudohomophone and orthographic control non-word conditions. These consisted of 60 triplets (target,

pseudohomophone, orthographic control non-word) that always shared at least the same first letter. Correct targets, pseudohomophones, and orthographic control non-words were roughly matched on length, mean bigram frequency, and bigram frequency by position. Additionally, the pseudohomophones and orthographic control non-words were also matched on lexical frequency (i.e., all had a lexical frequency of zero) and their degree of orthographic overlap with the correct target. Correct targets had an average log frequency of 9.7 (range 6.22 to 12.42). All critical words were on average 4.58 letters long (range 4 to 8). Summary statistics for the target words appear in Table 4.6.

For each set of critical words, three sentence frames were taken from Chapter 2 (Experiment 2) that rendered the correct target word predictable (assessed via cloze norming)²⁶, resulting in a total of 180 experimental sentences. In this way, for each set of critical words, each subject could read the correct target, pseudohomophone, and orthographic control non-word each in a different sentence and contribute data to all three conditions. The type of critical word presented in each sentence was counterbalanced across participants, such that across experimental lists, for every item, each type of critical word appeared in each of the three sentence frames an equal number of times. The 180 experimental sentences were presented along with 50 filler sentences. Simple comprehension questions appeared after 20 of the filler items, and comprehension accuracy was high (90.4%). Word type (correct target, pseudohomophone, orthographic control non-word) was

²⁶ For details regarding this and other norming procedures (e.g., sentence acceptability, fragment acceptability, pronunciation), see Chapter 2.

tested within participants, and, because there were three experimental sentences for each target triplet, each participant contributed data to all three conditions for each set of critical words. An example stimulus is shown in (2), with the correct target/pseudohomophone/orthographic control non-word italicized.

(2) Because of his insomnia, Caleb couldn't *sleep/sleap/slerp* even though he was tired.

Results

Data exclusion criteria were identical to Experiment 1 and resulted in 99.4% of the original data being retained for analysis.

Table 4.7. Means and standard errors for reading time measures in Experiment 2.

	Identical	Pseudohomophone	Orthographic control
Fixation Probability	0.62 (0.02)	0.67 (0.02)	0.64 (0.02)
Single Fixation Duration	225 (2.8)	256 (4.2)	261 (4.5)
First Fixation Duration	225 (3.3)	255 (3.9)	257 (3.9)
Gaze Duration	235 (3.3)	293 (6.1)	299 (6.0)
Go-Past Time	279 (7.9)	333 (8.3)	371 (12)
Total Time	264 (5.0)	364 (8.5)	400 (10)
Regressions Out	0.06 (.008)	0.08 (.008)	0.08 (.009)
Regressions In	0.09 (.009)	0.19 (.012)	0.22 (.013)

The same standard reading time measures as Experiment 1 are reported and all reading measures on the target word are summarized in Table 4.7. Results of the linear mixed-effects models (with the intercept representing the mean of the

pseudohomophone condition) are summarized in Table 4.8, and results of the general linear mixed-effects regression models in Table 4.9.²⁷

Fixation duration measures. Across all reading time measures, the correct target was fixated for significantly less time than the pseudohomophone (all t s > 3.63). As with Experiment 1, fixation durations on the pseudohomophone and orthographic control conditions were only significantly different in total time ($t = 2.04$), where the pseudohomophone was fixated for significantly less time than the orthographic control (all other t s < 1.45). Group means for all fixation duration measures appear in Figure 4.4.

Fixation probability measures. There was a significant difference in fixation probability, such that readers were more likely to skip (i.e., the fixation probability was lower for) the correct target than the pseudohomophone ($p = .02$), whereas the likelihood of fixating the pseudohomophone and orthographic control did not differ ($p = .49$). There were no significant differences in the likelihood of making a regression out of the critical word across conditions (both p s > .58). Finally, there was a significant difference in the likelihood of making a regression into the critical word, such that readers were less likely to make a regression into the correct target than the homophone ($p < .001$), and the regression in rate did not differ between the homophone and orthographic control ($p = .28$).

²⁷ In Experiment 2, due to convergence issues the random slope for items in the TVT model was removed, and the random slopes for subjects and items in the GZD model were removed.

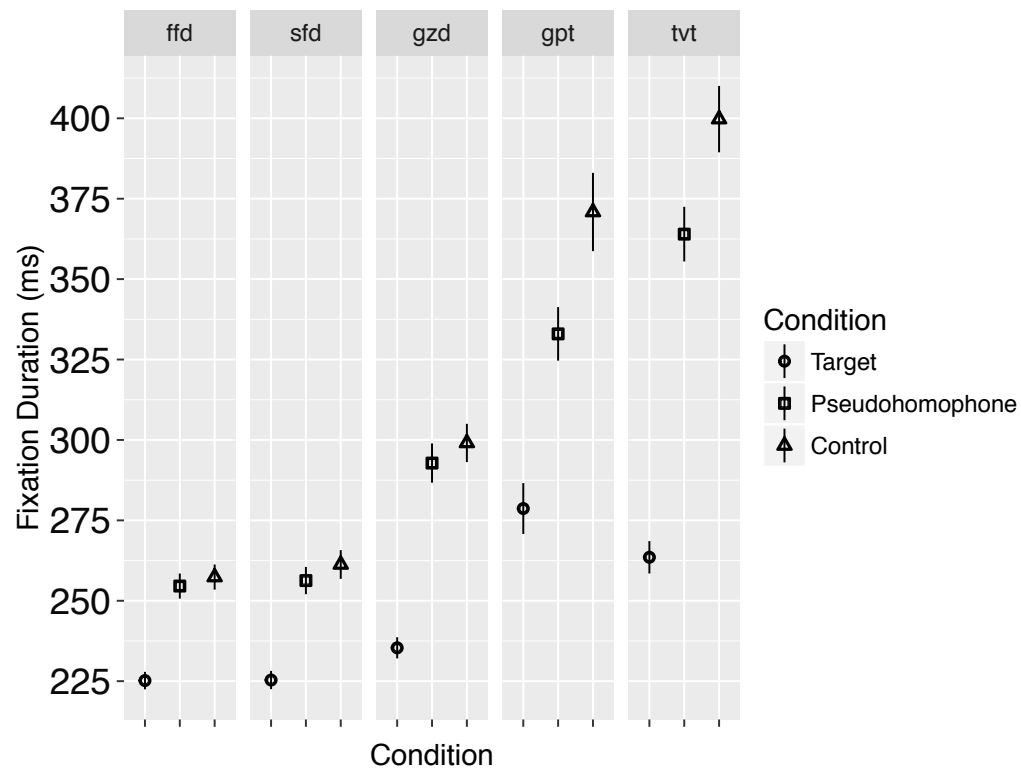


Figure 4.4. Reading time on the critical word as a function of condition (correct target, pseudohomophone, or orthographic control) across 5 reading time measures (ffd = first fixation duration, sfd = single fixation duration, gzd = gaze duration, gpt = go-past time, tvf = total time). Shape represents condition and error bars represent ± 1 standard error of the mean

Table 4.8. Results of linear mixed effects models for reading time measures on the critical word in Experiment 2. The intercept represents the mean duration for the pseudohomophone condition. Significant effects are indicated by boldface.

Measure	Contrast	Model		
		b	SE	t
First Fixation Duration	Intercept	249.62	9.40	26.56
	Target effect	-27.96	5.82	4.81
	Orthographic control effect	0.59	5.67	0.11
Single Fixation Duration	Intercept	252.37	10.16	24.84
	Target effect	-30.24	6.31	4.79
	Orthographic control effect	3.82	6.77	0.57
Gaze Duration	Intercept	284.12	13.14	21.62
	Target effect	-58.47	7.04	8.31
	Orthographic control effect	4.74	6.95	0.68
Go-Past Time	Intercept	319.78	23.36	13.69
	Target effect	-50.96	14.02	3.64
	Orthographic control effect	26.82	18.69	1.44
Total Time	Intercept	345.41	28.18	12.26
	Target effect	-90.17	20.67	4.36
	Orthographic control effect	27.72	13.57	2.04

Table 4.9. Results of the logistic regression models for fixation probability measures across condition in Experiment 2. The intercept represents the mean probability for the pseudohomophone condition. Significant effects are indicated by boldface.

Measure	Contrast	Model		
		b	z	p
Fixation Probability	Intercept	0.83	3.96	< .001
	Target	-0.25	2.34	0.02
	Orthographic control	-0.08	0.69	0.49
Regression-out Probability	Intercept	-3.64	6.39	< .001
	Target	0.03	0.06	0.95
	Orthographic control	0.20	0.54	0.59
Regression-in Probability	Intercept	-1.79	6.12	< .001
	Target	-1.09	4.13	< .001
	Orthographic control	0.17	1.09	0.28

Survival Analysis. As with Experiment 1, survival analyses were again computed to determine the earliest observable effect of assembled phonology on the eye movement record. The survival curves for the pseudohomophone and orthographic control condition are displayed in Figure 4.5 as well as the mean divergence point obtained by taking the mean of the individual subject divergence points. The pseudohomophone and orthographic control curves significantly diverged at 195 ms on average across all subjects ($M = 195$ ms, range = 120-338 ms, $SE = 14.9$, $N = 15$)²⁸, and 64.3% of individual subjects had divergence point estimates that were earlier than this group mean. Finally, across all subjects, only

²⁸ The divergence point estimate for one subject was unreliable and the divergence point estimate for one additional subject could not be computed (i.e., their curves never significantly diverged); therefore the data of all five subjects were excluded from the group divergence point estimate, however their raw fixation duration data are included in the survival figure.

33.1% of first fixations had durations shorter than this divergence point estimate, suggesting that the majority of fixations were influenced by phonology.

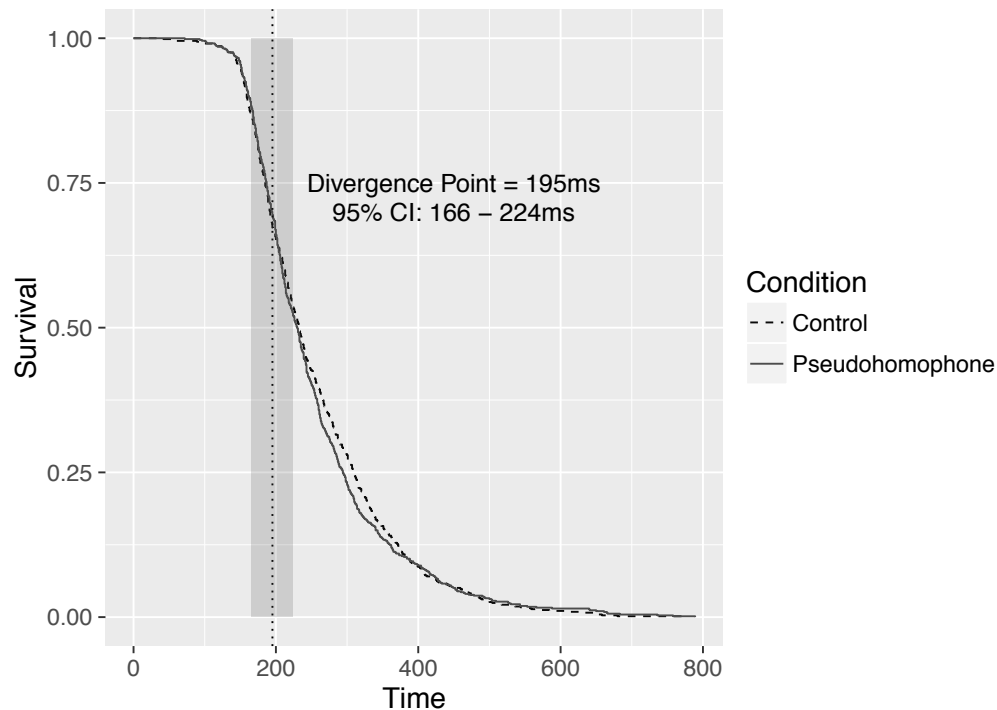


Figure 4.5. Proportion of fixations surviving as a function of time for Experiment 2. Line type represents the condition (pseudohomophone, control) and the dotted vertical line denotes the divergence point. The grey band surrounding the divergence point line represents the 95% confidence interval.

As with Experiment 1, analyses were carried out to determine if there was a relationship between the speed with which a reader generated phonological codes and their word identification speed. Unlike Experiment 1, a subject's divergence point estimate did not significantly predict their average gaze duration on correct targets ($b = 0.21$, $t(13) = 1.57$, $p = .14$, $R^2 = 0.16$, $F(1,13) = 2.46$, $p = .14$), though the data trended in the same direction (see Figure 4.6, Panel B). Additionally, although

the data again trended like Experiment 1, there was also no significant relationship between a subject's reading comprehension score and the rapidity with which they generated phonological codes ($b = -2.99$, $t(13) = -1.09$, $p = .3$, $R^2 = 0.08$, $F(1,13) = 1.18$, $p = .3$; Figure 4.6, Panel C). Like Experiment 1, there was again no significant relationship between a subject's reading comprehension score and their average gaze duration ($b = -1.45$, $t(15) = -0.98$, $p = .34$, $R^2 = 0.06$, $F(1,15) = 0.96$, $p = .34$; Figure 4.6, Panel A), again likely reflecting the fact that all subjects were skilled comprehenders sampled from a small range of high scores. Finally, consistent with Experiment 1, self-assessments of spoken English comprehension and spoken English production ability could not account for difference in the time course of phonological code generation across subjects (both $ps > .37$).

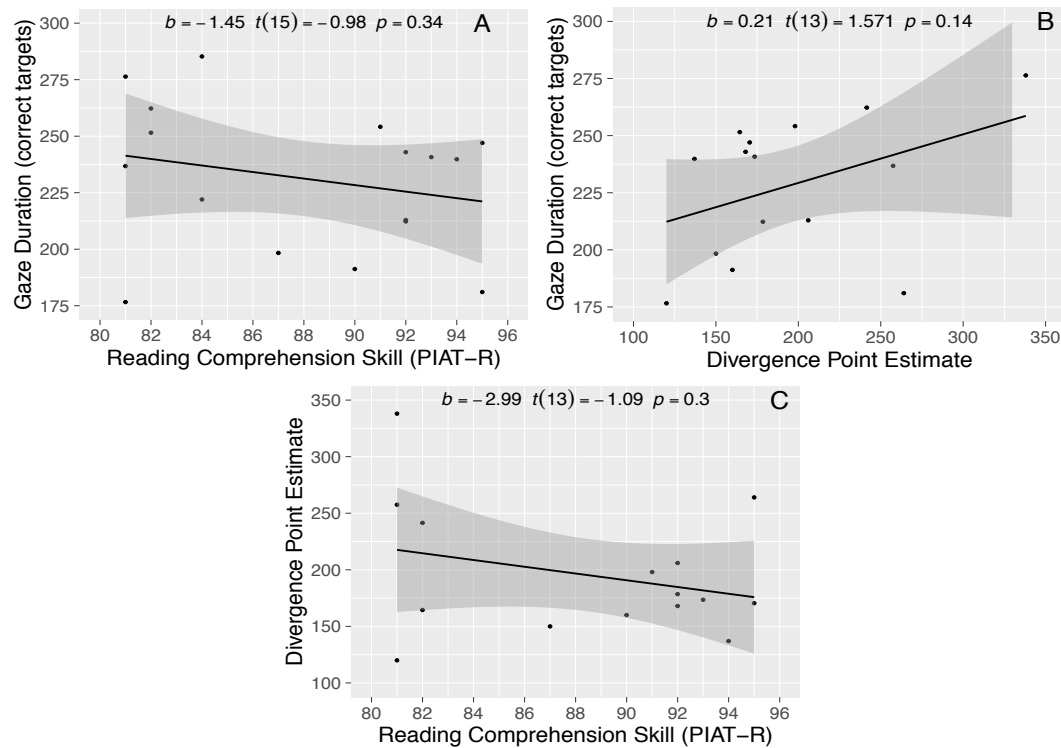


Figure 4.6. Relationships between divergence point estimates and different language assessment and eye movement measures. Panel A shows the non-significant correlation between divergence point and gaze duration (on correct targets), Panel B shows the non-significant correlation between divergence point and reading comprehension skill measured on the PIAT-R. In each panel, the regression line and 95% confidence interval are represented by the black line and grey band respectively.

Discussion

As with Experiment 1, a different picture emerges from analyses of means and survival curves. Means analyses seem to suggest only a very late role for phonological coding, which is only significant in total time, whereas survival analyses again reveal an earlier time course, where phonology exerts an effect on behavior within 195 ms on average across all subjects. Furthermore, the fact that this earlier effect of phonology was observed even for the processing of non-words is further suggestive of the early generation of phonological codes, as non-words

should largely not be accessible via the direct route alone (i.e., since they should not have representations in the lexicon).

Unlike Experiment 1, the relationships between reading comprehension skill and phonological coding, and phonological coding and gaze duration were not significant. The data trended in the same direction, such that better comprehenders were more likely to generate early phonological codes and readers who generated early phonological codes were more likely to be faster to identify words, but neither relationship was significant. This suggests that the relationships between these factors that were observed in Experiment 1 were somewhat tenuous, and might instead reflect the influence of other skills that were not directly tested. Again, self-rated spoken English comprehension and production ability were not related to the generation of phonological codes, likely reflecting their insensitivity to true differences in phonological awareness and phonemic decoding ability.

Finally, as with Experiment 1, there was again no significant relationship between reading comprehension ability and gaze duration among the highly skilled comprehenders that were tested.

General Discussion

Across both studies, survival analyses of first fixation durations revealed that deaf native signers who are skilled readers of English generate phonological codes. On average, these codes came online between 180-195 ms after fixation, suggesting that they were slightly delayed relative to the codes generated by hearing readers

(e.g., 160-173 ms for the same sets of stimuli in Chapter 2), but early enough to potentially contribute to word identification. Furthermore, the exact nature of these phonological codes is unclear. It is likely that they are impoverished at least to some extent (e.g., Kelly & Barac-Cikoja, 2007), yet, the significant relationship between divergence point estimate and gaze duration in Experiment 1 (and the trend in the same direction in Experiment 2) seems to suggest that these codes might be somewhat effective in contributing to deaf readers' word identification.

Surprisingly, the early generation of phonological codes was also associated with better reading comprehension ability in Experiment 1. This was unexpected both because prior research has failed to find differences in the use of phonological codes among skilled and less skilled deaf readers (e.g., Bélanger et al., 2012; Bélanger et al., 2013; see also Miller & Clark, 2011) and because no such relationship was observed for hearing readers tested on a subset of the same stimuli (Chapter 3). Because this effect was only significant in Experiment 1 and stands in contrast to previous research, it is unlikely to represent a strong relationship for all deaf readers. Instead, it more likely either reflects something specific about the group of subjects tested in this study, or reading comprehension ability is somewhat correlated with another skill that is a better predictor of phonological coding. For example, recent research by Hirshorn and colleagues suggests that phonemic awareness and phonological knowledge are highly correlated with reading comprehension among deaf readers who rely heavily on oral English for communication (e.g., Hirshorn et al., 2015). Unfortunately the present studies did

not employ a direct measure of phonemic awareness or phonemic decoding ability, but future research should measure these skills directly to further explore whether deaf readers' reliance on phonological coding for word identification varies as a function of their phonemic decoding ability as it does in hearing readers (e.g., Chapter 3).

As with hearing readers, not all skilled readers generate phonological codes early, or potentially even at all. Indeed, the range of divergence point estimates was large (i.e., 91 – 338 ms across both experiments) and the survival curves for some subjects never significantly diverged, suggesting no differential processing as a function of shared phonology. Yet individuals who do not show effects of phonology (or for whom effects of phonology are delayed) are still highly efficient readers and skilled comprehenders, suggesting that they rely on different strategies to efficiently identify words. While it is certainly possible that they rely more heavily on activation from the direct route to meaning for the reading of homophones, could the same be true for the processing of pseudohomophones that do not have representations in the lexicon? Simulations of the PDP model in which the indirect route was disabled (i.e., leaving only the direct route intact), revealed that the direct route alone could correctly activate the semantic features of some pseudohomophones, so long as they were orthographically similar to the target and either the target or pseudohomophone (or both) had few word neighbors (words differing in only one letter). In other words, so long as the pseudohomophone was visually similar to the target, and not also visually similar to many other words, the

model was better able to activate the semantic features of the target than it was when tested on controls. Just over a quarter of the pseudohomophone stimuli in the present study meet these criteria, as they all were relatively high on degree of orthographic overlap and in 26.7% of the target/pseudohomophone pairs one or both words have sparse orthographic neighborhoods (defined as having a Coltheart's *N* (Coltheart, Davelaar, Jonasson, & Besner, 1977) less than or equal to 1, per Harm & Seidenberg, 2004). This suggests that it may have been possible for readers to activate the semantic representation of the target word from the pseudohomophone via activation in the direct route alone on roughly a quarter of the trials. However, it is still not clear why activation via the direct route would be more advantageous for processing the pseudohomophones than the orthographic controls. The orthographic controls were equally matched on degree of orthographic overlap and in 36.7% of the target/orthographic control pairs one or both words have sparse orthographic neighborhoods. If pseudohomophones activate their corresponding target due to a high degree of orthographic overlap and few other similar competitors, the same should be true for the orthographic controls.

One potential is that previous simulations of the PDP model have not done a very good job at accurately simulating the processes used by deaf readers. For instance, before any simulations were run, the model was first trained extensively on associations between phonology and meaning. This was done to represent a developing reader's knowledge of the spoken language that they bring to bear on

the task of learning to read. For many deaf readers, this prior knowledge of spoken English does not exist (or is not built up to the same degree as it is for hearing readers). Perhaps without prior training on the route from phonology to meaning the model would organize and behave differently, for example potentially creating richer, or more precisely specified mappings from orthography to meaning (e.g., the *word-processing efficiency hypothesis*; Bélanger & Rayner, 2015). Even among deaf readers who do generate and use both routes to meaning, such a modification might be expected, since their underspecified phonological codes may not be able to contribute as meaningfully to word identification as the higher fidelity codes of a hearing reader.

Consistent with the notion of the word-processing efficiency hypothesis (e.g., Bélanger & Rayner, 2015, subjects in this study had high skipping rates (37% and 36% in Experiments 1 and 2, respectively) and low refixation rates (9% and 11% in Experiments 1 and 2, respectively), though these rates (particularly refixation rates) were not substantially higher than for hearing subjects reading the same sentences in Experiments 1 and 2 of Chapter 2 (hearing skipping rates were 33% and 28% in Experiments 1 and 2, respectively and refixation rates were 10% and 12% in Experiments 1 and 2, respectively).

Finally, the results of these two experiments reveal the advantage to conducting distributional analyses in conjunction with traditional means analyses. If only means analyses had been carried out in these experiments, the conclusions would be very different. The addition of survival analyses allowed for detection of

processing differences more than 150 ms before differences emerged in mean fixation durations.

Conclusions

Across two studies, survival analyses revealed that deaf native signers, who are skilled readers of English, can generate phonological codes during reading. Furthermore, the data suggest that the early generation of phonological codes was associated with more efficient word identification (i.e., shorter gaze durations) and also better reading comprehension ability in the group of highly skilled readers tested, though these effects were only significant in Experiment 1. Regardless, there was a high degree of variability in the time course of phonological code generation among deaf readers that paralleled what has been observed for hearing readers (e.g., Chapter 3). This suggests that skilled deaf readers, like skilled hearing readers, likely adopt different strategies for or rely more heavily on different routes to word identification, with some readers using phonological codes to help them identify the meanings of words and others relying more exclusively on the direct route to meaning.

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Chapter 4, in full is currently being prepared for submission for publication of the material. The dissertation author was the sole investigator of this paper.

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CHAPTER 5:
GENERAL DISCUSSION

Together the studies in this dissertation demonstrate that skilled readers (both hearing and deaf) can generate phonological codes rapidly during reading and use these codes to help them identify the meanings of words. More importantly though, the results of these studies demonstrate that the cognitive system is flexible and adaptive, and that the processes associated with word identification can be adjusted to a given reader's skills in order to maximize word recognition efficiency during reading.

In Study 1, I addressed the time course of phonological coding in skilled, hearing readers. Survival analyses revealed that effects of phonology emerged quite rapidly (i.e., on the order of 160-173 ms) during normal, silent reading. Additionally, the time course was similar regardless of the lexical status of the stimuli being read (i.e., real-word stimuli or non-word stimuli). Finally, across subjects, earlier code generation was associated with faster word identification. These results suggest that, during normal silent reading, skilled hearing readers rapidly assemble phonological codes from print and in turn use those codes to help them identify the meanings of words.

In Study 2, I addressed whether general reading ability (i.e., reading comprehension and vocabulary) was predictive of the early or late use of phonological codes, or if instead phonemic decoding ability more specifically might explain the variability in phonological coding across subjects. The rapidity with which subjects generated phonological codes was not related to their general reading skill. Instead, higher phonemic decoding ability specifically was associated

with the early generation of phonological codes. Additionally, higher language scores on every test (i.e., comprehension, vocabulary, phonemic decoding) were associated with faster word identification independent of the time course of phonological code generation. Finally, the rapidity with which a given reader generated phonological codes was more predictive of word identification speed among certain groups of readers: highly skilled phonemic decoders and readers with lower general reading skill.

These results suggest a number of things. Although the ability to rapidly generate phonological codes is associated with more efficient word identification in general, not all readers use phonological codes to the same degree. Readers who are very skilled at phonemic decoding likely generate high fidelity phonological codes that contribute meaningfully to word identification, whereas less skilled decoders likely generate imprecise or underspecified codes that cannot aid word identification to the same degree. Similarly, good comprehenders with large vocabularies are likely so quick to identify words (i.e. primarily via the direct route), that by the time phonological codes are generated, there is not enough time for them to contribute substantially to word identification, whereas the addition of phonological coding may significantly aid word identification for less skilled comprehenders with small vocabularies. Together, the results of Study 2 suggest that readers with strengths in different language skills might adjust their reliance on the different routes to meaning and even strategically (though almost certainly

unconsciously) compensate for weaknesses in one area by relying more heavily on their other language skills in order to efficiently identify words.

In Study 3, I addressed the time course of phonological code generation in skilled deaf readers. Survival analyses revealed that skilled deaf readers can rapidly generate English phonological codes, although these analyses did not make it possible to determine the nature or specificity of the codes that deaf readers generate. Additionally, in one experiment the early generation of phonological codes was associated with more efficient word identification and better reading comprehension. The latter result was unexpected and potentially reflects the presence of an unmeasured skill that is a better predictor of phonological code use in deaf readers than general reading comprehension ability. I speculated that a candidate skill might be English phonological awareness or decoding ability, as these have been found to correlate with reading comprehension ability in certain subsets of deaf readers (e.g., Hirshorn, Dye, Hauser, Supalla, & Bavelier, 2015). Finally, as with hearing readers, there was a high degree of variability in the time course of phonological coding across individuals, despite the narrow range of reading skill that I sampled from. Since these readers were all highly skilled and very efficient (e.g., Bélanger & Rayner, 2015) despite the variability in phonological coding, this suggests that deaf readers also adjust their reliance on the different routes to meaning in accordance with their own language skills, such that some rely on phonological coding to some degree and others rely more exclusively on the direct route to meaning.

Summary

Skilled readers are amazingly efficient at identifying words as they read. The studies in this dissertation suggest that this is in part due to the generation of phonological codes to support word identification, but even more so to the flexible cognitive system capable of adapting to the relative strengths and weaknesses of any individual. From Study 1, we know that skilled readers are able to rapidly generate phonological codes and use those codes to help identify the meanings of words. From Study 2, we know that readers vary the extent to which they rely on each of the different routes to meaning as their own language skills allow. From Study 3, we know that even some deaf readers, without full access to the phonology of the language in which they read, are able to generate and use phonological codes during word identification, and that they too are able to adjust their reliance on each route as a function of their language skills.

It is interesting to note that the necessary architecture for such an adaptive system already exists within Harm and Seidenberg's parallel distributed processing model (2004). Indeed, when discussing the function of the routes (i.e., components) the authors state that:

performance of each component is subject not only to its own intrinsic capabilities but also to the successes and failures of other components...the error that one component is slow or unable to reduce creates pressure for the system to make up the difference somewhere else. Hence, each component of the system is sensitive to the successes and failures of other components. (p. 671)

Therefore, the model already has the architecture necessary to generate shifts in the extent to which an individual relies on each of the routes. Although the studies in

this dissertation only scratch the surface of the full interactivity of the word identification system, they give us a sense of how flexible and adaptive it is. This work constitutes a small but important step toward understanding the remarkably efficient, and surprisingly adaptive process of word identification during reading.

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