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Investigating the Roles of Phonology and Orthography in Visual Word Recognition

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Lindsey Meyer

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

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Abstract

The nature of visual word recognition, the process of identifying written words, involves a relatively unknown importance of the letters (orthography) vs. the sounds that those letters represent (phonology). Anadromes are a pair of words that have either the same phonemes or letters in reverse order, and they offer a unique way to study the nature of visual word recognition by allowing the transpositions of letters and sounds and measuring the resulting activation trends. The relative influences of phonology and orthography in visual recognition can be studied by using three types of anadromes: orthographic (*flow*, *wolf*), phonological (*tube*, *boot*), and both orthographic and phonological (*pot*, *tube*). In an eye-tracking experiment using the Visual World Paradigm (VWP), we assessed which types of anadromes were activated by highly skilled readers. A number of t-tests determined that phonological anadromes received significant activation, both orthographic and phonological anadromes were not significantly activated though they were trending in the right direction, and orthographic anadromes were not significantly activated. The results suggest that phonology serves a significant role in the process of visual word recognition and overlapping orthography may actually hinder activation, although there were a variety of limitations.

Introduction

Word recognition is an integral aspect of language processing. The practice of visual word recognition is the process of identifying a written word. Major theories of how written words are recognized suggest that the specific order of letters has limited importance and that highly familiar words make a direct decoding route from orthography to recognition without activating phonology. However, limitations from previous research can not make definite conclusions. The current study will use anadromes to investigate the extent to which phonology and orthography are important for word recognition within the visual word recognition process. In the following sections we will review empirical work and theories of spoken recognition and written recognition.

1.1 Spoken word recognition

To fully understand the complex process of word recognition, we need to take a step back and consider its two modalities. Words are recognized by spoken language through auditory means and by written language by visual means. These two expressions of language are different in the way they are perceived. In spoken word recognition, words are revealed temporally, and the listener perceives the word piece-by-piece as it is articulated. Conversely, written word recognition allows the reader to perceive the word as a whole at one point in time. Although both modalities result in successful recognition of an intended message, the manners of these two processes are different and utilize different cognitive mechanisms.

Research on spoken recognition has laid the groundwork for visual recognition, so it is beneficial to discuss some findings from spoken recognition first. The motivation in studying spoken word recognition is the temporary ambiguity in the speech signal. As a word is spoken, listeners do not wait for the completion of the word to begin comprehending it. This means there are moments in which the speaker has begun saying the word and only partial information (“*pl”)* is available to attempt to identify the word (*plant*). In these moments, listeners activate all words which are phonetically congruent with the input (*plan, plow, plum)* while rapidly integrating cues to narrow down the possibilities (McClelland & Elman, 1986; Toscano, Anderson, & McMurray, 2013). It is at this point that all the possible lexical items are competing against each other in parallel for recognition (Luce & Pisoni, 1998). As the speaker continues articulating the word, more information about the target word (*plant)* is revealed, and activated words whose sounds do not align are suppressed (*plow, plum*). (Dahan & Gaskell, 2007; Frauenfelder, Scholten & Content, 2001). Eventually*,* the entire word is revealed, and it becomes clear that the target word is "*plant*".

Certain types of words compete for recognition more than others. These lexical candidates are words that have some type of phonological or orthographic relationship to the target word. For example, if the target word is *loop*, then a rhyme (*coop*) and a cohort (a word with overlapping word-initial sounds [e.g., *loom*]) would both be activated as potential targets to various degrees. Previous research on spoken word recognition has informed theory on word types that compete, the magnitude in which they compete, and how this competition process unfolds in real-time (Marslen-Wilson, 1987; Allopenna, Magnuson, & Tanenhaus, 1998). Studying the details of competition allows researchers to identify the nature of these processes.

These rapidly unfolding cognitive processes are largely studied via eye-tracking technology using the Visual World Paradigm (VWP) (Allopenna et al., 1998; Tanenhaus, Spivey-Knowlton, Eberhard & Sedivy, 1995). The VWP offers a unique method of measuring the decision-making process undergone throughout word recognition. On every trial, participants see four pictures: one in each of the four quadrants of the screen. The target word is presented aurally as the participant scans the screen to find the image representing the target word. The eye movements of participants are recorded as they glance around the computer screen to identify the corresponding image. These eye movements have shown to be temporally reflective of the lexical competitors as they compete for recognition (Farris-Trimble & McMurray, 2013). As participants' eyes fixate on the images for various lengths of time, researchers can identify which words compete in word recognition, to what extent, and at what temporal points in the cognitive process.

The traditional theories of spoken word recognition suggest that we recognize words in a slot-based schema. These slot-based theories suggest that words that have the same phonemes that overlap in the same position within both words will be activated and compete for word recognition (McClelland & Elman, 1986; Luce & Pisoni, 1998; Gaskell & Marslen-Wilson, 1997). In these theories, the amount of activation a word has would directly correlate with how many phonemes were found in the same word position as the target. More recent research has challenged this speculation that overlapping phonemes must be in the same position within a word to be activated and there has been more investigation into how slot-specific these overlapping phonemes really must be. Toscano et al. (2013) used anadromes to study whether phonemes need to be overlapping in the same place within a word to be activated and compete for spoken word recognition. These phonological anadromes are a pair of words that have the same phonemes in backward order (e.g. *sub* and *bus*). The researchers found that anadromes were indeed activated significantly more than unrelated words (*well*) and words that shard the same vowel but not the same set of phonemes (*sun*), concluding that words with overlapping phonemes in differing orders can solicit activation and compete for recognition when perceived aurally. Ultimately, they suggest that a more flexible encoding of phonemes would better reflect how the brain processes spoken words rather than a strict sequence of phonemes as previously thought.

Overall, the competitive nature between similar words is the result of various similarities between spoken words as they are revealed over time. Anadromes are a type of word that exhibit this competitive nature, and this finding suggests that there is a loose, not slot-based coding of how humans recognize spoken words. Although there is some research on how this translates to written word recognition, the quantity and magnitude of research is far less.

1.2 Written word recognition

Unlike spoken words, in which the challenge is temporary ambiguity of the speech signal, the challenge with written words is identifying letters and their positions within a word. Just as theories of spoken word recognition suggest that similar sounding words compete for recognition, major theories of written word recognition suggest that visually similar words compete for recognition (Coltheart et al., 2001; McClelland and Rumelhart, 1981). These theories of written word recognition similarly assume that word recognition is achieved when a lexical item reaches a critical level of activation.

In the interactive activation model of visual word recognition, the visual features of each letter (e.g. horizontal lines, vertical lines, intersections) are coded. This allows the reader to recognize a letter, further equips the reader to associate a group of letters to recognize a word, and ultimately allows meaning to be associated with the orthography (printed text) in a hierarchical manner (McClelland and Rumelhart, 1981).

In addition to the features of each letter, the order in which they appear also proves important for identifying written words. Just as in spoken word recognition, slot-based coding schemes of written word recognition suggest that the specific position of each letter within a word must be in the correct spot to drive activation (McClelland and Rumelhart, 1981). This ability to differentiate letter positions allows us to distinguish words like *SALT* and *SLAT* which share the same letters but in different positions. However, this slot-based coding is likely not as strict nor as final as originally suggested. *SALT* and *SLAT* have overlapping letters in only two positions with the other two letters being transposed, while *SALT* and *SPIT* also have overlapping letters in only two positions with the other two letters being substituted. These words have the same slot-based overlap, yet *SLAT* is perceived as being more similar to *SALT* than *SPIT*. (Forster & Davis, 1984). This suggests that readers do not only look at each letter individually but also at the word as a whole (Grainger & Whitney, 2004).

Letter transposition within a word still allows for the successful recognition of a written word. When presented with two intentionally imperceptible primed stimuli of *SEVRICE and SEDLICE,* readers were able to identify the target of *SERVICE* more quickly with the first option (Schoonbaert & Grainger, 2004). Although the two primes have the same amount of slot-based overlap, the first prime had the two letters transposed while the other had the two letters substituted. This trend extends to extreme modifications in which the transposed prime of *SNAWDCIH* was identified more quickly than *SKUVGPAH* for the target of *SANDWICH* (Guerrera & Forster, 2008). These findings highlight that classical theories of strict slot-based codings, such as McClelland & Rumelhart (1981) are inadequate. Rather, it suggests that orthographic representations code letter position in a relative and adaptive, rather than absolute, matter.

This dynamic coding of letter position can be reflected with a spatial coding scheme, such is used in the SOLAR Model (Davis, 2001). This abstract representation of letters suggests that the letter "*A*" for example, can be activated no matter the context, visual form, or position within a word. The letter is assigned a temporary value at each representation that depends on its probability of appearing in that position in a word via Gaussian distributions. The model compares these spatial codings of the input to the abstractly stored target word and calculates the difference between the two. According to this model, words that have adjacent letter transpositions have a higher chance of being activated while words that have distant transpositions have a lower chance of being activated. This modeling reflects the findings of Schoonbaert & Grainger (2004) and Guerrero & Forster (2008) that originally challenged McClelland & Rumelhart (1981). This model would predict that words such as cohorts would display similar levels of activation as they have comparable letter transpositions. As anadromes (e.g. *gulp* and *plug*) are an example of more distant transpositions, this model predicts that they would display less activation than cohorts and rhymes.

The timing and magnitude of competition between cohorts and anadromes in written word recognition were studied by Hendrickson, Goodwin, Blomquist, Klein, & McMurray (2020). They compared cohorts and anadromes to tease apart the relative contributions of order and degree of overlap to inform theories of word recognition. Cohorts preserve order word-initially, but only a portion of the sounds and letters overlap. Anadromes largely disrupt order, but they preserve sound and letter overlap with the target word. They found that, in written word recognition, anadromes were activated to the same extent as cohorts (e.g. for *pot*, its anadrome *top* has the same amount of activation as its cohort *pond*). This suggests that in written word recognition, preserved order is not necessarily important for lexical activation.

The previous study failed to answer a very important question: did the anadrome activation result from the overlapping orthography or phonology of the competing words? Indeed, Hendrickson et al. (2020) did not control for the degree of orthographic vs. phonological overlap in their anadrome pairs. To illustrate, some of the anadromes used were both phonetic and orthographic anadromes (e.g. *tip* and *pit*), however, some pairs had phonological but not perfect orthographic overlap (e.g. *read* and *deer*), as well as pairs with perfect orthographic, but imperfect phonological overlap (e.g. *wolf* and *flow*). Thus, it is unknown the degree to which phonology and orthography drove anadrome activation in written words. The fact that there are three different types of anadromes (both phonetic and orthographic, mostly phonetic, and mostly orthographic uniquely allow anadromes to directly compare the influences of orthography and phonology in written word recognition.

1.3 The current study

The current study aims to further investigate how orthography and phonology influence visual word recognition of highly familiar words by studying anadrome competitors. We seek to determine what extent written word recognition relies on the letters that make up a word vs. the extent it relies on the sounds that those letters represent. We hope to inform major theoretical accounts by investigating which types of anadromes compete for recognition, compare the magnitude of their competition, and learn how this competition unfolds in real-time.

We use the Visual World Paradigm (VWP) to study these processes in real-time. Participants' eye-movements are tracked as they experience the decision-making processes in written word recognition. A higher proportion of eye fixations reflects higher activation, and it reveals when the resulting competition happens in real-time. This allows us to compare the three conditions of anadromes to each other to gain insight into these cognitive functions.

Based on the research by Hendrickson et al. (2020), we can predict that anadromes with identical phonology and orthography will have a significant amount of activation. What is unsure is whether phonological anadromes or orthographic anadromes will have substantial activation, which will have more activation, and how the competition processes unfold in real-time.

If the study finds that phonological anadromes have more activation than orthographic anadromes, we can assume that readers activate phonology as they read highly familiar words and rely much less on the actual letters than originally anticipated. If orthographic anadromes have more activation, we can assume that visual word recognition somewhat bypasses phonological processes and progresses directly from the orthographic input to the semantic association. This would be of particular interest, seeing that reading is a learned skill that is often built off of the naturally learned knowledge of spoken language. It would be interesting to find that humans can become so skilled at reading that they can bypass spoken language which equipped them to learn written language to begin with. These findings would reveal a lot of the “hidden” and very difficult-to-study cognitive activity and cue us into the visual word recognition system. This will allow us to learn how successful word recognition is achieved and may later be useful with populations that have difficulties reading.

Materials and Methods

Participants

A group of 18 subjects participated in the study; all were monolingual English-speaking adults with normal or corrected-to-normal vision. Students were recruited from the University of Iowa psychology participant pool, signed an informed consent document, and received academic credit for a university-level psychology course.

Stimuli

Visual stimuli images were animated, clip art-style images produced with a standard lab protocol. Several candidates were identified collected from an online clip art library for each image. An experienced focus group reviewed and identified the exemplar that best represented each word. Alterations were suggested to ensure each image was uniform and easily identifiable. Many images were retrieved from a pre-existing database of images used for other studies in which the uniform protocol for visual saliency, style, size, and other physical features was used.

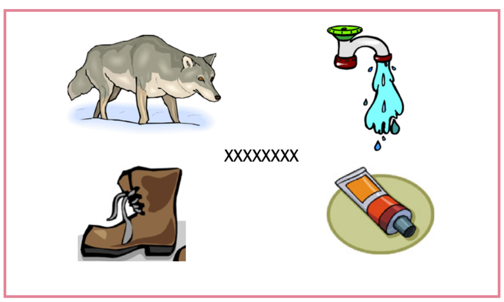
Design

This study used eye-tracking via the Visual World Paradigm (VWP) as discussed earlier. In each trial, participants see four pictures: one in each of the four quadrants of the screen (see Figure 1). Rather than receiving auditory input as done in previous spoken word studies, a printed target word is instead presented in the middle of the screen for 75 msec. The participant then scans the screen to find the image representing the target word and selects the correct image using the computer mouse. The eye movements of participants are recorded every 4 msec as they observe the printed word and glance around the computer screen to identify the corresponding image. These eye movements are temporally reflective of the lexical competitors as they are activated. As their eyes fixate on the images for various lengths of time, researchers can identify which words compete in word recognition, to what extent, and at what temporal points in the cognitive process.

To measure phonological and orthographic overlap effects, three conditions were created within the experiment. For each condition, words are grouped in pairs: the pairs are monosyllabic anadromes of each other with no semantic overlap. The first condition included word pairs that are orthographic anadromes (O): these word pairs contained the same graphemes when spelled forward and in reverse but had ≤75% phonemic overlap (e.g., *flow, wolf*). The second condition consisted of word pairs that are phonological anadromes (P): these pairs contained identical phonemes in reverse order but had ≤75% orthographic overlap (e.g., *tube, boot*). The third condition included word pairs that are both orthographic and phonological anadromes (OP): these words contained the same graphemes and phonemes in reverse order (e.g., *pot, top*). In each of the three conditions, 11 word pairs were used for a total of 44 word pairs, or 88 words.

Previous studies have revealed that high-frequency words are activated more often (Cortese & Balota, 2012). Thus, word frequency was controlled across conditions to ensure substantial differences in word frequency did not impact results. The frequency of each word was calculated by a survey sent to 21 members of the lab. We used the protocol used by Balota, Pilotti, & Cortese (2001) in which each word is ranked on a scale of one to seven. This 7-point scale indicated how often the participant encountered each word:1 = never, 2 = once a year, 3 = once a month, 4 = once a week, 5 = every two days, 6 = once a day, 7 = several times a day. The frequency score received from each survey participant was averaged for each word, averaged within each condition, and compared across conditions. The mean frequency score across conditions was 4.1 with a standard deviation of .031.

To construct each trial, word pairs from the three conditions were combined. Word pairs were matched with a word pair from another condition to make up the four images pictured on the screen. These two pairs had no semantic, phonological, or orthographic overlap with each other. This experiment had a target-anadrome-unrelated-unrelated (TAUU) design. Each set of four words contained a target word (e.g. *flow*), the anadrome competitor of the target (*wolf*), and two phonologically and semantically unrelated words (*tube, boot*). Another anadrome pair was used as the unrelated competitors to make the design more efficient, so each trial was able to be used in data analysis. For example, when the previously unrelated word (*tube)* serves as the target word, the other unrelated word is the anadrome competitor (*boot*), while the initial target and anadrome are now the unrelated items (*flow, wolf*). The role of each word varies depending on the target word and its relation to it (see Figure 2). Each trial set was repeated three times for a total of 396 trials (33 trial sets x 4 items/set x 3 reps).



Trial Type	wolf	flow	tube	boot
TAUU	**Target**	Anadrome	Unrelated	Unrelated
TAUU	Anadrome	**Target**	Unrelated	Unrelated
TAUU	Unrelated	Unrelated	**Target**	Anadrome
TAUU	Unrelated	Unrelated	Anadrome	**Target**

Figure 1 (left): Example of a set of stimuli seen on screen using VWP
Figure 2 (above): Example item set with various trial types

Procedure

The participants completed the eye-tracking task on a computer in a sound-attenuated room. First, they participated in a familiarization task to introduce the images used in the study with the appropriate labels that the images represent one-at-a-time. Following familiarization and calibration, and verbal and written instructions, subjects completed the visual word recognition task via computer monitor, mouse, and eye-tracker.

For each trial, one picture appeared in each of the four quadrants on the screen. A blue dot appeared in the middle of the screen, and after 500 msec, it changed to a red dot. Participants were instructed to click the red dot at which point the target word was presented for 75 msec, immediately followed by a backward mask of hash marks to control visual after-effects. Participants were instructed to then click the corresponding picture of the target word. The positions of each image on the screen were randomized so that the target, anadrome, and unrelated items appeared an even number of times in each of the four quadrants, each word was the target for an equal number of trials, and trials were randomized so that each participant received a different presentation order.

Eye-tracking and data processing

Eye-movements were recorded with a desktop mounted Eyelink 1000 eye-tracker in the chin rest configuration. Once the experimenter adjusted the chin rest to a comfortable position and a clear image of the pupil and corneal reflection were obtained, a 9-point calibration and validation procedure was completed. Every 33 trials, a drift correction was completed to ensure the sustained accuracy of calibration for a total of 12 breaks. No participants failed drift correction during the experiment. For analysis, saccades and successive fixation were combined into a single unit called a “look” (McMurray, Tanenhaus, & Aslin, 2002).

Results

We conducted two sets of paired t-tests. The first set was used to determine if there was significant activation for each competitor type. For this, we compared proportion fixations or "looks" to the competitor to the average proportion looks to the unrelated for each competitor type. We corrected for multiple comparisons using a Bonferroni correction resulting in a threshold p-value of .05/3 = .016. For phonological anadrome condition (P-only), there was a significant difference in proportion of fixations, $t(35) = 2.4$, $p = .020$. The phonological and orthographic anadrome condition (OP) did not reach significant activation when compared to the unrelated condition, but it is trending in the numerical right direction $t(33) = 1.4$, $p = .18$. The orthographic anadrome condition (O-only) was not significantly activated and was not trending in the right direction, $t(36) = -.96$, $p = .33$.

In the next set of t-tests, we compared each condition to determine if there were significant differences between the different types of anadrome competitors. To find this, we subtracted the average unrelated fixations from each competitor type and compared across conditions. We again corrected for multiple comparisons by using a Bonferroni correction resulting in a threshold p-value of .05/3 = .016. The difference between the P-only and O-only condition proved significant, $t(32) = -4.1$, $p < .001$. The O-only and OP conditions also showed to be significantly different, $t(31) = -2.7$, $p = .012$. However, the difference between the P-only and OP conditions resulted in insignificant differences, $t(36) = -.98$, $p = .33$. See Figure 3 for graphic representations.

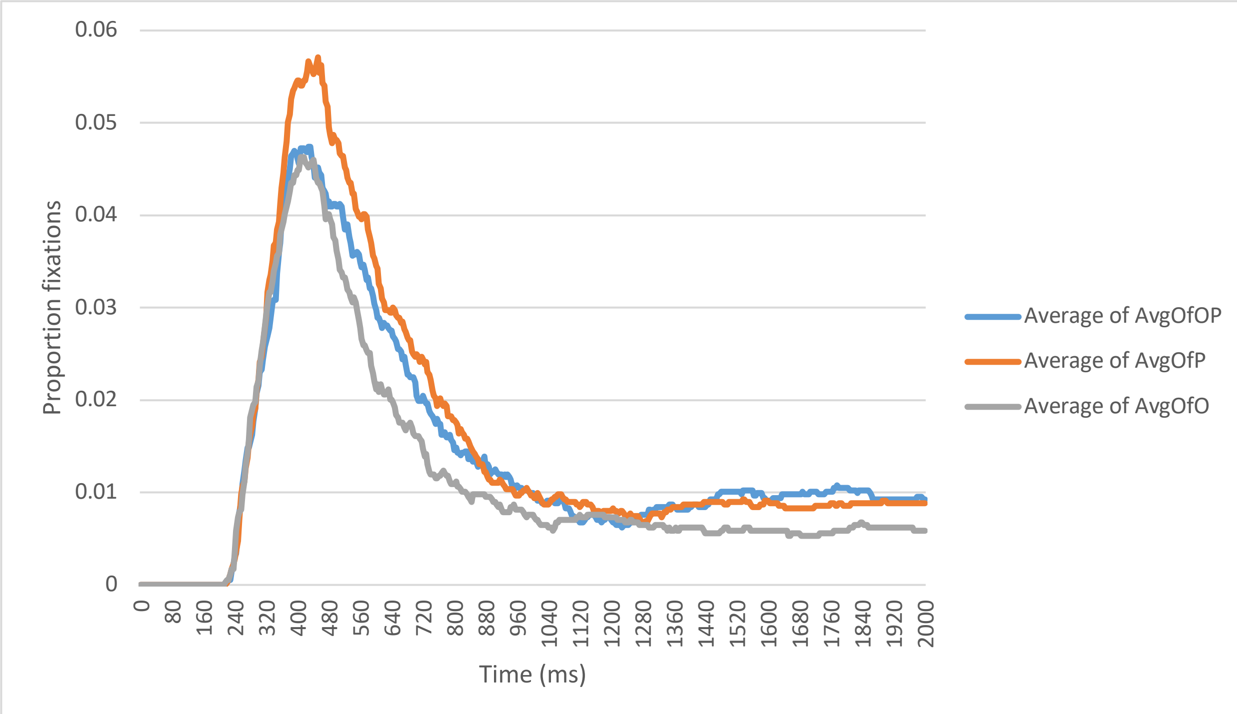


Figure 3: Proportion looks to the three anadrome types (Orthography & Phonology [OP], Phonology only [P], and Orthography only [O]), over time. Both anadrome conditions with Phonological Overlap (OP and P) show more activation than the condition with just Orthographic overlap (O).

Discussion

These results offer a variety of findings relating to visual word recognition. P anadromes received a significant amount of activation from the unrelated item baseline, while O anadromes were not significantly activated nor were they even trending in the right direction. This finding answers the question left unanswered by Hendrickson et al. (2020): was it overlapping phonology or orthography that drove activation? Indeed, these findings propose that *not only* does the visual word recognition pathway include a component of phonology, but that phonology seems to be driving the way. Furthermore, adding orthography does not offer any supplemental benefits.

Although there was no difference between activation for the OP and P-only conditions, P-only anadromes showed significantly more activation than the unrelated items, while OP did not. To explain why words with overlapping sounds and letters had less activation than words with only overlapping sounds, there are a few possibilities. First, this could suggest the previously mentioned theory that having overlapping orthography actually hinders competition. In this case, phonology is the most important factor for activation, and orthography interestingly decreases activation. Second, it could be that the experiment was underpowered with too few participants to see a true trend or significance. Third, it may have been a result of limitation in the experimental design.

The lack of dependency on orthography could also be a result of the short amount of time that participants had access to the written word. Each word was displayed on the screen for a brief 75 msec. If participants had longer access to the word, it could have changed the degree to which phonology vs. orthography is activated. Since visual word recognition is a very time-sensitive process, longer temporal access to analyze orthography could result in more orthographic activation.

There are several limitation of the current study that must be noted. Previous research (Hendrickson et al., 2020) found significant activation for OP anadromes, and while the current study was trending that way, it did not reach significance. This could have been caused by too few participants or a design error in which the unrelated items were not carefully controlled. Curiously, the unrelated items received an unexpectedly high proportion of fixations consistently throughout the experiment and across subjects. The high activation of unrelated items likely diluted the anadrome effects across conditions.

When analyzing why the unrelated items received such a surprisingly high proportion of fixations, we have a few hypotheses. Discreet similarities in visual features are one possibility for this effect. In design preparation, the anadrome pairs were combined into sets of four with screenings to prevent overlapping orthography, phonology, and semantics. However, this did not account for the visual overlap of the images used to represent each word. For example, the anadrome pairs *pool, loop* and *war, raw* were combined to create a set of four. When examining the words, one can determine they have no phonological, orthographic, or semantic overlap. However, when all four visual stimuli were displayed on-screen, it became clear that each image had a circular shape which could cause additional competition *not* due to the word itself but from the images. Additionally, there were substantial differences in the complexities of each image that may have affected unrelated item activation. For example, the image representing *loop* was a simple, uncomplicated coil of ribbon. On the other hand, *war* was an entire detailed scene that likely required longer looking times to identify whether the target word matched. This extended to words like *dam* and *gel* which were both pictured with descending, blue liquids and also to words like *dial, laid,* and *warts* which were all of approximately the same color.

Partial responsibility for large unrelated effects could also be caused by words that were difficult to depict. Because each chosen stimulus had to be an anadrome, the options were inherently limited. This prompted using words that were more difficult to picture such as *nod* and *laid*. These more difficult-to-picture stimuli may have resulted in an increased number of fixations because of their complexity and infrequency, thus requiring a longer amount of time to determine the word it was representing.

The current study was one of the first to use a VWP design with only one competitor and two unrelated items. Typical experiments have a T(target)-C(cohort)-R(rhyme)-U(unrelated) design, but the nature of the research question with anadromes required a different design. We employed a TAUU design and assigned another pair of anadromes as the two unrelated objects to make the experiment more efficient, but it resulted in many problems as outlined above. We could not have predicted what effects would occur from using two unrelated items, but it led to an unexpected effect in the semi-automatic visual word recognition process. There are top-down semantic and frequency effects that influence recognition in real-time. Participants may have been fighting against these higher-level processes which resulted in high unrelated activation effects.

To control for these problems, we have begun to redesign the experiment. Rather than combining two sets of anadromes to create a set, a pair of anadromes should be combined with two very controlled unrelated words. The criteria for these unrelated words should be monosyllabic, roughly CVC-shaped, no orthographic overlap, no phonological overlap, no semantic overlap, similar visual complexities, and highly controlled visual overlap including shape, characteristics, and color. Extensive consideration should assess any possible semantic or visual overlap among the four-item set of stimuli to prevent large unrelated item activation.

Creating three run-lists to randomly present to participants would help control for high proportions of fixations to unrelated items. By creating three run-lists, each unrelated item would appear and compete across each of the three conditions. With this configuration, any high proportion of looks that an unrelated item receives (due to complexity, frequency, etc.) would occur when competing in every condition. With this cross-condition comparison, those effects would be washed out so they do not falsely inflate the proportion of fixations to unrelated items.

This study strongly suggests that phonology serves an important purpose in the process of visual word recognition, although there are a variety of limitations. This means that the cognitive pathway from perceiving orthography to recognizing meaning likely includes a strong phonological processing component. However, this study really outlines a variety of factors to consider when using an experimental design outside of the typical approach. In future studies, top-down influences should be accounted for and visual stimuli should be highly controlled for no visual overlap.

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