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Abstract

A number of studies suggest that attention can modulate the extent to which lexical processing influences phonological processing. We propose dampening of activation as a neurophysiologically-plausible computational mechanism that can account for this type of modulation in the context of an interactive model of speech perception. Simulation results from two concrete implementations of this mechanism indicate that each of the implementations can account for attentional modulation of lexical feedback effects but that they have different consequences on the dynamics of lexical activation. We also present a behavioral test of attentional modulation of lexical effects that is not contaminated by task or stimulus effects.

Introduction

Lexical knowledge can influence listeners' recognition of speech sounds. As just one example, speech sounds in words are recognized more quickly than speech sounds in nonwords (Rubin, Turvey, & van Gelder, 1976; see also Mirman, McClelland, & Holt, 2005). Some researchers have suggested that lexical effects such as this are modulated by attention. Cutler, Mehler, Norris, and Segui (1987) found that this type of lexical facilitation emerged when stimulus lists were variable (with respect to consonant-vowel structure of the stimuli) but not when the lists were monotonous (only CVC stimuli). Studies have also shown that lexical effects emerge more strongly when listeners perform a lexical task than when they perform a non-lexical task (Eimas, Hornstein, & Payton, 1990; Vitevitch & Luce, 1999). Some critics have argued that feedback effects are obligatory in interactive models and thus that interactive models are not consistent with attentional modulation of lexical effects (Norris, McQueen, & Cutler, 2000).

Our first goal is to describe a mechanism of attentional modulation that is consistent with interactive processing and to demonstrate that this mechanism can account for the basic modulation effects. Our second goal is to test two computational implementations of the general mechanism of attentional modulation. Our third goal is to describe an experimental paradigm that provides a robust and well-controlled test of attentional modulation of lexical effects on speech perception. This is important because in previous experiments effects of attention were inferred from comparisons across different stimulus types (e.g., CV vs. CVC) or across different task conditions (e.g., lexical decision vs. tone judgment) and thus, were open to alternative accounts. In contrast, we present an experiment in which the critical stimuli and task were identical across attention conditions.

Attention Mechanism and Implementations

Single-unit recording studies of visual attention in monkeys have found that neurons are less responsive when their preferred input is to be ignored (e.g., Moran & Desimone, 1995). Similarly, fMRI studies in humans have found that neural response in motion-responsive area MT is dampened when participants are instructed to ignore moving stimuli (O'Craven et al., 1997). Extending this principle to speech processing, attention to lexical information may be modeled by excitability of the lexical layer. That is, task or stimulus conditions that cause participants to direct attention away from lexical processing may operate by causing an overall dampening of lexical activity. In an interactive model such as the TRACE model of speech perception (McClelland & Elman, 1986) lexical feedback to phoneme processing is proportional to lexical activation. Thus, dampening of lexical layer activity would reduce lexical effects on speech processing.

To examine concrete implementations of this attentional modulation mechanism, we extended the TRACE model of speech perception (McClelland & Elman, 1986). The TRACE model consists of processing units grouped into an acoustic/articulatory feature level, a phonemic level, and a lexical level with excitatory bi-directional connections between consistent units at different levels and inhibitory connections between inconsistent units within each layer. We examined two possible implementations of the general mechanism of dampening a layer's activity. The first is modulation of the lexical layer's responsiveness to input. In the TRACE model, as in the original interactive activation model of visual word recognition, the change in activation of a unit is a function of the net input to that unit and the unit's current activation state relative to its maximum and minimum activation levels (see McClelland & Rumelhart, 1981 for details). Modulation of responsiveness to net input was implemented by adding an attentional scaling parameter (α) to the function specifying the net input to a lexical unit:

$$\text{net input} = \alpha(\Sigma a_p * W_{p \rightarrow l} + \Sigma a_l * W_{l' \rightarrow l}) \qquad (1)$$

Here the portion in parentheses is the standard net input equation that is based on feedforward input from the phoneme layer (first term) and inhibitory lateral interactions within the lexical layer (second term). When α=1.0, this is the standard TRACE model as implemented by McClelland and Elman (1986), when α<1.0, net input is scaled down and thus lexical responsiveness is dampened and lexical effects are reduced. This implementation is similar to manipulations of gain that have been used by other researchers to model the effects of attention at the level of neuromodulation (e.g., Servan-Schreiber, Printz, & Cohen, 1990) and at the level of strategic control (e.g., Kello & Plaut, 2003).

In the second implementation, a negative bias input was added to lexical units to dampen lexical activity. The negative bias (β) provided a constant inhibitory input to each lexical unit on each processing cycle (i.e., just like an additional input source that has constant activity and negative connection strength):

$$\text{net input} = (\Sigma a_p * W_{p \rightarrow l}) + (\Sigma a_l * W_{l' \rightarrow l}) - \beta \qquad (2)$$

Similar implementations have been used in other models of attentional modulation (e.g., Cohen, Dunbar, & McClelland, 1990) and this implementation accords well with the neurophysiologically-based biased competition theory of attention (Desimone & Duncan, 1995). In the following sections we present results of simulations that examine the effect of each of these implementations of modulation of lexical attention on two classic lexical effects on speech perception.

Simulation 1: Ganong Effect

The finding that ambiguous phonemes tend to be perceived such that they form a word (e.g., an ambiguous /g/-/k/ sound is heard as /g/ when followed by "ift" and as /k/ when followed by "iss"; Ganong, 1980) provides a simple test bed for an attention mechanism. A number of studies have suggested that this effect is modulated by lexical attention (see Pitt & Samuel, 1993, for review and meta-analysis of this effect). That is, under conditions favoring lexical attention there is a robust lexical influence, but under condition disfavoring lexical attention, the influence is reduced or non-existent. For the simulations, late-occurring phonemes were replaced with ambiguous phonemes to test the lexical influence. Two ambiguous phonemes were tested: a fricative (which could be interpreted as either /s/ or / /) and a stop (which could be interpreted as either /t/ or /d/). For each ambiguous phoneme an equal number of lexical contexts for each interpretation were tested (4 for /s/, 4 for / /; 5 for /t/, 5 for /d/). The simulations were carried out at high lexical attention (α=1.0; β=0.0) and low lexical attention (α=0.5; β=0.1) in each implementation. Standard values for all other parameters and a slightly expanded version of the original TRACE lexicon were used (McClelland & Elman, 1986; Mirman et al., 2005).

Activations for lexically-consistent and inconsistent interpretations of ambiguous phonemes are shown in Figure 1. For both implementations of attentional modulation, when lexical attention was high, the lexically consistent phoneme won quickly and clearly for ambiguous phoneme input. When lexical attention was low, the lexically consistent phoneme had a smaller advantage and this advantage was slower to build up. This was because lexical items were less active and thus provided less feedback to the lexically consistent phoneme. The size of the lexical influence depends on the specific attention parameter values; the next simulation will demonstrate this point explicitly.

These simulations show that both of the implementations of the mechanism of attentional modulation can account for variability in the lexical influence on interpretation of ambiguous phonemes.

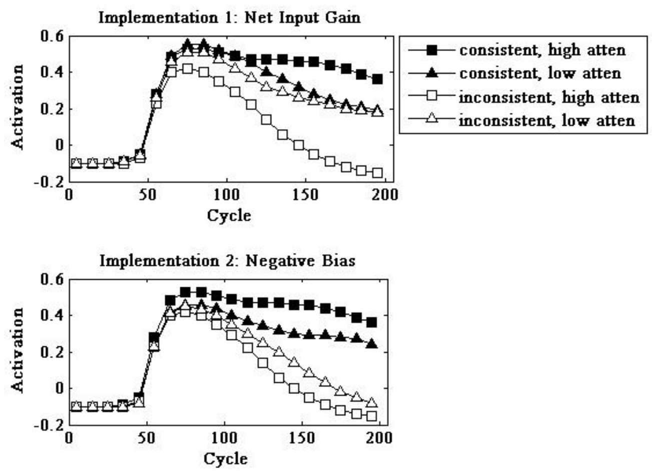

Figure 1: Two implementations show attentional modulation of the lexical influence on identification of ambiguous phonemes. Lexically consistent phonemes (black) are more active than lexically inconsistent phonemes (white), but this difference is smaller under low lexical attention (triangles) compared to high lexical attention (squares).

Simulation 2: Word Advantage

These simulations were based on the word advantage in phoneme detection (i.e., faster phoneme detection in words than nonwords), which researchers have suggested is sensitive to attentional modulation (Cutler et al., 1987; Eimas et al., 1990). The inputs were 14 words and 14 nonwords with the target phoneme (/t/) in the final position. Nonwords were created by swapping the onsets between words (the same nonword creation technique was used in Experiment 1 to control for phonotactic effects, see discussion below). Several different attention values were tested for each of the implementations.

Simulated phoneme recognition times (in processing cycles from target position) for the words and nonwords are shown in Figure 2 for each of the tested attention values in each of the implementations (model RT was computed as the number of cycles required for a phoneme to reach Luce choice probability of 0.95, as in previous studies e.g., Mirman et al., 2005). For each implementation, TRACE was faster to recognize phonemes that were embedded in words at high lexical attention. As lexical attention was reduced, lexical items were less active. Thus they provided less support to their constituent phonemes and phonemes in words had a smaller speed of recognition advantage over phonemes in nonwords.

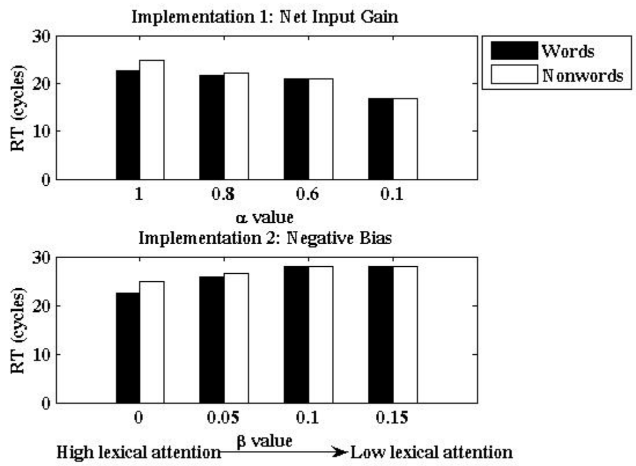

Figure 2. Two implementations show attentional modulation of the word advantage in phoneme recognition. Phonemes are detected more quickly in words (black) than nonwords (white); this difference decreases as lexical attention decreases.

Both implementations showed a graded decrease in word advantage with decrease in lexical attention, but there was a subtle difference between them. When net input gain was reduced (Figure 2, top panel), response times decreased for both words and nonwords and the word advantage was eliminated in virtue of the greater RT decrease for nonwords. In contrast, when negative bias (β) was increased (bottom panel), response times for words and nonwords increased and the word advantage was eliminated in virtue of the greater RT increase for words. Note that this difference was also evident in the Simulation 1; for implementation 1 at low attention the inconsistency disadvantage was reduced, but for implementation 2 the consistency advantage was reduced. This difference was due to the effect of the different implementations on the dynamics of activation and competition at the lexical layer. Modulation of net input gain made individual lexical units less responsive to all inputs: the lexical units were slower to become active in response to excitatory input and were less inhibited by lateral interactions. This decrease in competitiveness among lexical units allowed many lexical units to remain active at low activation levels rather than forcing a single unit to dominate activity. The population of active words then tends to reinforce activation at the phoneme level about equally for both words and nonwords. This hypothesis was confirmed by testing a gain manipulation that was restricted to excitatory inputs. When the excitatory-only gain parameter was reduced (lower lexical attention) network performance matched the results of simulations manipulating negative bias (i.e., reaction time increased for phonemes in words and nonwords).

One quantitative way to examine this is to consider the maximum number of lexical units that passed a minimal activation threshold (0.05; note that the threshold for interacting with other units was 0 and the rest activation was -0.1) at each of the attention parameter values. Figure 3 shows the maximum number of active lexical units (averaged across the 28 trials) for each of the three implementations (net input gain, excitatory-only gain, and negative bias). To equate the three implementations, maximum active word units is plotted against magnitude of the word advantage in Figure 3 (i.e., RT(NW)-RT(W); the implementations produced very similar patterns of decrease of the word advantage with decrease of lexical attention). The data in Figure 3 illustrate that for manipulation of excitatory gain and negative bias, a decrease in word advantage is associated with fewer active words, but for manipulation of net input gain, the decrease in word advantage is associated with an increase in number of active words.

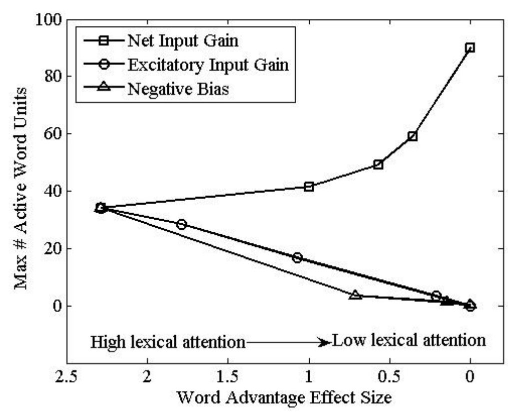

Figure 3. Maximum number of active words as a function of lexical attention (indexed by magnitude of the word advantage). For modulation of net input gain, the number of active words increases with decreased lexical attention, but for the other two implementations the number of active words decreases with decreased lexical attention.

This indicates that as net input gain is decreased, lexical feedback becomes dominated by the cumulative effects of many words rather than the activity of any particular word. Since the stimuli for this simulation were designed to control transitional probabilities, words and nonwords become equal when individual item effects are removed. One of the interesting properties of the TRACE model of speech perception is that it is sensitive to the overall statistics of the lexicon as well as the effects of individual items (McClelland & Elman, 1986), but this dual sensitivity depends on the balance of excitatory and competitive dynamics, which is disrupted by manipulation of net input gain. In contrast, manipulation of excitatory gain and negative bias appear to reduce group and individual item effects together (i.e., the number of active words decreases in concert with decreases in magnitude of the word advantage).

In sum, attentional modulation by selective dampening is a neurophysiologically-plausible mechanism that is consistent with interactive processing and each of the implementations that we tested can account for attentional modulation of lexical facilitation of phoneme detection. However, different implementations offer somewhat different accounts: under the net input gain implementation, reduced lexical attention allowed large cohorts of lexical items to dominate lexical feedback, thus providing feedback support to phonemes in words and nonwords alike and producing faster response times for both types of items. Under the excitatory gain and negative bias implementations, reduced lexical attention produced less lexical activity (fewer lexical units active at lower levels of activation) and thus less lexical feedback support. In these cases, individual item support for phonemes in words was reduced along with a reduction in cohort support for phonemes in both words and nonwords. Consequently, response times increased overall, particularly for words.

Experiment 1

A number of researchers have appealed to attentional modulation to account for variability in the magnitude of the word advantage in phoneme recognition. In their experiments effects of attention were inferred from comparisons across different stimulus types (e.g., CV vs. CVC, Cutler et al., 1987) or across different task conditions (e.g., lexical decision vs. tone judgment, Eimas et al., 1990). However, differences in processing of acoustic material in different contexts and differential demands of tasks may account for these results. An experimental paradigm in which the critical items and task are matched across attention conditions is required for a clear assessment of attentional modulation of lexical effects on phoneme recognition. Experiments that manipulate the proportion of words in an experimental block provide a paradigm in which critical items and task can be controlled while attention is manipulated. This manipulation is based on the assumption that participants will dis-attend to information that is not useful to task performance, specifically, lexical information when the proportion of words is low. Previous studies have shown that manipulation of the proportion of words affects the use of word level information in single word reading (Monsell et al., 1992), speech production (Hartsuiker, Corley, & Martensen, 2005), and spoken word recognition (Vitevitch, 2003). The present experiment tests whether this manipulation can also modulate lexical effects on speech sound identification.

Methods

Critical Stimuli. The critical stimuli were 40 word-nonword pairs (20 /t/-final and 20 /k/-final) created to be equated for phonotactics and containing phoneme targets in the final position. Nonwords were created by swapping consonant onsets between the words (as for the input patterns in Simulation 2; e.g., “hemlock”-“lemlock” and “logic”-“hogic”). Since the nonwords only differ from words by their onsets, controlling for pre-lexical phonotactic effects was accomplished by matching the onset-vowel rates of occurrence between the words and nonwords. To minimize pre-lexical consequences of swapping onsets, critical words were constrained to have two syllables with stress on the first syllable. Each participant heard only one member of a word-nonword pair (i.e., half heard “hemlock” and the other half heard “lemlock”; likewise, half heard “logic” and half heard “hogic”).

Filler stimuli. The purposes of the filler stimuli were to vary phoneme target position and the stress and syllabic structure in the experiment items (critical words were all two-syllable with primary stress on the first syllable), and to equate target-present and target-absent trials. Two and three syllable words and nonwords with targets in initial and medial positions were included. In addition, target-absent words and nonwords were chosen such that phoneme targets occurred in 50% of the words and 50% of the nonwords.

Attention-shifting filler stimuli. The purpose of the attention-shifting filler stimuli was to modulate participants’ lexical attention by manipulating the overall proportion of words in the experimental session. To this end, attention-shifting filler stimuli were either 120 words *or* 120 nonwords (60 target-present, 60 target-absent), depending on the attention condition. Thus, each participant completed a block of 200 trials of which 80% were words and 20% were nonwords (high lexical attention condition) or 20% were words and 80% were nonwords (low lexical attention condition).

Stimulus Construction. All stimulus materials were spoken by a male native speaker of American English in the context of the sentence “Say [item] again” and digitally recorded at a 22050 Hz sampling rate (nonwords were spoken in their nonword form, e.g., “lemlock”). All tokens were digitally excised from the sentence and filtered to remove background noise. An identical final consonant burst (i.e., the phoneme target) was spliced to each member of a critical word-nonword pair. For half of the items the phoneme was spliced from the word to the nonword, for the other half it was the opposite. This method insured that the phoneme target was identical in each member of a word-nonword pair and that there was no systematic bias induced by splicing.

Procedure. Participants were seated in sound attenuating booths where they heard words and nonwords presented through headphones at comfortable listening levels and made “yes” / “no” responses using an electronic button box. For each token, participants were asked to determine whether the spoken item contained the target phoneme (/t/ or /k/) or not. Half of the participants were assigned to the high lexical attention condition (80% words, 20%

nonwords) and half to the low lexical attention condition (20% words, 80% nonwords). Target phoneme was counterbalanced across participants; half of the participants monitored for /t/ and half for /k/. Button label assignments were also counterbalanced across participants. The first forty trials were constrained to be filler trials with feedback presented on the first 20 trials.

Participants. Participants were 98 students at Carnegie Mellon University who received course credit or a small payment for participation. All participants reported normal hearing and English as their native language.

Results and Discussion

Eighteen participants were excluded from analyses because their critical item accuracy was below 80% (low accuracy may indicate a hearing problem or low motivation; further, since reaction time analyses were based on correct trials only, low accuracy reduces the number of trials in each condition for each participant). The remaining 80 participants were more accurate when detecting a phoneme in words than nonwords ($F(1,76)=15.4$, $p<0.001$), but there was no interaction with attention condition ($F<1$) nor any other main effects or interactions (all other $F<1$). Mean critical item response times (± standard error) for the same 80 participants are shown in Figure 4. Response times were measured from target offset and only trials on which the participant provided the correct response were included in analyses. Overall, the word advantage was greater in the high lexical attention (80% words) condition (119.4 ms) than in the low lexical attention (20% words) condition (36.5 ms). Full ANOVA results showed a main effect of lexical status (i.e., phoneme detection was faster in words than nonwords; $F(1,76)=17.2$, $p<0.001$) and a lexical status by attention condition interaction (i.e., the word advantage was bigger in the high lexical attention condition than in the low lexical attention condition; $F(1,76)=4.872$, $p=0.03$). No other reliable effects were found (all other $F<1$).

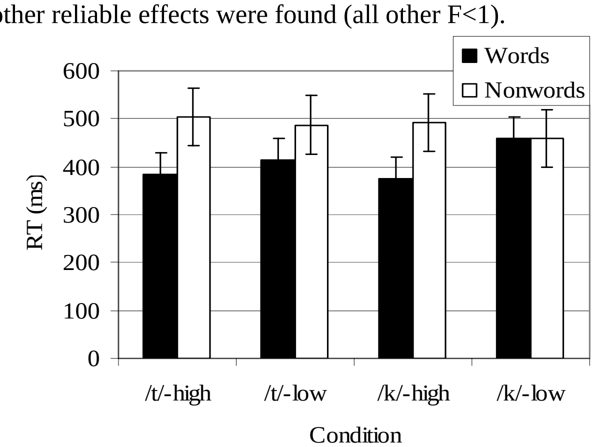

Figure 4. Mean latency (± standard error) for recognition of /t/ and /k/ in words and nonwords.

Differences between the implementations discussed in Simulations 1 and 2 raised the question of whether the difference in word advantage effect size is due to increases or decreases in response times for targets in words or nonwords or both. In the low lexical attention condition relative to the high lexical attention condition, there was a 57 ms increase in RT to targets in words ($t(78)=1.27$, $p=0.21$) and a 25 ms decrease in RT to targets in nonwords ($t(78)=0.43$, $p=0.67$). Some researchers have suggested that there may be additional processing demands for nonwords that are not captured by mere lexicality (Wurm & Samuel, 1997) and it is possible that these additional demands are reduced when nonwords occur frequently during an experimental block. Thus, the data suggest that a decrease in lexical attention reduces the word advantage primarily due to increased reaction times to targets in words. The current data fall intermediate between the two model implementations discussed above and further investigation is necessary to distinguish between the implementations. However, results from previous studies (Hartsuiker et al., 2005; Monsell et al., 1992) are consistent with the negative bias implementation: slower RT under reduced lexical attention.

The results of this experiment demonstrate that the word advantage in phoneme monitoring is susceptible to attentional modulation by manipulation of the proportion of words in the stimulus list. This demonstration confirms that attention can modulate the effects of lexical influence on speech sound recognition. This experimental paradigm may be useful for further exploration of attention and speech processing.

General Discussion

This report described a general neurophysiologically-inspired mechanism of attentional modulation based on selective dampening of activation. We presented two concrete implementations of this mechanism that are consistent with the principle of interactive processing and used simulations of an extension of the TRACE model of speech perception to demonstrate that each of these implementations can account for attentional modulation of lexical effects on speech sound recognition. Critics of the interactive view of speech perception have argued that interactive models can not account for such attentional modulation effects (Norris et al., 2000). The present simulations refute this claim.

In addition to computational investigations, this report described an experimental paradigm well-suited to studying attentional modulation of speech perception. In this paradigm, attention is shifted between lexical and pre-lexical levels by the proportion of words relative to nonwords among the filler items, thus allowing tight control of critical stimuli and task across attention conditions. Consequently, results from experiments using this paradigm are not open to alternative explanations based on task demands. Results from an experiment using this paradigm demonstrate an effect of attentional modulation on the word advantage in phoneme detection but do not clearly distinguish between different implementations of the attention mechanism. Further experiments are necessary to develop a clear understanding of the interactions between attention and speech perception.

An important prediction of the attention mechanism described here is that neurophysiological signatures of word-level processing should be reduced under conditions of reduced lexical attention. A recent study found that the N400m MEG response to syllables became most similar to that evoked by words when these syllables were presented among words and sentences compared to when they were presented in isolation (Bonte, Parviainen, Hytonen, & Salmelin, 2006). Note that this design is very similar to the design of our experiment: the same stimuli in the same task are compared when they are presented in meaningful contexts (among words and sentences) to when they are presented in meaningless contexts (among nonwords) and the results are consistent with the claim that when syllables are presented in meaningless contexts lexical processing is dampened.

In sum, we proposed and tested activation dampening as a mechanism of attentional modulation of lexical effects on perception of speech sounds. Simulations of two concrete implementations of this mechanism in the context of an interactive model of speech perception demonstrated that this mechanism can modulate the strength of lexical effects. A recent MEG experiment provided electrophysiological data consistent with this approach. We also presented behavioral data showing attention modulation of lexical feedback effects using a paradigm in which critical stimuli and task are matched across attention conditions.

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References

Bonte, M., Parviainen, T., Hytonen, K., & Salmelin, R. (2006). Time Course of Top-down and Bottom-up Influences on Syllable Processing in the Auditory Cortex. *Cerebral Cortex, 16*, 115-123.

Cohen, J. D., Dunbar, K., & McClelland, J. L. (1990). On the control of automatic processes: A parallel distributed processing account of the Stroop effect. *Psychological Review, 97*(3), 332-361.

Cutler, A., Mehler, J., Norris, D., & Segui, J. (1987). Phoneme identification and the lexicon. *Cognitive Psychology, 19*(2), 141-177.

Desimone, R., & Duncan, J. (1995). Neural mechanisms of selective visual attention. *Annual Review of Neuroscience, 18*, 193-222.

Eimas, P.D., Hornstein, S.M., & Payton, P. (1990). Attention and the role of dual codes in phoneme monitoring. *Journal of Memory & Language, 29*, 160-180.

Ganong, W. F. (1980). Phonetic categorization in auditory word perception. *Journal of Experimental Psychology: Human Perception & Performance, 6*(1), 110-125.

Hartsuiker, R. J., Corley, M., & Martensen, H. (2005). The lexical bias effect is modulated by context, but the standard monitoring account doesn't fly: Related beply to Baars et al (1975). *Journal of Memory & Language, 52*(1), 58-70.

Kello, C.T., & Plaut, D.C. (2003). Strategic control over rate of processing in word reading: A computational investigation. *Journal of Memory & Language, 48*, 207-232.

McClelland, J.L., & Elman, J.L. (1986). The TRACE model of speech perception. *Cognitive Psychology, 18*, 1-86.

McClelland, J. L., & Rumelhart, D. E. (1981). An interactive activation model of context effects in letter perception: I An account of basic findings. *Psychological Review, 88*(5), 375-407.

Mirman, D., McClelland, J. L., & Holt, L. L. (2005). Computational and behavioral investigations of lexically induced delays in phoneme recognition. *Journal of Memory & Language, 52*(3), 424-443.

Monsell, S., Patterson, K. E., Graham, A., Hughes, C. H., & Milroy, R. (1992). Lexical and sublexical translation of spelling to sound: Strategic anticipation of lexical status. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 18*(3), 452-467.

Moran, J., & Desimone, R. (1985). Selective attention gates visual processing in the extrastriate cortex. *Science, 229*(4715), 782-784.

Norris, D., McQueen, J. M., & Cutler, A. (2000). Merging information in speech recognition: Feedback is never necessary. *Behavioral & Brain Sciences, 23*(3), 299-370.

O'Craven, K. M., Rosen, B. R., Kwong, K. K., Treisman, A., & Savoy, R. L. (1997). Voluntary attention modulates fMRI activity in human MT-MST. *Neuron, 18*, 591-598.

Pitt, M. A., & Samuel, A. G. (1993). An empirical and meta-analytic evaluation of the phoneme identification task. *Journal of Experimental Psychology: Human Perception & Performance, 19*(4), 699-725.

Rubin, P., Turvey, M.T., & Van Gelder, P. (1976). Initial phonemes are detected faster in spoken words than in spoken nonwords. *Perception & Psychophysics, 19*, 394-398.

Servan-Schreiber, D., Printz, H., & Cohen, J. D. (1990). A network model of catecholamine effects: Gain, signal-to-noise ratio, and behavior. *Science, 249*(4971), 892-895.

Vitevitch, M.S. (2003). The influence of sublexical and lexical representations on the the processing of spoken words in English. *Clinical Linguistics & Phonetics, 17*(6), 487-499.

Wurm, L. H., & Samuel, A. G. (1997). Lexical inhibition and attentional allocation during speech perception: Evidence from phoneme monitoring. *Journal of Memory & Language, 36*(2), 165-187.