# Orthographic Neighborhood Size and Task Presentation Modulate ERP Amplitudes in Lexical Decision

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**Abstract**

This study examined the effects of orthographic neighborhood size, the number of words that can be created from a target word by changing only one letter, and task presentation, emphasizing either accuracy or speed to subjects, on event-related potentials during lexical decision. Subjects performed a lexical decision task while ERPs were recorded from their scalp. Neighborhood size and task presentation were manipulated. Large neighborhood words elicited greater negativities in the N400 time frame, as seen previously. However, contrary to predictions, the accuracy condition elicited greater differences in N400 amplitude due to neighborhood size than the speed condition. Finally, qualitative source estimation analysis suggested a differential pattern of activation between large and small neighborhood words in the temporal lobe. This study provides an exploratory test and support for several aspects of the Multiple Read-Out Model (MROM), which proposes two distinct decision mechanisms used for lexical decision: (a) a slow lexical access mechanism and (b) a fast-guess global activation mechanism. These results also call into question several other aspects of the MROM and its predictions for lexical decision tasks. Thus, further research is necessary to fully articulate the effects of neighborhood size and task presentation on lexical decision.

**Introduction**

Lexical access, or how words are stored and retrieved in the brain, has been studied for decades in the fields of psycholinguistics and neurolinguistics. Lexical access can be best understood by first discussing the lexicon. The lexicon is essentially a mental dictionary of every known word in a speaker's mind. The meaning, sound, spelling, etc. of a given word are all stored in its lexical entry. Lexical access is the process of accessing that lexical entry. When a speaker hears or sees a particular word, it is theorized that the brain forms a representation of that word and attempts to match that representation with a stored entry, choosing the best candidate (Grainger and Jacobs, 1996). Several features of words are known to affect lexical access, including length, frequency, familiarity, concreteness, and age of acquisition (Balota et al., 2006). This thesis will focus on the effects of orthographic neighborhood size on lexical decision.

*The Neighborhood Size Effect*

Orthographic neighborhood size is a measure of how similar the orthography of a word is to that of other words in the language. There are several ways to measure orthographic neighborhood size. Coltheart's N measures the number of words that can be created by changing one letter of a target word (Coltheart et al., 1977). While the N metric is the most commonly used measure of orthographic neighborhood size, it can be restrictive and may ignore several key similarities between words by including only words created through letter substitutions. For instance, letter transposition (switching two letters next to each other) plays a key role in orthographic similarity. In recent years, a new metric of orthographic neighborhood size has been proposed called the Levenshtein distance (OLD20 – orthographic Levenshtein distance 20). Instead of considering only substitution neighbors, OLD20 considers several levels of similarity between words, whether it be through letter substitution, transposition, addition, or deletion. Thus words of different lengths can also be compared. OLD20 has been shown to be a more accurate measure of the effects of orthographic neighborhood size, and thus is a more useful and precise metric (Yarkoni et al., 2008). Both Coltheart's N and OLD20 are used in this thesis as measures of orthographic neighborhood size.

There is some disagreement in the literature concerning the effect of orthographic neighborhood size on lexical access, called the neighborhood size effect. Namely there are inconsistencies in the effects of neighborhood size within and across certain tasks. In naming tasks[1], there is a clear facilitatory neighborhood size effect, where naming times are faster for words with larger neighborhoods compared to smaller neighborhoods (Andrews, 1989; Andrews, 1992; Sears et al., 1995). Semantic classification tasks[2] find a similar facilitatory effect (Forster and Shen, 1996). On the other hand, eye fixation times[3] during reading find an inhibitory neighborhood size effect (Pollatsek et al., 1999). These studies, although they disagree, have found significant effects specific to each task; however, there is even more disagreement about the effects of orthographic neighborhood size in lexical decision tasks.

Lexical decision involves presenting subjects with a series of letter strings and asking them to decide whether each is a word or not. Although lexical decision was originally thought to be the most "pure" measure of lexical access (Forster, 1976), more recent evidence suggests that performance in a lexical decision task can be affected by strategic decision processes, rather than being true lexical access (Balota and Chumbley, 1984). It has thus been proposed that comparing data across tasks is best in order to develop a fuller understanding of lexical access (Andrews, 1997); however, the inconsistent effects seen with lexical decision merit further study in order to understand why and how they occur.

Lexical decision tasks provide the most seemingly contradictory neighborhood size effects of any task used to measure lexical access. When first studied, effects of orthographic neighborhood size were reported as inhibitory for nonwords and null for words[4] (Coltheart et al., 1977). Other early experiments found a facilitatory neighborhood size effect for words, meaning that subjects had shorter reaction times for words with larger orthographic neighborhood sizes than smaller (Andrews, 1989; Andrews, 1992). However, many of these early studies did not

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[1] Subjects are presented with words (and/or nonwords) and asked to name the words as quickly as possible.
[2] Subjects are presented with words and asked to respond only if the word fits a specific category, e.g. animal.
[3] Fixation time denotes the time a subject's eyes focus on a particular stimulus. Longer fixation times during sentence reading are associated with more difficulty in accessing words.
[4] Inhibitory meaning longer reaction times for words with larger neighborhoods than smaller neighborhoods.

effectively control for word frequency or the presence of high frequency neighbors, which was not yet known to have an effect on lexical access. Since then, studies have shown that the presence of a single high frequency neighbor may act as a salient competitor, slowing the lexical access process (Grainger and Jacobs, 1996; Grainger et al., 1989). Later experiments, which controlled for both frequency and the presence of a high frequency neighbor, found facilitatory effects of neighborhood size for words (Sears et al., 1995; Forster and Shen, 1996), while a few others found inhibitory (Johnson and Pugh, 1994) or null effects of neighborhood size (Carreiras et al., 1997). These inconsistencies have complicated the field for decades, but the majority of recent studies have found an overall facilitatory effect of neighborhood size on words. Indeed, more recent studies have suggested that these disparate results are likely caused by variations in experiment design.

The nature of the nonword environment in lexical decision tasks has been shown to modulate the neighborhood size effect for words. In lexical decision tasks, an equal number of words and nonwords are presented to the subject. These nonwords can vary in how wordlike they are. Consonant strings, or illegal nonwords, are extremely unlikely to be a word of any language and thus are the least wordlike. Pseudowords are nonwords that have similar consonant and vowel distributions to real words, and thus are more wordlike. Pseudowords themselves can also vary in how wordlike they are. Johnson and Pugh (1994) found an inhibitory neighborhood size effect for real words when the nonword environment consisted of legal pseudowords, but they found facilitatory effects when the nonword environment consisted of illegal nonwords. Other studies have seen a more robust facilitatory effect when words were contrasted with illegal nonwords, compared to the small facilitatory effect seen with legal pseudowords (Forster and Shen, 1996; Andrews, 1989). This difference in the degree of facilitation was also seen when comparing pseudowords that were more or less wordlike, where less wordlike pseudowords caused a more facilitatory neighborhood size effect (Grainger and Jacobs, 1996). The type of nonword competitor in the task can thus modulate the neighborhood size effect.

The nature of task presentation also seems to modulate the neighborhood size effect. Grainger and Jacobs (1996) emphasized the importance of either speed or accuracy to subjects during a lexical decision task and found a significant modulation of the neighborhood size effect. When accuracy was emphasized, they saw a more inhibitory effect, but when speed was emphasized, they found a more facilitatory effect of neighborhood size (Grainger and Jacobs, 1996). Thus, both the nature of the task and the nonword environment can change the neighborhood size effect. The null or inhibitory effects previously seen in the literature could be due the lack of control over one or both of these variables, because both could be mistakenly manipulated. These observations are the basis of a model of lexical access that proposes two different mechanisms of lexical decision, called the Multiple Read-Out Model (MROM).

*The Multiple Read-Out Model*

The MROM, proposed by Grainger and Jacobs (1996), is intended to model the cognitive mechanisms used during lexical decision tasks and other tasks measuring lexical access. It proposes three different criteria (M, Σ, and T) that can be used for lexical decision. The M criterion is based on the individual lexical access of a word and involves what is thought to be “true” lexical access of an individual lexical entry. The time needed to perform this lexical access is theorized to be fixed regardless of word features, but neighboring words can still act as competitors of access in this context. The Σ criterion is based on the global activation of neighboring words. Many models of lexical access assume that when a speaker sees or hears a word, all the neighboring words are partially activated in the lexicon via spreading activation[5], along with the target word itself being activated (Balota et al., 2006). In the MROM, the Σ criterion depends on the total level of neighbor activation, or global activation, and is thus theorized to vary as a function of word features or task demands. The M and Σ criteria deal exclusively with responses given to word stimuli. Nonword responses are based on the T criterion, a temporal deadline used for giving negative responses. This criterion is also thought to depend on global activation, and its existence is hotly debated in the field (Braun et al., 2006); however, an in depth discussion of nonword effects in lexical decision is beyond the scope of this thesis. If either the M or Σ criterion are reached before the T criterion times out, a positive response is given. Necessarily, the use of the M criterion vs. Σ criterion is theorized to change the cognitive decision process by which the subject responds during a lexical decision task.

The presence of two different criteria for decision creates essentially two separate processes that can be used for decision with words. The M criterion generates a slower, lexical access based decision process. This process is true lexical access of a specific lexical entry. On the other hand, the Σ criterion generates a fast-guess, global activation-based decision process. It is strategic and involves guessing mechanisms. Jacobs et al. (2003) argues that the existence of this type of "fast-guess" mechanism is crucial in the understanding and interpretation of lexical decision results. These two mechanisms can be referred to as the lexical access mechanism and the global activation mechanism, respectively. Crucially, each decision mechanism is predicted to cause opposing neighborhood size effects.

When a subject uses the lexical access mechanism, an inhibitory, or less facilitatory, neighborhood size effect is seen. This is due to neighboring words acting as competitors during

[5] The spreading of lexical activation involves the activation of the target entry followed by the subsequent activation of similar lexical entries, such as orthographic neighbors.

true lexical access, causing a higher level of competition from neighbors for words with large neighborhoods than with small. This results in an increase in reaction times and thus an inhibitory (or less facilitatory) effect. The size of the inhibitory effect can depend on other aspects of task design; thus, inhibitory and less facilitatory effects are equivalent in this context[6]. On the other hand, when a subject uses the global activation mechanism, one expects to see a strong facilitatory effect of neighborhood size. For this mechanism, words with larger neighborhoods elicit increased levels global activation, which is the criteria for decision. This leads to faster reaction times for words with larger neighborhoods and thus a facilitatory effect of neighborhood size. Experiments by Grainger and Jacobs (1996) have shown that the use of one decision mechanism over another can indeed lead to measurable differences in reaction times during lexical decision, as predicted.

How do speakers choose between using the M or Σ criteria for lexical decision? Grainger and Jacobs (1996) describe the criteria as having thresholds. The lower the threshold for a particular criterion, the more likely it is to be used, and the more likely its corresponding decision mechanism will be used for decision. Perhaps most crucially, an experimenter can induce the use of one decision mechanism over the other through manipulation of design variables discussed above: nonword environments and emphasizing speed vs. accuracy. In a wordlike nonword environment, i.e. when words must be contrasted with wordlike nonwords during the task, subjects are less able to use global activation as a marker for words, because many of the nonwords in the experiment will generate levels of global activation equal to that of the word stimuli. For this reason, the lexical access mechanism is more likely used, leading to the inhibitory neighborhood size effect seen in several studies (Johnson and Pugh, 1994;

[6] A study by Siakaluk et al., 2002 found that the MROM seems to overestimate the inhibitory effects of the lexical access mechanism, arguing that the result of using one decision mechanism over another is more of a modulation of the degree of facilitation, rather than a dichotomy of inhibition vs. facilitation.

Grainger and Jacobs, 1996). When less wordlike nonwords or even illegal nonwords are presented instead, the subject is able to use global activation as a criterion for decision, leading to a facilitatory effect of neighborhood size. The difference in neighborhood size effects seen when speed vs. accuracy is emphasized can also be described through these two decision mechanisms. Specifically, when accuracy is emphasized, subjects are subconsciously more concerned with being precise during the task. These subjects become more likely to use the lexical access mechanism, a more precise and methodical mechanism, leading to an inhibitory effect. However, when speed is emphasized, subjects are more likely to use the fast-guess global activation mechanism to accommodate the speed constraints of the task. Use of the global activation mechanism leads to a facilitatory neighborhood size effect (Grainger and Jacobs, 1996). Thus, the use of the lexical access mechanism vs. the global activation mechanism of decision in certain situations can explain and correctly predict the behavioral results seen with manipulation of task design.

The MROM has been thoroughly tested by Grainger and Jacobs (1996) in the lexical decision paradigm, as well as with perceptual identification. However, it is unclear to what extent the MROM can be applied beyond lexical decision and perceptual identification. On one hand, DeMoor et al. (2005) found support for the MROM when they studied orthographic neighbor priming in lexical decision, where stimuli were preceded by either neighboring or unrelated masked words. When speed was stressed to subjects, they saw a facilitatory neighbor priming effect, but when accuracy was stressed to subjects, they saw an inhibitory neighbor priming effect. Thus, the MROM seems to extend to neighbor priming effects within the lexical decision paradigm. On the other hand, a test of the MROM in semantic categorization was not supportive of the model (Sears et al., 1999). Most models of lexical access assume that true lexical access is necessary in order to reach the meaning of a word (Balota et al., 2006). With this assumption, the MROM predicts the use of only the lexical access mechanism in semantic categorization, since the task necessitates true lexical access, and one would expect to see only inhibitory neighborhood size effects. However, Sears et al. (1999) found only facilitatory effects of neighborhood size in a semantic categorization task, failing to support the predictions of the MROM. These results suggest that while the MROM is a good predictor of behavior during lexical decision tasks, it is not an overall model of lexical access across tasks. The MROM can be used to further understand mechanisms of lexical decision, but it should not be extended to all lexical access. Furthermore, lexical access is likely more complex than the models propose and more research is required to develop a fuller understanding of this process.

### *EEG and Lexical Decision*

The MROM, particularly the presence of two distinct lexical decision processes, has been thoroughly tested through behavioral measures and holds up well in the lexical decision context (Grainger and Jacobs, 1996; De Moor et al., 2005; Siakaluk et al., 2002; Sears et al., 1999). However, there have been few tests of the MROM beyond reaction time studies. The model theorizes two different decision mechanisms that utilize either direct lexical access or global activation. If this theory is indeed reflective of processes occurring in the brain, then the difference should be detectable through measurements of brain activity. If tests such as these turn out supportive of the predictions of the MROM, it would be a strong argument for the model, whereas the reverse would be true if the tests contradict the model. Regardless, a rigorous test of the cognitive predictions of the model is required to determine its accuracy. This thesis utilizes EEG to study the two mechanisms of lexical decision.

Electroencephalography (EEG) has been used for decades as a measure of overall or regional brain activity. EEG recordings have been used to study topics from language and facial processing to semantic memory. In language processing, EGG has been used to investigate the neural basis of language comprehension and cognition, lexical access lying within these topics. The N400 waveform is implicated in language processing and has been studied in a variety of language contexts (Kutas and Federmeier, 2011). It is commonly associated in linguistics with semantic mismatch. Sentence anomalies that are unexpected in the context and require semantic reevaluation will elicit more negative N400 amplitudes (Osterhout and Holcomb, 1992; Kutas and Federmeier, 2000). However, further studies have also shown that the N400 is associated with the overall level of semantic activation. N400 amplitudes show significantly more negativity when a word has more semantic associations (Kounios and Holcomb, 1992; Holcomb et al., 1999). More negative N400 amplitudes can also be elicited by unmasked semantic priming, due to increased semantic activation; however, these effects have not been seen for masked semantic priming, indicating that the N400 is most closely associated with the semantic integration of words (Brown and Hagoort, 1993).

Within studies of the neighborhood size effect and the MROM, ERP results suggest that larger global activation is associated with an increase in the semantic activation of neighboring words, resulting in a larger negativity of the N400 waveform. For example, Holcomb et al. (2002) measured ERPs for words and pseudowords with large and small neighborhoods during a lexical decision task. They found that words and pseudowords with larger neighborhoods were associated with more negative N400 amplitudes, as compared to items with smaller neighborhoods. Their data suggests that the N400 is sensitive not only to the semantic properties of the word stimulus itself, but also to the increased semantic activation of neighboring words for both lexical and non-lexical items with large neighborhoods. However, these effects were small and only significant in midline analyses. Another more recent study used a semantic categorization task, with OLD20 instead of Coltheart's N as a measure of neighborhood size, and also found an increase in N400 deflection for words with larger neighborhoods (Vergara-Martinez and Swaab, 2012). Measured by either Coltheart's N or OLD20, larger neighborhood size has been seen to be associated with more negative N400 amplitudes, perhaps due to the global semantic activation of neighbors.

However, neighborhood size is only an estimation, not a direct measurement, of global activation. Indeed, Braun et al. (2006) more thoroughly tested the MROM by creating a computational model that determined the predicted global activation of each word or nonword stimulus in a lexical decision task. By modeling the global activation of each word, rather than using neighborhood size as an estimation, they argued they could more accurately measure the association between global activation and brain activity. They found an increase in N400 negativity for words and nonwords with larger estimated global activation (Braun et al., 2006). Their results suggest that global activation can indeed be measured through ERP size and that neighborhood size holds up as a useful estimation of global activation.

The aim of this study was to utilize EEG to test the cognitive predictions of the MROM. When the global activation mechanism is used for lexical decision, which can be induced through the emphasis of speed to the subject, global activation is used as the main criterion for decision. The difference in global semantic activation between words with large and small neighborhoods when speed is emphasized should be measureable in the size of the N400 waveform. Furthermore, since the lexical access mechanism, induced by the emphasis of accuracy, utilizes true lexical access to make the decision, then the difference in the N400 size between words with large and small neighborhoods may be smaller than for the global activation mechanism. This is due to the fact that lexical access is theorized to be fixed for all words, regardless of neighborhood size. There will likely be some difference in N400 size between words with large and small neighborhoods, even if the decision is made based on true lexical access, but this difference should be smaller when the lexical access mechanism is used compared to when the global activation mechanism is used. These predictions provide a vigorous test of the predictions of the MROM by measuring the expected difference in brain activity between the two mechanisms.

In this study, neighborhood size was manipulated for low frequency words in a lexical decision task. Subjects classified items as words or nonwords while reaction times and ERPs were measured for each lexical item. Half of subjects were told to respond as accurately as possible while the other half were told to respond as quickly as possible, in order to induce the use of one decision mechanism over the other. Orthographic neighborhood size was defined for each word as either large or small using both Coltheart's N and the Levenshtein distance OLD20 to control for variations between the two measures. Due to the decreasing number of neighbors for longer words, only four- and five-letter words were utilized in this experiment. An effect of neighborhood size on N400 amplitude that was modulated by the presentation of the task was expected to be seen.

## Methods

*Participants*

This study included 28 students (19 female, 9 male) from the Claremont Colleges who were native speakers of English (20 monolingual, 8 bilingual), ages 18-23. All participants had normal or corrected-to-normal vision and only one was left-handed (excluded from ERP analysis). Twelve of the subjects were in the accuracy condition and 16 were in the speed condition.

*Stimuli*

The experimental stimuli consisted of 160 lexical and non-lexical items. Stimuli were balanced between two factors: stimulus type (word or pseudoword) and number of letters (four or five letters). Lexical items were then split based on neighborhood size (large or small). The lexical items were 80 singular, mono-morphemic nouns of English taken from the English Lexicon Project database (Balota et al., 2007). The non-lexical items were 80 minimally wordlike pseudowords chosen through a ratings task administered via Amazon Mechanical Turk and Ibex Farm. Ten participants were asked to rate 160 pseudowords, generated by the English Lexicon Project, on a scale of 1 to 7 based on how wordlike they are. The least wordlike 80 pseudowords were chosen for this experiment. Words and pseudowords were chosen so as to not be neighbors of each other and to not have any high frequency neighbors.

Frequency (Brysbaert and New, 2009) was held constant (mean 12.11, sd 6.83) across all lexical items. Neighborhood size, defined using both the N-metric (Coltheart et al., 1977) and the OLD20 metric (Yarkoni et al., 2008), was manipulated for word stimuli. Lexical items with small neighborhoods had an mean N of 3 (sd 1.92) and mean OLD20 of 1.78 (sd 0.16), and lexical items with large neighborhoods had a mean N of 12 (sd 3.36) and mean OLD20 of 1.37

(sd 0.20). Note that small neighborhood size corresponds to smaller N values but larger OLD20 values. Other measures, including HAL frequency, bigram frequency, and syllable count, were recorded for the stimuli but not controlled for or manipulated.

*Task Procedure*

Stimuli were presented on a PC computer with white text on a black background using E-Prime 2.0 Software (Psychology Software Tools, 2014). Each trial consisted of a fixation cross (+) shown for 500ms, followed by the stimulus for 200ms in the same location. The stimulus was followed by a blank screen for 2500ms or until the subject responded. After responding, the subject was provided with visual feedback for 1500ms. Subjects in the speed condition were presented with their reaction time after responding and were instructed to respond faster than 400ms for each trial. Subjects in the accuracy condition were presented with a red “X” if they responded incorrectly, or a fixation cross (+) if they responded correctly. The inter-trial interval was 2000ms and involved the presentation of a capital letter “B” in the center of the screen, indicating to the subject that they may blink. All stimuli were presented in uppercase letters to control for letter width. Subjects were instructed to press one button (using their left index finger) if the stimulus was a real word of English and to press another button (using their right index finger) if the stimulus was not a real word of English. Subjects were asked not to move (expect for the button press) or to blink unless the capital “B” was on the screen. Each subject performed a practice session of 8 trials (4 lexical and 4 non-lexical items) before beginning the experiment. Trials were randomized within two 80 trial blocks, the order of which was also randomized. A short break was provided between each block. Each experimental session lasted approximately 15 minutes.

*EEG Acquisition*

EEG was continuously recorded on a Mac computer running Net Station Software (Electrical Geodesics, 2014). Participants were seated in a comfortable chair in a quiet room, and an Electrical Geodesics Inc. 128-channel Hydrocel Geodesic Sensor Net soaked in potassium chloride saline solution was fitted to their scalp (Electrical Geodesics, 2014). The electrodes were Ag/AgCl-plated carbon-fiber pellets connected to a gold pin by a lead-shielded wire. Eye movements and blinking were measured by electrodes placed around the eyes. Recording electrodes were referenced to the subject's vertex electrode. The net was connected to a DC-coupled high impedance (200 MΩ) Net Amps 300 amplifier, and analog voltages were amplified by a gain of 1,000. A bandpass filter of .3-100 Hz was used during recording.  Voltages were digitized with a 24-bit A/D converter at 250 Hz. Electrode impedances were kept below 100 kΩ.

*ERP Analysis*

For each stimulus, participant, and condition, calculations were done to determine mean reaction time, proportion errors, and standard deviations. Incorrect responses were excluded from reaction time and EEG analyses. NetStation 4.5 software was used to process raw EEG data (Electrical Geodesics, 2014). Raw data was filtered using a 30 Hz lowpass filter. ERPs were segmented beginning with 200ms prior to stimulus onset and ending 1000ms after onset. Trials containing ocular artifacts (greater than 140µV difference between eye channels for eye blinks, greater than 55µV difference for eye movements) or more than ten bad channels (200µV difference between successive samples) were excluded from further EEG analysis. Ocular Artifact Removal (OAR) was used on subjects with less than 75% artifact-free trials (blink slope threshold of 14µV/ms). Participants with less than 40% artifact-free trials per condition after OAR were excluded from further analysis. This resulted in the elimination of one participant in the accuracy condition and six participants in the speed condition. Single participant ERP averages were calculated separately for large and small neighborhood words, followed by grand averages calculated across subjects for the accuracy and speed conditions. The N400 effect of neighborhood size has been seen predominantly along the midline from Cz to Pz (Holcomb et al., 2002; Braun et al., 2006). Therefore, this analysis focused on ERPs from the electrodes Cz to Pz (Cz, #55, and Pz) in the 250-400ms window after stimulus onset, corresponding to the latency range for the N400 waveform. ERP data was quantified by performing t-tests and repeated measures ANOVAs on mean amplitudes and adaptive means (relative to a baseline 200-0ms before stimulus onset) both for each electrode and averaged across the electrodes. The adaptive mean was used in order to minimize individual differences in the N400 as well as differences in response times, seen particularly in the accuracy condition.

*Source Estimation*

Intracerebral current sources of the scalp potential were estimated using a linear inverse minimum norm solution with standardized low-resolution brain electromagnetic tomography constraint, or sLORETA (Pascual-Marqui, 2002). The version of sLORETA used in this experiment was implemented by EGI GeoSource 2.0 software (Electrical Geodesics, 2014). A finite difference head (FDM) model was used for calculation of the lead field in relation to the head tissues. The FDM model was constructed from a subject (Colin27) who most closely resembled the Montreal Neurological Institute average head (MNI305) (Holmes et al., 1998). Conductivity values of the scalp, skull, CSF, and brain are 0.44, 0.018, 1.79, and 0.25 S/ml, respectively. Source space consisted of 2,447 cortical voxels (7 mm) with three orthogonal orientations. Source estimation was performed on the grand average ERP scalp data and superimposed upon the Colin27 MRI.

## Results

### *Behavioral Data*

Twenty-eight subjects aged 18-23 (M = 20, sd = 1.44) were included in the behavioral analyses. Reaction times and proportion errors for each condition can be found in Table 1. Overall, 11% of trials resulted in errors. Between-subjects analysis resulted in significant differences between reaction times and proportion errors for accuracy vs. speed (Figure 1). The accuracy condition elicited significantly longer reaction times (M = 622ms) than the speed condition (M = 433ms), $t(27)=12.62, p<.01, d=2.82$. Subjects in the accuracy condition also had significantly lower proportion errors (M = .018) than in the speed condition (M = .270), $t(27)=12.62, p<.01, d=2.88$. No effects of word length or neighborhood size in the accuracy or speed conditions nor any interactive effects between condition types were seen.

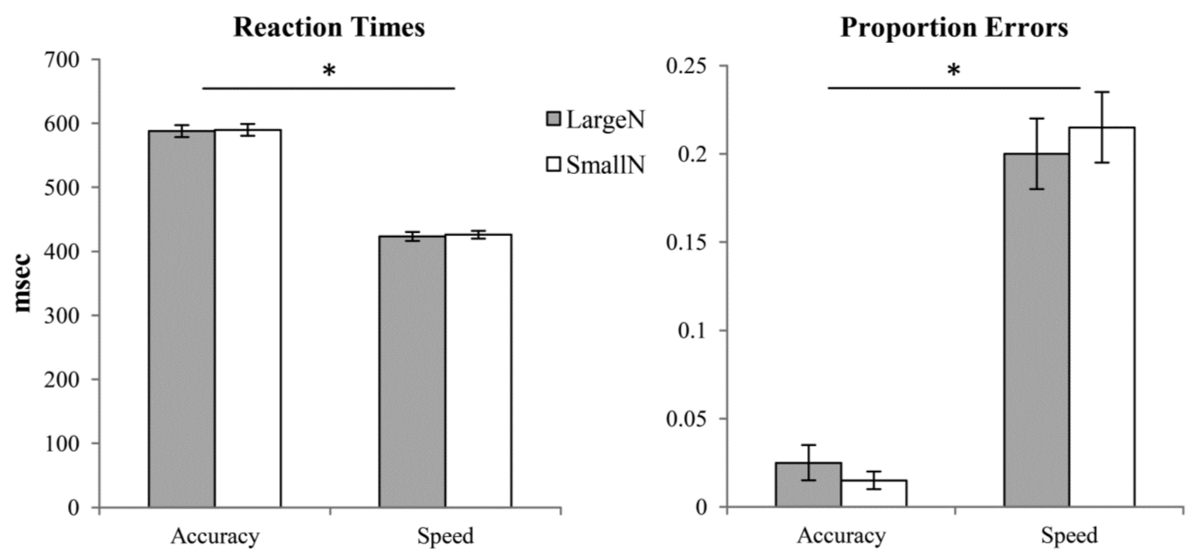


**Figure 1**. Reaction times and proportion errors by condition
Mean reaction times and proportion errors for each condition are graphed. Error bars are shown. Reaction times were significantly slower in the accuracy condition compared to speed (p<.01). Proportion errors were significantly lower for the accuracy condition compared to speed (p<.01). No effects of neighborhood size or interactions of the two condition types were seen.

**Table 1.** Behavioral Data

| | | | *Reaction Times* | | *Proportion Errors* | |
|---|---|---|---|---|---|---|
| | | | *Mean* | *SD* | *Mean* | *SD* |
| *Accuracy* | *SmallN* | *4 letters* | 586.76 | 150.59 | 0.03 | 0.17 |
| | | *5 letters* | 593.75 | 131.58 | 0.00 | 0.00 |
| | | ***Total*** | ***590.31*** | ***141.46*** | ***0.02*** | ***0.09*** |
| | *LargeN* | *4 letters* | 588.95 | 122.02 | 0.03 | 0.18 |
| | | *5 letters* | 586.53 | 157.07 | 0.02 | 0.13 |
| | | ***Total*** | ***587.73*** | ***140.95*** | ***0.03*** | ***0.16*** |
| | ***Total*** | | ***589.02*** | ***141.37*** | ***0.02*** | ***0.12*** |
| *Speed* | *SmallN* | *4 letters* | 427.19 | 109.07 | 0.21 | 0.40 |
| | | *5 letters* | 431.09 | 104.63 | 0.22 | 0.41 |
| | | ***Total*** | ***429.13*** | ***107.01*** | ***0.22*** | ***0.41*** |
| | *LargeN* | *4 letters* | 428.01 | 157.38 | 0.22 | 0.41 |
| | | *5 letters* | 418.08 | 98.15 | 0.18 | 0.39 |
| | | ***Total*** | ***422.94*** | ***130.76*** | ***0.20*** | ***0.40*** |
| | ***Total*** | | ***426.03*** | ***119.04*** | ***0.21*** | ***0.40*** |
| ***Total*** | | | ***507.55*** | ***128.81*** | ***0.11*** | ***0.26*** |

### *ERP Data*

Twenty-one subjects were included in the ERP analysis. Subjects were excluded if they were left-handed, did not follow directions, or more than 40% of trials per condition were rejected due to incorrect responses, eye blinks, or eye movements. Approximately 25% of trials were rejected from the subjects included in analysis. The ERP grand average waveforms for Cz and Pz by condition are shown in Figure 2.

ERPs in the speed condition have an initial negative deflection between 50-150 ms after stimulus presentation (N1). This is followed by a positive deflection between 150-250 ms (P2). A sharp N400-like deflection occurs between 250-350 ms, peaking at approximately 300ms. A final broad positive deflection occurs around 600ms (P3). However, the waveforms in the accuracy condition have less clear peaks, likely due to the variability in response time seen in the accuracy condition. There is a relatively broad initial negative deflection between 50-150 ms, followed by a small positive deflection between 150-200 ms after stimulus onset. A broad negative-going N400-like peak occurs between 250-400 ms, followed by two other broad peaks at 600ms (P3) and at 800ms (P6).

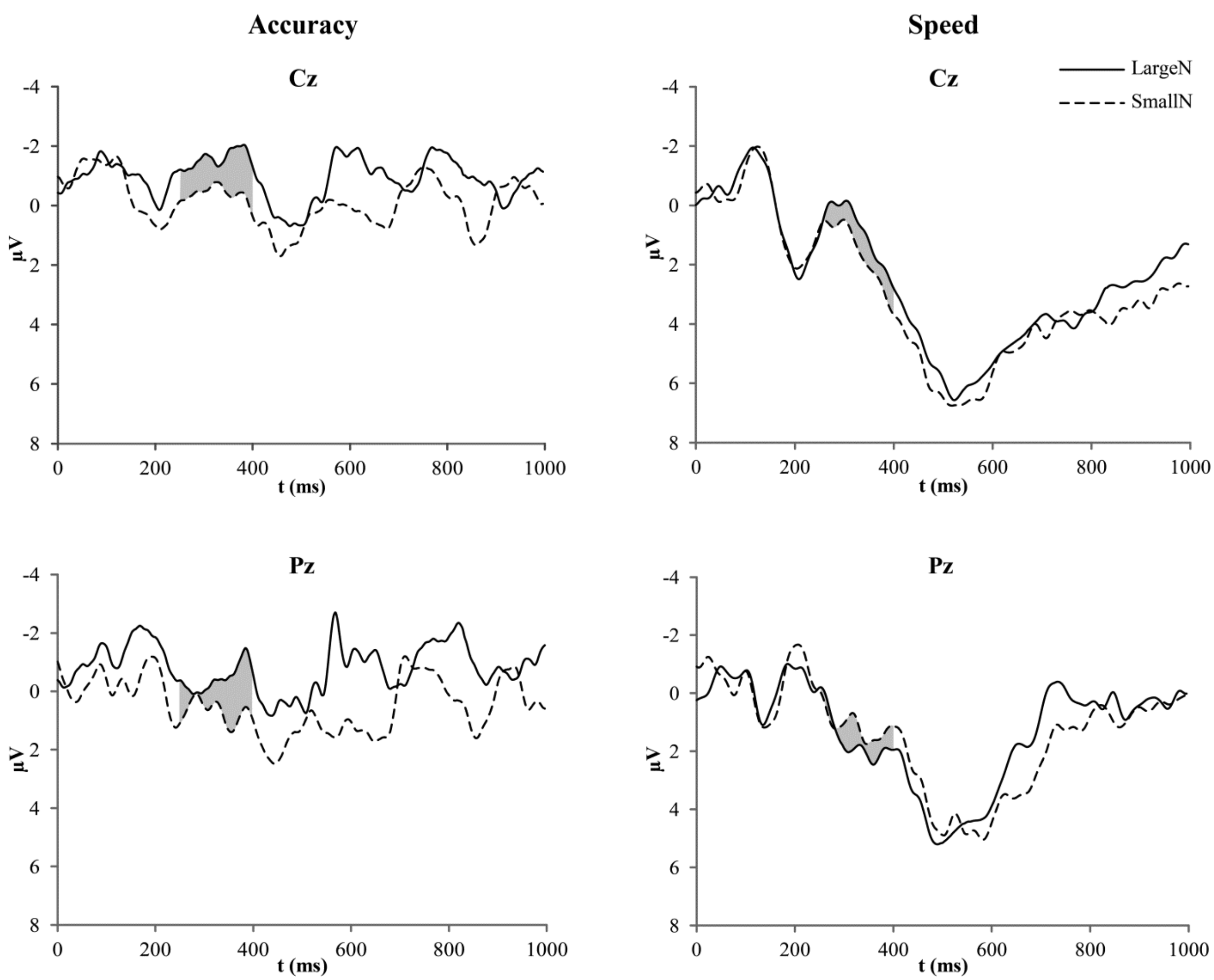


**Figure 2.** Grand average ERPs by task condition and neighborhood size
This figure plots the grand average ERPs for the accuracy and speed conditions, and within that, neighborhood size. Solid lines are ERPs from large neighborhood words, and dashed lines are ERPs from small neighborhood words. Differences in the N400 waveform between large and small neighborhood words in the 250-400 ms time frame (i.e. the time frame included in statistical analysis) are shaded grey.

Statistical analyses of ERP waveforms focused on the Cz to Pz electrodes, where the N400 is most commonly measured and where the most prominent neighborhood size effects were seen. An early analysis of mean amplitude (mean) and adaptive mean (ADmean) from Cz to Pz within the 250-400ms time frame across all subjects showed a small to moderate effect of neighborhood size, where large neighborhood words elicited more negative N400 amplitudes than small neighborhood words [mean: $t(20)=2.09, p=.17, d=.17$; ADmean: $t(20)=2.09, p=.08, d=.29$]. This effect was driven by Cz and Pz, where Cz showed a significant mean amplitude effect and a moderate adaptive mean effect [mean: $t(20)=2.09, p=.03, d=.26$; ADmean: $t(20)=2.09, p=.10, d=.26$], while Pz showed a significant adaptive mean effect [ADmean: $t(20)=2.09, p=.02, d=.40$].

A 2x2 ANOVA was run between condition (speed vs. accuracy) and neighborhood size (large vs. small) such that moderate interaction effects averaged across Cz to Pz were seen between condition types. Larger differences in mean amplitude were seen between accuracy and speed for large neighborhood words than for small [mean: $F(1,20)=1.10, p=.31, eta^2=.06$]. Larger differences in adaptive mean between accuracy and speed were also seen for large neighborhood words than for small [ADmean: $F(1, 20)=1.56, p=.23, eta^2=.08$]. When looking at Cz, no interactions were seen with mean amplitude, but moderate interactions were seen with adaptive mean values, such that larger differences in adaptive mean values were seen between speed and accuracy for large neighborhood words than for small [mean: $F(1,20)=0.31, p=.59, eta^2=.02$; ADmean: $F(1, 20)=1.94, p=.18, eta^2=.09$]. When looking at Pz, no interactions were seen with mean amplitude, but a small to moderate interaction was seen with adaptive mean, such that again larger differences were seen between speed and accuracy for large neighborhood words, while no differences were seen between accuracy and speed for small neighborhood

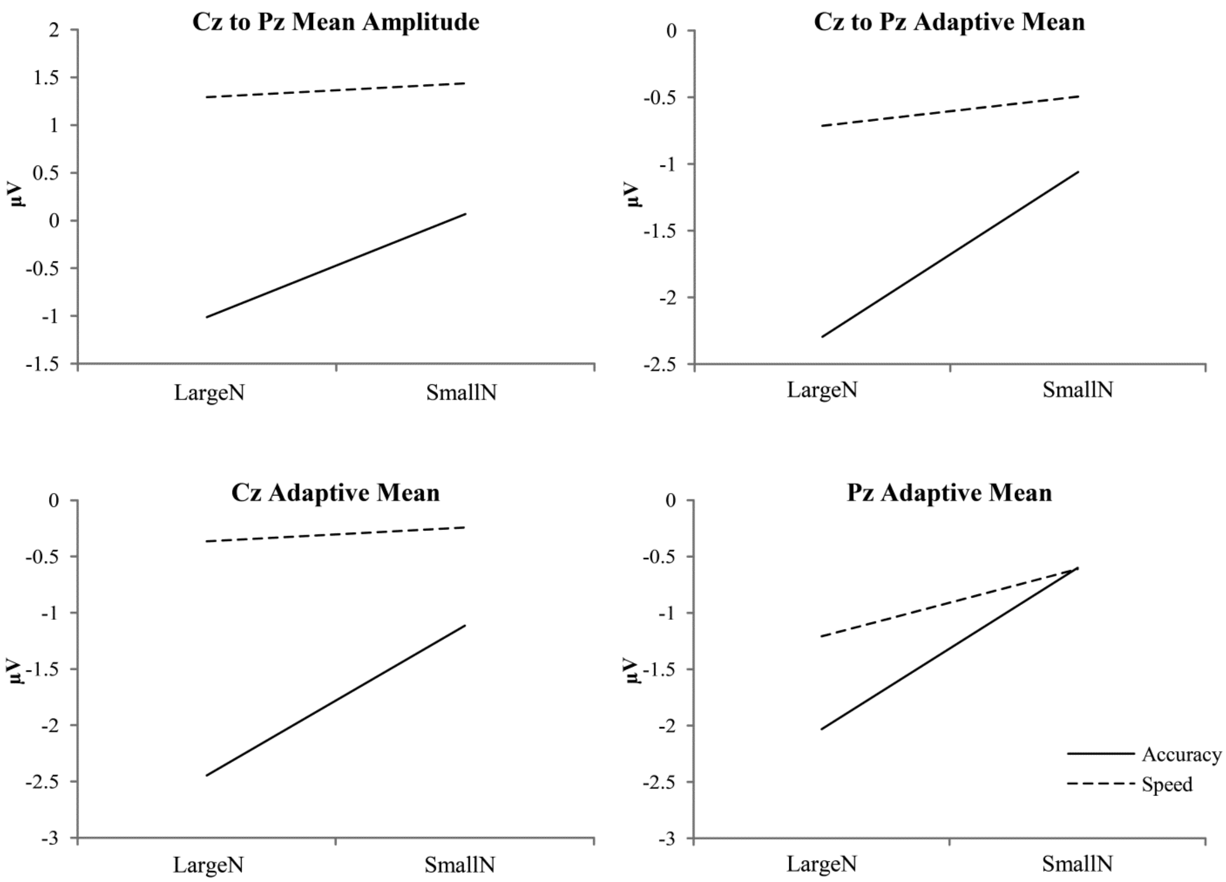


**Figure 3.** Interactions between task presentation and neighborhood size for Cz and Pz
This figure plots the interaction effects at Cz and Pz of the mean amplitude and adaptive mean values between task condition (accuracy vs. speed) and neighborhood size (largeN vs. smallN). Across Cz to Pz and for both Cz and Pz individually, moderate interactions were seen between these two variable types, such that larger differences in mean amplitude and adaptive mean values between accuracy and speed were seen for large neighborhood words than for small neighborhood words.

words [ADmean: *F(1, 20)=.98, p=.34,* $eta^2$*=.05*]. Mean amplitude and adaptive mean interactions across Cz to Pz and adaptive mean interactions for Cz and Pz individually are shown in Figure 3.

Within the accuracy condition, small to moderate effects of neighborhood size were seen averaged across Cz to Pz, such that large neighborhood words had more negative N400 waveforms than small neighborhood words [mean: *t(10)=2.23, p=.18, d=.29*; ADmean: *t(10)=2.23, p=.12, d=.43*]. For Cz, medium to large effects were seen, where large neighborhoods words had more negative amplitudes than small [mean: *t(10)=2.23, p=.13, d=.34*; ADmean: *t(10)=2.23, p=.10, d=.42*]. For Pz, moderate to large effects were also seen, such that again large neighborhood words had more negative N400 amplitudes than small neighborhood words [mean: *t(10)=2.23, p=.14, d=.29*; ADmean: *t(10)=2.23, p=.08, d=.50*].

Within the speed condition, a small effect of neighborhood size was seen with adaptive mean values from Cz to Pz, such that large neighborhood words had more negative N400 amplitudes than small neighborhood words [ADmean: *t(9)=2.26, p=.46, d=.10*]. For Pz, small effects with mean amplitude in the same direction were seen, where large neighborhood words had more negative N400 mean amplitudes than small [mean: *t(9)=2.26, p=.13, d=.19*]. For Cz, small to moderate effects with adaptive mean values were seen, such that again large neighborhood words had more negative adaptive mean values than small neighborhood words [ADmean: *t(9)=2.26, p=.14, d=.25*].

*Source Estimation Data*

Source estimation was performed on the ERP data in order to localize the source of N400 activity, shown in Figure 4. Activity from the 250-400ms time frame was predominantly localized in the left temporal lobe. Qualitative differences were seen between large and small neighborhood words. In both the accuracy and speed conditions, activation for small neighborhood words was localized posterior and superior in the temporal lobe. Some activation of the orbitofrontal cortex was also seen for small neighborhood words, particularly in the accuracy condition. In contrast, activation for large neighborhood words was localized anterior in the temporal lobe, along with comparatively less activation in the posterior temporal lobe. In the speed condition, activation for large neighborhood words was more widespread, showing activation across more voxels in the majority of the temporal lobe. The largest differences in intensity between large and small neighborhood words were in the anterior temporal lobe, reflecting the larger activation in that area for large neighborhood words (data not shown).

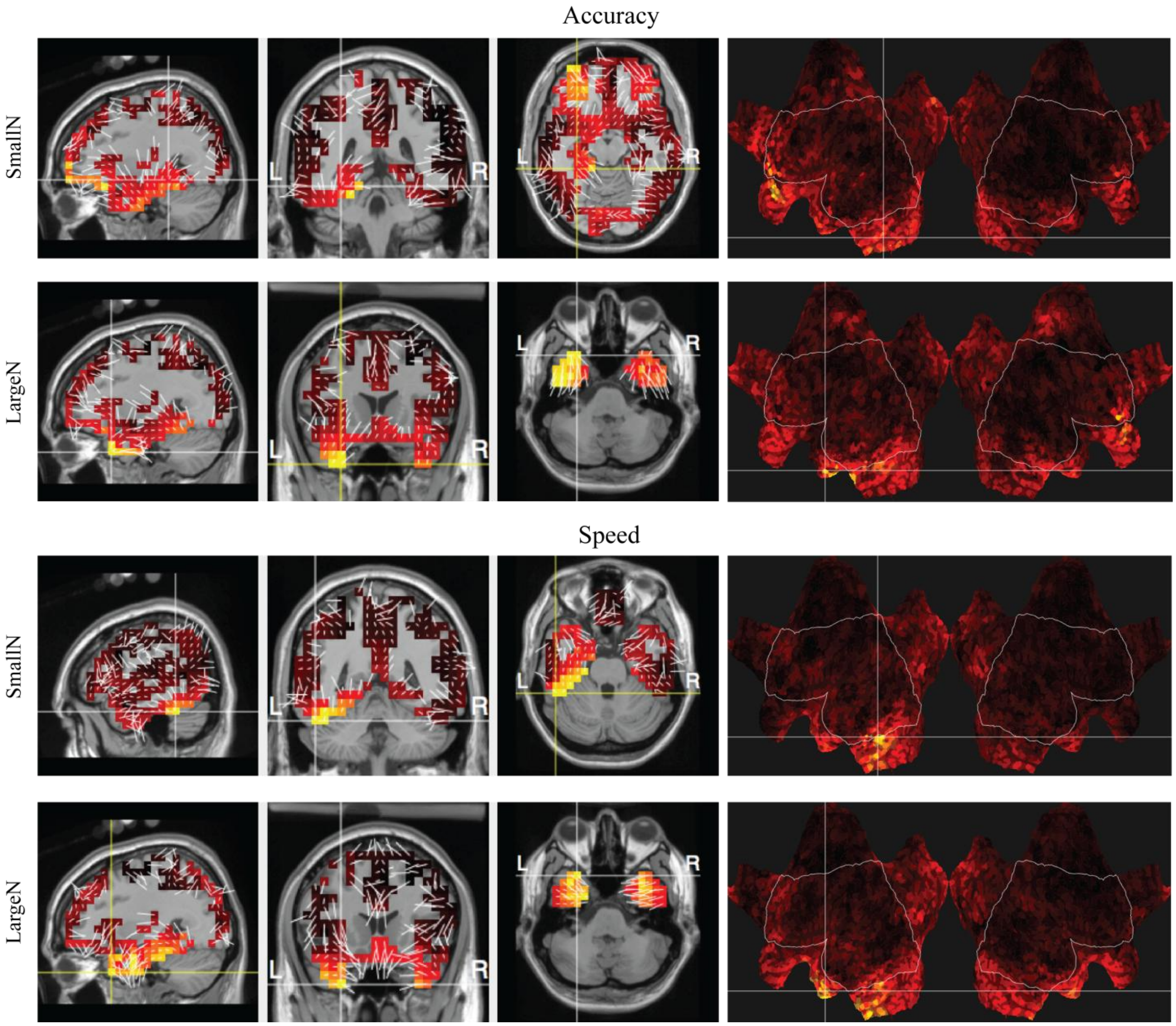


**Figure 4.** Source estimation of the N400 waveform by condition
This figure shows the source estimation results for each condition at 350ms after stimulus onset. This time was chosen because it coincides with the N400 peak and was most representative of the data. Sagittal, coronal, and axial slices are shown, along with a flat map representation of the brain. The voxel with the highest intensity is marked in each image. In both the accuracy and speed conditions, activation for large neighborhood words was localized more anterior, while activation for small neighborhood words was localized more posterior. In the speed condition, activation was spread across more voxels for large neighborhood words than for small neighborhood words. The largest differences in intensity between large and small neighborhood words were seen in the anterior temporal lobe (data not shown).

## Discussion

This study investigated the effects of task presentation and neighborhood size on visual word recognition using ERP measures of brain activity. The purpose of this study was to test the predictions of the Multiple Read-Out Model, which posits two distinct cognitive mechanisms during the processing of words in a lexical decision task, and to attempt to measure the neurological counterparts of these two mechanisms. One mechanism is a slow, lexical access mechanism, where the lexical representation of a word is accessed directly at a fixed time duration. This mechanism is elicited by emphasizing accuracy to subjects. The other is a fast-guess global activation mechanism, where characteristics of the target word, such as neighborhood size, are used to make speeded decisions. This mechanism is elicited when speed is emphasized to subjects. Following from these mechanisms, the MROM predicts a lack of a neighborhood size effect when accuracy is emphasized, while it predicts a larger neighborhood size effect when speed is emphasized. These modulations of the neighborhood size effect were predicted in this experiment to be reflected in behavioral and ERP measures.

### *Behavioral Findings*

Significant differences in reaction times and proportion errors were seen between the speed and accuracy conditions. As expected, subjects in the speed condition responded significantly faster and had significantly more errors than subjects in the accuracy condition (Figure 1). However, in contrast with previous studies (Andrews, 1992; Sears et al., 1995; Forster and Shen, 1996), no reaction time or proportion error effects of neighborhood size were seen in this data. The lack of any neighborhood size effect is not completely unfounded, as previous studies involving neighborhood size have shown a variety of results, including that of null effects of neighborhood size in lexical decision tasks (Andrews, 1992). Further, this study tightly controlled for variables such as the presence of a high frequency neighbor, which many previous studies have not consistently held constant (Grainger et al., 1989). The lack of control over certain variables in previous studies may be responsible for the stronger effects of neighborhood size that have been reported.

That being said, the lack of a neighborhood size effect eliminates the possibility of any interaction between neighborhood size and task condition as predicted by the MROM. Thus the more facilitatory effect of neighborhood size for the speed condition as compared to the accuracy condition seen by Grainger and Jacobs (1996) and De Moor et al. (2005) could not be replicated in this study. This raises the question of whether the ERP effects discussed in this thesis are in fact reflective of the MROM, or if they have departed from the MROM entirely. Indeed, to date the MROM has only been tested in French, Dutch, and German (Grainger and Jacobs, 1996; De Moor et al., 2005; Braun et al., 2006); thus no English data exists to support the MROM. There then exists the possibility that the MROM is not replicable in English. However, no current theories exist regarding language-specific neighborhood size effects, so it is extremely unlikely that the MROM applies to French, Dutch, and German, but not to English. This thesis will therefore assume that the effects discussed in the MROM are still at play in the data discussed here, but that these effects were too subtle to be significant within the behavioral data and small sample sizes of this experiment.

*ERP Findings*

Although no effects of neighborhood size were seen in the behavioral data, the ERP data showed several effects of neighborhood size. A moderate effect of neighborhood size across all subjects was seen along the midline, such that large neighborhood words produced greater negativity from 250-400 ms than small neighborhood words. This result was in line with previous findings, in which greater N400 negativites were found for words with large neighborhoods (Holcomb et al., 2002; Braun et al., 2006). Previous studies have found the N400 component is sensitive to the amount of semantic information from the target word itself (Brown and Hagoort, 1993; Holcomb et al., 1999). However, both these results and those from Holcomb et al. (2002) suggest that the N400 is sensitive to the semantic activation of neighboring words as well. Holcomb et al. (2002) argues that the greater negativity for large neighborhood words is precisely due to the increased semantic activation of neighboring words. The ERP results from this study are consistent with this semantic interpretation of the N400 waveform.

Several interaction effects between task condition and neighborhood size were found. The overall interaction effect, seen averaged across electrodes and within each Cz and Pz, showed a larger difference in ERP amplitudes between the accuracy and speed task conditions for large neighborhood words than for small neighborhood words. This suggests that the effect of task condition is perhaps most prominent when comparing large neighborhood words across condition. This is in line with the predictions of the MROM, which posits that global activation of neighboring words is the key difference between stressing accuracy and speed to subjects. Whereas small neighborhood words cannot have a large difference in global neighbor activation across task condition, since they do not have very many neighboring words to begin with, large neighborhood words have a greater potential for variability in global activation. The interactions between task condition and neighborhood size point towards global activation playing a key role in the difference between the cognitive processes elicited by emphasizing accuracy vs. speed to subjects.

Within each task condition, varying effects of neighborhood size were seen on ERP amplitude. Namely, the greater N400 negativity seen for large neighborhood words, as compared to small neighborhood words, was more pronounced in the accuracy condition than in the speed condition. In other words, there was a greater difference between large and small neighborhood words in the accuracy condition than in the speed condition. These findings are contrary to the prediction that there would be a greater neighborhood size effect of ERP amplitude in the speed condition. This prediction was based on the cognitive mechanisms described in the MROM, in which large neighborhood words have more global activation when speed is emphasized to subjects, as compared either to small neighborhood words in the speed condition or to any of the words in the accuracy condition. However, this prediction was not supported by the results of this experiment.

This deviation from the prediction can be understood by taking a closer look at some of the predictions and results of the MROM. Neighborhood size and global semantic activation have been shown in several cases to affect ERP amplitude (Holcomb et al., 2002; Braun et al., 2006; Vergara-Martinez and Swaab, 2012), so it is unlikely that the MROM's predictions based on global activation are completely off-base. However, global activation of neighbors may play a larger role when accuracy is emphasized in lexical decision than the MROM suggests. A number of previous studies have found inhibitory effects of neighborhood size, meaning that words with larger neighborhoods elicited longer reaction times than words with smaller neighborhoods (Johnson and Pugh, 1994; Andrews, 1992). These results have been argued to be indicative of the competitive effects of neighbor activation on lexical access, such that neighboring words act as competitors during lexical access of a target word, making access slower and more difficult. Several behavioral tests of the MROM have found this same pattern when accuracy was emphasized, where large neighborhood words elicited longer reaction times than small neighborhood words (Grainger and Jacobs, 1996; De Moor et al., 2005). In these cases, neighboring words were also theorized to act as competitors of lexical access. In order for this to be true, the neighboring words must be activated, just as they are in the speed condition. However, subjects have much more time in the accuracy condition, on the order of ~200ms in this experiment, to reach their decision. Thus, because the task is not speeded, neighboring words can become more fully activated in the accuracy condition, rather than being only partially activated as in the speed condition, which leads an increase in overall semantic activation. This increase in the semantic activation of neighboring words, while potentially competing with lexical access, would also result in a more negative-going N400 waveform and a larger difference in N400 amplitude between small and large neighborhood words. Although the results of this experiment appear at first glance to be in opposition to the predictions of the MROM, upon deeper examination, they may in fact still be consistent with the findings of the MROM.

The ERPs between the accuracy and speed conditions had qualitatively different shapes. The speed grand average ERPs were much tighter and reflective of ERP shapes previously seen in lexical decision (Holcomb et al., 2002; Braun et al., 2006). On the other hand, the accuracy grand average ERPs were more variable and did not follow the tight shape previously seen. This is likely a result of the variable response times in the accuracy condition. In the accuracy condition, subjects were told to respond as accurately as possible, even if this caused them to respond much slower than they would otherwise. The non-speeded nature of the task resulted in more variable response times between subjects; some were able to respond quickly while maintaining accuracy, but others responded much slower. This fluctuation in reaction time, and by extension decision time, resulted in more variability in ERP timing, and thus the ERPs were not as tightly matched as in the speed condition.

Another difference found between ERPs for accuracy and speed was the presence of a late positive waveform. A late positivity peaking around 500ms (P3) was seen in the speed condition but not in the accuracy condition. This is also likely due to the nature of the task. Similar late positivities are often associated with speeded responses, as was the case in the speed condition (Polich and Kok, 1995). However, this late positive waveform is often lacking in non-speeded tasks or tasks not requiring a response. Holcomb et al. (2002) found a similar lack of late positivity when they had subjects perform a semantic categorization task, requiring no response, as compared to a lexical decision task. Thus, the lack of a late positivity in the accuracy condition is likely due to the non-speeded nature of the task.

*Source Estimation Findings*

The source estimation data, although exploratory and thus not warranting strong conclusions, showed an effect of neighborhood size and, to an extent, task presentation on the localization of brain activity during lexical decision. During the 250-400ms time frame, activation was seen predominantly in the left temporal lobe, which is consistent with the source of the N400 waveform (Van Petten and Luka, 2006). This confirms that the ERP effects seen in this time frame were indeed related to the N400. A comparison of large vs. small neighborhood words showed qualitative differences in source localization within the temporal lobe between the two conditions. Activation for small neighborhood words was localized in the superior posterior temporal lobe. This area coincides with the left ventral occipitotemporal cortex, dubbed the visual word form area (VWFA), which has been implicated in visual word recognition (Ludersdorfer et al., 2013; Kronbichler et al., 2009). Similar to results from this study, the VWFA has been shown to have higher activation for unfamiliar orthographic forms (Kronbichler et al., 2009) and for small neighborhood words when accuracy was emphasized (Binder et al., 2003). On the other hand, activation for large neighborhood words was localized in the anterior temporal lobe, with comparatively less activation in the superior posterior temporal lobe. This differential localization of peak activation due to neighborhood size has not been previously characterized. Studies using fMRI have failed to find greater activation in a specific area of the brain for words with large neighborhoods than with small (Binder et al., 2003; Fiebach et al., 2007). Fiebach et al. (2007) argues that although their results are a null effect and thus do not warrant strong conclusions, they may in fact suggest a null effect of neighborhood size on the localization of activation due to their replication across two studies. However, the results of the present experiment suggest otherwise.

The fact that previous studies have not seen an effect of neighborhood size on localization of brain activity may be a result of the poor temporal resolution of fMRI, making it difficult to measure the differences in activation during the rapid time course of lexical decision. Comparatively, EEG-based source localization, despite have lower spatial resolution, is much more sensitive at the time scale of lexical decision. EEG-based source localization may therefore be a more appropriate measure of brain activation when studying lexical access. In light of these limitations of previous studies, the results from this experiment suggest that there may indeed be a difference in the localization of peak activation between large and small neighborhood words, where small neighborhood word activation is localized in the superior posterior temporal lobe (VWFA), while large neighborhood word activation is localized in the anterior temporal lobe.

In addition to differences in the location of peak activation, large neighborhood words had a higher intensity of activation in the anterior temporal lobe than small neighborhood words. Further, activation for large neighborhood words was more widespread, showing activation across more voxels in the speed condition. These results are consistent with the predictions of the

MROM, which suggest that lexical access of large neighborhood words involves more global semantic activation of neighbors. This global activation is reflected in the increased intensity for large neighborhood words in the accuracy and speed conditions. The fact that more widespread activation for large neighborhood words was seen in the speed condition is also consistent with the predictions of the MROM, in which widespread global activation is used as the primary decision mechanism when speed is emphasized to subjects as opposed to accuracy.

While the source estimation results of this study support the predictions of the MROM, this is in contrast to the ERP results, which seemed to oppose the predictions of the MROM. These results may be conflicting because ERPs and source estimation may be measuring different aspects of lexical access. Perhaps source estimation is more sensitive to the partial global activation of neighbors, as is predicted to occur in the speed condition, while ERPs are more sensitive to the full lexical access of neighbors, as was suggested earlier to occur in the accuracy condition. However, this was only an exploratory study that should serve as a jumping-off point for further research. There seems to be a measurable difference in brain activation modulated by neighborhood size and task presentation, but further research is necessary to fully characterize these differences and their effects on lexical decision.

*Conclusions and Future Directions*

Overall, this was a small, exploratory study that is inherently limited by its scope and sample size. The overall effect of neighborhood size was small, with only a few of the comparisons reaching significance, and effects were only analyzed along the midline. However, these results still point towards the role of neighborhood size and the global activation of neighbors in the processing of lexical items. Consistent with previous findings (Holcomb et al., 2002; Braun et al., 2006), large neighborhood words elicited more negative N400 amplitudes, which is arguably due to increased semantic activation of neighboring words. Greater differences between speed and accuracy were seen for large neighborhood words as compared to small, suggesting that neighborhood size and global activation are indeed playing a role in the different cognitive processes between the speed and accuracy conditions. Further, a larger effect of neighborhood size was seen in the accuracy condition than in the speed condition, contradictory to the predictions of this study. This may be understood as a result of the non-speeded nature of the accuracy condition, allowing neighboring words to become more fully activated and resulting in more negative N400 amplitudes for words with large neighborhoods. Finally, neighborhood size was qualitatively seen to affect the localization of peak brain activity, with large neighborhood words eliciting activation more anterior in the temporal lobe than small neighborhood words. Large neighborhood words were also seen to have greater and more widespread activation than small neighborhood words, in line with the predictions of the MROM. These results seem to be in opposition to the ERP results of this study, and this inconsistency may indicate that ERPs and source estimation are measuring different aspects of lexical access.

Generally, these data confirm the presence of two different decision mechanisms in lexical decision. Usually subjects are instructed to respond both as rapidly and as accurately as possible in lexical decision tasks. However, this experiment follows in the footsteps of previous studies in highlighting how emphasizing both speed and accuracy to subjects can lead to variable or non-controlled results. This phenomenon warrants further research in order to fully understand how task presentation can affect behavioral and neurological responses. The results of this study point towards a true neurological difference between the lexical access and global activation mechanisms put forth in the MROM. Future studies should expand the scope of this experiment by including more subjects, manipulating the pseudoword environment (also theorized to induce the use of one decision mechanism over another), and further exploring the localization of brain activity due to neighborhood size and task presentation. These manipulations will further explore and flesh out the effects predicted by the MROM, and their results would have the potential to affect how lexical decision tasks are designed and administered in future studies.

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