November 2014

Examining the Tools Used to Infer Models of Lexical Activation: Eye-tracking, Mouse-tracking, and Reaction Time

Joshua Levy
University of Massachusetts Amherst

Examining the tools used to infer models of lexical activation:
Eye-tracking, mouse-tracking, and reaction time

A Thesis Presented

By

JOSHUA W. LEVY

Submitted to the Graduate School of the
University of Massachusetts Amherst in partial fulfillment
of the requirements for the degree of

MASTER OF SCIENCE

September 2014

Cognitive Psychology

Examining the tools used to infer models of lexical activation:
Eye-tracking, mouse-tracking, and reaction time

A Thesis Presented

By

JOSHUA W. LEVY

Approved as to style and content by:

Adrian Staub, Chair

Charles Clifton, Member

John Kingston, Member

Melinda A. Novak, Department Head
Department of Psychological and Brain Sciences

ABSTRACT

EXAMINING THE TOOLS USED TO INFER MODELS OF LEXICAL ACTIVATION: EYE-TRACKING, MOUSE-TRACKING, AND REACTION TIME

SEPTEMBER 2014

JOSHUA LEVY, B.Mus., McGILL UNIVERSITY

B.A., McGILL UNIVERSITY

M.S., UNIVERSITY OF MASSACHUSETTS AMHERST

Directed by: Professor Adrian Staub

Most models of auditory word recognition describe the activation of lexical items in a continuous and graded manner. Much evidence in favor of these models comes from the visual-world paradigm, using either eye fixations or computer cursor trajectories as dependent measures. In particular, Spivey, Grosjean and Knoblich (2005) relied on their observation of unimodality in the distribution of cursor trajectories to argue in favor of a single cognitive process consistent with a continuous model of lexical activation. The present study addresses two questions: (1) whether the logic of inferring the number of cognitive processes from distributional analyses can be extended to a different dependent variable – reaction times, and (2) how robust the distribution of cursor trajectories is to changes in cursor speed (mouse gain). In Experiment 1, eye movements and reaction times were recorded in a visual-world paradigm and reaction times were modeled using ex-Gaussian curve-fitting. Participants responded slower to trials with a phonological competitor presented alongside the target than to trials with a control image presented alongside the target. Crucially, this difference was manifested as a shifting of the distribution rather than as a skewing of the distribution and lends additional support for a continuous model of lexical activation. Experiment 2 measured eye and mouse movements concurrently in a similar visual-world task to investigate the relationship between these two dependent measures at the level of the individual trial. In addition, Experiment 2 manipulated the speed of the cursor (mouse gain) between subjects. The low mouse gain served to reduce the effect of phonological competition. Moreover, the shape of the distribution of cursor trajectories across phonological competitor and control conditions was indistinct with low mouse gain, while the shape of the distributions across the two conditions differed with high mouse gain. This effect of mouse gain shows that the distribution of cursor trajectories is not robust to changes in mouse gain. Moreover, it raises questions about the strength of the linking hypothesis necessary to interpret the distribution of cursor trajectories.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

Most models of auditory word recognition describe the activation of lexical items in a continuous and graded manner. Examples of such models include TRACE (McClelland & Elman, 1986) and the Cohort model (Marslen-Wilson, 1987) wherein multiple lexical entries that are phonologically similar to the auditory stimulus are initially activated. Over time as the auditory stimulus unfolds, a single lexical entry becomes activated more than all other lexical candidates, thereby disambiguating the auditory stimulus.

One important line of research supporting such models comes from the visual-world paradigm. In this paradigm, an auditory stimulus is presented concurrently with an array of images consisting of a target image depicting the auditory stimulus and one or more foil images. Eye fixations tend to be divided between the target and foil images prior to disambiguation of the auditory stimulus and converge on the target over time. Critically, convergence of eye fixations on the target image is delayed when one or more foil images depict lexical entries that are phonologically similar to the auditory stimulus. For example, convergence of eye fixations on a target image depicting the auditory stimulus *candy* is delayed when a foil image depicting the phonologically similar *candle* is also in the array; this is compared to instances where the foil image depicts a lexical entry that is not phonologically similar to the auditory stimulus, such as *seahorse*. This effect has been observed in several studies (e.g. Eberhard, Spivey-Knowlton, Sedivy, & Tanenhaus, 1995; Allopenna, Magnuson, & Tanenhaus, 1998; Magnuson, Dixon, Tanenhaus, & Aslin, 2007) and is known as phonological competition because phonologically similar lexical entries appear to compete for activation.

However, it is possible that eye fixations in the visual-world paradigm have been misinterpreted. The appearance of a delayed convergence of fixations on the target image during trials with a phonological competitor may instead be an average of two distinct subsets of trials: one where participants' fixations converge on the target image early during the trial, and a second where participants' fixations converge on the target image later during the trial. Where the first subset of trials may reflect correct initial identification of the auditory stimulus, the second subset of trials may reflect an initial misidentification of the auditory stimulus such that participants initially map the auditory stimulus to the lexical entry depicted by the phonological competitor. Such instances of initial misidentification would require additional time to overcome. This description is reminiscent of a class of models applied to syntactic parsing where only a single syntactic representation is considered at any one time (e.g., Frazier & Clifton, 1996; van Gompel, Pickering, & Traxler, 2000). According to such models, a listener considers only a single representation at a time and only abandons that representation if new evidence inconsistent with that representation is encountered. Such models as applied to lexical activation have not been favored, nor is there any evidence supporting such a hypothetical model. Nevertheless, considering such a hypothetical model is useful. If the interpretation of a particular measure is ever consistent with such a hypothetical and unsupported model, researchers find themselves in a position of having either to argue in favor of such a hypothetical model or to doubt the evidentiary reliability of that particular measure in being able to answer the question at hand.

Spivey, Grosjean, and Knoblich (2005; SGK) shared this concern that eye fixations are not a reliable source of evidence in favor of continuous models of lexical activation. Therefore, they used a similar visual-world paradigm as the eye-tracking studies described above, but rather than registering participants' discrete eye fixations, they recorded the continuous movements of a computer cursor manipulated by participants' movements of a computer mouse. Participants were presented with two images and were instructed to move the cursor from the start position to the image associated with their response and to click on this image. By measuring the curvature of the cursor towards the unselected alternative, SGK inferred the degree to which the unselected alternative was considered as a plausible response. The logic is that movement of the cursor along a near-linear path towards the target with little curvature towards the foil is symptomatic of little competition from the foil, while increased curvature of the mouse towards the foil is symptomatic of increased competition from the foil. SGK observed that there was more curvature towards the unselected alternative when it was a phonological competitor than when it was not, consistent with findings of phonological competition in the eye-tracking literature.

SGK extended their findings by briefly outlining a plausible instantiation of a discrete model of lexical activation and then comparing the predicted distribution of cursor trajectories under such a model against the empirical distribution of cursor trajectories. If lexical activation proceeds in a manner similar to what has been proposed for syntactic parsing, the prediction is that listeners would commit themselves to a single lexical representation and only abandon that representation in the presence of evidence inconsistent with that representation. In the context of SGK's phonological competition task, that would mean listeners initially commit themselves to either the target or foil representation. In the event that a listener initially commits herself to the target, she will never receive evidence inconsistent with the initial representation. However, in the event that a listener initially commits herself to the foil, she will be presented with evidence inconsistent with the initial representation at the point of lexical disambiguation and will be forced to consider an alternate representation, which will likely be restricted to the name of the single alternative image presented on the screen. Applied to cursor trajectories, this model would predict a bimodal distribution of cursor trajectories composed of one subset of trajectories that exhibit near-linear paths from the start position to the target (corresponding to an initial and unwavering commitment to the target) and a second subset of trajectories that exhibit an initial movement to the foil and a subsequent movement to the target (corresponding to an initial commitment to the foil followed by a revised interpretation in favor of the target). By contrast, a continuous model of lexical activation predicts that neither the target nor the foil is strongly activated initially, and that over time activation of the target increases while activation of the foil decreases (though not necessarily monotonically). Applied to cursor trajectories, a continuous competition model predicts a unimodal distribution of cursor trajectories where the cursor always takes a curved path towards the target, with increased curvature reflecting increased competition from the foil.

SGK observed greater curvature towards the foil image in the phonological competitor condition than in the control condition. However, there was no indication of bimodality of the distribution of cursor trajectories. Moreover, the distribution of cursor trajectories in both conditions displayed a slight deviation from normality in the direction of high kurtosis or “peakiness” and away from bimodality. SGK argued that since the trajectories appeared to be sampled from the same unimodal distribution, lexical activation is likely achieved via a single process wherein activation is graded and is distributed across several lexical candidates, consistent with continuous models of lexical activation and ruling out a discrete model of lexical activation.

SGK’s reliance on the distribution of cursor trajectories to arbitrate between a continuous model and a discrete model of lexical activation raises the question of whether the distribution of reaction times (RTs) could be relied on for the same purpose. According to SGK’s interpretation of mouse movements, trajectories with increasing curvature reflect either increased competition or initial misanalysis, either of which should also be reflected in RTs. Continuous models, such as TRACE, make a general prediction independent of the task that increased competition will result in an increased mean reaction time for correct responses (McClelland & Elman, 1986). Similarly, a discrete model in which there is occasional initial misanalysis should also predict an increase in mean reaction time for correct responses; crucially, however, this increase in mean reaction time should result from a mixture of both fast and slow responses.

A common approach in analyzing the distribution of reaction times is to use ex-Gaussian curve-fitting (Ratcliff, 1979; Brown & Heathcote, 2003; Balota and Yap, 2011), where the ex-Gaussian distribution is the convolution of a Gaussian and an exponential distribution. As a result, the ex-Gaussian distribution has three parameters: μ and σ defining the central tendency and dispersion of the Gaussian component, respectively, and τ defining the rate parameter of the exponential component. The resulting distribution therefore has a mean of $\mu + \tau$ and a variance of $\sigma^2 + \tau^2$ (Matzke & Wagenmakers, 2009).

When comparing the distributions of two experimental conditions, a difference in μ signifies a shift in the one of the distributions, relative to the other, and implies an effect observed across all trials. Commonly, a difference in μ is accompanied by a difference in σ as the two parameters are correlated (Schmiedek, Oberauer, Wilhelm, Süß, & Wittmann, 2007). In visual word recognition, such effects of shifting characterize semantic priming (Balota, Yap, Cortese, & Watson, 2008) and predictability (Staub, 2011). By contrast, a difference in τ signifies a change in skewness and implies a selective lengthening of RTs on only a subset of trials. To elucidate the interpretations implied by a difference in either μ or τ, imagine a distribution of RTs that have each been lengthened by a constant amount. Such consistent lengthening yields a distribution shifted rightward compared to the original distribution and results in a change of the μ parameter. By contrast, if only a subset of the slowest trials were lengthened, the resulting distribution would have a longer right tail compared to the original distribution, but the distribution as a whole would not be shifted rightward. This second manipulation results in a τ effect. Such selective τ effects characterize the transposed-letter neighborhood effect (Johnson, Staub, & Fleri, 2012) and individual differences in working memory and reasoning (Schmiedek et al., 2007). Some effects, such as the effect of lexical frequency (Andrews & Heathcote, 2001; Balota & Spieler, 1999; Plourde & Besner, 1997; Staub, White, Drieghe, Hollway, & Rayner, 2010; Yap & Balota, 2007), are characterized by both a shifting and a skewing of the distribution.

If lexical activation proceeds in a continuous manner, with ongoing competition between activated representations, trials in the phonological competitor condition should exhibit RTs that are consistently longer than trials in the phonological control condition.

This effect would manifest itself as a difference in μ across the two distributions of RT. On the other hand, if lexical activation proceeds in a discrete manner, only a subset of trials in the phonological competitor condition should exhibit RTs that are longer than trials in the phonological control condition – namely, the longer trials that presumably required a revision in interpretation. Such an effect would manifest itself as a difference in τ across the two distributions.

The only prior work examining the distribution of RTs in the context of lexical activation was conducted by Goh, Suárez, Yap, & Hui Tan (2009) using an auditory lexical decision task in which participants discriminated words from non-words. Stimuli comprised English words varying in phonological neighborhood density and in lexical frequency, as well as non-word fillers conforming to English phonotactics. The authors found that words with high neighborhood density (those with many valid words differing from the auditory stimulus by a single phoneme) took longer to identify as words than did words with low neighborhood density (those with few valid words differing from the auditory stimulus by a single phoneme). At both levels of neighborhood density, participants took longer to discriminate low-frequency words than high-frequency words. In the distribution of RTs, the neighborhood density effect manifested itself as a difference in μ and σ, but not in τ. This shifting as a function of neighborhood density was present in both low- and high-frequency words. This result implies that the lengthening of RTs in response to words with high neighborhood density is present on most, if not all trials, and does not target only a subset of trials. Therefore, the shifting of the RT distribution associated with the neighborhood density effect is supportive of continuous models of lexical activation.

At present, the literature supports continuous models of lexical activation. However, there still remain many questions pertaining to the mouse-tracking methodology, which has provided a persuasive source of evidence in adjudicating between the two classes of models. In particular, though SGK's explicit argument against a discrete model of lexical activation is sound, it relies on a crucial assumption of the mouse-tracking methodology that cursor trajectories reflect the continuous updating of a participant's commitment (tentative or otherwise) to two or more response alternatives throughout the trajectory. This assumption has since been stated formally by several authors (Spivey & Dale, 2006; Freeman, Dale, & Farmer, 2011) and is hereafter referred to as the "Hand-Mind Hypothesis". As Freeman et al. (2011) write,

> [M]anual action exposes the real-time unfolding of underlying cognitive processes. We describe how simple hand motions may be used to continuously index participants' tentative commitments to different choice alternatives during the evolution of a behavioral response. As such, hand-tracking can provide unusually high-fidelity, real-time motor traces of the mind (p. 1).

This is a compelling hypothesis and has served as the theoretical basis for mouse-tracking studies across a wide variety of other disciplines including semantic categorization (Dale, Kehoe, & Spivey, 2007), syntactic parsing (Farmer, Anderson, & Spivey, 2007), social cognition (Freeman & Ambady, 2009), and judgment and decision-making (Koop & Johnson, 2013). While these prior studies provide strong evidence that motions of the hand are influenced by cognitive processes, it remains unknown if the degree of this influence can be modulated according to either changes in the mouse-tracking paradigm or to various strategies employed by the participant. For instance, one possible modulation might be in the temporal alignment between cognitive process and the physical movement of the mouse. This alignment might reasonably vary as a function of task difficulty and might affect cursor trajectories. Another way of phrasing the question is to ask how strong a Hand-Mind Hypothesis is warranted. A strong Hand-Mind Hypothesis would be supported if movements of the cursor in a phonological competition task cannot be modulated by task demands or strategic effects, while a weak Hand-Mind Hypothesis would be supported if movements of the cursor in a phonological competition task are modulated by such effects.

This paper will present two experiments using a word-picture matching task similar to SKG. Experiment 1 will provide a bridge between SGK's and Goh et al.'s (2009) results by examining the distribution of RTs in a word-picture matching task, rather than a word/non-word judgment task. Responses will be indicated by button press. In addition, eye movements will be recorded during the experiment and will be used as a predictor of reaction times. Concurrent recording of eye movements will provide an opportunity to assess whether slow reaction times are associated on a trial-by-trial basis with direct inspection of the foil.

Experiment 2 is a methodological exploration by which the strength of the Hand-Mind Hypothesis will be addressed. Following up on the examination of the relationship between eye movements and RT in Experiment 1, Experiment 2 examines the relationship between eye movements and mouse movements through concurrent recording of both measures. Here, concurrent recording of eye movements will provide an opportunity to assess the extent to which particularly curved mouse trajectories are associated on a trial-by-trial basis with direct inspection of the foil. In addition, Experiment 2 examines task demands and strategic effects that might influence cursor trajectories. The task demand that is examined is the ratio between the distance moved by the cursor and by the mouse, known as mouse gain. With high mouse gain, a small movement of the mouse can induce a large movement of the cursor; with low mouse gain, the mouse must move a greater distance to cause the cursor to move a comparable distance. Any interaction between the mouse gain parameter and the phonological manipulation would argue in favor of the weak Hand-Mind Hypothesis.

We also ask, in Experiment 2, whether cursor trajectories are affected by the latency of participants' initial mouse movement. In a state of uncertainty, participants may choose to wait to move the mouse until more information has been accumulated. This strategy may be relied upon even more often with low mouse gain when movements of the mouse are particularly costly, as measured by the physical movements of the hand, which must traverse a greater distance, and by the time required to carry out such movements. Similarly, if movements of the cursor towards the foil are viewed as costly, this strategy could be relied upon with high mouse gain where early movements under conditions of high uncertainty risk moving the cursor closer to the foil than with low mouse gain. Such a strategy predicts that delaying the initial mouse movement – perhaps until after lexical disambiguation of the auditory stimulus – is associated with subsequent movements of the cursor that display less deviation towards the foil image. Evidence of such a strategy would present itself in the form of an inverse relationship between the curvature of cursor trajectories and the latency of initial mouse movements, as well as an interaction between latency of initial mouse movement and mouse gain. If participants are able to employ such a strategy to reduce these costs, it would serve as further evidence of a weak Hand-Mind Hypothesis.

Another factor that may influence performance in the current word-picture matching task is the degree of concordance within each word-picture pair. In a similar word-picture matching task, Bergelson and Dahan (2012) observed that the proportion of eye fixations on a foil image was greater when participants had previously assigned a name to the foil that served as a phonological competitor to the target (e.g. *pillar* when the target was *pillow*) than when participants had previously assigned a name to the same foil that did not serve as a phonological competitor to the target (e.g. *column* when the target was *pillow*). Therefore, the third question that is addressed by Experiments 1 and 2 is how the reliability of assigning a specific name to a particular image influences the dependent measures of both experiments. In contrast to Bergelson and Dahan (2012), who examined the proportion of eye fixations as a function of how each individual participant previously named an image, we instead norm the visual stimuli for relative nameability. This relative nameability is used to predict RT, mouse movements, and eye movements.

In sum, we present two experiments designed to further assess the evidence for continuous models of lexical activation through the analysis of three dependent measures: reaction times, eye fixations, and computer cursor trajectories. Furthermore, these experiments assess the extent to which cursor trajectories in a mouse-tracking task can be regarded as reliable indicators of cognitive processing.

CHAPTER II

EXPERIMENT 1

Methods

Participants

In exchange for course credit, 40 undergraduates from the University of Massachusetts Amherst participated. All were native speakers of English and naïve to the experimental hypotheses.

Materials

Visual stimuli were selected from Magnuson et al.'s (2007) database of 540 images, of which the Snodgrass and Vanderwort (1980) images are a subset. Eighty-six experimental items were constructed. In each item a target and a foil image were presented in one of two conditions: a phonological competitor condition in which the name of the foil image, as labeled in the Magnuson et al. (2007) database, overlapped in the initial 2-3 phonemes with the target (e.g. *pancakes/panda*), and a phonological control condition in which the name of the foil overlapped in none of the initial phonemes with the target (e.g. *pancakes/football*). To increase the number of trials in the phonological competitor condition that satisfied the above constraints, the 86 items include 23 additional images that do not appear in the Magnuson et al. database. The images corresponding to *angle*, *cave*, *chin, clog, cucumber, sickle, deck, dish, dove, eel, elevator, freight train, gum,* and *whisk* were targets, while *ark, braces, brick, chandelier, lamb, Maine, panda,* and *shell* were foils in the competitor condition. *Chive* was a foil in the control condition. These images were all freely available clip art.

To assess the degree to which each assigned name is associated with the corresponding image, nameability norms were gathered. Image nameability was assessed by presenting 43 participants who were not enrolled in either the current or the subsequent experiment with 258 images corresponding to the target and foil images used in the competitor and control conditions of the current experiment. Presentation order of the images was randomized. Participants were instructed to name the object that the image depicts.

Responses in the norming study were scored as correct if the response matched the assigned label. Otherwise, the response was scored as incorrect. The proportion of correct responses for each image was then calculated. The resulting mean proportions of correct responses for images in each condition did not differ: target images 0.82; phonological competitor foil images 0.80; and control condition foil images 0.81. Figure 1 shows a histogram of the difference in the proportions of target and foil nameability for the 85 critical items by condition. Both distributions have modal values of approximately zero, suggesting that the nameability of target and foil images are roughly equal on the majority of trials. The distribution of target nameability is left-skewed, as shown in Figure 2. The nameability of the target and of the foil were allowed to differ within trials.

Procedure

The experiment was presented using SR Research Experiment Builder software (SR Research, Toronto, Ontario, Canada) as a visual world task, in which participants were visually presented with target and foil pictures in the upper left and right corners of a 19-inch computer monitor. Participants were seated approximately 26 inches from the screen. Each picture's dimensions were 200 square pixels, subtending approximately 6.175° of visual angle. Eye movements were recorded using an SR Research EyeLink 1000 eyetracker with remote desktop camera at a sampling rate of 500 Hz and a spatial resolution of less than 0.1°. All auditory stimuli were digitally recorded by the same male speaker using Audacity software.

Following the presentation of five practice trials to acclimate participants to the task, participants were presented with 43 competitor trials, 43 control trials, and 86 filler trials. The filler items consisted of images distinct from those used in the critical items. As in the phonological control condition, none of the filler items contained foil images whose names overlapped with any of the initial phonemes of the target image. Forty-three trials per critical condition were included to allow for ex-Gaussian parameter fitting, satisfying Balota and Yap's (2011) recommendation that at least 40 observations be presented per condition.

The order of presentation of the 172 trials was randomized for each participant. Additionally, the position of the target and foil were balanced such that half of the critical and filler items depicted the target in the upper left corner and half depicted the target in the upper right corner. The items were divided into two lists to which subjects were arbitrarily assigned.

At the beginning of each trial, subjects were instructed to fixate on a circle in the center of the screen. The experimenter used this fixation for purposes of drift correction and advanced the trial by pressing a button on the experimenter's keyboard. Upon advancement, the fixation circle disappeared and the two images appeared on the screen without any accompanying auditory stimulus to allow participants to familiarize themselves with the two images. After 500 ms, the images remained on the screen and the word corresponding to the target picture was auditorily presented through headphones. Participants indicated which of the pictures on the screen (left or right) matched the auditory stimulus by pressing the corresponding left or right trigger on a hand-held video-game controller.

The names of the target and foil were balanced for lexical frequency as measured in the Subtlex corpus (Brysbaert & New, 2009) and reported by the English Lexicon Project (Balota, Yap, Cortese, Hutchison, Kessler, Loftis, Neely, Nelson, Simpson, & Treiman, 2007). For compound words whose frequencies are not included in Subtlex, frequencies were calculated by mulitplying the Subtlex frequency of the first morpheme in the compound by the ratio of the number of google.com search hits for that morpheme to the number of search hits for the entire compound. The resulting mean frequencies, per million words, in each condition are as follows: targets 22.5; competitor foils 25.7; control foils 30.4. Paired t-tests indicate that the differences in lexical frequency between the target and foil images were non-significant both within phonological competitor trials ($t(85) = 0.57$; $p > 0.1$) and within control trials ($t(85) = 1.36$; $p > 0.1$). Additionally, the lexical frequency of the foil images did not differ across lists ($t(85) = 0.30$; $p > 0.1$), nor across experimental conditions ($t(85) = 0.80$; $p > 0.1$). Finally, in order to control for prosodic and durational effects, the primary stress of the names of each pair of the target and foil images was an equal number of syllables from the left edge of the word. A list of stimuli is included in Appendix A.

Results

Due to a coding error in one item in the competitor condition, the auditory stimulus of the foil, rather than the target was presented. All results exclude this item in both the competitor and control condition. Accuracy on control trials and filler trials was above 98%, while accuracy on competitor trials was 91.9%. A logistic regression confirms that the difference in accuracy between the competitor and control trials is significant ($z = 7.85$; $p < 0.001$). In addition, the mean reaction time of trials on which subjects responded correctly was 898 ms on competitor trials and 849 ms on control trials. A linear mixed-effects model including random slopes and intercepts for subjects and items confirms that this difference in means is significant ($t = 4.43$; $p < 0.001$). (Further details on the methods of mixed-effects modeling will be explained below in subsection *Multiple Regression*.) The decreased accuracy and increased reaction time on competitor trials suggest that visual and auditory stimuli were successful in inducing the desired effect of phonological competition.

The eye-movement record corroborates the behavioral data. Each trial on which a subject responded correctly was segmented into 25 ms bins. Trials during which there were neither fixations on the target nor on the foil image after the onset of the auditory stimulus were excluded from analysis. Figure 3 plots the fixation proportions on the target and foil images in each time bin by condition. The proportions of fixation on the target and foil images diverge from one another earlier in the control condition (approximately 250-300 ms after word onset) than in the competitor condition (approximately 350-400 ms after word onset). These results are consistent with other visual-world studies (e.g. Allopenna et al., 1998) showing delayed divergence of fixation proportions on the target and foil images when the foil is a phonological competitor, providing further evidence that the manipulation was successful.

Ex-Gaussian Parameter Fitting

In order to determine whether the increased mean reaction times in the competitor condition are driven by an increased reaction time on all trials – consistent with a continuous model of lexical activation – or by an increase in reaction time on select trials – consistent with a discrete model of lexical activation – ex-Gaussian parameters were fit to each subject's reaction time distributions separately by condition using QMPE software (Brown & Heathcote, 2003; http://www.newcl.org/software/qmpe.htm). QMPE fits ex-Gaussian parameters to a vector of quantiles using maximum likelihood estimation. For all reported analyses, ex-Gaussian parameters were fit to the maximum number of calculable quantiles, corresponding to the number of trials to which a subject responded correctly, minus 1. Incorrect responses were excluded from analysis.

The means of the best-fitting ex-Gaussian parameters are presented in Table 1. They show no difference in the τ parameter across phonological competitor and control conditions via paired t-test by subjects ($t(39) = 0.47$; $p > 0.2$). Rather, the distribution of RTs differs across condition in the μ parameter ($t(39) = 3.27$; $p < 0.01$) and in the σ parameter ($t(39) = 3.60$; $p < 0.001$). However, it is conceivable that differences in the τ parameter were reduced by trials on which no fixation was made on the foil image after the onset of the auditory stimulus. Such occurrences represent trials during which participants were able to rule out the foil image as a possible referent of the auditory stimulus based upon information gathered during the 500 ms of preview, without necessitating a fixation after hearing the auditory stimulus. Such responses are particularly efficient, given the availability of visual preview in this paradigm, but are a minority of responses representing 16.7% of competitor trials and 19.6% of control trials. It is possible that these efficient responses may mask differences in τ driven by the slower responses in each condition. When these responses are excluded from the ex-Gaussian parameter fitting, the mean RT of the remaining trials is greater in both conditions, but there remains no difference in the τ parameter across the phonological competitor and control conditions ($t(39) = -0.25$; $p > 0.2$). Rather, the distribution of RTs differs across condition in the μ ($t(39) = 3.06$; $p < 0.01$) and σ ($t(39) = 2.35$; $p < 0.025$) parameters. These findings indicate that the distribution of RTs shifts rightward in the competitor condition, compared to the control condition, and support a continuous model of lexical activation.

Corresponding Vincentile plots of the difference in reaction times across conditions including all trials and including only trials with at least one foil fixation after onset of the auditory stimulus are presented in Figures 4 and 5, respectively. Vincentizing consists of rank ordering the reaction times by participant and condition. These ordered reaction times are then separated into ten equally-sized bins within which the reaction times are averaged. The ten resulting values are then averaged across participants and are known as Vincentiles. The differences between Vincentiles in the competitor and control conditions are then plotted. The relatively constant increase in slowing across the Vincentiles reflects a change in both the μ and σ parameters. Critically, there is no evidence of a τ effect, which would be reflected in increased slowing at higher Vincentiles (i.e., a steeper slope than at lower Vincentiles).

These results replicate Goh et al.'s (2009) finding that phonological competition affects the μ parameter of a RT distribution, but not the τ parameter. These results can be interpreted to mean that, overall, responses on phonological competitor trials tend to be slower than responses on control trials. This is in contrast to a difference in τ across conditions, which would be indicative of only a subset of responses on phonological competitor trials being slower than responses on control trials. The observed effect is consistent with continuous models of lexical activation, which predict the visual presence of a phonological competitor to slow responses reliably due to the phonological competitor's automatic activation and initial plausibility as a potential target.

Variance Sign Test

One final distributional analysis was conducted to compare the predictions of the continuous and discrete models of lexical activation. Since discrete models predict that the increased mean reaction times in the phonological competitor condition are driven by only a subset of responses, these models predict that the variance in reaction times should be greater in the competitor condition than in the control condition. The continuous models make no explicit prediction pertaining to the variance of the reaction time distributions and are compatible with equal variances across conditions. Though the ex-Gaussian parameter fits show that the σ parameter is greater in the competitor condition than in the control condition, the positive correlation between the σ and μ parameters warrants an independent test of variance. Therefore, a non-parametric test of the variances of the RT distributions across the phonological competitor and control conditions was conducted.

The variance of RTs was calculated separately for each subject and for each item in each condition. Then the variance in the control condition was subtracted from the variance in the competitor condition and subjected to a sign test. This procedure was conducted on both raw RTs, which are right-skewed, and log-transformed RTs, which are approximately normally-distributed (see Figure 6). The distributions of the difference in variance by both subject and items for raw RT are visualized in Figure 7. By subjects, the variance in the phonological competitor condition was not significantly greater than the variance in the control condition when considering either raw RTs ($s = 21$ [of 40]; $p > 0.1$) or log-transformed RTs ($s = 23$ [of 40]; $p > 0.1$). By items, the difference in variance across the two conditions was slight. The variance in the phonological competitor condition was marginally greater than the variance in the control condition when considering raw RTs ($s = 52$ [of 85]; $p = 0.05$) and was not significantly greater than the variance in the control condition when considering log-transformed RTs ($s = 49$ [of 85]; $p > 0.1$).

The overall lack of difference in variance across conditions argues against a discrete model of lexical activation. The following section will explore several of the factors that contributed to RT in this task.

Multiple Regression

The ex-Gaussian parameter fitting showed that trials in the phonological competitor condition are reliably slower than in the control condition. We now examine other factors that may contribute to differences in reaction time. A multiple regression analysis examined reaction time as a function of phonological condition, whether the foil was fixated at least once on a given trial, and the nameability of the target and foil images in the array.

The fixed effects structure of the model includes the following four predictors: condition (phonological competitor vs. control), foil fixation (the presence of at least one foil fixation after onset of the auditory stimulus vs. zero foil fixations after the onset of the auditory stimulus), the nameability of the target image, and the nameability of the foil image. Their two-, three-, and four-way interactions were also included. Each predictor was centered. Binary predictors were coded with difference contrasts. The mean of each continuous predictor – target and foil nameability – was subtracted from each observation of the respective predictor. These predictors were analyzed using mixed-effect models with the lme4 package for R (Bates, Maechler, & Bolker, 2011). Random subject and item intercepts were included. In addition, random slopes for the fixed effects of condition, foil fixation and foil nameability were included by both subjects and items. Random slopes for the fixed effects of target nameability were included by subjects. Attempts to include additional random interaction slopes did not converge. The summary of the fixed effects is presented in Table 2, with effects whose *t*-values are greater than 2 in bold.

The main effect of foil fixation indicates that reaction times increased when there was at least one fixation on the foil image after onset of the auditory stimulus. This effect may be due to a combination of two factors. First, trials during which there was as least one fixation on the foil image have, on average, more fixations than trials during which there were no fixations on the foil. Since it takes time to execute a fixation, trials with more fixations may take longer than trials with fewer fixations. Second, trials with no foil fixations after auditory onset may be faster than trials with at least one foil fixation after auditory onset because in the former set of trials participants may have been able to rule out the foil image as a possible referent to the auditory stimulus based upon information gathered during the 500 ms of preview and without necessitating a fixation after hearing the auditory stimulus. This increased efficiency in being able to gather information about the visual array before the auditory onset would allow participants to respond faster overall.

Even more interesting is the interaction between condition and foil fixation. Figure 8 shows that the effect of foil fixation is greater in the competitor condition than in the control condition. When participants fixate the foil image in the phonological competitor condition after the onset of the auditory stimulus, RT is longer than when participants fixate the foil image in the control condition after the onset of the auditory stimulus. This suggests that the foil image in the competitor condition is more attractive as a plausible response than the foil image in the control condition in that it delays the final button press. However, when participants do not fixate the foil after the onset of the auditory stimulus, there is no difference in reaction time. Thus, when participants are able to gather enough information about the visual array before the onset of the auditory stimulus such that no foil fixation is necessary after the onset of the auditory stimulus, there is no difference in reaction times across phonological condition. The phonological competition effect seems only to be present when participants fixate the foil after the onset of the auditory stimulus.

The main effect of nameability of the target image indicates that reaction times decrease as the target image becomes more nameable. This effect is shown in Figure 9.

For purposes of visualization, target nameability was divided into quintiles, separately by condition. Quintile 5 represents trials on which the target image was most nameable; quintile 1 represents trials on which the target image was least nameable. The mean nameability proportion in each quintile is as follows: Q1 = 0.37, Q2 = 0.79, Q3 = 0.93, Q4 = 0.98, Q5 = 1.00. The figure indicates that responses were slowest when the target was least nameable (quintile 1). RTs did not differ greatly between quintiles 2 through 5. There was no effect of foil nameability on RTs.

In sum, Experiment 1 used both parametric ex-Gaussian curve-fitting and a non-parametric test of variance in analyzing reaction times in a word-picture matching task. Reaction times were shown to be sensitive to the nameability of the target image. Moreover, the phonological similarity effect was present only on trials with at least one foil fixation after the onset of the auditory stimulus. Experiment 2 will examine how these and other methodological factors affect mouse movements as a dependent variable in a similar visual-world task.

CHAPTER III

EXPERIMENT 2

Introduction

Experiment 2 uses a variation in the task of Experiment 1: participants are presented with the same word-picture matching paradigm, but the method of response has been altered. Rather than simply pressing a button to indicate a response, participants are required to move a visual cursor controlled by a computer mouse and to click on the image depicting the auditory stimulus. While reaction times have been used successfully to model the time-course of the decision making process using the diffusion model (Ratcliff, 1979), the resulting drift rate parameter describing the rate of decision making is an aggregated measure over all trials. It has been argued that cursor trajectories can yield a trial-by-trial measure of the decision-making process by examining the curvature of cursor trajectories towards the foil image as the cursor moves from its starting position to its ultimate response (Koop & Johnson, 2013). The reliability of cursor trajectories as a trial-by-trial measure of the decision-making process would provide an advantage over the analysis of reaction times. Thus, where Experiment 1 examined RT as the dependent variable, Experiment 2 examines the curvature of cursor trajectories to assess the reliability of this measure as an index of the decision-making process.

In addition, eye movements were recorded concurrently with mouse movements to allow the relationship between eye and mouse movements to be explored. In the literature, mouse movements and eye movements have yielded convergent results when used as dependent measures of on-line processing and integration of visual and auditory stimuli. However, the extent to which eye movements and mouse movements relate to the same cognitive states is still unclear. For instance, eye movements have been shown to guide initial mouse movements, with one to two target fixations generally preceding a mouse movement towards the target (Kennedy & Baccino, 1995). However, beyond this initial guidance, eye and mouse movements are decoupled. Kennedy and Baccino (1995) showed that the path of the moving cursor is not tracked by the eyes. It is possible that the eyes continue to inspect the array while the mouse is in flight. However, it is unclear if these fixations alter the course of the moving cursor, or not. To examine this relationship between eye and mouse movements, trials will be subdivided into two groups according to whether or not at least one foil fixation was made after the onset of the auditory stimulus. As in the previous experiment, these two groups will be used as a predictor of the dependent variable.

Experiment 2 also assesses the strength of the Hand-Mind Hypothesis by examining three additional factors that may affect cursor trajectories and the distributions thereof: mouse gain, the latency to begin a mouse movement, and the angle of departure at the time of initial mouse movement. Mouse gain is a manipulated factor of the paradigm, while the latter two factors are at least partially under the control of participants and may be strategic in nature. The theoretical implications of the distribution of cursor trajectories and of these three factors are described below.

Distribution of cursor trajectories

SGK's reliance on the distribution of cursor trajectories to arbitrate between a continuous model and a discrete model of lexical activation is based on the claim that the number of cognitive processes involved in a particular task can be inferred either from the distribution of cursor trajectories (Freeman & Dale, 2013) or from the geometry of cursor trajectories associated with a particular task (Tomlinson et al., 2013). Common arguments are that a cognitive task relies upon either a single cognitive process, indicated by a unimodal distribution of trajectories, or two or more serial processes, such as an initial analysis followed by an optional reanalysis should the initial analysis prove incorrect. It is interesting to note that the majority of studies using mouse-tracking have observed a unimodal distribution of cursor trajectories (see Freeman et al., 2011; Freeman & Dale, 2013 for review) and have thus argued in favor of either a single cognitive process or contemporaneous cognitive processes that proceed in parallel. One clear exception is Song and Nakayama's (2008) study of visual search in which participants were presented with three shapes, two of one color and the third of a different color. Participants were tasked with selecting the shape that differed in color from the others. In this task, Song and Nakayama observed a bimodal distribution of cursor trajectories and argued that the two modes reflect serial processes of analysis and occasional reanalysis.

SKG predicted that serial processes involving initial lexical activation and subsequent reanalysis would be supported by evidence of bimodality in the distribution of response trajectories in the phonological competitor condition, or distributions that otherwise differed in shape across conditions (see also Freeman & Dale, 2013 for similar arguments). Instead, SGK observed a unimodal distribution of response trajectories that did not differ across conditions, which they interpreted as evidence of lexical activation characterized by dynamic competition between alternatives within a phonological cohort, as has been hypothesized by continuous mapping models such as TRACE (McClelland & Elman, 1986).

Though mouse-tracking evidence in support of serial cognitive processes has been hypothesized, the application of such a model to lexical activation has not been fully instantiated. In describing such a model, I will borrow van Gompel et al.'s (2000) nomenclature and refer to this alternate theory as an unrestricted race account of lexical activation. The race refers to an accumulation of evidence in favor of a single lexical analysis. This race is said to be "unrestricted" because in addition to linguistic factors that influence lexical activation, such as phonological neighborhood, many potential non-linguistic factors can also influence the initial lexical activation that subjects pursue. Such factors may include the image(s) on which the eyes are fixated at any given time and the ease with which each image can be named. Crucially, this model proposes that there is an initial commitment to only one lexical analysis. In the event that this initial commitment is later disconfirmed, the lexical analysis must be revised. Such a revision would weigh the evidence accumulated during the first analysis, along with the evidence that has since been presented, to arrive at a new analysis.

In the context of the visual-world paradigm, this race commences at the onset of the auditory stimulus and the competitors are the names of the two images in the array to which the auditory stimulus might refer. Conceptually, this race model is slightly different from a typical race model where the possible competitors constitute a set whose size is larger and typically unknown. With such a small number of given competitors, it is likely that the race may exhibit different dynamics than with a greater number of competitors that are not necessarily given in the visual array. For instance, with few competitors the race may begin earlier, or earlier evidence that is typically under-informative – such as the onset of the first syllable – may receive greater weight. In fact, where only two alternatives are presented, it is possible that a reanalysis could simply be achieved by process of elimination. In such a scenario, a participant may have fixated only the foil and not the target before it becomes clear that the referent of the auditory stimulus does not correspond to the foil image. At this point, the participant can be sure that the target image that had not yet been fixated is the correct response. It may be possible to arrive at this inference without lexical reanalysis. Therefore, this model of word recognition is not necessarily generalizable beyond the visual-world paradigm. However, it is important to keep in mind when examining methodologies associated with the visual-world paradigm.

If mouse movements are indicative of cognitive processes, this unrestricted race model would predict a bimodal distribution of cursor trajectories in the phonological competitor condition where one mode corresponds to trials on which the initial lexical analysis proves correct and no reanalysis is necessary. The second mode would correspond to trials on which initial lexical analysis proves incorrect and reanalysis is necessary. Trials during which reanalysis occurs are predicted to show initial movement to the foil image followed by a corrective movement to the target image.

Many tests of bimodality have been proposed (see Freeman & Dale, 2013). One simple method implemented by SGK is to compare the shapes of distributions across conditions. If they do not differ, it is unlikely that reanalysis was pursued to different degrees in the two conditions. If they do differ and the variance is greater in the condition where reanalysis is predicted to occur more often, it is supportive of a discrete model of lexical activation where reanalysis is pursued on some proportion of trials.

Mouse Gain

One factor that may influence cursor trajectories is the mouse gain (the ratio of the distance travelled by the physical mouse to the distance travelled by the virtual cursor). SGK chose to reduce the mouse gain in their experiment "to a pretty low level (not the lowest, but close)," which required subjects to move the mouse "about a foot on each trial" (Michael Spivey, personal communication, 18 May, 2012). This choice was made in an effort to exaggerate the curvature of the cursor trajectories. However, this choice may have undermined the methodological utility of the MT paradigm for four possible reasons: (1) such a reduced mouse gain is unergonomic in that it tends to increase response times and decrease response accuracy in motor control tasks (Sandfeld & Jensen, 2005); (2) such increased response times may allow for more time during which the competing lexical entry can be activated; (3) it may have caused participants to adopt strategies intended to compensate for the constraints of the low mouse gain, thus introducing geometric artifacts in the cursor trajectories; and (4) it is possible that a low mouse gain facilitates the superposition of independent motor responses, such that two independent and discrete movement plans temporally overlap, yielding a continuously curved cursor trajectory. Such a superposition would reduce, rather than exaggerate, the amount of curvature towards the phonological competitor (van der Wel et al., 2009). To address these possibilities, two mouse gains – one typical of human-computer interaction and one lower mouse gain akin to SGK's – were presented as a between-subjects manipulation.

Latency to move mouse

Related to (3) above, subjects may adopt compensatory task strategies to avoid moving the mouse a great distance. The first possible strategy is motoric. Subjects may avoid direct mouse movements to either response alternative in an effort to minimize the distance required to move the mouse in the event of a response revision. This strategy would manifest as an interaction between phonological condition and mouse gain, such that an intermediate amount of curvature is observed with low mouse gain regardless of phonological condition, while a greater effect of phonological condition is observed with high mouse gain.

A second strategy, which can be adopted in either level of mouse gain, is for participants to delay their initial mouse movement in an effort to disambiguate the auditory stimulus before movement. By delaying the initial mouse movement, more of the decision-making process occurs before participants even move the mouse, and less of the decision-making process is reflected in the cursor trajectories. Such a strategy would minimize the likelihood of an alteration in cursor trajectory and any associated costly mouse movements.

Angle of departure

Finally, a strong Hand-Mind Hypothesis states that “hand-tracking can provide unusually high-fidelity, real-time motor traces of the mind” (Freeman et al., 2011). If the angle of departure is a strong predictor of overall deviation towards the foil, this finding would undermine the claim that mouse-tracking indexes cognitive processes in “real-time,” in that the unfolding of cursor trajectories may disproportionately reflect earlier decisions, rather than contemporaneous decisions. It may be the case that mental processes are reflected only in the early portions of each cursor trajectory and that the remaining trajectory reflects mostly motoric responses.

Methods

Participants

In exchange for course credit, 80 undergraduates from the University of Massachusetts Amherst who had not been enrolled in Experiment 1 participated in Experiment 2. All were native speakers of English, experienced computer users, and naïve to the experimental hypotheses.

Materials

Visual stimuli were selected from Magnuson et al.'s (2007) database of 540 images, of which the Snodgrass and Vanderwort (1980) images are a subset. Forty experimental items were constructed in the same manner as in Experiment 1. To increase the number of phonological competitors that satisfied the above constraints, three additional items that do not appear in the Magnuson et al. database were also used. These items are *asterisk*, *hamster*, and *panda*. *Asterisk* and *hamster* are targets, while *panda* is a foil in the competitor condition. These images were all open-source clip art.

Image nameability was assessed by presenting 120 images corresponding to the target and foil images used in the competitor and control conditions of Experiment 2 in the same norming session and to the same 43 participants who completed the image nameability norms for images used in Experiment 1. Eighty of the 120 images were also used in Experiment 1, but were only presented once in the norming session. Presentation order of the images was randomized. Participants were instructed to name the object that the image depicts.

Responses were scored as correct if the response matched Magnuson et al.'s (2007) label. Otherwise, the response was scored as incorrect. The one exception was for the image labeled *mask*. All participants labeled this image *goggles*. Since responses for this image were unanimous and the image was used as a foil in a control trial, all responses of *goggles* were scored as correct. The proportion of correct responses for each image was then calculated. The mean proportion of correct responses for target images was 0.80; the mean proportion of correct responses for foil images in the phonological competitor condition was 0.78; and the mean proportion of correct responses for foil images in the control condition was 0.77. The difference in nameability across these three groups was non-significant ($F_{(2,117)} < 1$). Figure 10 shows a histogram of the difference in the proportions of target and foil nameability for the 40 items in each condition. The majority of trials have roughly equal proportions of target and foil nameability (difference of zero). The distribution of target nameability is left-skewed, as shown in Figure 11.

The trials were divided into two lists to which subjects were arbitrarily assigned. Half of the trials in each list were presented in the phonological competitor condition and half in the control condition. An additional 40 filler trials consisting of images distinct from those used in the experimental items were presented. As in the phonological control condition, none of the filler items contained foil images whose names overlapped with any of the initial phonemes of the target image.

As in Experiment 1, the names of the target and foil were balanced for lexical frequency as measured in the Subtlex corpus (Brysbaert & New, 2009) and reported by the English Lexicon Project (ELP) (Balota et al., 2007). The resulting mean frequencies in each condition are as follows: targets 16.1; competitor foils 15.2; control foils 21.1 All frequencies are per one million words. Paired t-tests indicate that the differences in lexical frequency of the target and foil images were non-significant both within the phonological competitor condition ($t(39) = 0.22$; $p > 0.1$) and within the control condition ($t(39) = 1.41$; $p > 0.1$). Additionally, the lexical frequency of the foil images did not differ across lists ($t(39) = 0.50$; $p > 0.1$), nor across experimental conditions ($t(39) = 1.40$; $p > 0.1$). In all cases, the names of the target and foil images were constrained so that the primary stress was placed the same number of syllables from the left edge of the word. A list of stimuli is included in Appendix B.

Procedure

The same word-picture matching paradigm was presented as in Experiment 1, except that the participants were instructed to indicate their response using an optical mouse by moving the cursor from the launch pad and clicking on the image corresponding to the auditorily presented word. After clicking on one of the two images, an 'x' appeared at the location of the launch pad. Clicking on the 'x' triggered the following trial.

Streaming x, y coordinates of the cursor were recorded using the Experiment Builder software at a sampling rate of 85 Hz. Subjects were randomly assigned to one of two conditions manipulating the level of mouse gain. The higher level of mouse gain was presented using the default mouse gain of the Windows XP operating system (hereafter referred to as 'high'). This corresponds to fundamental mouse-to-cursor ratio of approximately 1:5 (with greater ratios at increasing mouse speeds). The lower level of mouse gain was presented using the second-to-lowest mouse gain of the Windows XP operating system (hereafter referred to as 'low').

In analyzing cursor trajectories, the dependent measure was the maximum deviation (MD) of the cursor towards the foil image. This measure was derived from the raw mouse-tracking data through the use of the MouseTracker software package (Freeman & Ambady, 2010). MD is a measurement of distance and is defined as the maximum perpendicular deviation of the cursor's trajectory from an idealized linear trajectory. This idealized trajectory is the line segment connecting the cursor's start and end positions. Therefore, greater MDs indicate greater deviation of the cursor towards the foil picture. MouseTracker automatically performs space-rescaling of cursor trajectories to allow for comparison of data collected on monitors of varying dimensions. Therefore, the units of MD are relative to the standardized dimensions 2 x 1.5. To allow for comparison of trajectories across trials of varying duration, MouseTracker interpolates the x and y coordinates between raw samples and calculates the x and y coordinates at 101 evenly spaced time points across each trajectory. Accuracy and response reaction times were also recorded.

Results

Trials on which a subject responded incorrectly were excluded from analysis. Accuracy was above 98% in each condition of the experiment.

Validation of task

To verify that the phonological manipulation worked as intended, the proportions of eye fixations on both the target and foil were analyzed. Figure 12 shows the fixation proportions with high and low mouse gain. Previously, Allopenna et al. (1998) had found that subjects consider the phonological competitor as a more plausible distractor than the control foil image, reflected in increased proportions of eye fixations that persist past the onset of the word. Our results show the same pattern. Overall, the probability of fixating on the foil was greater in the competitor condition than in the control condition. Also, the proportion of target fixations deviates from the proportion of foil fixations later in the competitor condition than in the control condition. This suggests that the competitor foil is considered as a plausible response for a greater amount of time compared to the control foil. In the high mouse gain condition, the proportion of fixations on the target and foil in the competitor condition deviate about 100ms later compared to the corresponding deviation in fixation proportions in the control condition. The low mouse gain condition also shows that the proportion of fixations on the target and foil deviate later in the competitor condition than in the control condition; however, visual inspection of the fixation proportions suggests that there is a smaller difference in the time of deviation between the two conditions with low mouse gain.

Distributional Analyses

Before examining the mean maximum deviations in the phonological competitor and control conditions in detail, which confirm the expected phonological similarity effect – particularly with high mouse gain – we present distributional analyses of the maximum deviations in each condition for the purposes of assessing the variance of the distributions of cursor trajectories. Assessing the variance of the distributions of cursor trajectories tests a general version of the hypothesis that lexical activation is more variable in the competitor condition, a hypothesis that some prior studies have assessed by measuring the bimodality of the same distributions. This approach has the advantage of not needing to assume a specific parametric shape of the distributions in question. Differences in the location and shape of the distributions were assessed using a Kolmogorov-Smirnov (KS) test and variance was directly assessed using a variance sign test.

A Kolmogorov-Smirnov comparison, using *z*-scores of MD transformed separately for each participant in the phonological competitor and control conditions, assesses whether the distributions differ in shape across conditions when the means of the two distributions are equated. These distributions are shown in Figure 13. This test confirms that across phonological competitor and control trials with high mouse gain the distributions of MD are statistically distinguishable ($D = 0.1045$; $p < 0.001$). The distributions of MD across phonological competitor and control trials with low mouse gain are also statistically distinguishable ($D = 0.0708$; $p = 0.036$) but to a lesser extent.

The variances of the distributions of MD across phonological competitor and control conditions were also compared. The variance of MDs was calculated separately for each subject and each item in each condition. Then the variance in the control condition was subtracted from the variance in the competitor condition and subjected to a sign test. In the high mouse gain condition, the variance in the phonological competitor condition was significantly greater than in the control condition by both subjects ($s = 37$

[of 40]; $p < 0.001$; median diff = 0.147) and items ($s = 33$ [of 40]; $p < 0.001$; median diff = 0.118). In the low mouse gain condition, the variance in the competitor condition was not greater than in the control condition by subjects ($s = 21$ [of 40]; $p > 0.1$; median diff = 0.004) or by items ($s = 20$ [of 40]; $p > 0.1$; median diff = 0.012). When collapsing across experiments, the difference in variance remained significantly greater in the phonological competitor condition by both subjects ($s = 58$ [of 80]; $p < 0.001$; median diff = 0.097) and items ($s = 33$ [of 40]; $p < 0.001$; median diff = 0.076). Histograms of the differences in variance are shown in Figure 14.

Finally, we also directly tested the bimodality of each distribution using Hartigan's Dip Statistic (Hartigan & Hartigan, 1985; Maechler, 2012) and the bimodality coefficient (BC) (SAS Institute Inc, 1990; Pfister et al., 2013). Recent work suggests that these two tests should be used in tandem and that bimodality is most reliably inferred when results of the two tests converge (Farmer & Dale, 2013; Pfister et al., 2013). According to the BC, where a value greater than 0.555 indicates bimodality, the distribution in the phonological competitor condition with high mouse gain is bimodal (BC = 0.605) while the distribution in the control condition with high mouse gain (BC = 0.472) and the competitor and control conditions with low mouse gain (BC = 0.409 and BC = 0.469, respectively) are all unimodal. However, Hartigan's Dip does not identify the distribution of either condition with either level of mouse gain as bimodal (Ds < 0.01; ps > 0.2).

These distributional analyses suggest that the effect of the phonological manipulation, measured by the degree of movement towards either the target or foil, was more variable in the high mouse gain condition than in the low mouse gain condition.

With a low mouse gain, the variance of MDs does not differ across the competitor and control conditions; while the variance of MDs does differ across the competitor and control conditions with a high mouse gain. Thus, when the mouse gain is low, our results concur with SGK's finding that the distributions of cursor trajectories do not differ across condition. However, when the mouse gain is high, our results diverge from SGK's. This finding suggests that the different shapes of the distributions of cursor trajectories in the competitor and control condition may be an artifact of the mouse gain. The distinction between serial and parallel models of lexical activation – and perhaps the distinction between single and dual cognitive processes, more generally – is not as easily inferred from cursor trajectories as previously thought.

Angle of Departure

MD was also examined as a function of the angle at which the cursor leaves an approximately 20-pixel radius around the start position. This factor was not included in the regression model because of the necessary motoric dependence between early and later hand movements in the context mouse-tracking. Assuming an ultimately correct response with a smooth trajectory, an initial movement of the mouse in the direction of the foil image will entail an MD that is larger than if the initial mouse movement is in the direction of the target. No other predictor forms a motoric dependency with MD.

Many researchers tacitly assume that since the streaming coordinates produced by the movement of a mouse are continuous and the decision-making process unfolds over time before settling upon an ultimate response, the movements of a mouse are contemporaneous with the decision-making process(es) that they reflect. Recall the claim outlined in the introduction that “hand-tracking can provide unusually high-fidelity, real-time motor traces of the mind” (Freeman et al., 2011). It was hypothesized that a trajectory whose path initially leaves the radius in the direction of the foil should display a greater MD than a trajectory whose path initially leaves the radius in the direction of the target. Such a pattern would support an account where overall deviations towards the foil largely reflect motor and/or cognitive processes that occur at the time of initial mouse movement, rather than cognitive processes that unfold over the course of the entire trial.

The angle at which the cursor leaves the radius was calculated from the *x*- and *y*-coordinates of the cursor at the time that the cursor left the radius, after normalizing all trajectories to reflect the target image on the right and the foil image on the left. Trials on which subjects made an incorrect response were excluded. These angles, reported in polar coordinates, were binned separately by experiment and by condition into quintiles using the same procedure as the analysis of the times of initial mouse movement. Quintile 1 corresponds to the smallest angles, where the cursor leaves the radius horizontally towards the target, and Quintile 5 corresponds to the largest angles, where the cursor leaves the radius horizontally towards the foil. A direct path to the target is 57.6° from horizontal, falling between Quintiles 1 and 2, while a direct path to the foil image is 122.4° from horizontal, falling in Quintile 5. Figure 15 shows MD as a function of the angle at which the cursor leaves the radius in either phonological condition with high and low mouse gain.

Differences in MD as a function of the angle of departure were tested using linear mixed-effects models separately for each mouse gain. Phonological condition, angle of departure, and their interaction were treated as fixed effects. Random intercepts and slopes for the main effects were included by subject and item, and the angle of departure was centered. With high mouse gain, the hypothesis is confirmed in that a trajectory whose path initially leaves the radius in the direction of the foil (greater angle) displays a greater MD than a trajectory whose path initially leaves the radius in the direction of the target (smaller angle) ($t = 7.723$). However, the same pattern is not observed with low mouse gain, where there is neither an effect of angle of departure from the radius ($t = 1.599$), nor of phonological condition ($t = 0.682$).

Multiple Regression

MD was regressed on six factors and their interactions in a linear mixed-effects model with random slopes and intercepts for subjects and items (Baayen, Davidson, & Bates, 2008). A simpler model excluding the five- and six-way interaction terms was also run. Comparison of these models did not reveal a significant difference in model fit ($\chi^2(7) = 2.156$), therefore the simpler model is reported. The six factors are condition (phonological competitor vs. control), the presence of foil fixations (at least one after onset of the auditory stimulus vs. none after onset of the auditory stimulus), mouse gain (high vs. low), the nameability of the target image and of the foil image, and the time when participants first initiate a mouse movement. Each of the three categorical factors was coded such that a positive value of MD is associated with the first listed level. The remaining factors are continuous predictors and are described in more detail below. Random participant slopes were included for each main fixed effect except mouse gain, since each subject performed the task with a single mouse speed. Random item slopes were included for the three main effects manipulated within items: condition, mouse gain, and foil nameability. Attempts to include additional random interaction slopes did not converge. Binary predictors were centered using difference contrasts; continuous predictors were centered by subtracting the mean of the predictor from each observation of that predictor. A summary of the resulting mixed-effects model is presented in Table 3, with significant effects and interactions marked in bold.

All main effects, except foil nameability, have a significant impact on the observed maximum deviations of the cursor trajectories. Removing the main effect of foil nameability and all interactions involving this factor from the model had a negative impact on the model fit ($\chi^2(36) = 52.67$; $p < 0.05$) and thus this factor remains in the reported model. Each significant effect will be interpreted in turn.

The effect of condition resembles SGK's finding that deviation of the mouse towards the foil was greater in the competitor condition than in the control condition. The effect of the presence of a foil fixation indicates that deviation of the mouse towards the foil was greater in trials where the subject looked at the foil at least once. This is expected, as looking at the foil is required in order to consider an image as a candidate response. The lack of an interaction between condition and presence of foil fixations, as visualized in Figure 16, shows that this effect does not differ across condition. Table 4 shows the proportion of trials during which the foil was never fixated in each phonological condition and mouse gain condition, along with the marginal means.

The effect of mouse gain indicates that deviation of the cursor towards the foil was larger in the low mouse gain condition than in the high mouse gain condition. On the surface, this finding supports SGK's argument that low mouse gain exaggerates mouse curvature. However, this effect is overpowered by two interactions: between condition and mouse gain and between the presence of foil fixations and mouse gain. The magnitudes of both interactions are larger than the main effect of mouse gain and are in the opposite direction. Figure 17 shows the interaction between condition and mouse gain. The effect of condition is greater with high mouse gain than with low mouse gain. Furthermore, the deviation towards the foil is greatest in the competitor condition with high mouse gain and an intermediate amount of deviation towards the foil is observed in both conditions with low mouse gain. This interaction argues against SGK's claim that low mouse gain exaggerates mouse curvature.

Figure 18 shows the interaction between the presence of foil fixations and mouse gain. The effect of the presence of foil fixations is also greater with high mouse gain than with low mouse gain. This interaction also argues against SGK's claim that low mouse gain exaggerates mouse curvature; however care should be taken in its interpretation as the proportion of trials during which no foil fixation was made is nearly three times greater with high mouse gain than with low (see Table 4). This is likely due to the greater reaction times associated with low mouse gain, increasing the likelihood that foil fixations will occur. Table 5 shows the reaction times associated with each phonological condition and each mouse gain, along with the marginal means.

The main effect of time to initiate a mouse movement indicates that as participants wait longer to initiate a mouse movement, deviation towards the foil decreases. Since participants are free to move the mouse at any time during the trial, this finding suggests that on some trials participants may have adopted a strategy of waiting to hear more of the auditory stimulus before initially moving the mouse. Time to initiate a mouse movement was measured as the time, relative to auditory onset, at which participants moved the mouse outside an approximately 20 pixel radius from the initial mouse position. This radius corresponds to the dimensions of the ‘x’ that subjects are required to click to advance to the next trial.

Figure 19 visualizes the effect of time of initial mouse movement on MD in the high and low mouse gain conditions, respectively, after binning the times of initial mouse movement into quintiles, separately by condition. Quintile 1 represents the fastest times, while quintile 5 represents the slowest. This binning resulted in 157 observations per quintile in the competitor condition with high gain (range of times out of the radius: 18 – 1559 ms), 158 observations per quintile in the control condition with high gain (range of times out of the radius: 18 – 1800 ms), 158 observations per quintile in the competitor condition with low gain (range of times out of radius: 524 – 3037 ms), and 158 observations per quintile in the control condition with low gain (range of times out of radius: 535 – 3239 ms). The remainder of total observations in each condition not divisible by five was added to quintile 5.

The effect of time is much larger in the high mouse gain condition than in the low mouse gain condition. This interaction indicates that participants move more directly to the target in the high mouse gain condition when they wait to move the mouse, while the degree of deviation towards the foil remains largely unaffected by the time of initial mouse movement in the low mouse gain condition. It is also interesting to note that the values of MD associated with low mouse gain display a consistently intermediate amount of deviation towards the foil. By contrast, the values associated with the high mouse gain display more variability, with more extreme values that are indicative of both greater deviations of the mouse towards the foil (Quintile 1) and of nearly direct movements towards the target (Quintile 5). Moreover, the fastest times (524ms) for the cursor to leave the radius with low mouse gain correspond to times in the fourth quintile for high mouse gain. Even with the additional time that participants take to move the mouse in the low mouse gain condition, the cursor still does not take a direct path towards the target.

The three-way interaction between condition, presence of foil fixations and time of initial mouse movement indicates that the effect of time on MD is greatest in the competitor condition on trials where participants fixate the foil at least once after the onset of the auditory stimulus. Figure 20 shows this three-way interaction. For purposes of visualization, time of initial mouse movement was binned into quintiles separately by phonological condition. Only when participants fixate the foil in the phonological competitor condition does time of initial mouse movement have an effect on MD. In the control condition and when participants do not fixate the foil, participants move the cursor on a path with little curvature towards the foil regardless of the time of initial mouse movement.

Finally, the effect of target image nameability indicates that as the target image increased in nameability, MD decreased. Figure 21 shows the effect of target nameability on MD with high and low mouse gain. Quintiles are calculated the same way as in the analysis of the time of initial mouse movement above. Quintile 1 represents the trials where the target image is least nameable, while quintile 5 represents the trials where the target image is most nameable. Target nameability has the most pronounced effect on cursor trajectories in the competitor condition with high mouse gain. In this condition, deviations towards the foil are greater when the target is less nameable. The effect of target nameability is not pronounced in either the control condition or when presented with low mouse gain.

CHAPTER IV

DISCUSSION

The purpose of Experiment 1 was to bridge the literature on reaction time distributions pertaining to phonological competition with a word-picture matching task used frequently in mouse-tracking paradigms. The ex-Gaussian parameter fits showed that phonological competition in such a task results in effects of μ and σ, but not of τ. In other words, trials with a phonological competitor result in a shift of the reaction time distribution compared to trials without a phonological competitor. These results are consistent with Goh et al.'s (2009) findings using a word/non-word judgment task.

The distribution of reaction times was also used to corroborate Spivey et al.'s (2005) conclusion that lexical activation proceeds in a continuous rather than discrete manner. Spivey et al. compared the distribution of cursor trajectories in the competitor and control conditions, finding no difference in shape of the distributions. The variance sign test conducted in Experiment 1 found no difference in the variance of the reaction times in the two conditions, either by subjects or by items. This finding leads to the same conclusion drawn by Spivey et al. that lexical activation is better modeled by continuous activation of lexical entries than by discretely activating alternative lexical entries in series. Furthermore, Experiment 1 shows that the analysis of the distribution of reaction times can yield results consistent with the analysis of the distribution of cursor trajectories.

Moreover, the results from the regression analysis of Experiment 1 show that slow RTs are associated with direct inspection of the foil and that inspection of the foil image after the onset of the auditory stimulus is associated with slower reaction times in the competitor condition than in the control condition. Experiment 1 also establishes that the ease with which the target image is named speeds reaction times. The ease with which the foil image is named does not speed reaction times.

Experiment 2 was a methodological exploration of mouse-tracking designed to assess the strength of the Hand-Mind Hypothesis. Three effects observed in Experiment 2 bear on this assessment: mouse gain, time of initial mouse movement, and the angle of departure of the mouse.

The mouse gain was manipulated between subjects at two levels: a low level similar to the gain used by Spivey et al. (2005), and a high level typical of the default gain on most computers. In the distributional analyses of cursor trajectories with low mouse gain, the distributions of maximum deviations of the cursor towards the foil image did not differ in variance between the phonological competitor and control conditions by a variance sign test. However, when comparing the same conditions with high mouse gain, the variances did differ. When comparing the shape of the distributions using a K-S test, the competitor and control distributions differed in shape with both high and low mouse gain; however, the difference was greater with high mouse gain. In fact, one measure of bimodality finds bimodality in the distribution of cursor trajectories in the competitor condition with high mouse gain but in no other condition with either gain. Thus, high mouse gain appears to increase the difference in variability between conditions and appears to be associated with an increased amount of bimodality in the distribution of mouse trajectories in the phonological competitor condition.

Mouse gain also affects the mean maximum deviation of cursor trajectories across conditions. Most striking is the interaction between phonological condition and mouse gain, where the differences in mean maximum deviation between phonological and control conditions are exaggerated with high mouse gain. The effect of phonological similarity was not significant with low mouse gain. It is possible that the low mouse gain used in Experiment 2 was even lower than used by SGK, such that the task effects associated with the low mouse gain overwhelmed the phonological similarity effect. High mouse gain also exaggerates the effect of foil fixation, where at least one foil fixation results in increased deviation of the mouse towards the foil. No effect of foil fixation was observed with low mouse gain. These effects show that a physical parameter of the mouse-tracking response mechanism (i.e. mouse gain) can have a significant effect on the response itself.

In addition to the mouse gain parameter, which is outside of participants' control, there also appears to be at least one strategy within participants' control that influences cursor trajectories and interacts with the critical manipulation. This strategy is the time of initial mouse movement. The longer participants wait to move the mouse, the more directly the cursor moves towards the target. The three-way interaction between phonological condition, foil fixations and time of initial mouse movement shows that the effect of time of initial mouse movement is largest in the competitor condition when there is at least one fixation on the foil. In other words, waiting to move the mouse most decreases deviations of the cursor towards the foil when the foil image is the most plausible as a response. If the process of lexical identification in the visual-world paradigm proceeds regardless of the time that participants initiate a mouse movement, this suggests that the degree to which cursor trajectories reflect this process of lexical identification varies as a function of the time of initial mouse movement. Cursor trajectories with a longer latency of initial mouse movement may temporally overlap with less of the lexical identification process than cursor trajectories with a shorter latency of initial mouse movement, and these trajectories with a longer latency of initial mouse movement appear to reflect less of the lexical identification process.

In fact, the amount of deviation of the cursor towards the foil is dependent not only on the time when the participant initially moves the mouse, but also on the angle of departure when the initial mouse movement occurs. The maximum deviation of the cursor towards the foil image is directly proportional to the angle of initial departure of the mouse towards the foil. A combination of two possible factors likely accounts for this effect. First, the momentum inherent in a mouse movement necessitates a dependency between successive mouse movements. Second, the lexical identification that mouse-tracking is intended to capture may be occurring early in the trial such that only a fraction of the trajectory of the cursor reflects lexical identification. Under either account, it appears that a large proportion of cursor trajectories does not reflect the "real-time unfolding of underlying cognitive processes" (Freeman et al., 2011) as the strong Hand-Mind Hypothesis purports. At best, only the early components of cursor trajectories reflect "real-time" cognitive processes.

These three effects of mouse gain, time of initial mouse movement, and angle of departure show that both task demands and strategic effects can manipulate the reliability of cursor trajectories to capture cognitive processes. Moreover, only early components of cursor trajectories seem to reflect “real-time” cognitive processes. Together, these effects argue against a strong Hand-Mind Hypothesis.

To be clear, this does not argue against the utility of mouse-tracking in its entirety. However, it does suggest that some steps be taken to ensure the reliable interpretation of mouse trajectories. First, mouse gain should always be reported, with a preference for a naturalistic mouse gain over an exaggeratedly low mouse gain. A low mouse gain is more prone to strategic task effects that serve to dampen effects associated with the phonological manipulation. Second, trials with long latencies to initiate mouse movement are strong candidates for exclusion. Introducing a deadline by which participants must initiate (but not necessarily complete) a mouse movement is another option, but researchers should be aware of the potential strategies that participants might employ in response to such a deadline. Third, researchers should use caution in inferring the time-course of mental processes from the time-course of cursor trajectories, as the mental processes that mouse-tracking is intended to index may be complete at an early stage in the trial. Though it is tempting to record cursor movements throughout an entire trial, only a small fraction of that data may be informative.

Lastly, across both experiments there seems to be a pattern in the variability of the distribution of the dependent variable in the competitor and control conditions. With high mouse gain, the distributions of MD clearly differ across the competitor and control conditions such that the distribution in the competitor condition appears bimodal; with low mouse gain, the distributions are unimodal and differ little by a K-S test and not significantly by a variance sign test. One possible account for this effect is that with low mouse gain, movement of the cursor requires the mouse to be moved a greater distance than participants are accustomed to with high mouse gain, resulting in movements of the cursor being viewed as more costly with low mouse gain. As a result, to minimize any cursor movements associated with a correction in trajectory, participants in the low mouse gain condition avoid direct movements of the cursor to either image. The resulting trajectories instead exhibit an intermediate path that is roughly equidistant from the two images until auditory disambiguation. Such an intermediate path will also exhibit an intermediate amount of curvature towards the foil and the distributions of MD will not differ greatly across phonological conditions. By contrast, since there is a lesser cost of initiating an ultimately incorrect response with high mouse gain, participants are not as pressured to conserve their mouse movements and a greater proportion of trajectories deviate towards the foil. Any direct movements to the foil are then followed by a correction in trajectory towards the target and yield large deviations towards the foil. As a result, the distributions of MD will be more likely to differ across phonological conditions. It is possible that the high cost associated with low mouse gain is inherent, but it is also possible that it is simply due to participants' relative unfamiliarity to low mouse gain. Training participants in the use of a mouse with low gain such that they are as skilled in its use as with high gain may help to identify the basis of this cost.

Similar logic based upon the cost of the task may also be able to account for the fact that in Experiment 1 the RT distributions do not differ in either the ex-Gaussian τ parameter or in the variance sign test. When required to indicate a response using a button press, the cost of initiating an ultimately incorrect response is very high. Once a participant has begun to press the button corresponding to the foil image, there is very little opportunity to abort the button press and/or initiate the correct button press in time.

This seems to contribute to a lack of difference in shape of RT distributions across phonological conditions. Thus, it seems that as the cost of initiating an ultimately incorrect response increases, participants allocate greater scrutiny to the response mechanism itself. This could be phrased as either an increased response threshold or as a conscious strategy to optimize some weighted combination of accuracy, motor movements, and time. In any event, the method of indicating a response appears to affect the response distribution.

CHAPTER V

CONCLUSIONS

A preponderance of previous evidence from reaction time studies (Goh et al., 2009), eye tracking studies (Eberhard, Spivey-Knowlton, Sedivy, & Tanenhaus, 1995; Allopenna, Magnuson, & Tanenhaus, 1998; Magnuson, Dixon, Tanenhaus, & Aslin, 2007), and computational modeling (McClelland & Elman, 1986) converges on a model of distributed and graded lexical activation in which activation of a particular word necessarily and automatically triggers the parallel activation of similar words and the inhibition of unrelated words. The recent popularization of mouse tracking as an inexpensive and continuous measure for observing on-line decision-making has led to further corroboration of the distributed and graded nature of lexical activation (Spivey et al., 2005).

The present study employs eye tracking, reaction times, and mouse tracking to address two goals: (1) To revisit the graded nature of lexical activation; in particular, whether the distribution of cursor trajectories can reliably be interpreted as evidence for either discrete or continuous models of lexical activation, and (2) to provide a methodological exploration of the factors that influence cursor trajectories, with the aim of assessing the strength of the Hand-Mind Hypothesis.

Experiment 1 established that the forced-choice paradigm and stimuli elicited the expected phonological similarity effects in two dependent measures: reaction time and eye movements. Distributional analyses of response reaction times revealed that the shape of the RT distributions in the phonological competitor and control conditions were indistinct, further corroborating continuous models of lexical activation. Experiment 1 also demonstrated an effect of image nameability on reaction times.

Experiment 2 was similar to Experiment 1, with the exception that subjects indicated their response by moving the mouse to one of the two images and clicking on it. Mouse gain was manipulated between-subjects so as to observe any influence of the effector on the mouse movements, themselves. Concurrent eye-tracking allowed eye and mouse movements to be compared directly. Results from Experiment 2 show similar effects of phonological similarity and image nameability on eye movements as in Experiment 1. They also show that deviations of the mouse to the foil image are predicted by foil fixations. However, the low mouse gain served to reduce the effect of phonological competition, as expressed by maximum deviation of the cursor towards the foil, and resulted in a change in the shape of the distribution of cursor trajectories in the phonological competitor condition such that it was statistically indistinct from the shape of the distribution of cursor trajectories in the control condition. We account for this effect in terms of cost, such that the cost of moving the cursor with low gain is higher than with high gain. We observe that when the cost of initiating an ultimately incorrect response is high, the distribution of the dependent variable becomes less distinct across phonological conditions. Moreover, Experiment 2 shows that cursor trajectories are influenced both by the time that participants first initiate a mouse movement and by the angle of departure of this first movement. That both of these factors are not manipulated and are partially under participants' control suggests that cursor trajectories do not index lexical identification in real-time over the course of the entire trial. These observations that cursor trajectories can be manipulated by both task demand (mouse gain) and participant strategies (the time and angle of initial mouse movement) argue against a strong Hand-Mind hypothesis.

SGK's seminal work on mouse tracking now requires a revision in interpretation. The authors' conclusion that the statistically indistinct distributions of cursor trajectories in the phonological competitor and control conditions support a continuous model of lexical activation is tempered by our weak Hand-Mind Hypothesis. Even if lexical activation proceeds in a continuous and graded manner, the evidence from mouse tracking may not be a reliable basis for this conclusion. In fact, if the cost the initiating an incorrect response can alter the distribution of a dependent variable, the shape of the distributions – regardless of the dependent variable – may not be a meaningful indicator of the continuous or discrete nature of lexical activation. Without a fully articulated process model of mouse movements and with data in hand showing that the observation of bimodality of cursor trajectories can be manipulated according to mouse gain, mouse-tracking as a method of demonstrating the continuous nature of lexical activation appears to be unreliable. Further studies may wish to explicitly manipulate the cost of initiating an incorrect response by button press to test this account.

TABLES

Table 1: Mean RT and means of the best-fitting ex-Gaussian parameters by condition, averaged over subjects

Experiment 1	**N_{subj}**	**mean**	**μ**	**σ**	**τ**
Competitor	40	898	729	144	178
Excluding Trials w/o Foil Fixations	40	916	745	151	200
Control	40	849	682	136	179
Excluding Trials w/o Foil Fixations	40	859	692	124	205

Table 2: Summary of fixed effects from experiment 1 regressed on RT

	Estimate	Std. Error	*t*-Value
Intercept	837.75	36.82	22.75
Condition	12.83	15.87	0.809
Foil.Fix	**126.07**	**21.05**	**5.990**
Target Nameability	**-305.52**	**34.53**	**-8.847**
Foil Nameability	69.92	89.79	0.779
Condition:Foil.Fix	**91.69**	**22.82**	**4.017**
Condition:Target Name	6.33	56.05	0.113
Foil Fix:Target Name	-20.84	51.82	-0.402
Condition:Foil Name	46.70	65.21	0.716
Foil.Fix:Foil Name	-24.94	51.55	0.484
Target Name:Foil Name	18.81	174.45	0.108
Cond:Foil.Fix:Target Name	20.98	102.56	0.205
Cond:Foil.Fix:Foil Name	77.66	102.49	0.758
Cond:Target Name:Foil Name	-44.10	260.33	-0.169
Foil.Fix:Target Name:Foil Name	13.59	221.70	0.061
Cond:Foil.Fix:Target Name:Foil Name	-599.68	442.72	-1.355

Table 3: Summary of fixed effects from experiment 2 regressed on MD

Predictor	Coefficient	SE Coefficient	*t*-value
Constant	0.20	0.019	10.92
MouseGain	**-0.14**	**0.036**	**-3.96**
Condition	**0.08**	**0.031**	**2.64**
Presence of Foil Fixations	**0.07**	**0.026**	**2.72**
Time	**-2.4e-04**	**3.9e-05**	**-6.25**
Target Nameability	**-0.28**	**0.067**	**-4.24**
Foil Nameability	0.07	0.054	1.33
MouseGain * Condition	**0.20**	**0.055**	**3.64**
MouseGain * Presence of Foil Fixations	**0.15**	**0.052**	**2.98**
Condition * Presence of Foil Fixations	0.08	0.049	1.729
MouseGain * Time	**-5.1e-04**	**7.7e-05**	**-6.581**
Condition * Time	1.4e-06	6.5e-05	-0.021
Presence of Foil Fixations * Time	-1.2e-04	6.6e-05	-1.858
MouseGain * Target Nameability	-0.08	0.128	-0.627
Condition * Target Nameability	-0.04	0.107	-0.390
Foil Fixation * Target Nameability	0.06	0.104	0.593
Time * Target Nameability	4.5e-06	1.3e-04	0.034
MouseGain * Foil Nameability	0.10	0.098	1.047
Condition * Foil Nameability	0.16	0.085	1.875
Foil Fixation * Foil Nameability	0.02	0.097	0.231
Time * Foil Nameability	-9.2e-05	1.2e-04	-0.749

Target Nameability * Foil Nameability	0.26	0.196	1.316
MouseGain * Condition * Foil Fix	-.009	-0.095	-0.937
MouseGain * Condition * Time	-1.8e-04	1.3e-04	-1.441
MouseGain * Foil Fix * Time	8.1e-05	1.3e-04	0.616
Condition * Foil Fix * Time	**-3.0e-04**	**1.3e-04**	**-2.401**
MouseGain * Condition * Target Name	-0.29	0.191	-1.497
MouseGain * Foil Fix * Target Name	-0.35	0.210	-1.659
Condition * Foil Fix * Target Name	0.06	0.153	0.418
MouseGain * Time * Target Name	4.6e-05	2.6e-04	0.180
Condition * Time * Target Name	1.0e-06	2.3e-04	0.004
Foil Fix * Time * Target Name	1.4e-04	2.6e-04	0.530
MouseGain * Condition * Foil Name	0.07	0.175	0.382
MouseGain * Foil Fix * Foil Name	0.03	0.186	0.164
Condition * Foil Fix * Foil Name	-0.14	0.127	-1.100
MouseGain * Time * Foil Name	1.7e-04	2.5e-04	0.710
Condition * Time * Foil Name	-8.0e-05	2.1e-04	-0.374
Foil Fix * Time * Foil Name	3.4e-05	2.4e-04	0.140
MouseGain * Target Name * Foil Name	-0.13	0.407	-0.319
Condition * Target Name * Foil Name	-0.43	0.278	-1.564
Foil Fix * Target Name * Foil Name	-0.20	0.307	-0.656
Time * Target Name * Foil Name	-1.5e-04	4.2e-04	-0.366
MouseGain * Condition * Foil Fix * Time	1.2e-04	2.5e-04	0.463
MouseGain * Condition * Foil Fix * Target Name	0.25	0.386	0.639

MouseGain * Condition * Time * Target Name	4.3e-04	3.7e-04	1.179
MouseGain * Foil Fix * Time * Target Name	2.8e-04	5.0e-04	0.571
Condition * Foil Fix * Time * Target Name	6.5e-05	5.0e-04	0.130
MouseGain * Condition * Foil Fix * Foil Name	-0.05	0.343	-0.138
MouseGain * Condition * Time * Foil Name	-3.4e-04	3.2e-04	-1.053
MouseGain * Foil Fix * Time * Foil Name	-7.3e-04	5.1e-04	-1.438
Condition * Foil Fix * Time * Foil Name	-4.3e-04	4.5e-04	-0.964
MouseGain * Condition * Target Name * Foil Name	0.40	0.530	0.751
MouseGain * Foil Fix * Target Name * Foil Name	0.73	0.837	0.873
Condition * Foil Fix * Target Name * Foil Name	**1.23**	**0.492**	**2.494**
MouseGain * Time * Target Name * Foil Name	-6.4e-04	5.9e-04	-1.083
Condition * Time * Target Name * Foil Name	-3.3e-04	5.2e-04	-0.623
Foil Fix * Time * Target Name * Foil Name	-6.1e-04	9.2e-04	-0.668

Table 4: Proportion of trials during which no foil fixations were made

	High Gain	**Low Gain**	Mean
Competitor	0.36	0.13	0.25
Control	0.44	0.15	0.30
Mean	0.40	0.14	0.27

Table 5: Mean reaction times in milliseconds by phonological and mouse gain conditions

	High Gain	**Low Gain**	Mean
Competitor	1268	2140	1706
Control	1200	2086	1643
Mean	1234	2113	1674

FIGURES

Figure 1: Difference in proportion of target and foil nameability in the phonological competitor condition (left panel) and control condition (right panel) of Experiment 1

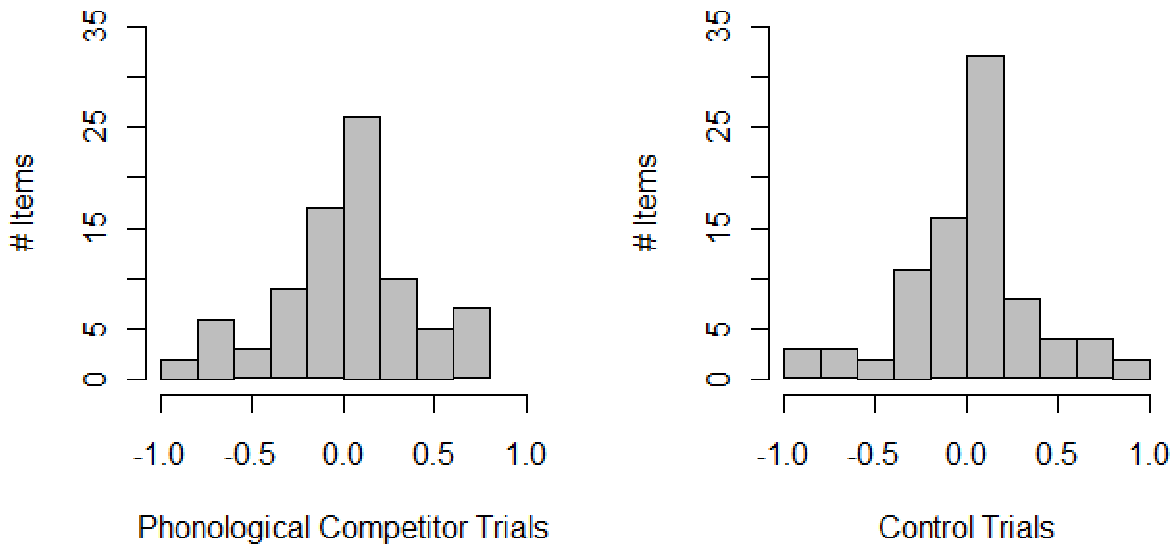


Figure 2: Histogram of target nameability in Experiment 1

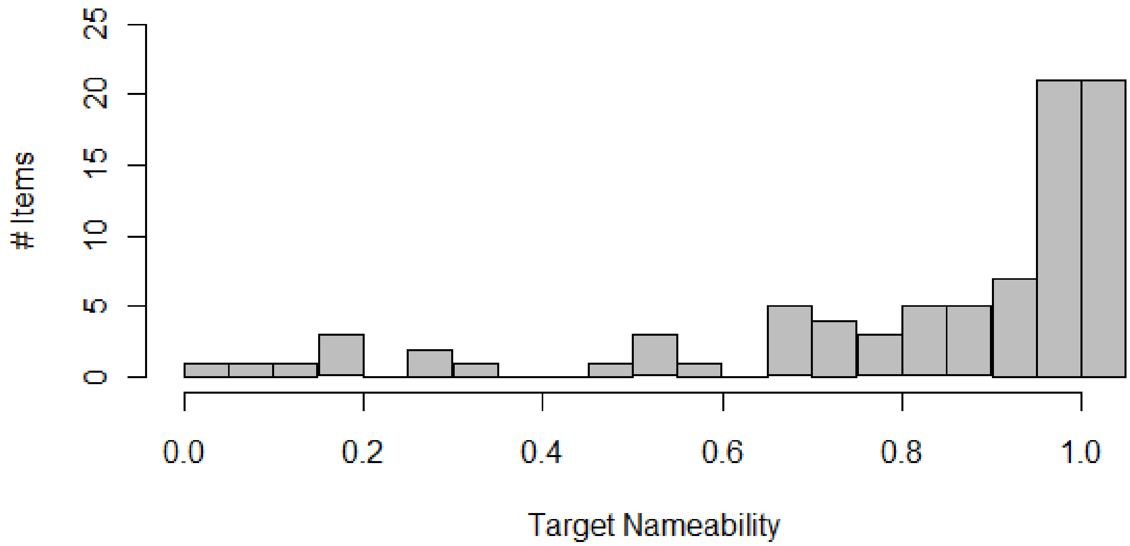


Figure 3: Fixation proportions in Experiment 1

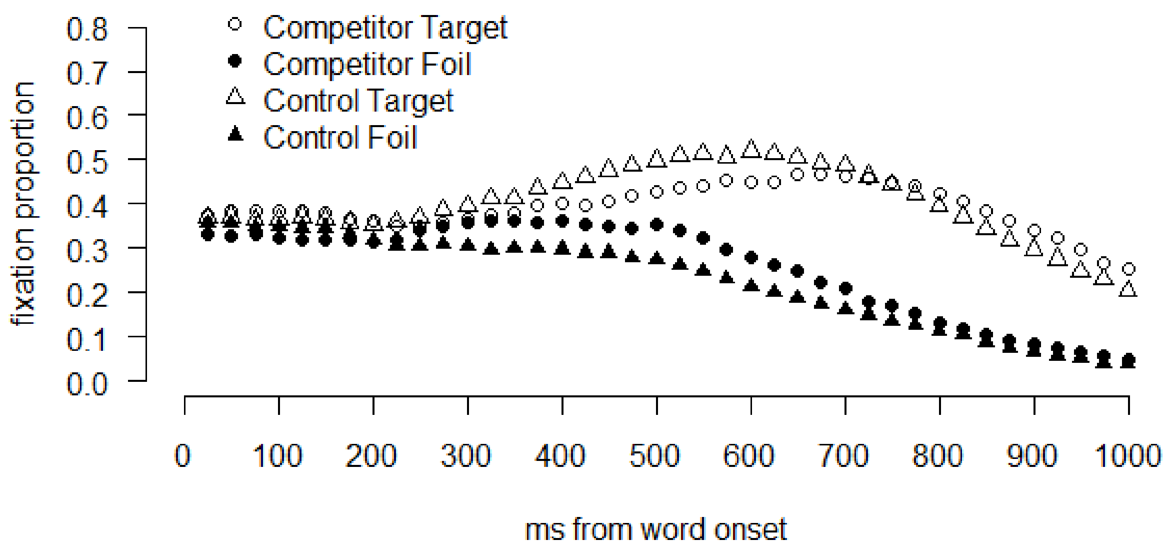


Figure 4: Vincentile plot of correct RT data (Competitor – Control) on all trials

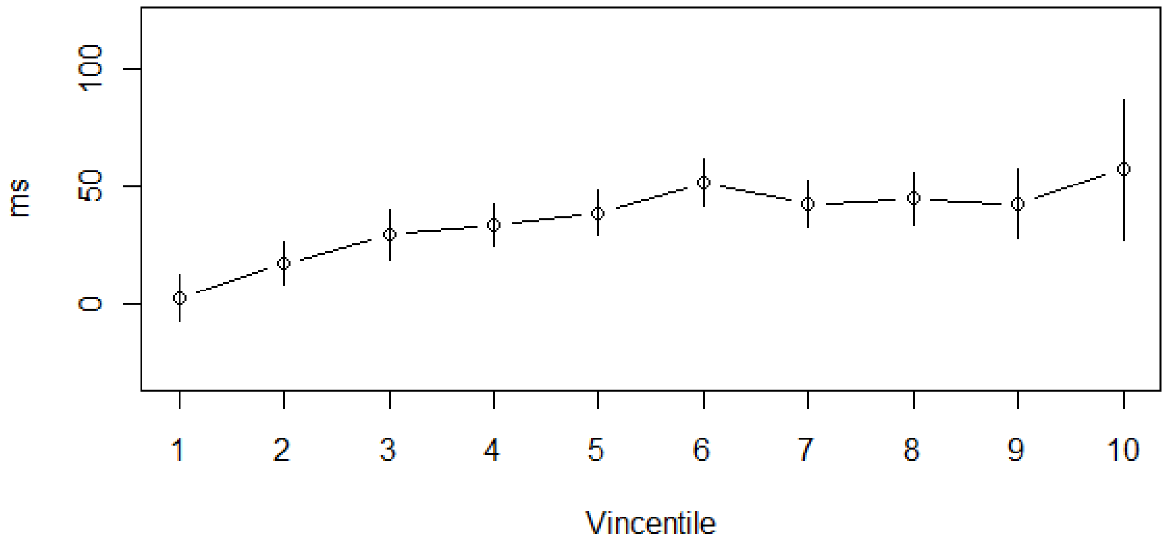


Figure 5: Vincentile plot of correct RT data (Competitor – Control) on trials with at least one foil fixation

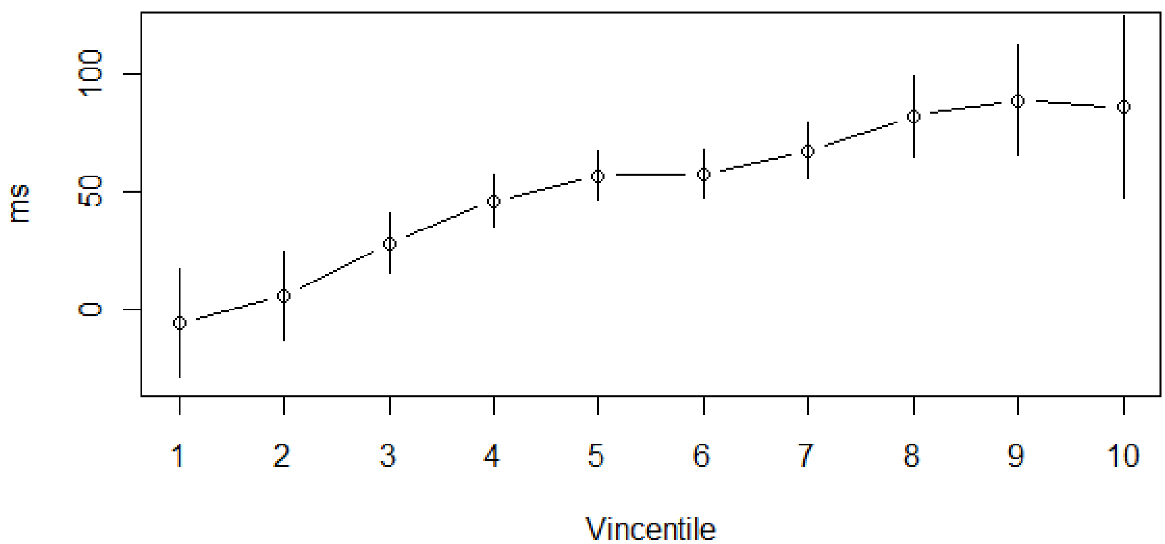


Figure 6: Distribution of raw RTs (left panel) and long-transformed RTs (right panel)

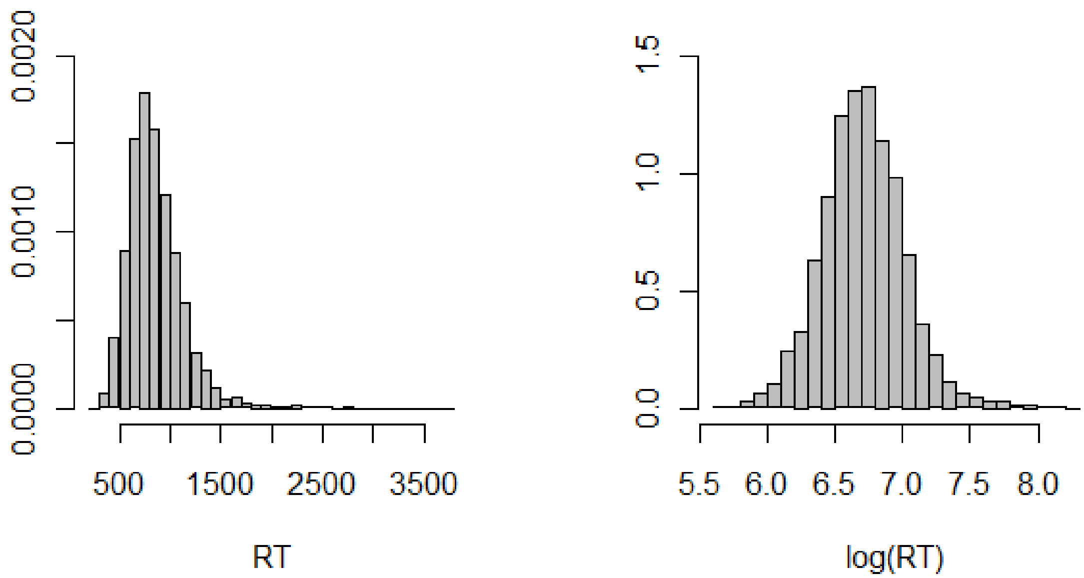


Figure 7: Difference in RT variance across conditions by subjects (left panel) and by items (right panel) in ms

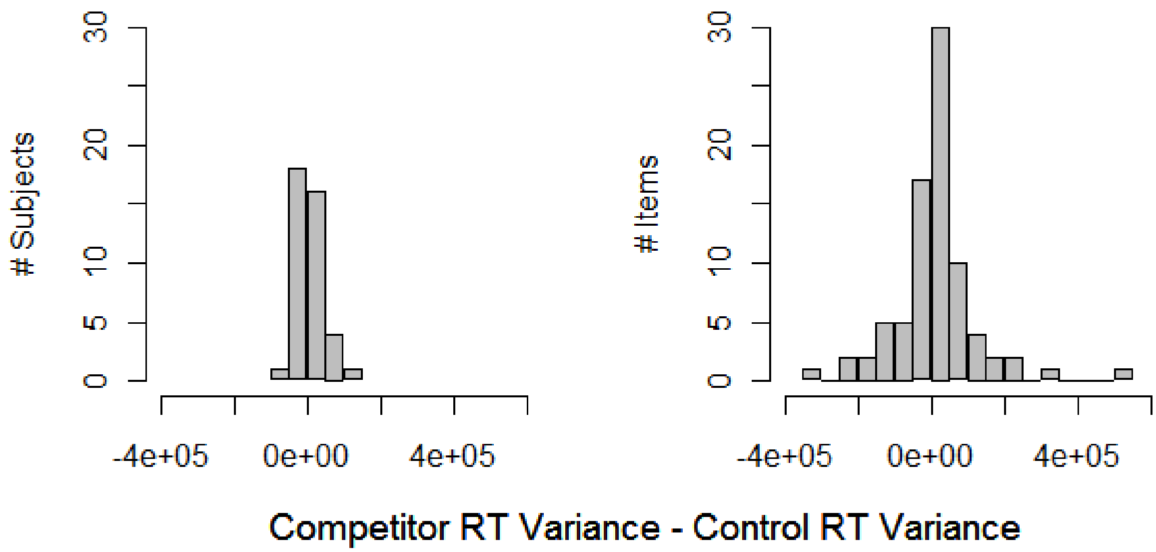


Figure 8: RT as a function of condition and foil fixation

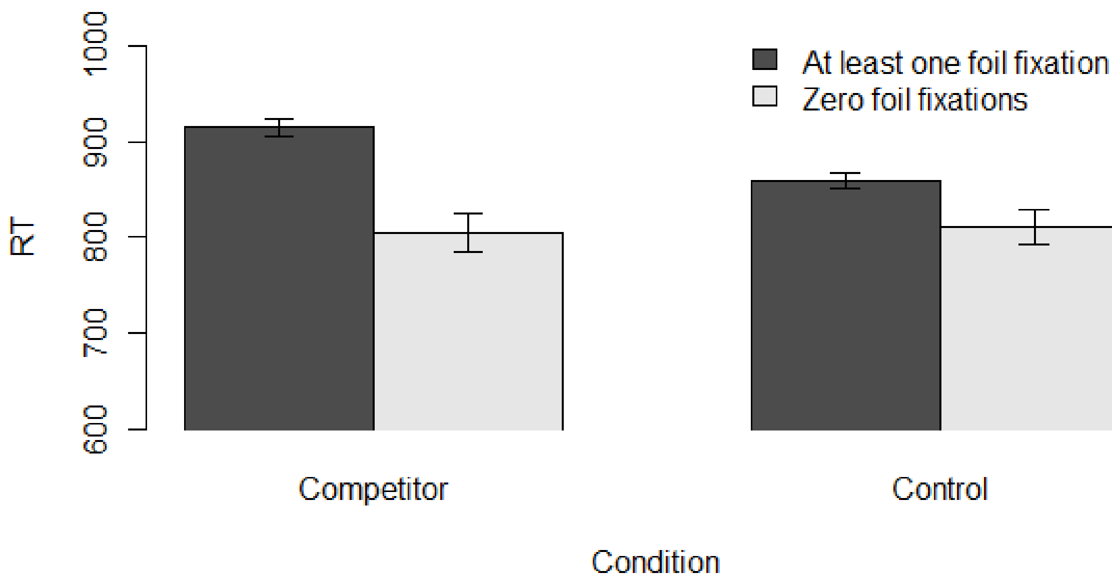


Figure 9: RT as a function of condition and nameability

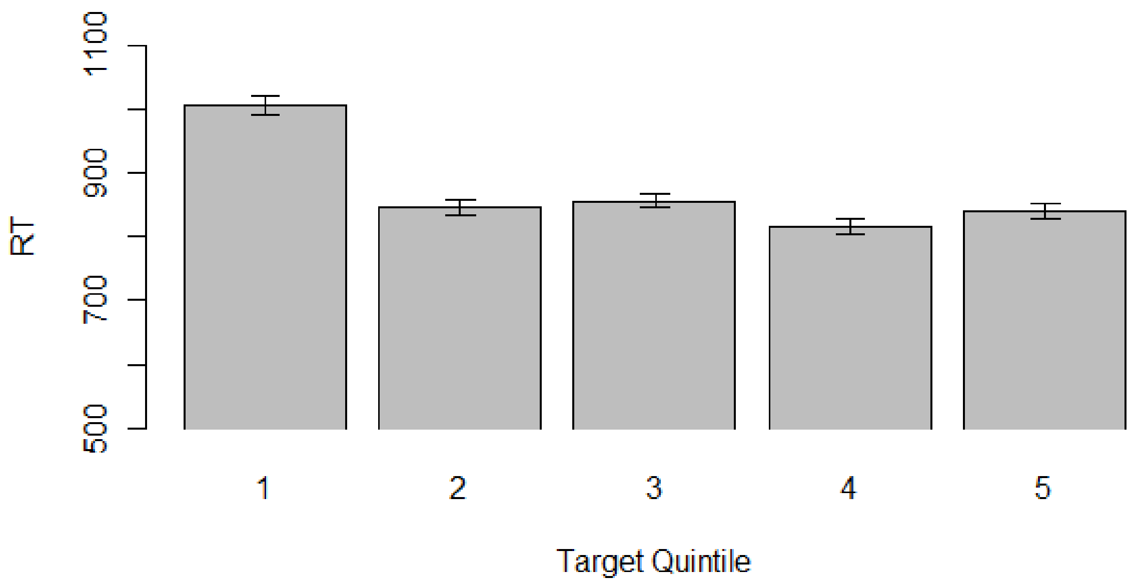


Figure 10: Difference in proportion of target and foil nameability in the phonological competitor condition (left panel) and control condition (right panel) of Experiment 2

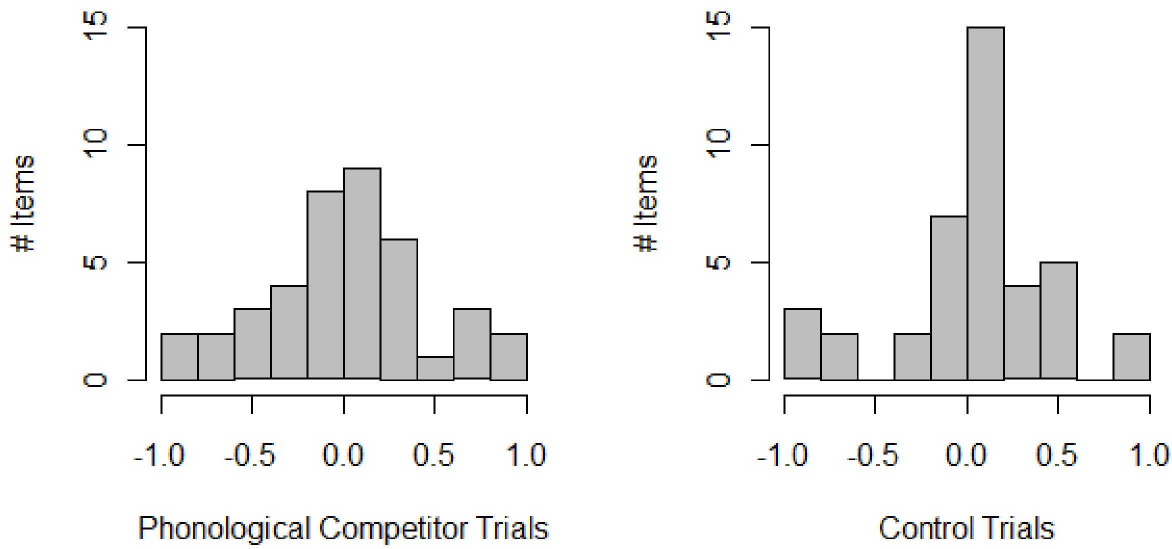


Figure 11: Histogram of target nameability in Experiment 2

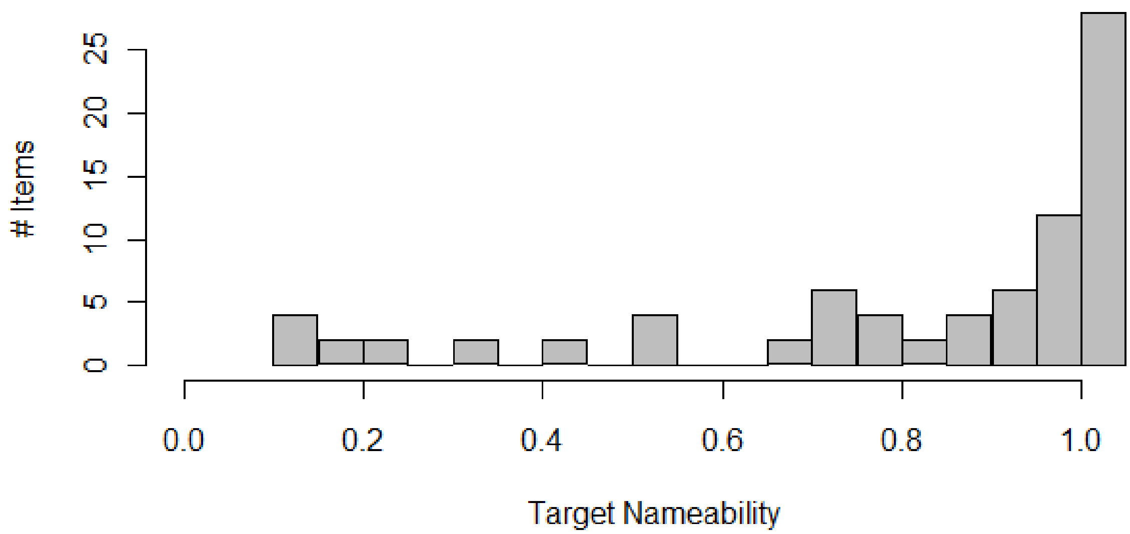


Figure 12: Fixation proportions in Experiment 2 with high mouse gain (top panel) and low mouse gain (bottom panel)

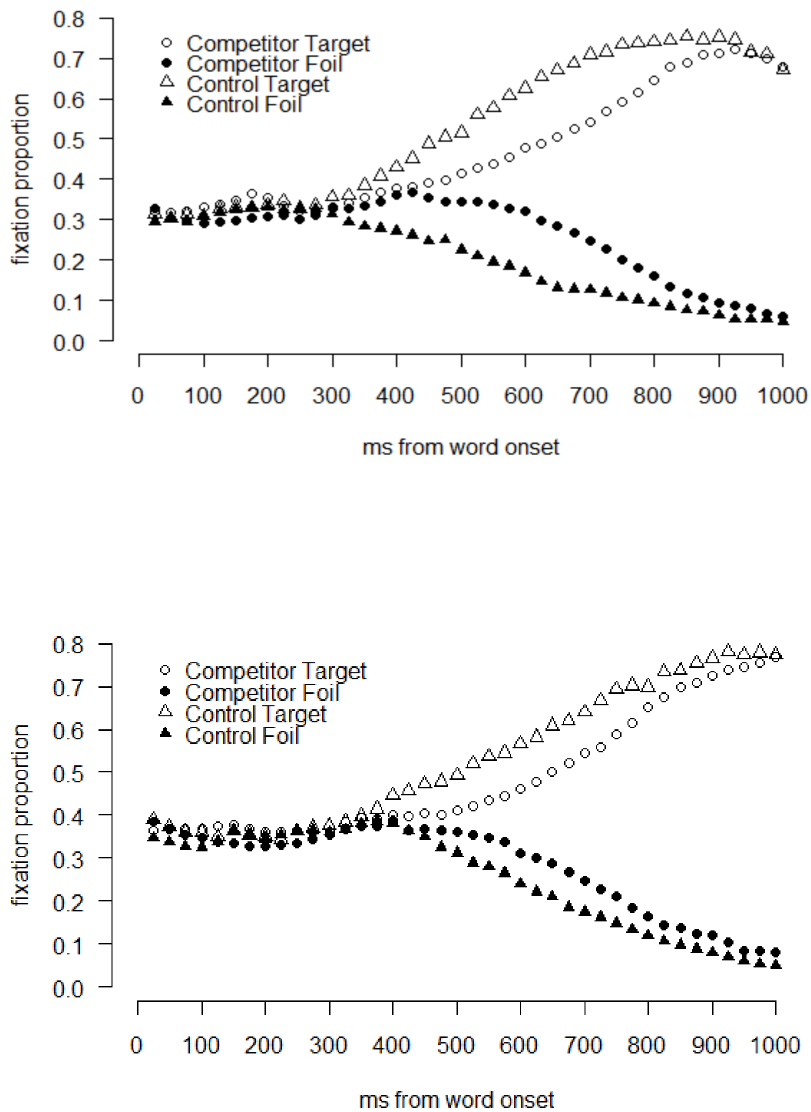


Figure 13: Distributions of MD z-scored within participants with high mouse gain (left panel) and low mouse gain (right panel)

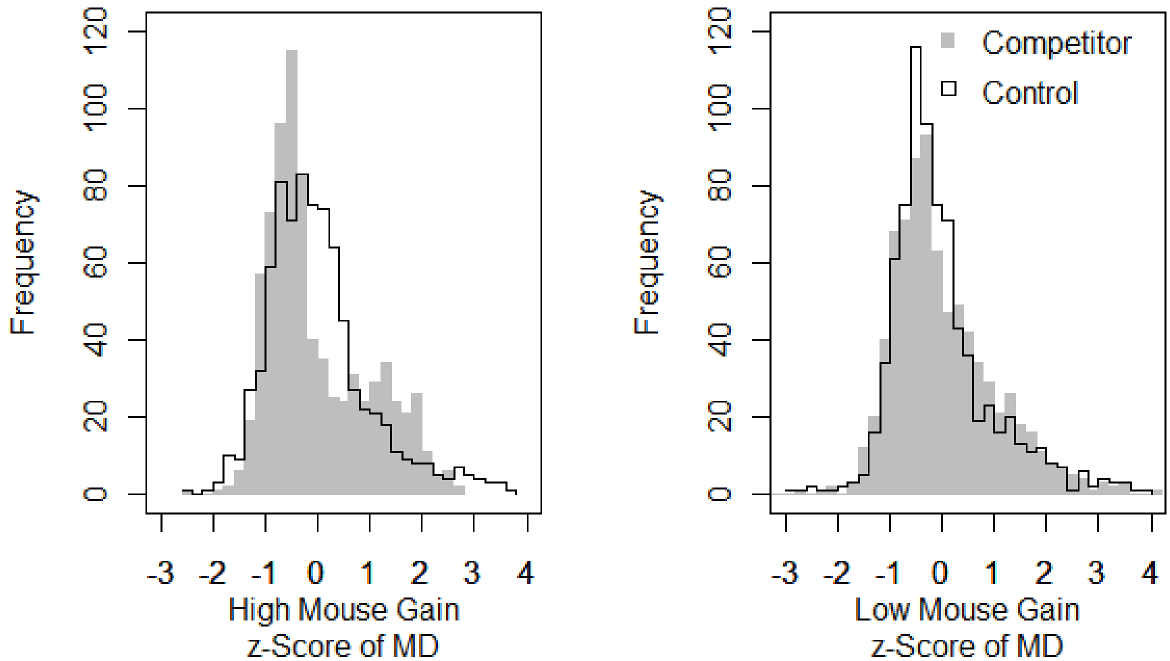


Figure 14: Difference between variances in the phonological competitor and control condition by subjects (top row) and items (bottom row) with high mouse gain (left column), low mouse gain (center column), and collapsed across both mouse gains (right column)

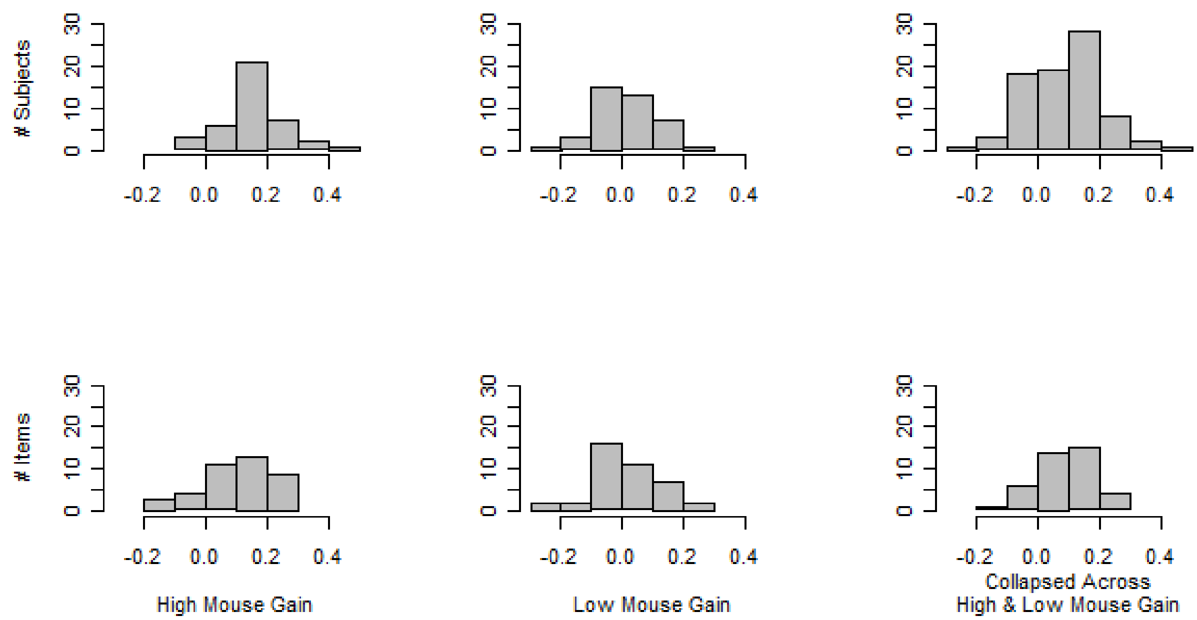


Figure 15: MD as a function of angle out that the cursor first leaves the 20-pixel radius around the start position and phonological condition with high mouse gain (left panel) and low mouse gain (right panel)

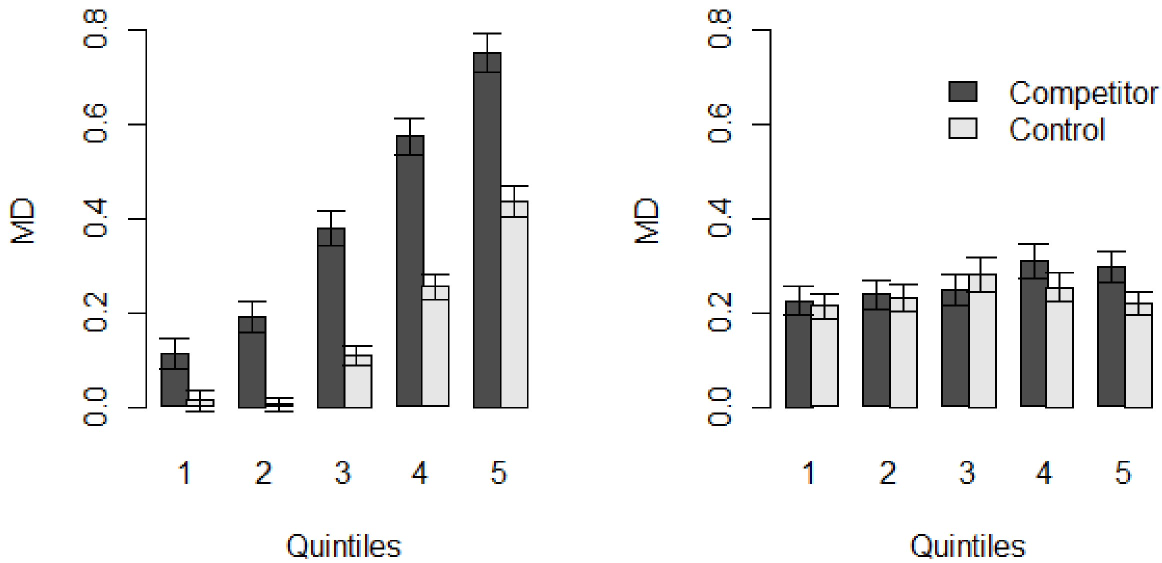


Figure 16: MD as a function of condition and foil fixation

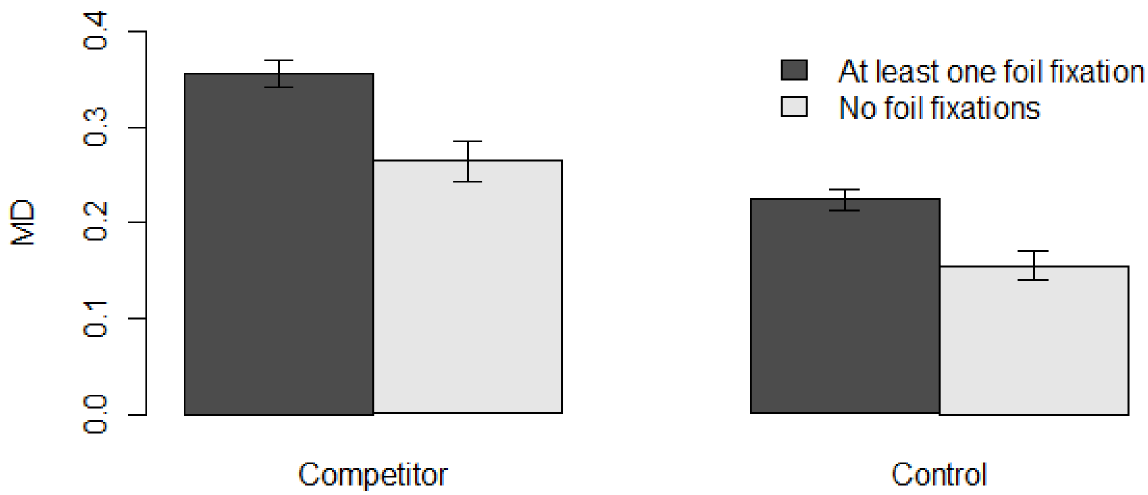


Figure 17: MD as a function of condition and mouse gain

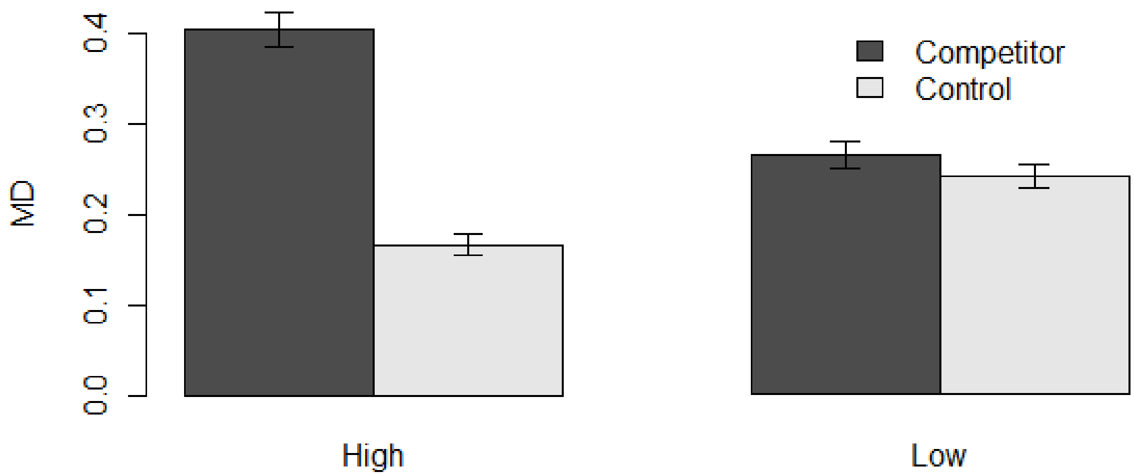


Figure 18: MD as a function of foil fixation and mouse gain

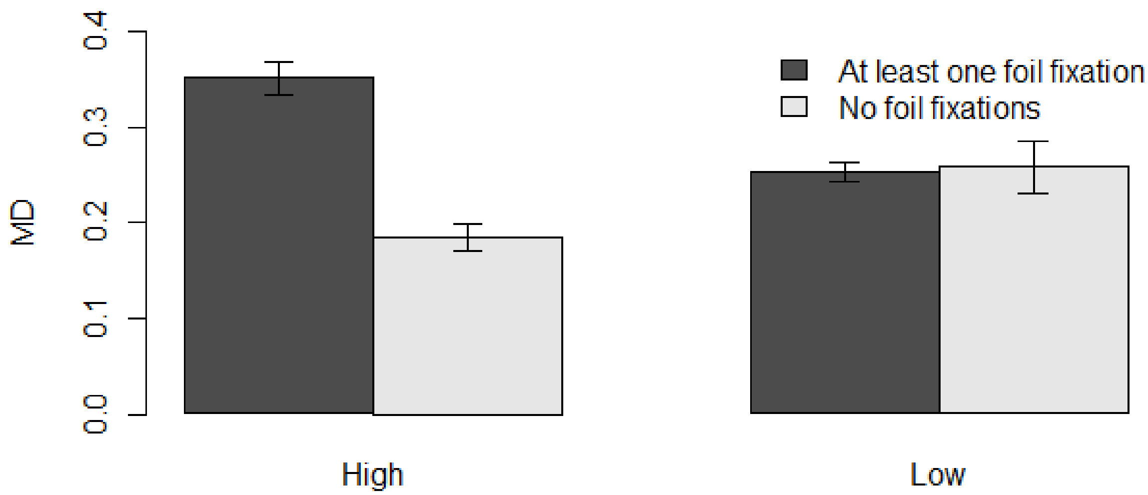


Figure 19: MD as a function of phonological condition and time by Quintile with high mouse gain (left panel) and low mouse gain (right panel)

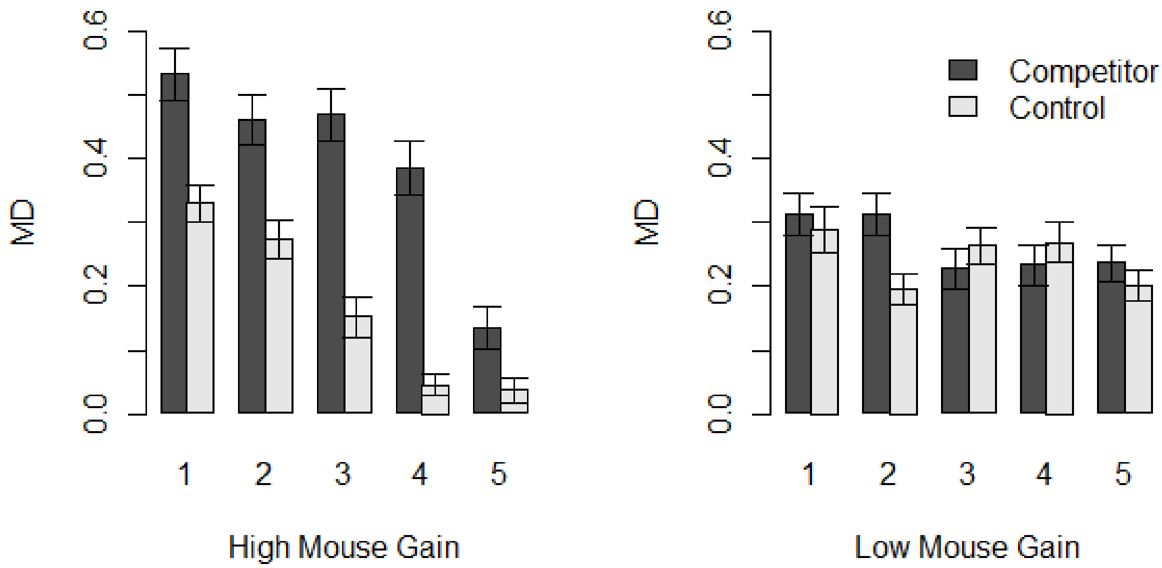


Figure 20: MD as a function of foil fixation and time by Quintile in the phonological competitor condition (left panel) and the control condition (right panel)

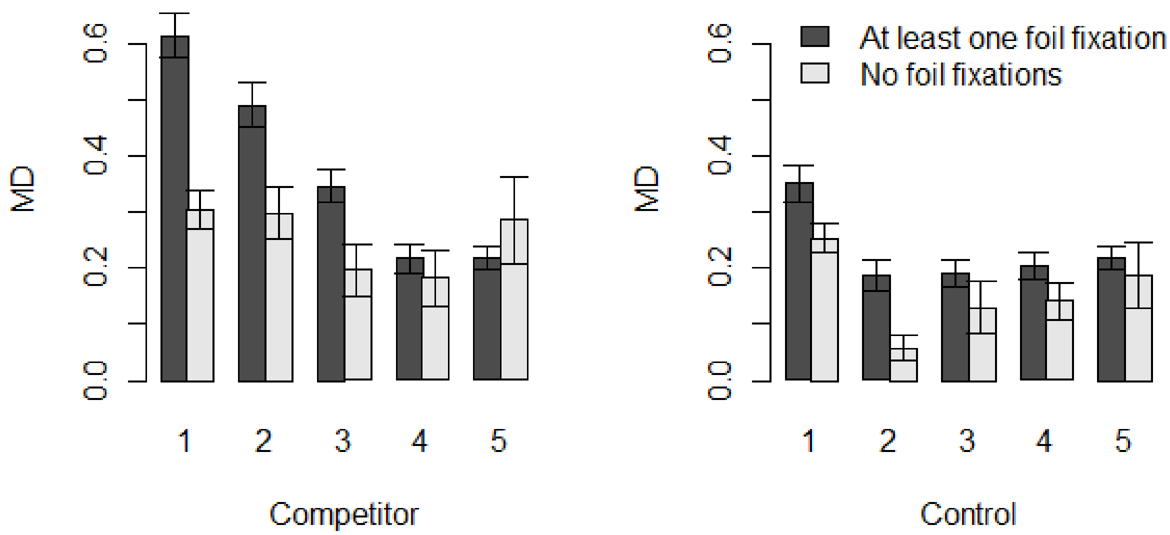
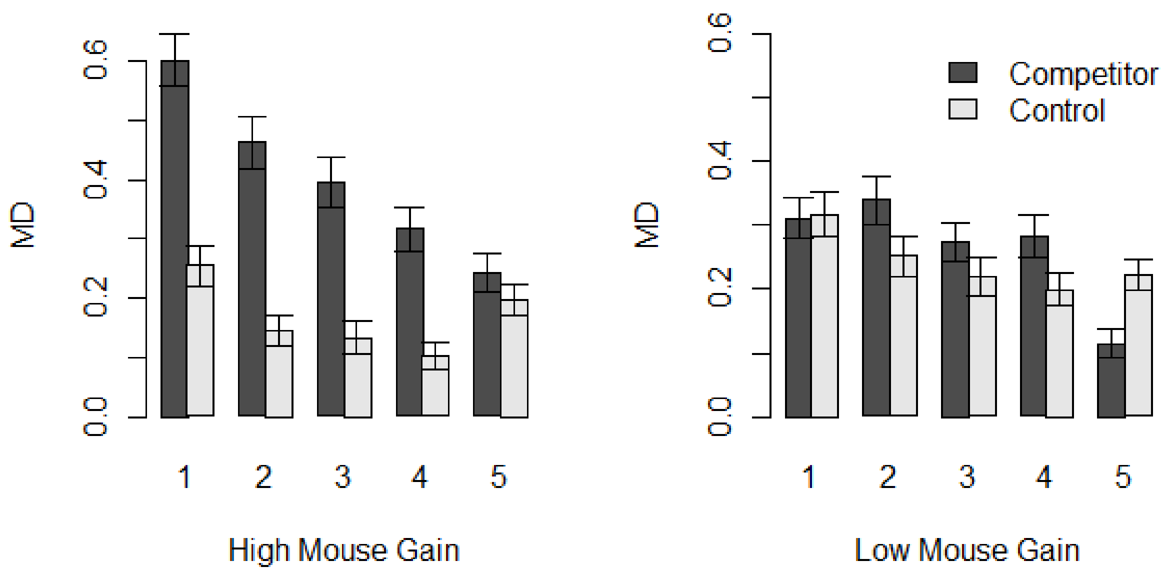


Figure 21: MD as a function of phonological condition and Target Nameability by Quintile with high mouse gain (left panel) and low mouse gain (right panel)



APPENDIX A

STIMULI FOR EXPERIMENT 1 AND CORRESPONDING WORD FREQUENCIES

Experimental Trials								Filler Trials			
List 1				List 2							
Competitor				Competitor							
Target		Foil		Target		Foil		Target		Foil	
anvil	0	ant	2	hamster	0	hammer	1	ace	4	cart	4
artist	23	artichoke	0	crown	12	crowd	27	angel	1	blender	2
snail	2	snake	5	moon	24	moose	0	microscope	0	octagon	1
pancakes	3	panda	0	palette	0	palace	22	blimp	0	tee	0
bell	7	belt	15	bear	31	barrel	17	tomato	0	cereal	10
bolt	3	bowl	11	peacock	0	peanut	1	drill	4	couch	3
butter	8	buckle	2	puppy	0	puzzle	7	duck	11	wagon	14
bull	10	bush	5	collar	1	column	1	glove	0	axe	0
candle	1	cannon	7	ruler	1	rooster	0	nun	0	harp	0
carriage	5	carrot	0	sheep	5	sheet	0	nut	1	rod	1
cat	5	cap	15	shovel	0	shutter	0	gun	10	owl	8
chisel	0	chicken	12	tie	7	tire	5	oval	6	guitar	3
clown	0	cloud	16	whistle	6	wishbone	0	pants	2	nail	2
forest	0	fortune	11	windmill	2	window	24	ring	9	corn	9

cone	2	comb	0
cradle	6	crayon	0
knight	8	knife	2
dollar	21	dolphin	1
root	0	roof	10
stapler	4	steak	3

	Target	Foil
Avg	5.4	5.85
Stdev	6.46	5.751659

Control

Target		**Foil**	
hamster	0	engine	19
crown	12	box	17
moon	24	fly	20
palette	0	tiger	4
bear	31	nose	21

wreath	0	reel	1
viking	1	violin	1
camera	11	camel	3
asterisk	0	astronaut	0
banana	3	balloon	3
basket	4	battery	3

	Target	Foil
Avg	5.4	5.8
Stdev	8.463	8.918343

Control

Target		**Foil**	
anvil	0	vase	0
artist	23	satellite	8
snail	2	goat	2
pancakes	3	football	5
bell	7	salt	9

keg	0	grill	1
shark	0	pear	0
bone	6	cow	6
tree	21	match	19
pen	0	whale	0
witch	21	fruit	17
outlet	2	mitten	0
ink	4	mouse	4
kettle	2	potato	5
pig	2	lock	5
ladder	7	toe	8
parrot	0	onion	0
net	26	arm	21
pan	18	horse	16
patch	1	grapes	2
scissors	1	pheasant	0
phone	17	target	15
tape	11	bag	14
pie	3	mop	2
rhinoceros	0	accordian	0

peacock	0	seahorse	0	bolt	3	cake	4
puppy	0	dentist	1	butter	8	sandwich	8
collar	1	falcon	0	bull	10	pot	9
ruler	1	acorn	1	candle	1	zebra	0
sheep	5	pool	13	carriage	5	rocket	5
shovel	0	bathtub	0	cat	5	bread	14
tie	7	lip	7	chisel	0	toilet	3
whistle	6	apple	5	clown	0	yarn	1
windmill	2	cactus	0	forest	0	razor	2
wreath	0	kite	0	cone	2	flute	3
viking	1	eraser	0	cradle	6	flower	12
camera	11	poison	3	knight	8	bus	18
asterisk	0	flamingo	0	dollar	21	garage	10
banana	3	cricket	5	root	0	mask	3
basket	4	celery	1	stapler	4	peach	1

	Target	Foil
Avg	5.4	5.85
Stdev	8.463	7.617673

	Target	Foil
Avg	5.4	5.85
Stdev	6.46	4.987089

badge	3	vest	3
trunk	10	wheel	10
watch	28	suit	27
arrow	0	racoon	0
barn	5	hook	5
boat	7	jail	7

	Target	Foil
Avg	6.075	6.1
Stdev	7.651	6.89035

APPENDIX B

STIMULI FOR EXPERIMENT 2 AND CORRESPONDING WORD FREQUENCIES

Experimental Trials				Filler Trials			
List 1				**List 2**			
Competitor				**Competitor**			
Target		**Foil**		**Target**		**Foil**	
anvil	0	ant	2	anvil	0	sled	2
artist	23	artichoke	0	artist	23	satellite	8
snail	2	snake	5	snail	2	ace	4
pancakes	3	panda	0	pancakes	3	football	5
gum	7	gun	10	gum	7	ring	9
butter	8	buckle	2	butter	8	sandwich	8
bull	10	book	72	bull	10	heart	64
candle	1	cannon	7	candle	1	target	15
chisel	0	chicken	12	chisel	0	flower	12
clown	0	cloud	16	clown	0	yarn	1
puppy	0	puzzle	7	puppy	0	rabbit	5
cone	2	comb	0	cone	2	peach	1
knight	8	knife	2	knight	8	bus	18
dollar	21	dolphin	1	dollar	21	scissors	1
root	0	roof	10	root	0	dog	13
stapler	4	steak	3	stapler	4	flute	3
angle	1	anchor	2	angle	1	kettle	2
arm	21	ark	2	arm	21	tree	21
bag	14	badge	3	bag	14	train	12
bat	4	backpack	3	bat	4	grenade	2
brain	46	braces	2	brain	46	turtle	1
blender	2	blimp	0	blender	2	tee	0

boat	7	bone	6
bottle	14	box	17
lettuce	3	leopard	1
dish	4	disk	3
airplane	4	arrow	2
cashregister	0	caterpillar	4
lightbulb	0	lightning	8
cucumber	1	cube	0
maze	6	maine	2
lamp	7	lamb	2
net	26	necklace	1
peanut	1	peacock	0
pentagon	12	pencil	2
rocket	5	rockingchair	3
fireextinguisher	3	filecabinet	5
rolodex	0	rollingpin	21
glasses	9	glass	29
magnet	1	magnifyingglass	0
graveyard	2	grapes	2
truck	24	trunk	10
iron	26	eye	53

	Target	Foil
Avg	8	7.72093
Stdev	10	13.85009

Competitor Cond. 2

Target		**Foil**	
skunk	0	skull	2
moon	24	moose	0
bear	31	barrel	17

boat	7	jail	7
bottle	14	chive	0
lettuce	3	berry	2
dish	4	pipe	4
airplane	4	squirrel	2
cashregister	0	pingpongpaddle	1
lightbulb	0	monkey	3
cucumber	1	pump	2
maze	6	lip	7
lamp	7	pants	2
net	26	island	34
peanut	1	seahorse	0
pentagon	12	horseshoe	4
rocket	5	envelope	2
fireextinguisher	3	alligator	3
rolodex	0	piano	15
glasses	9	lion	9
magnet	1	refrigerator	2
graveyard	2	brush	8
truck	24	branch	10
iron	26	flag	8

	Target	Foil
Avg	8	7.72093
Stdev	10	11.06545

Control Cond. 1

Target		**Foil**	
skunk	0	harp	0
moon	24	frog	2
bear	31	nose	21

pear	0	parrot	0	pear	0	mitten	0
forest	0	fork	6	forest	0	barn	5
collar	1	column	1	collar	1	donkey	1
ruler	1	rooster	0	ruler	1	acorn	1
tie	7	tire	5	tie	7	broom	3
whisk	1	whistle	6	whisk	1	apple	5
windmill	2	window	24	windmill	2	pumpkin	7
viking	1	violin	1	viking	1	octagon	1
camera	11	camel	3	camera	11	sausage	4
banana	3	balloon	3	banana	3	needle	3
basket	4	battery	3	basket	4	celery	1
chef	6	shell	17	chef	6	fruit	17
chin	7	chimney	1	chin	7	dragon	1
sickle	16	cigar	1	sickle	16	toilet	3
clog	1	clock	10	clog	1	tank	7
corn	9	corkskrew	1	corn	9	honey	8
champagne	6	chandelier	2	champagne	6	umbrella	2
cup	18	compass	1	cup	18	platter	4
deck	4	desk	10	deck	4	salt	9
calf	2	cat	5	calf	2	goose	5
doorknob	0	door	54	doorknob	0	sun	48
dresser	3	dress	26	dresser	3	fly	20
dove	2	duck	11	dove	2	owl	8
eel	0	ear	18	eel	0	milk	15
cave	5	cake	4	cave	5	hook	5
pot	9	pocket	7	pot	9	ladder	7
elevator	4	elephant	3	elevator	4	potato	5
freighttrain	1	frame	7	freighttrain	1	cross	10
cards	11	cart	4	cards	11	bow	11
garage	10	gorilla	0	garage	10	microscope	0
swing	13	switch	6	swing	13	groom	6

screw	4	screen	7
bell	7	belt	15
helicopter	11	helmet	2
horse	16	horn	3
lock	5	lobster	1
bridge	15	brick	6
chain	23	chair	33
bowl	11	bowlingpin	2
suit	27	suitcase	3
	Target	Foil	
Avg	8	7.697674	
Stdev	8	10.4734	

screw	4	bread	14
bell	7	cheese	15
helicopter	11	shower	2
horse	16	spoon	3
lock	5	wheelchair	2
bridge	15	fox	6
chain	23	hair	35
bowl	11	strawberry	6
suit	27	diamond	4
	Target	Foil	
Avg	8	7.72093	
Stdev	8	9.330762	

REFERENCES

Allopenna, P., Magnuson, J. & Tanenhaus, M. (1998). Tracking the time course of spoken word recognition using eye movements: evidence for continuous mapping models. *Journal of Memory and Language*, *38*, 419-439.

Andrews, S., & Heathcote, A. (2001). Distinguishing common and task-specific processes in word identification: A matter of some moment? *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *27*, 514-544.

Baayen, R. H., Davidson, D. J., & Bates, D. M. (2008). Mixed-effects modeling with crossed random effects for subjects and items. *Journal of Memory and Language*, *59*, 390–412.

Balota, D. A., Aschenbrenner, A. J., & Yap, M. J. (2013). Additive effects of word frequency and stimulus quality: The influence of trial history and data transformations. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, *39*, 1563-1571.

Balota, D. A., & Spieler, D. H. (1999). Word frequency, repetition, and lexicality effects in word recognition tasks : Beyond measures of central tendency. *Journal of Experimental Psychology: General*, *128*, 32-55.

Balota, D. A., & Yap, M. J. (2011). Moving beyond the mean in studies of mental chronometry: The power of response time distributional analyses. *Current Directions in Psychological Science*, *20*, 160-166.

Balota, D. A., Yap, M. J., Cortese, M. J., Hutchison, K. A., Kessler, B., Loftis, B., Neely, J. H., Nelson, D. L., Simpson, G. B., & Treiman, R. (2007). The English Lexicon Project. *Behavior Research Methods*, *39*, 445-459.

Balota, D. A., Yap, M. J., Cortese, M. J., & Watson, J. M. (2008). Beyond mean response latency: Response time distributional analyses of semantic priming. *Journal of Memory and Language*, *59*, 495-523.

Bates, D., Maechler, M., & Bolker, B. (2011). lme4: Linear mixed-effects models using S4 classes. R package version 0.999375-42.

Bergelson, E., & Dahan, D. Preferred labels for objects influence but do not stifle lexical competition in the visual-world paradigm. *Psychonomic Society Annual Meeting*. Minneapolis, Nov. 2012.

Brown, S., & Heathcote, A. (2003). QMLE: Fast, robust and efficient estimation of distribution functions based on quantiles. *Behavior Research Methods, Instruments & Computers*, *35*, 485-492.

Brysbaert, M., & New, B. (2009). Moving beyond Kučera and Francis: A critical evaluation of current word frequency norms and the introduction of a new and improved word frequency measure for American English. *Behavior Research Methods*, *41*, 977-990.

Dale, R., Kehoe, C., & Spivey, M. J. (2007). Graded motor responses in the time course of categorizing atypical exemplars. *Memory & Cognition*, *35*(1), 15-28.

Eberhard, K.M, Spivey-Knowlton, M.J., Sedivy, J.C. & Tanenhaus, M.K. (1995). Eye movements as a window into real-time spoken language comprehension in natural contexts. *Journal of Psycholinguistic Research*, *24*, 409-436.

Farmer, T. A., Anderson, S. E., & Spivey, M. J. (2007). Gradiency and visual context in syntactic garden-paths. *Journal of Memory and Language*, *57*, 570-595.

Freeman, J.B. & Ambady, N. (2009). Motions of the hand expose the partial and parallel activation of stereotypes. *Psychological Science*, *20*, 1183-1188.

Freeman, J.B. & Ambady, N. (2010). MouseTracker: Software for studying real-time mental processing using a computer mouse-tracking method. *Behavior Research Methods*, *42*, 226-241.

Freeman, J.B. & Dale, R. (2013). Assessing bimodality to detect the presence of a dual cognitive process. *Behavioral Research Methods*, *45*, 83-97.

Freeman, J.B., Dale, R. & Farmer, T.A. (2011). Hand in motion reveals mind in motion. *Frontiers in Psychology*, *2*, 59.

Goh, W. D., Suárez, L., Yap, M. J., & Hui Tan, S. (2009). Distributional analyses in auditory lexical decision: Neighborhood density and word frequency effects. *Psychonomic Bulletin & Review*, *16*, 882-887.

Hartigan, J. A., & Hartigan, P. M. (1985). The dip test of unimodality. *Annals of Statistics*, *13*, 70-84.

Johnson, R. L., Staub, A., & Fleri, A. M. (2012). Distributional analysis of the transposed-letter neighborhood effect on naming latency. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *38*, 1773-1779.

Kennedy, A., & Baccino, T. (1995). The effects of screen refresh rate on editing operations using a computer mouse pointing device. *The Quarterly Journal of Experimental Psychology*, *48A* (1), 55-71.

Koop, G. J., & Johnson, J. G. (2013). The response dynamics of preferential choice. *Cognitive Psychology*, *67*, 151-185.

Maechler, M. (2012). *diptest: Hartigan's dip test statistic for unimodality – corrected code*. R package version 0.75-1. Available online at: http://CRAN.R-project.org/package=diptest.

Magnuson, J.S., Dixon, J.A., Tanenhaus, M.K. & Aslin, R.N. (2007). The dynamics of lexical competition during spoken word recognition. *Cognitive Science*, *31*, 1-24.

Marslen-Wilson, W. D. (1987). Functional parallelism is spoken word recognition. *Cognition*, *25*, 71-102.

Matzke, D., & Wagenmakers, E.-J. (2009). Psychological interpretation of the ex-Gaussian and shifted Wald parameters : A diffusion model analysis. *Psychological Bulletin & Review*, *16*, 798-817.

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

Pfister, R., Schwartz, K. A., Janczyk, M., Dale, R., & Freeman, J. B. (2013). Good things peak in pairs: A note on the bimodality coefficient. *Frontiers in Psychology*, *4*, 1-4.

Plourde, C. E., & Besner, D. (1997). On the locus of the word frequency effect in visual word recognition. *Canadian Journal of Experimental Psychology*, *51*, 181-194.

Ratcliff, R. (1979). Group reaction time distributions and an analysis of distributional statistics. *Psychological Bulletin*, *86*, 446-461.

Sandfeld, J. & Jensen, B.R. (2005). Effects of computer mouse gain and visual demand on mouse clicking performance and muscle activation in a young and elderly group of experienced computer users. *Applied Ergonomics*, *36*, 547-555.

SAS Institute Inc. (1990). *SAS/STAT user's Guide,* Version 6, 4th Edn. Cary, NC: Author.

Schmiedek, F., Oberauer, K., Wilhelm, O., Süß, H.-M., & Wittmann, W. W. (2007). Individual differences in components of reaction time distributions and their relations to working memory and intelligence. *Journal of Experimental Psychology: General*, *136*, 414-429.

Snodgrass, J. G., & Vanderwart, M. (1980). A standardized set of 260 pictures: Norms for name agreement, image agreement, familiarity, and visual complexity. *Journal of Experimental Psychology: Human Learning and Memory, 6,* 174–215.

Song, J.-H., & Nakayama, K. (2008). Target selection in visual search as revealed by movement trajectories. *Vision Research*, *48*, 853-861.

Spivey, M. J., & Dale, R. (2006). Continuous dynamics in real-time cognition. *Current Directions in Psychological Science*, *15*, 207-211.

Spivey, M.J., Grosjean, M. & Knoblich, G. (2005). Continuous attraction towards phonological competitors. *Proceedings of the National Academy of Sciences*, *102*, 10393-10398.

Staub, A. (2011). The effect of lexical predictability on distributions of eye fixation durations. *Psychonomic Bulletin & Review*, *18*, 371-376.

Staub, A., White, S. J., Drieghe, D., Hollway, E. C., & Rayner, K. (2010). Distributional effects of word frequency on eye fixation durations. *Journal of Experimental Psychology: Human Perception and Performance*, *36*, 1280-1293.

Strauss, T. J., Magnuson, J. S., & Harris, H. D. (2005). jTRACE: A reimplementation and extension of the TRACE model of speech perception and spoken word recognition. *Proceedings of the 27th Annual Conference of the Cognitive Science Society*.

Tomlinson, J. M., Jr., Baily, T. M., Bott, L. (2013). Possibly all of that and then some: Scalar implicatures are understood in two steps. *Journal of Memory and Language*, *69*, 18-35.

van der Wel, R.P.R.D., Eder, J.R., Mitchel, A.D., Walsh, M.M. & Rosenbaum, D.A. (2009). Trajectories emerging from discrete versus continuous models in phonological competitor tasks: A commentary on Spivey, Grosjean, and Knoblich (2005). *Journal of Experimental Psychology: Human Perception and Performance*, *35*, 588-594.

van Gompel, R .P. G., Pickering, M. J., & Traxler, M. J. (2000). Unrestricted race: A new model of syntactic ambiguity resolution. In: A. Kennedy, R. Radach, D. Heller, & J. Pynte (Eds.), Reading as a perceptual process (pp. 621-648). Oxford: Elsevier.

Vincent, S. B. (1912). The function of vibrissae in the behavior of the white rat. *Behavioral Monographs*, *1*(Whole No. 5).

Yap, M. J., & Balota, D. A. (2007). Additive and interactive effects on response time distributions in visual word recognition. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *33*, 274-296.