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# PUPIL SIZE AS A PHYSIOLOGICAL CORRELATE FOR FACILITATORY AND INHIBITORY EFFECTS IN MASKED PRIMING

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Partial fulfillment of the

Requirements for the Degree of

Masters of Science

BY

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# VITA

The author was born in Arlington Heights, Illinois, February 16, 1987. He graduated from West Leyden High School, received his Bachelor of Arts degree from Concordia University of Chicago in 2009.

# TABLE OF CONTENTS

# List of Tables

List of Figures

# CHAPTER I

## INTRODUCTION

In word recognition, priming occurs when identification of a target is facilitated or inhibited by a related word or nonword prime compared to an unrelated word or nonword control prime. A fruitful method to assess factors subserving word recognition is the masked priming paradigm, originally developed by Forster and Davis (1984). In a prototypical masked priming experiment, a fixation point (500 milliseconds) serves as a forward mask, usually a row of seven hash marks. The mask is immediately followed by the prime, usually for 60 milliseconds. Subsequently, the target string supplants the prime, which remains on the screen until a participant makes a word/nonword decision. Many studies employing this procedure assess the orthographic similarity of word and nonword primes to targets, and how this relationship affects identification (Bijeljac-Babic, Biardeau, & Grainger, 1997; Davis & Lupker, 2006; Forester & Davis, 1984; Grainger, Cole, & Segui, 1991; Massol, Grainger, Dufau, & Holcomb, 2010; Nakayama, Sears, & Lupker, 2008, 2010). Purportedly, the procedure allows examination of unconscious, automatic factors (the prime is presented with short stimulus onset asynchronies), which influence recognition without relying on conscious strategies (e.g., figuring out the relationship between the prime and the target). Therefore, researchers can attribute effects to lexical organization, not cognitive resources. Much debate exists, however, on the role orthography plays in word recognition. That is, what effect do orthographic related neighbors (see Coltheart, Davelaar, Johnasson, & Besner, 1977, for a detailed discussion on neighborhood size) *really* have on lexical access?

To date, mostly behavioral measures (e.g., RTs) have analyzed the existence of facilitatory and inhibitory effects associated with orthographic related word and nonword primes; however, a physiological measure, pupil size, used in conjunction with a behavioral measure, can potentially corroborate the effects found when examining orthographic relatedness (i.e., inhibition and facilitation), as well as possibly contribute an alternative methodological tool to assess effects associated with lexical processing. Pupil dilation has been shown to correlate with central nervous system activity, making it an observable index of human cognitive processing in the brain (Beatty & Lucero-Wagoner, 2000). The sympathetic and parasympathetic systems regulate pupil dilation in the autonomic nervous system, with the sympathetic system being sensitive to emotionally arousing material, as well as mental effort, or cognitive load (Beatty & Lucero-Wagoner, 2000; Steinhauer, Siegle, Condray & Pless, 2004). In masked priming, orthographically related word primes often produce inhibitory effects, resulting in longer latencies for identifying the target word; orthographically related nonword primes produce facilitatory effects, resulting in shorter latencies for identifying the target word (e.g., Colombo, 1986; Davis & Lupker, 2006). Ostensibly, longer latencies would be indicative of more cognitive effort, and shorter latencies would suggest less cognitive effort. Therefore, pupil size should serve as a correlate for the effects found in masked priming studies. Overall, the combining of behavioral and physiological measures help increase the validity of a construct or model, in this case, facilitatory and inhibitory effects associated with an activation-based model of word recognition.

## Facilitatory and Inhibitory Effects in Masked Priming

One of the most popular models for explaining facilitatory and inhibitory effects in masked priming is the Interactive Activation (IA) Model (McClelland & Rumelhart, 1981). McClelland and Rumelhart's (1981) IA model makes explicit assumptions and predictions that guide word recognition theory. Theoretically, the IA model works at three different levels: presentation of a word first activates the feature level, followed by the letter level, and then the word level, in a process that culminates in the recognition of the word. The links or nodes between levels are facilitatory, and there is intra-level inhibition at the word level. For example, if the first letter position in a word is "b," the letter "b" receives activation from the feature, letter, and word level for words sharing the letter "b" in the first position. This process occurs for each letter in the word. Words that share letters in the same positions compete with one another until one word, the target, becomes more activated and finally recognized. For example, let us take the high frequency word prime *blue*, and the low frequency word target *BLUR*. *Blue* is activated at the word level, and in order to correctly identify the target word *BLUR*, inhibitory processes, at the word level, need to occur before recognition. One of the main features of the IA model is that it takes into account competition from other, orthographically similar words. For example, if the high frequency word prime *blue* precedes the low frequency target word *BLUR*, much more competition arises due to orthographic overlap, as well as word frequency (higher frequency word primes serve as stronger competitors; e.g., Nakayama, Sears, & Lupker, 2008, 2010), therefore producing longer recognition latencies due to the relative prime not being resolved. Conversely, nonword primes do not ever reach the word level of representation; related nonword primes pre-activate processing of the target, resulting in shorter latencies compared to unrelated nonword primes (e.g., Davis & Lupker, 2006; Forster, 1987). Results obtained from masked priming paradigms examining orthographically similar word primes support the assumptions broached by activation-based models (e.g., IA model; see Andrews, 1997; Coltheart, Davelaar, Jonasson, & Besner, 1977; Davis & Lupker, 2006; De Moor & Brysbaert, 2000; Grainger, O'Regan, Jacobs, & Segui. 1989). In sum, The IA model provides a useful framework for explaining masked priming effects.

The IA model predicts inhibitory effects from orthographically related word primes and facilitatory effects for related nonword primes because of representation in the lexicon. This is because words appear in the lexicon while nonwords do not. There are discrepancies, however, in the results obtained using related word primes in the masked priming paradigm. For example, some studies found inhibitory effects (e.g., Colombo, 1986; Davis & Lupker, 2006; Bijeljac-Babic, Biardeau, & Grainger, 1997; Segui & Grainger, 1990), while others found facilitation or null effects (e.g., Forster, 1987; Forster & Veres, 1998; Grainger, Cole, & Segui, 1991; Nakayama et al., 2010). Conversely, it is clear nonword primes reliably elicit facilitation or null effects (Colombo, 1986, Experiment 1; Davis & Lupker, 2006; Forster, 1987; Forster & Veres, 1998). One of the main reasons for these discrepancies centers on the complicated nature of the English language. Some studies using English stimuli failed to produce the inhibitory effects predicted by the IA model (e.g., Forster & Sheen, 1996; Sears, Campbell, & Lupker, 2006) while studies using word lists in others languages (e.g., Dutch and Hebrew; Bijeljac-Babic et al., 1997; De Moor & Brysbaert, 2000; Drews & Zwitserlood, 1995, Experiment 3B) produced these effects. Nonetheless, an important test of the IA model is utilizing a procedure incorporating both word and nonword primes to test its assumptions. If the related word primes induce longer latencies, and thus act as competitors, and related nonword primes induce shorter latencies, the best way to test the effects of orthographic relatedness is in a mixed design. The utilization of this procedure is sparse, and as of now, only the Davis and Lupker (2006) study show clear facilitation and inhibitory effects in a single experiment using English stimuli. Therefore, to test the validity of the effects observed, both word and nonword primes need examination in isolation. In sum, the results obtained by Davis and Lupker are congruent with the assumptions made by the IA model. The paradigm proposed allows for further testing of the IA model, utilizing a new methodology, pupillometry.

## Factors Affecting Pupil Size

Psychological research examining factors mediating pupil size spans approximately 50 years (Laeng, Sirois, & Gredback, 2012). One widely known factor affecting pupil size is luminance. When light reaches the eye, the sphincter pupillae, innervated by parasympathetic nerves, constrict the pupil (Beatty & Lucero-Wagoner, 2000). Conversely, factors such as arousal, emotion/valence, and mental effort engender pupil dilation. Dilation occurs when stimulation of the dilator pupillae, innervated by sympathetic nerves from the superior cervical ganglion, reduces the size of the iris and increases the size of the pupil (Beatty & Lucero-Wagoner, 2000). Under constant illumination, the neurotransmitter norepinephrine (NE) released form the locus coeruleus mediates pupil dilation in tasks involving memory, attention, and behavioral decisions (Einhauser, Koch, & Carter, 2010; Laeng et al., 2012).

Pupil dilation provides accurate indices of cognitive and emotional processing. Early research posited that positive stimuli made pupils dilate, and negative stimuli made them constrict (Hess, 1965). For example, pictures of arousing, pleasant stimuli (e.g., female pin-ups) caused greater pupil dilation than unpleasant stimuli. The assumption of pupil dilation differing for negative and positive/pleasant stimuli proved inaccurate (see Janisee, 1974). Both negative and positive stimuli elicit pupil dilation (Partala & Surakka, 2003). Aside from the affective component indexed by the papillary system, cognitive load or task complexity plays a role in pupil dilation.

Research suggests pupil dilation is a direct measure for assessing complexity of a task (Beatty & Wagoner, 1971; Bijleveld, Custers, & Aart, 2009; Hess, 1965; Hess & Polt, 1964; Kahneman & Beatty, 1966; Kuchinke, Vo, Hofmann, & Jacobs, 2007). Tasks testing memory provide evidence for the interrelationship between pupil dilation and task complexity. In an early experiment assessing pupil dilation, Kahneman and Beatty (1966) subjected participants to a short-term memory recall task (participants recalled digits). Pupil diameter increased when number of items, or digits to be recalled increased, as well as when the task complexity increased (participants had to transform the digits: add 1 to each digit at recall). Furthermore, in relation to word recognition, pupillometry provides an accurate measure of word frequency (e.g., Papesh & Goldinger, 2012; Kuchinke et al., 2007). For example, in

Kuchinke et al.'s (2007) study, 28 participants engaged in a lexical decision task on a list of words of varying valence. The valence of the words did not produce pupil dilation. Low frequency words, however, did. Individuals can correctly identify high frequency words with relative ease, but low frequency words take more effort, resulting in an increase in pupil size.

Finally, pupil dilation is sensitive to the effect of primes in relation to task complexity. Bijleveld et al. (2009) found that higher monetary rewards (50 cents compared to 1 cent) engendered greater pupil dilation insofar as the task was more complex; thus suggesting that stimuli at the subliminal level can have an effect on pupil size. Overall, these studies suggest that pupil size is highly sensitive to the demands of a task.

No other study, to my knowledge, examined pupil dilation as a correlate for masked priming effects. Some studies, however, used eye measurements (i.e., fixations and gaze) as correlates for inhibitory effects caused by related word primes (i.e, the neighborhood frequency effect; Gringer, O'Regan, Jacobs, and Segui, 1989). Gaze and fixation, like pupil size, assesses task difficulty (e.g., Pateron, Liversedge, & Davis, 2009; Perea & Pollatsek, 1998; Sears et al., 2006). Two studies (i.e., Paterson et al., 2009; Perea & Pollatsek, 1998) observed longer fixations and gaze when the target word was preceded by a related high frequency word prime. Sears et al. (2006) had contrasting results, denoting inhibitory effects in one experiment (i.e., longer reaction times and gaze), but failing to find these effects in their other experiments. As seen, eye measurements, such as fixation and gaze, show sensitivity to inhibitory effects in word recognition, making the exploration of pupil dilation a worthwhile endeavor.

Overall, mental effort and pupil dilation share a strong association. Pupil dilation controlled by the sympathetic nervous system reacts to task difficulty; pupil size increases when asked to recall difficult information, such as digit transformation or multiplication, and immediately subsides after recall (Hess & Polt, 1966; Kahneman & Beatty, 1966). Pupil dilation is sensitive to task demand and difficulty, making it an ideal tool, potentially, to examine inhibitory and facilitatory effects hypothesized to occur according to the IA model.

## Rationale

There is not a clear consensus in the masked priming literature on inhibitory effects. There is much contention regarding the effects of word primes. Do word primes engender inhibitory, facilitatory, or null effects? If a physiological correlate such as pupil size shows sensitivity to both word prime induced inhibitory effects and nonword prime induced facilitatory effects, it could provide researchers with a new tool to analyze the role of orthography, and other factors in word recognition.

Reaction times for orthographically similar nonword primes preceding a word target produced shorter latencies than a word prime paired with a word target (Davis & Lupker, 2006). More specifically, related high frequency word primes preceding low frequency target word pairs should produce the most inhibition because higher frequency primes are more powerful competitors, thus resulting in slower latencies; nonword related primes, on the other hand, elicit no competition due to having no lexical representation, thus yielding faster latencies (Davis & Lupker, 2006; Nakayama, Sears, & Lupker, 2008, 2010; Segui & Grainger, 1990).

In the lexical decision task employed by Kuckinke et al. (2007), pupil dilation and reaction times correlated with word frequency. Specifically, higher frequency words engender shorter latencies and less pupil dilation and low frequency words produce longer reaction times and more pupil dilation. Thus, hypothetically, pupil size and reaction times in a masked priming paradigm should be correlated as well. Longer latencies for related high word prime-lower frequency target pairs should be positively associated with mental effort, producing greater mean pupil dilation. The opposite should be true for nonword primes. Related high word prime-lower frequency target pairs produce more competition and thus should involve more mental effort than nonword primes.

Reaction times and pupil dilation in this study serve as dependent measures to assess target frequency and prime relatedness. Study 1 examined inhibitory effects of orthographically similar word primes. In study 2, nonword prime lists (taken from Davis & Lupker, 2006) tested facilitatory effects.

## Statement of Hypotheses

Study 1

Hypothesis I. I predict a main effect for the factor of target frequency. Individuals respond to higher frequency targets faster than to lower frequency or nonword targets. Further, higher frequency targets elicit smaller pupil size than low frequency targets.

Hypothesis II. I predict a main effect for the factor of prime relatedness. Related word responses will be slower than unrelated word response. Further, related primes elicit larger pupil size than unrelated primes. I predict no difference between related and unrelated nonword targets

Hypothesis III. I predict an interaction between frequency and relatedness. Specifically, related high frequency primes-low frequency target pairs engender longer latencies compared to unrelated high frequency-low frequency primes, and related/unrelated low frequency prime-high frequency target pairs, therefore producing stronger inhibitory effects. Further, more pupil dilation results for related, high frequency prime-low frequency targets than for unrelated high frequency prime-low frequency target pairs, and related/unrelated low frequency prime-high frequency target pairs/

Study 2

Hypothesis I. I predict a main effect for the factor of target frequency. Higher frequency target responses are much quicker for lower frequency or nonword targets. Further, higher frequency targets have smaller pupil size than low frequency targets.

Hypothesis II. I predict a main effect for the factor of prime relatedness. Related nonword primes produce faster responses than unrelated nonwords. Further, related primes elicit smaller pupil dilation than unrelated primes. I predict no relatedness effect for related and unrelated nonword targets.

Hypothesis III. I predict an interaction between target frequency and prime relatedness. Specifically, related primes-low frequency target pairs engender shorter latencies compared to unrelated prime-low frequency target pairs and related/unrelated prime-high frequency target pairs , therefore producing stronger facilitatory effects. Further, related prime-low frequency target pairs elicit smaller pupil sizes than unrelated prime-high frequency target pairs, and related/unrelated prime-high frequency target pairs.

# CHAPTER II

# METHOD (STUDY 1)

The first study serves to explore the relationship between physiological (i.e., pupil dilation) and behavioral measures (i.e., RTs) in a masked priming experiment using only word primes. More specifically, can related word primes cause inhibition and increase pupil size?

## Participants

Twenty-three (n=23) students from DePaul's psychology department's automated sign-up system agreed to participate in the study. Participants received one and a half points of credit to fulfill a general psychology requirement Participants had normal-to-corrected normal vision.

## Stimuli

64 pairs of words and 32 pairs of nonword targets are used. The words and nonwords are 4-5 letters long, adopted from Davis and Lupker (2006). Each pair of words consisted of either a high frequency target, related or unrelated low frequency word prime, or a low frequency target, related or unrelated high frequency word prime. Nonword targets were preceded by related or unrelated word primes. Each of the word pairs consisted of a high frequency word (Kucera & Francis, 1967, mean frequency= 365.5, N=2.2) and a low frequency (Kucera & Francis, 1967, mean

frequency=5.4, N=2.4) word. For the related conditions, if a high frequency word is designated as the target, a low frequency, related word will be the prime and vice versa. The related word prime differs from the target word by one letter (e.g., *blur-BLUE*) to produce a high level of orthographic overlap, which should induce competition effects. For the unrelated word conditions, if a high frequency word is designated as the target, a low frequency, unrelated word is the prime (Kucera & Francis, 1967, mean frequency = 7.8, N = 2.4) and if the target is of low frequency, a high frequency, unrelated word is the prime (Kucera & Francis, 1967, mean frequency = 370.7, N = 2.5). The unrelated word pairs differed on every letter position (e.g., round-SKATE). Related and unrelated words prime nonword targets similarly. For the related word prime-nonword target pairs, the word prime (Kucera & Francis, 1967, mean frequency = 24.4, N = 3.4) differed from the nonword target at one letter position. For the unrelated condition, the word prime (Kucera & Francis, 1967, mean frequency = 20.0, N = 3.9), differed from the nonword target at every letter position. Appendix A lists stimuli used.

Four different counterbalances, with 96 word and nonwords, were created. Each of the four lists comprised 64 word targets and 32 nonword targets with a length of 4 to 5 letters. In all four lists, related and unrelated high frequency words, low frequency words, and nonwords counterbalanced one another.

Experimental Procedure and Apparatus

Data was collected using a desk-mounted EyeLink 1000 eye tracker (SR Research, Mississauga,Ontario,Canada) positioned 40 inches from the display PC, and sampling at 1000 Hz. Viewing was binocular, but only the left eye was sampled. Stimuli were displayed on a 20-inch CRT monitor set at 1024 x 769 pixel resolution. Pupil data collection occurred on a computer adjacent to the display PC. SR Research Experiment Builder software created the experiment. Additionally, participants used a gamepad to input their responses.

Testing occurred individually. Before each session, calibration and validation of participants' eyes ensured gaze accuracy during the experiment. To calibrate, participants followed a small circle as it moved around the screen. Recalibration, using the same methods aforementioned, occurred as needed. Each trial consisted of five events: (1) a pre-fixation stimulus for 1500 ms; (2) a forward mask on the screen for 500 ms; (3) a prime, in all lowercase letters, following the mask, for 58 ms; (4) the target word, in all uppercase letters, appearing immediately after the prime, and remaining on the screen until a response on the gamepad is made; and (5) a post-fixation stimulus remaining on the screen for 6000 ms. Each of the stimuli appeared at the center of the screen.

Words appeared on screen in black print on a white background. The words appeared in Arial font, size 40. Measurement of reaction times took place from target onset until the participant made a response. Pupil dilation measurement occurred throughout the duration of the trial.

Twenty-eight practice trials preceded the 96 experimental trials. Participants were instructed to press the left trigger of the gamepad for nonword strings and the right trigger for word strings. After a response, the target disappeared from the screen and a post-fixation stimulus (6000 ms) supplanted the target. Each participant received one of the four counterbalanced lists. The experiment lasted approximately 30 minutes.

Pupil Data Preparation and Analysis

Pupil data were prepared using code written in AWK and R. Major blinks and artifacts were removed from analysis, and pupil size was linearly interpolated for the missing data. Pupil data was examined from a time window between 200 ms before stimulus onset until 4800 ms. Baseline pupil diameter was defined as the average pupil diameter recorded during 200 ms (prefixation stimulus) and subtracted from the raw pupil data. Raw pupil data was then standardized to a mean of 0 and a standard deviation of 1. The standardized mean pupil dilation for each trial served as the dependent variable. Luck (2005) made explicit several advantages to using the mean instead of peak amplitude (cf. Kuchinke et al., 2007) in relation to psychophysiology data. Two of those advantages being: (1) less sensitivity to noise and (2) leniency when using longer measurement windows.

Separate 2 (relatedness: related vs. unrelated) x 2 (frequency: high vs. low) ANOVAs with RTs as one dependent variable, and mean pupil dilation as another dependent variable, assessed mean differences. For the behavioral data, by subjects, the factors of frequency and relatedness were treated as within-subject factors; by items, relatedness was treated as a within-item factor, and frequency as a between item factor. For the physiological data, mean pupil data were examined within-subjects. For both behavioral and pupil data, nonwords were analyzed separately, using *t*-tests to examine mean differences.

# CHAPTER III

## Results (STUDY 1)

Incorrect responses (7 %) and latencies longer than 2,000 ms and shorter than 300 ms (4 %) were excluded from RT analysis. To assess the validity of the hypotheses and research question purposed above, a 2 (relatedness: related vs. unrelated) x 2 (target frequency: high vs. low) ANOVA was run, both by subject $F_1$ and by items $F_2$ (see Clark, 1973). For within-subject analysis, prime relatedness and target frequency served as within-subject variables; for within-item analysis, prime relatedness served as a within-item factor and target frequency served as a between-item factor. For all nonword targets, *t*-tests, by subject and by item, examined mean differences between related and unrelated word primes. A .05 alpha level tested hypotheses unless otherwise specified. Table 1 lists mean latencies and error rates for the subject analysis.

For the pupil data, incorrect responses, RT outliers, and trials where a blink occurred during a response, were excluded from analysis (11 % of the data). A within-subjects design, with relatedness and frequency as independent variables, assessed mean differences in pupil size.

Table 1

*Latencies (in Milliseconds) and Error Rates (in Percentages) for Word and Nonword Targets as a Function of Prime Relatedness and Word Frequency*

| | Word Target |
|---|---|

| | High frequency | Low Frequency | Nonword |
|---|---|---|---|
| Related | 727 (.02) | 838 (.16) | 935 (4.0) |
| Unrelated | 704 (.02) | 835 (.12) | 978(4.3) |
| Effect | -23 (0) | -3 (-.14) | +43 (+0.3) |

Hypothesis I

Hypothesis I suggested a word frequency effect for the behavioral and physiological data. Specifically, low frequency words produce longer latencies and increased pupil size.

Examining the behavioral data, the effect of word frequency was significant, word frequency was the only significant main effect in both analyses, $F_1$(1,22) = 106.70, *MSE* = 3,021, $p < .001$; $F_2$ (1, 249) =75.95, *MSE* =14,198, $p < .001$. Low frequency words had longer latencies than high frequency words. Examination of the error rates partially confirmed this. Error rates between low frequency and high frequency words were significant by subject, $F_1$(1,19) = 5.41, $p = .03$. In the item analysis, the main effect was marginally significant, $F_2$(1,53) = 3.10, $p = .08$. Participants made more errors for low frequency words than high frequency words. Moreover, the pupil data yielded null results. The word frequency effect did not reach significance, *F*(1,22) = .43, *ns*.

Hypothesis 2

Hypothesis 2 suggested that related word primes would result in longer latencies compared to unrelated word primes, as well as increase pupil size. The hypothesis of relatedness in both analyses were disconfirmed for low and high frequency target pairs—no significant differences existed between RTs, $F_1$(1,22) = 1.22, *MSE* = 3,233, *ns*, $F_2$(1,249) = 1.27, *MSE* = 14,918, *ns*, or pupil size, *F*(1,22) = .16, *ns*, although the inhibitory trend (i.e., longer RTs for related word primes vs. unrelated word primes) in the RT data lend support to the hypothesis. Error responses between related and unrelated words were also non-significant, $F_1$(1,19) = .37, *ns*; $F_2$(1,53) = .62, *ns*. Analysis of nonword target responses resulted in a marginally significant, by subject, relatedness effect, $t_1$ (22) = -1.76, *p* = .09, as well as a marginally significant by item relatedness effect, $t_2$(62) = -1.82, *p* = .07. Furthermore, error responses showed no significant differences between related and unrelated nonword targets (*t*s < 1). Moreover, related word primes did not elicit greater pupil dilation than unrelated word primes, either for word targets, *F*(1,22) = .77, *ns*, or nonword targets, *t*(22) = .32, *ns*.

Hypothesis 3

Hypothesis 3 suggested an interaction between frequency and relatedness. Specifically, related high frequency primes-low frequency target pairs engender longer latencies compared to unrelated high frequency prime-low frequency target pairs, therefore producing stronger inhibitory effects. Further, there will be more pupil dilation for related, high frequency prime-low frequency target than for unrelated high frequency prime-low frequency targets. Reaction time analysis yielded nonsignificant results, $F_1$ (1, 22) = .60, *MSE* = 2,672, *ns*; $F_2$ (1, 249) = .68, *MSE* = 14,918, *ns*. Further, error responses were not significantly different, $F_1$ (1, 19) = .26, ns; $F_2$ (1,53) = .39, *ns*. Finally, pupil size did not differ between conditions, *F*(1,22) = .34, *ns*, thus disconfirming the hypothesis. See table 3 for mean pupil sizes for each condition.

Table 3

*Standardized Mean Pupil Size and Standard Deviation, In Parentheses, for Word and Nonword Targets as a Function of Word Prime Relatedness and Word Frequency*

| | *Word Target* | | |
|---|---|---|---|
| | High frequency | Low Frequency | Nonword |
| Related | .05(.36) | .03 (.37) | .00 (.51) |
| Unrelated | .02(.30) | .06 (.35) | .11 (.37) |
| Effect | -.03 | +.03 | +.11 |

# Chapter IV

## Discussion (STUDY 1)

The results from both sets of data, behavioral and physiological, do not corroborate the hypotheses proposed. Importantly, the results, using word primes, are incongruent with the obtained results of Davis and Lupker (2006), using similar word lists. Similarity did exist between this study and that of Davis and Lupker when examining target frequency using latency measures (i.e., hypothesis 1); that is, low frequency words produced longer latencies than high frequency words. The pupil data, however, did not show similar word frequency trends (cf. Kuchinke et al., 2007). Related word primes compared to unrelated word primes showed no mean differences in latency, which is antithetical to assumptions made by lexical access models (i.e., IA Model; McClelland & Rumlehart, 1987). In fact, word primes produced null effects. The discrepant results are not rare when using word primes. Several researchers obtained facilitatory and null effects (see Colombo, 1986; Davis & Lupker, 2006; Bijeljac-Babic, Biardeau, & Grainger, 1997; Grainger & Ferrand, 1994; Segui & Grainger, 1990). Moreover, just as the behavioral data did not elicit significant effects, the physiological data did not either. Pupil size did not differ between conditions. If related word primes resulted in more competition between the prime and the target, as inferred by increased latency, there should have been a difference in mean pupil size, which there was not. Overall, these results further add to the discrepancy of orthographically related word primes on target recognition obtained using the masked priming procedure.

# Chapter V

## Method (STUDY 2)

The goal of study 2 assesses, through reaction times and pupil sizes, whether related nonword primes produce shorter latencies than unrelated nonword primes, thus resulting in facilitation. As in study 1, this is an experimental study.

## Participants

Nineteen participants (*n*=19) from DePaul's psychology department's automated sign-up system agreed to participate in the study. Participants received one and a half points extra credit for their participation. Participants had normal-to-corrected normal vision.

## Stimuli

The target words in this experiment were identical to the ones in study 1. The main difference is nonword primes replaced the word primes from the first study. The stimuli list comprised 64 pairs of words and 32 pairs of nonword targets. The words and nonwords were 4 to 5 letters in length. The nonword prime, related conditions, consisted of either a high frequency (mean prime N = 2.2) or low frequency target (mean prime N = 2.2), with a nonword prime differing from the target word by one letter. For the unrelated conditions, unrelated nonword primes preceded high (mean prime N = 2.4) or low frequency (mean prime N = 2.5) targets. Nonword unrelated primes did not share any letter positions with the target. For the related nonword prime-nonword target pairs, the nonword prime (N = 3.6) differed from the nonword target at one letter position. For the unrelated condition, the nonword prime (N = 3.3) differed from the Nonword target at every letter position. Appendix B lists all stimuli used.

For nonword targets, creation of four different counterbalances with equal pairs was required. Each of the four lists consists of 96 pairs of

4 to 5 letter word and nonword targets. In all four lists, high frequency, low frequency, and nonwords counterbalance one another.

## Experimental Procedure and Apparatus

Study 2 used a similar experimental procedure and apparatus to that of Study 1. The only difference being, related and unrelated nonword primes preceded the presentation of the target.

## Pupil Data Preparation and Analysis

Pupil data, as well as the behavioral RT data, were prepared and analyzed in the same way as study 1.

# Chapter VI

Results (STUDY 2)

For the behavioral data, incorrect responses (8 %) and latencies longer than 2,000 ms and shorter than 300 ms (1%) were excluded from analysis. To assess the validity of the hypotheses and research question purposed above, a 2 (relatedness: related vs. unrelated) x 2 (target frequency: high vs. low) ANOVA was run, both by subjects $F_1$ and items $F_2$ (see Clark, 1973). For within-subject analysis, prime relatedness and target frequency served as within-subject variables; for within-item analysis, prime relatedness and target frequency served as between-item variables. Nonword targets preceded by related and unrelated nonword primes were analyzed with *t*-tests, by subject, $t_1$, and by item, $t_2$. Table 2 lists mean latencies and error rates for the by subject analysis.

For the pupil data, incorrect responses, RT outliers, and trials in which a blink or saccade occurred during a response, were excluded from analysis (11% of the data). A within-subjects design, with relatedness and frequency as independent variables, assessed mean differences in pupil size.

Table 2

*Latencies (in Milliseconds) and Error Rates (in Percentages) for Word and Nonword Targets as a Function of Prime Relatedness and Word Frequency*

| | *Word Target* | | |
|---|---|---|---|
| | High frequency | Low Frequency | Nonword targets |
| Related | 648 (.01) | 728 (.16) | 828 (6.9) |
| Unrelated | 649 (.01) | 776 (.12) | 844 (6.8) |
| Effect | + 1 (0) | + 48 (-0.4) | + 16 (-0.1) |

Hypothesis I

Hypothesis I suggested a word frequency effect for the behavioral and physiological data. Specifically, low frequency words have longer latencies and engender increased pupil size. The hypotheses purposed were partially confirmed. Similar to study 1, the main effect of frequency was significant in both RT analyses, $F_1$(1,18) = 67.90, *MSE* = 3,011, $p <$ .001; $F_2$(1,248) = 48.28, *MSE* = 16,758, $p < .001$. Error rates between low frequency and high frequency words showed a significant difference by subject, $F_1$ (1,18) = 11.77, $p = .00$, but not by item, $F_2$(1,54) = .12, *ns*. Low frequency words had more errors than high frequency words. Moreover, in the pupil analysis, word frequency did not produce differences in pupil size, *F*(1,18) = .41, *ns*. Although the word frequency effect was non-significant, high frequency words (*M* = .04, *SD*= .36) showed less pupil dilation than low frequency words (*M* = .10, *SD* = .33).

Hypothesis 2

Hypothesis 2 suggested that related nonword primes would result in shorter latencies compared to unrelated nonword primes, as well as decreased pupil size. Examining by subject mean reaction times denoted a marginally significant effect of relatedness, $F_1$ (1,18) = 2.80, *MSE* = 3,367, *p* = *.08*; however, there was a non-significant by item effect, $F_2$ (3,248) = 1.86, *MSE* = 14,401, *ns*. Error rates by item and by subject were non-significant, $F_1$(1,18) = 2.94, ns; $F_2$ (1,57) = .25, *ns*. Similarly, the nonword target data did not produce significant differences in RTs ($t_1$ (18) = .30, *ns*; $t_2$(85) = -.78, *ns*) nor were errors significantly different (*t*s < 1).

The pupil data, however, did show a significant effect for the factor of relatedness, *F*(1,18) = 4.24, *p* = .05. Observation of the means for both related and unrelated primes showed smaller pupil dilation for related (*M* = .03, *SD* = .34) vs. unrelated (*M* = .10, *SD* = .35) nonword prime trials. Figure 1 shows a graphical depiction of pupil size for related vs. unrelated primes collapsed across subjects from stimulus onset (prime) until the end of the trial. Finally, a significant difference did not exist between related and unrelated prime-nonword target pairs, *t*(18) = -1.57, *ns*.

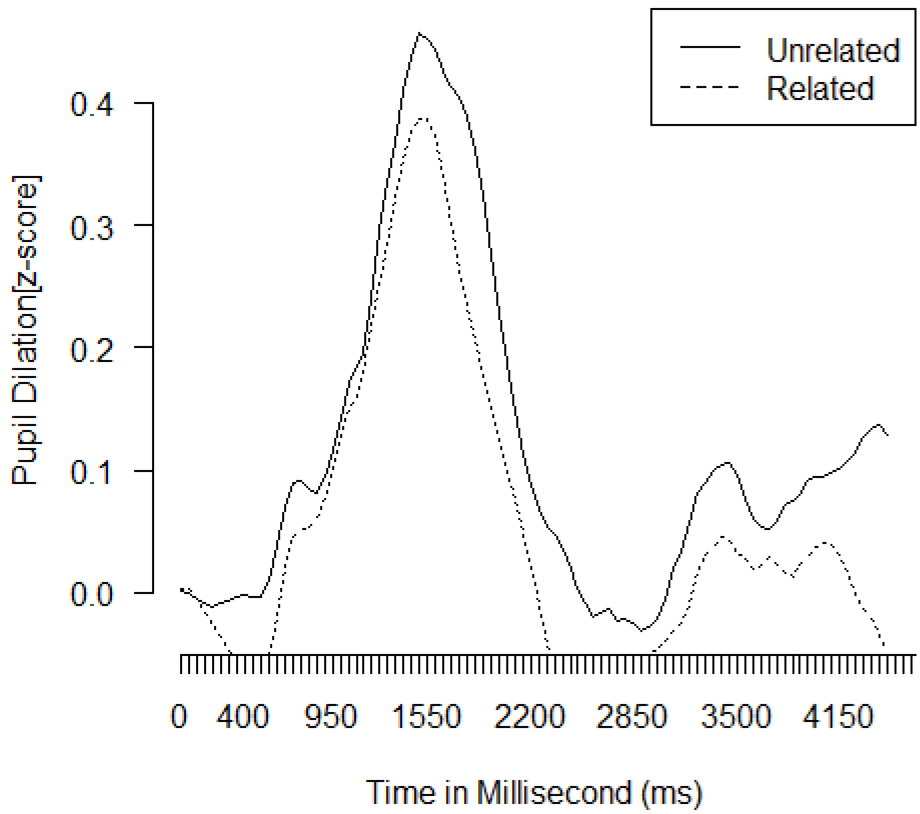


Figure 1. Standardized mean pupil size, collapsed by subject, from stimulus onset (prime) until end of trial for related nonword primes and unrelated (dotted line) nonword primes.

Hypothesis 3

Hypothesis 3 suggested an interaction between frequency and relatedness. Specifically, related high frequency primes-low frequency target pairs engender shorter latencies compared to unrelated high frequency prime-low frequency target pairs, therefore producing stronger inhibitory effects. Further, there will be less pupil dilation for related, high frequency prime-low frequency targets than for unrelated high frequency prime-low frequency targets. In the by subject analysis, but not the by item ($F < 1.20$) analysis, the frequency by relatedness interaction reached significance, $F_1(1,18)=5.75$, *MSE* = 1,850, $p = .05$. Simple effects analysis, using a Bonferroni corrected alpha level of .03, examined relatedness between high frequency and low frequency targets, by subject, denoted a significant facilitatory effect for related and unrelated nonword prime-low frequency target pairs ($t(18) = -2.58$, $p = .02$), but not for related and unrelated nonword prime-high frequency target pairs ($t(18) = .93$, *ns*). Low frequency targets, primed by related nonword primes, produced shorter latencies than when primed by unrelated nonword primes. Finally, error responses by subject, $F_1(1, 18) = .14$, *ns*, and by item, $F_2(1,57) = .01$, *ns*, were not significantly different.

Examination of the interaction between relatedness and frequency elicited non-significant results for the pupil data, $F(1,18) = .68$, *ns*. No significant interaction existed between word frequency and prime relatedness. See table 4 for means and standard deviations for each condition.

Table 4

*Mean Standardized Pupil Size and Standard Deviation, In Parentheses, for Word and Nonword Targets as a Function of Prime Relatedness and Word Frequency*

| | *Word Target* | | |
|---|---|---|---|
| | High frequency | Low Frequency | Nonword |
| Related | .01 (.38) | .07(.29) | .16 (.34) |
| Unrelated | .09 (.35) | .12 (.38) | .07 (.37) |
| Effect | +.10 | + .05 | -.09 |

# Chapter VII

## Discussion (study 2)

The results for study 2 confirmed one of the hypotheses. As shown in previous studies, nonword primes pre-activate processing of the target, denoted by shorter latencies (Colombo, 1986, Experiment 1; Davis & Lupker, 2006; Forster, 1987; Forster & Veres, 1998). First, the behavioral data showed a word frequency effect, similar to study 1. Participants took significantly longer to respond to low frequency words than high frequency words. Second, an interaction arose for related nonword prime-low frequency target pairs. Related nonword prime-low frequency targets produced more facilitation than related nonword prime-high frequency target pairs. This is congruent with what Davis and Lupker (2006) found in experiment 1, although their frequency by relatedness interaction term was non-signigicant, reactions times were in the right direction.

Directing attention to mean pupil size, some evidence exists relating to the sensitivity of pupil size in regards to lexical processing (viz., orthographic prime relatedness). Related nonword primes elicited smaller pupil sizes than unrelated nonword primes. This is congruent with the assumptions made by the IA model (Mcclelland & Rumleherat, 1981). That is, nonword primes never reach the word level of representation, thus do not serve as competitors. This resulted in lower levels of information processing as denote by smaller pupil sizes for related nonword primes compared to unrelated nonword primes. Past physiological research using a method that also tests mental activity, event-related potentials (EPRs) (e.g., Massol et al., 2010), denoted similar trends to this study—nonword related primes preceding word targets elicited less electrical activity compared to unrelated nonword primes. Nonetheless, the facilitatory nature of nonword prime relatedness and word frequency is unknown as it relates to pupil dilation due to the null interaction. Although the hypotheses pertaining to frequency and the interaction between frequency and relatedness were not bolstered, results indicate some sensitivity to nonword prime relatedness. Related nonword primes induced smaller mean pupil sizes compared to unrelated nonword primes. Nonetheless, for the first time, pupil size showed sensitivity to the influence of related nonword primes on target recognition.

# Chapter VIII

## Conclusion

Within the masked priming literature, discrepant evidence exists on the effect of word primes on target identification, finding an array of outcomes (facilitatory, null, and inhibitory; Bijeljac-Babic et al., 1997;Colombo, 1986; Davis & Lupker, 2006; Forster, 1987; Forster and Veres, 1998; Grainger et al., 1991; Segui & Grainger, 1990). While the experiments using nonword related primes clearly show processing advantage (i.e., shorter latencies) (Colombo, 1986, Experiment 1; Davis & Lupker, 2006; Forster, 1987; Forster & Veres, 1998). The central crux of the studies proposed were to access, in isolation, facilitatory and inhibitory effects using English words, as well as to utilize a new methodological tool to add validity to assumptions purported by the IA model. One study (i.e., Davis & Lupker, 2006) had successfully found facilitatory and inhibitory effects using both English word and nonword primes, in the same experiment, but no other study, to date, used pupil size as a measure for cognitive effort in masked priming. The studies herein did not utilize a mixed list, however. Ideally, It is important to show first, that word primes, independent of nonword primes, elicit inhibitory effects, and that nonword primes, independent of word primes, elicit facilitatory effects given the strong effects shown in the Davis and Lupker study. Second, it is important to show the effects are replicable, and indeed valid. The use of a pupil dilation as a measure of information processing tried to bolster and add validity to suppositions made in regards to orthographically related word and nonword primes. In study 1, inhibitory effects did not arise due to orthographical relatedness of word primes. Further, pupil data did not provide evidence for inhibition using word primes. In study 2, facilitatory effects emerged using nonword primes, showing nonword related primes produce facilitation. Mean pupil data further bolstered this postulation, to some extent. Related nonword primes produced smaller pupil sizes than unrelated nonword primes. The effects of nonword primes are clear; however, much debate still exists in relation to the effects of related word primes in masked priming.

## Limitations

There are several limitations to the studies herein. The small sample size for both experiments is one. Study 1 only had 23 participants; Study 2 only had 19 participants. Ideally, a study with a larger sample size increases power. Moreover, and most importantly, each of the lists contained an unequal number of word versus nonword responses, which could have shifted the response bias towards responding to the target as a word, thus confounding the results. Corroborating this supposition, Wagenmakers, Ratcliff, Gomez, and Mckoon (2008; Experiment 2) manipulated word/nonword proportions within the LDT task and found that more probable stimuli influence responses—that is, if there is more word stimuli vs. nonword stimuli, participants will be influenced by this and adopt a strategy biasing their responses. Therefore, the bias in responding created using an unbalanced list could account for the null results when examining pupil size for word primes. If a greater proportion of words appear more frequently, participants might adopt a strategy limiting the amount of attention directed towards the task, thus limiting mental effort.

Lastly, the pupil data showed a lot of noise. The methods employed for analyzation of pupil size herein varied from the extant literature. The possibility arises that the algorithms used by others to extract and clean pupil data were more sensitive. Given that this was one of the first studies to look at pupil dilation in a masked priming paradigm, consideration needs to be given on how to obtain the best signal to noise ratio.

## Future Directions

The strong effects of inhibition and facilitation in the Davis and Lupker (2006) study could have arisen due the use of an intermixed word and nonword prime design, with the facilitatory nature of nonword primes driving the inhibitory effects. Examination of a mixed list with RT and pupil indices will try to flesh out the inhibitory and facilitatory effects in one experiment. As aforementioned, across trial learning could have confounded the RTs with participants responding “yes” due to the learning associated with the higher probability of an actual word appearing on screen.  Some studies (i.e., Bodner & Masson, 2001; Masson & Bodner, 2003) suggest participants have the ability to strategically use the prime-target relationship when making a decision; thus, to ensure automatic processes are at play future experiments must examine words lists having an equal number of words and nonwords. Finally, to ameliorate upon the amount of noise in the data, a method used primarily in ERPs studies might be effective: Orthogonal Polynominal Trend Analysis of Variance (OPTA) (see Woestenburg, Verbaten, Van Hees, & Slangen, 1983, for a review of the procedure). This method increases signal in noisy data. Future studies will employ this method to increase the signal to noise ratio within the data.

# Chapter VIIII

## SUMMARY

Two studies examined the effects of word (study 1) and nonword (study 2) primes in word recognition, utilizing a masked priming procedure (Forster & Davis, 1984). The primary objective of both studies was to replicate the results obtained by Davis and Lupker (2006) using a common dependent measure, reaction time, and a measure not yet utilized in the word recognition literature—pupil dilation. In the masked priming literature, some common themes emerge. Orthographically related word prime-target pairs (e.g., *blue-Blur*) produce inhibition or longer reaction times, based on McCleland and Rumelhart's (1981) activation-based model, because orthographically similar words act as competitors against the recognition of the target. Discrepancy exists for the aforementioned supposition, with a range of results arising (i.e., facilitatory, null, and inhibitory effects). Conversely, related nonword prime-target pairs (e.g., *bilk-MILK*) produce shorter reaction times because nonwords pre-activate target identification. The reason being: competition occurs only for words. Based on this, pupil dilation, a correlate for mental effort, should be sensitive to the inhibitory and facilitatory effects observed in masked priming. That is, inhibition results from more cognitive effort and facilitation from less cognitive effort when trying to identify target words preceded by related primes.

Study 1 found nominal evidence corroborating the inhibitory nature of word primes.  In the RTs analysis, only word frequency effects arose. Further, pupil dilation analysis did not show mean differences across conditions. Study 2, utilizing nonword primes, elicited clearer results. High frequency nonword prime-low frequency targets produced stronger facilitory effects. Interestingly, pupil dilation showed, for the first time, sensitivity to relatedness in the masked priming procedure. Related nonword primes produced smaller mean pupil sizes than unrelated nonword primes. Thus, suggesting processing for nonword primes requires less processing resources than unrelated nonword primes. Although no differences arose for related word primes, utilizing pupillometry, it is shown herein, for the first time to be sensitive to some of the effects found in masked priming (viz. facilitatory effects driven by related nonwords). Future research, ameliorating upon the deficiencies in Davis and Lupker (2006) (i.e., unbalanced list of word and nonword targets), and replicating their study with nonword and word primes within the same trial block might produce the expected behavioral and physiological results.  Lastly, utilization of a new method might prove fruitful.

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# Appendix A

## Word list

| | | |
|---|---|---|
| alto | quiz | ALSO |
| icon | maul | IRON |
| oily | aura | ONLY |
| defy | prim | DENY |
| frog | pulp | FROM |
| burp | jive | BURN |
| awry | edit | AWAY |
| trek | lava | TREE |
| sigh | atom | SIGN |
| nigh | romp | HIGH |
| itch | meek | INCH |
| drip | chum | DROP |
| thud | fern | THUS |
| omen | flux | OPEN |
| clue | pond | CLUB |
| blur | gasp | BLUE |
| knit | chef | UNIT |
| verb | yolk | VERY |
| wren | void | WHEN |
| germ | wavy | TERM |
| aria | noun | AREA |
| duly | veil | DUTY |
| lazy | stem | LADY |
| skid | puff | SKIN |
| drum | jazz | DRUG |
| fury | twin | JURY |
| moth | puny | BOTH |
| stew | curl | STEP |
| hurl | scan | HURT |
| oven | folk | EVEN |
| axle | thug | ABLE |
| turf | chew | TURN |
| farce | puppy | FORCE |
| ankle | porch | ANGLE |
| yearn | hoist | LEARN |
| knack | flute | KNOCK |
| thump | vocal | THUMB |
| regal | smock | LEGAL |

| | | |
|---|---|---|
| angel | mould | ANGER |
| polar | buddy | SOLAR |
| cello | strut | HELLO |
| rotor | scalp | MOTOR |
| lance | mirth | DANCE |
| abort | slime | ABOUT |
| abode | flirt | ABOVE |
| thief | syrup | CHIEF |
| weave | groom | LEAVE |
| medic | fluff | MEDIA |
| draft | spoon | DRIFT |
| manic | dwell | MAGIC |
| untie | gamma | UNTIL |
| loyal | hedge | ROYAL |
| udder | hippy | UNDER |
| alter | blown | AFTER |
| mouse | frail | HOUSE |
| repay | motto | REPLY |
| skate | chunk | STATE |
| niece | shrug | PIECE |
| queer | villa | QUEEN |
| onion | chalk | UNION |
| otter | smash | OUTER |
| vault | ozone | FAULT |
| abide | furry | ASIDE |
| gruel | poppy | CRUEL |
| with | plus | DITH |
| soon | myth | SOUN |
| taut | dish | LAUT |
| tube | lamb | TUCE |
| blew | acid | BLEN |
| duet | self | DUIT |
| clip | soap | CLID |
| flat | prey | GLAT |
| pram | bulk | PHAM |
| shed | plot | SHEY |
| thin | golf | THID |
| acid | grey | AXID |
| paint | cheek | VAINT |
| fibre | tough | FABRE |
| check | storm | CHELK |
| chest | rapid | THEST |
| drone | pitch | DRODE |
| noise | cream | NOIST |
| unity | solve | ANITY |
| salon | coach | SILON |

| | | |
|---|---|---|
| alert | climb | ABERT |
| delve | straw | LELVE |
| mafia | crown | MEFIA |
| dense | trick | WENSE |
| poker | blind | POMER |
| snuff | shame | KNUFF |
| ingot | spell | ANGOT |
| quilt | prize | QUALT |

Related prime; unrelated prime; low, high, or Nowword targets

# Appendix B

## Nonword List

| | | |
|---|---|---|
| anso | quoz | ALSO |
| irol | jaul | IRON |
| ondy | auta | ONLY |
| feny | pril | DENY |
| frem | pule | FROM |
| buln | jave | BURN |
| anay | erit | AWAY |
| treb | liva | TREE |
| lign | alom | SIGN |
| hiph | remp | HIGH |
| unch | mees | INCH |
| drot | shum | DROP |
| phus | cern | THUS |
| opan | frux | OPEN |
| clab | pand | CLUB |
| blae | gisp | BLUE |
| unid | ches | UNIT |
| vedy | yolt | VERY |
| whun | poid | WHEN |
| tarm | waly | TERM |
| alea | nout | AREA |
| luty | veel | DUTY |
| ludy | spem | LADY |
| skun | poff | SKIN |
| crug | jozz | DRUG |
| jory | twan | JURY |
| boch | puly | BOTH |
| snep | corl | STEP |
| lurt | scap | HURT |
| evon | filk | EVEN |
| ible | shug | ABLE |
| tuln | shew | TURN |
| borce | punpy | FORCE |
| engle | borch | ANGLE |
| loarn | coist | LEARN |
| knosk | plute | KNOCK |
| trumb | vodal | THUMB |
| leral | smick | LEGAL |
| anver | mourd | ANGER |
| silar | bundy | SOLAR |

| | | |
|---|---|---|
| hollo | scrut | HELLO |
| modor | scilp | MOTOR |
| dalce | firth | DANCE |
| adout | slume | ABOUT |
| abeve | flist | ABOVE |
| choef | sarup | CHIEF |
| lenve | croom | LEAVE |
| melia | cluff | MEDIA |
| drist | shoon | DRIFT |
| sagic | dwoll | MAGIC |
| until | camma | UNTIL |
| royel | hidge | ROYAL |
| unver | hilpy | UNDER |
| afler | bloun | AFTER |
| hause | frain | HOUSE |
| retly | motta | REPLY |
| stite | churk | STATE |
| poece | thrug | PIECE |
| cueen | vilta | QUEEN |
| ulion | chark | UNION |
| ouler | smaph | OUTER |
| faurt | ozene | FAULT |
| asine | turry | ASIDE |
| crull | popsy | CRUEL |
| lith | plas | DITH |
| souk | ryth | SOUN |
| raut | dich | LAUT |
| tume | vamb | TUCE |
| arce | bolb | ARCA |
| snat | sheb | KNAT |
| anly | diph | AWLY |
| hirm | boit | HURM |
| blet | acil | BLEN |
| duin | sulf | DUIT |
| clib | doap | CLID |
| blat | brey | GLAT |
| plam | vulk | PHAM |
| shec | plit | SHEY |
| thip | galf | THID |
| alid | gley | AXID |
| maint | theek | VAINT |
| fubre | toush | FABRE |
| chenk | shorm | CHELK |
| shest | ralid | THEST |
| drope | putch | DRODE |
| noish | cleam | NOIST |

| | | |
|---|---|---|
| inity | sorve | ANITY |
| sulon | doach | SILON |
| adert | climp | ABERT |
| velve | steaw | LELVE |
| mufia | trown | MEFIA |
| vense | trich | WENSE |
| poter | blild | POMER |
| sluff | chame | KNUFF |
| ungot | sperl | ANGOT |
| qualt | preze | QUALT |

Related prime; unrelated prime; high, low, or nonword target