MECHANISMS OF MASKED PRIMING:

TESTING THE ENTRY OPENING MODEL

by

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This dissertation is dedicated to –

Dr. Kenneth I. Forster

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ABSTRACT

Since it was introduced in Forster and Davis (1984), masked priming has been widely adopted in the psycholinguistic research on visual word recognition, but there has been little consensus on its actual mechanisms, i.e. how it occurs and how it should be interpreted. This dissertation addresses two different interpretations of masked priming, one based on the Interactive Activation Model (McClelland & Rumelhart, 1981), in which priming is seen as a result of persisting activation from the prime, the other based on the Entry Opening Model (Forster & Davis, 1984), which sees priming as a savings effect. Five experiments are reported testing contrasting hypotheses about the role of prime duration and prime-target asynchrony (SOA) in masked priming using both identity and form priming. Overall, this dissertation lends support to the Entry Opening Model, demonstrating that masked priming is essentially a savings effect, and that as such, it is determined by the SOA, not the prime duration per se.

CHAPTER 1

INTRODUCTION

1.1 Introduction

Since it was introduced in Forster and Davis (1984), the masked priming technique has been widely adopted in research on visual word recognition. This technique typically employs a timed, successive presentation of stimuli on the computer screen, all stimuli being superimposed on one another. In a regular three-field masked priming paradigm (see Figure 1.1 below), a 500-ms forward mask is followed by a prime, which is very briefly presented for about 50 or 60 ms and then replaced by a 500-ms target, which also serves as the backward mask. The forward mask is usually a string of nonlinguistic signs such as a row of hash marks "#####." It serves two main functions, reducing the visibility of the prime and working as a fixation signal to alert the participant to the critical item. As a rule, the prime is displayed in lower case letters and the target in upper case so that the visual effect of physical overlap between the prime and the target can be minimized. In a typical masked priming paradigm, the prime is presented for such a short period of time and is so effectively masked that participants are largely unaware of the nature of the prime.

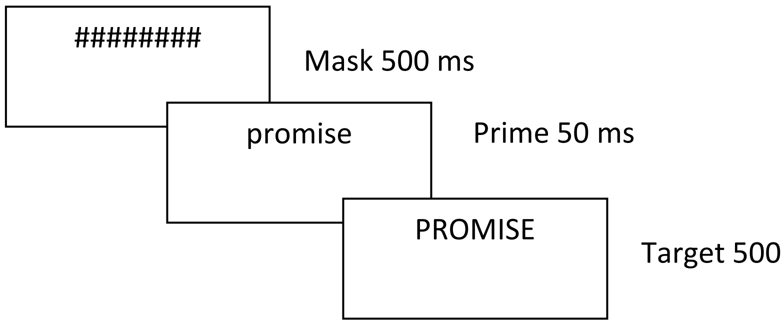

Figure 1.1. *A regular three-field masked priming paradigm.*

This reduced degree of awareness is a critical design feature of masked priming, which has proved to be particularly invaluable in research on lexical access. For one thing, it provides a sensitive measurement of the otherwise elusive very early processes of lexical access, namely the purely perceptual, automatic processes occurring well before awareness. Because participants are not aware of seeing the prime, the differences observed in reaction time can be more reliably attributed to automatic lexical access. Another crucial advantage of this technique is that many types of strategic effects can be averted. In a regular unmasked priming paradigm, the prime is usually displayed for a longer period of time and therefore is readily noticeable to participants. When participants are aware of the prime, they may develop strategies such as anticipation in performing the task. For example, participants may notice the fact that the prime and the target are related and start to anticipate what the target is before it is even presented. Such strategic effects can be effectively minimized in the masked priming paradigm. As demonstrated in a series of experiments by Forster and Davis (1984), the masked priming effect is different from the visible repetition priming effect by nature. Masked priming is a largely unconscious, lexical effect, not subject to episodic or strategic influences.

With these apparent advantages, the masked priming paradigm has become somewhat of a norm in lexical access studies. Robust masked priming effects have been reported in studies of both monolingual and bilingual lexical processing. Different types of primes have been examined as well, and priming effects have been obtained with many of them: for example, identity primes (e.g., *discover-DISCOVER*), 1-letter-different form primes (e.g., *discoper-DISCOVER*), transposed letter primes (e.g. *avcatino-VACATION*), morphologically related primes (e.g., *vowed-VOW*), semantically related or associated primes (e.g., *pledge-VOW*), and translation primes (e.g., *cheval-HORSE*). However, despite its wide applications, the masked priming technique itself has not received much focused or systematic attention regarding its actual mechanisms, i.e. how it occurs and how it should be interpreted. This dissertation represents an attempt to systematically explore these underlying mechanisms. It is hoped that this undertaking will advance our understanding of the masked priming technique as well as its wide applications in research on visual word recognition.

1.2 Masked Priming as Persisting Activation

Of the few interpretations of the masked priming effect, two views are dominant. One is the persisting activation account, which is widely adopted by Interactive Activation (IA) models of lexical processing (e.g., McClelland & Rumelhart, 1981; Grainger & Jacobs, 1996; Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001); the other is the savings model based on the Entry Opening Model of masked priming (Forster & Davis, 1984; Forster, Mohan & Hector, 2003, Forster, 1998, 2008). The persisting activation account follows the basic assumptions of IA models. That is, word recognition results from an interactive process of parallel activation at a number of representation levels of the word unit, such as the visual feature, letter, word, etc. (McClelland & Rumelhart, 1981). Since activation of the word units is parallel, all related word units are activated simultaneously by the input, the amount of activation being proportional to the degree of match between the input and the word unit. When the level of activation for the word unit reaches a certain criterion, it is assumed that word recognition occurs. In the case of masked priming, the assumption is that when the prime is activated, it activates a number of similar matching word units in parallel. If the target is a close or exact match of the prime, the target will be activated as well, so when the target replaces the prime, it builds on the activation persisting from the prime. As a result, the target takes less time to reach the criterion, hence a priming effect. To put it simply, an IA model assumes that masked priming is a result of persisting activation from the prime, which raises the target's level of activation above its normal resting level and thereby reduces its time to reach the criterion.

Following the basic assumptions of IA models, the persisting activation account assumes that the amount of priming is a function of the prime duration and the degree of orthographic match between the prime and the target. Namely, at a given prime duration, if the prime is an exact match of the target, the target should receive greater activation than if the prime is just a close match. Clearly, according to this persisting activation account, identity priming should always be greater than 1-letter-different (1-LD) form priming, as reported in a number of masked priming experiments (e.g., Forster, Davis, Schoknecht, & Carter, 1987; Forster & Davis, 1991; Sereno, 1991). In essence, identity priming and form priming are seen as the same process except that the persisting activation from an exact match is stronger than that of a partial match. In effect, form priming is considered just a weaker version of identity priming with a reduced priming effect.

This view has recently been challenged by the results of a set of experiments on the effect of inserting an unrelated word between the prime and the target (Forster, 2008). In this paper, it was found that inserting an unrelated word (termed an intervenor) between the masked prime and the target had a differential effect on identity priming and form priming. When the intervenor was visible, identity priming was reduced to the level of 1-LD form priming, but form priming remained at about the same level as in a normal priming experiment without any intervenor, i.e. roughly 30 ms of priming. When the intervenor was itself masked and presented for only 50 ms, identity priming remained at the same level as observed with a visible intervenor, but form priming was eliminated altogether. These results suggested that identity priming and form priming could be fundamentally different from each other, contrary to what an activation model predicts. As discussed earlier, the persisting activation account regards form priming and identity priming as essentially the same process and therefore it would predict that the intervenor should have the same effect on both forms of priming.

1.3 Masked Priming as a Savings Effect

The other dominant view argues that masked priming is a savings effect. This view was proposed by Forster and Davis (1984) as an extension to the Search Model (or "bin" model) of lexical access. The rudimentary assumption is that word recognition involves a search process and another separate process which produces priming. Specifically, it is assumed that the lexical processor locates a matching lexical entry by a search process, but before any information can be extracted from the entry there is another process that must be completed, which is analogous to the process of opening a file in a computer operating system. This post-search process is described as "entry opening," and it is this separate process that produces priming. More specifically, it is assumed that in processing the prime, the lexical processor locates and opens the entry of the prime as well as its close matches. If the prime is a close or exact match with the target, the entry for the target has already been opened by the prime when the target is presented and tries to open the entry. The time taken to open the entry of the target is therefore saved, giving the target a "head-start," thus a priming effect. This "head-start," i.e. the interval between prime onset and target onset, is often referred to as the stimulus onset asynchrony or SOA for short, which is equal to prime duration in a standard masked priming experiment[1]. In essence, therefore, priming is believed to be a savings effect: The prime provides a "head-start," so processing of the target is started before it is actually presented, hence saving time.

This Entry Opening Model (EOM) of masked priming, as an extension to the "bin" model, was originally designed to explain the equivalent priming effect obtained for high-frequency (HF) and low-frequency (LF) words (Forster & Davis, 1984). According to this model, the frequency effect (i.e. HF words are faster to recognize than LF words) is a function of the search time, i.e. the time taken to search the mental lexicon and locate the lexical entry that matches the input. In order to optimize the search, the lexical entries are ordered by frequency, so HF words are always searched before LF words, hence taking less time to locate. Masked priming, however, is a savings effect produced by the entry opening process. As discussed earlier, since masked priming and frequency involve distinct processes, they should be independent from each other, hence equal priming for HF and LF words. By contrast, an activation model interprets both priming and frequency effects as a function of activation level. HF words take less time to recognize because they have the advantage of starting from a higher resting level of activation compared to LF words. It is also because of this higher resting level that HF words should produce less priming than LF words. It is therefore inevitable that an

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[1] The SOA can be manipulated independently from the prime duration by inserting a neutral stimulus between the prime and the target. See Experiment 3 for further examination of the relationship between prime duration and SOA.

activation model predicts an interaction between priming and frequency, contrary to what EOM predicts.

In addition to the relationship between frequency and priming, this “head-start” view of the Entry Opening Model requires that the amount of priming be determined by the SOA along with the entry opening time (EOT). As a savings effect, masked priming should be first and foremost a function of the SOA. Increasing the SOA should produce a corresponding increase in the masked identity priming effect. For instance, extending the SOA by 20 ms should increase identity priming by approximately the same amount. That is, identity priming should be a linear function of the SOA, with a slope of 1 (Forster, Mohan & Hector, 2003). Additionally, it is clear that if masked priming is a savings effect, it could not be any greater than the SOA because the “head-start” sets the limit to the maximum amount of time that could be saved. On the other hand, if the entry opening process occurs very rapidly, e.g., within 10 ms, then the priming effect could not be greater than the EOT, i.e. 10 ms, regardless of how long the SOA is. Both variables, the EOT and the SOA, should limit the amount of priming, and the limit is whichever is the smaller of the two (Forster, Mohan, & Hector, 2003).

Another important assumption of the EOM is that form priming involves fundamentally different processes than identity priming. As Forster (2008) demonstrated in his paper on the effect of intervening words, these two forms of priming were dissociated from each other because inserting an intervenor produced markedly different patterns of results. It was therefore suggested that each word has two representations, one at the level of form and the other at the level of meaning. Entry opening may happen at two different levels. An identity prime opens the entry at the levels of both meaning and form, but a form prime opens the entry at the level of form only. That is, identity priming consists of two different elements, i.e. a semantic component and an orthographic component, but form priming involves only the orthographic component. It is further assumed that these two components of priming may be affected differentially by an intervenor. As Forster (2008) suggested, the orthographic component of priming may survive after a visible intervenor, but the semantic component does not, hence identity priming being reduced to the level of form priming. When the intervenor is invisible, only the semantic component is preserved and the orthographic component is eliminated altogether. Contrary to the assumption of an activation model, the EOM contends that form priming is not just a weaker type of identity priming; rather, it has unique properties of its own, which will be addressed in greater detail in the next section.

Finally, in order to explain the intervenor effects, it is necessary to assume that processing of the prime continues during the intervenor (unlike what happens in an IA model). Within the EOM, this amounts to arguing that once the search for the prime is initiated, it continues, and is no longer dependent on the physical presence of the original stimulus. If this was not the case, and the search terminated as soon as the prime was replaced, then one would expect much weaker priming for low-frequency words than for high-frequency words, since low-frequency words take longer to access.

To sum up, both an activation model and a Search model contend that masked priming is a facilitative effect, i.e. the processing of the prime lends an advantage to target processing, but they subscribe to different accounts of its underlying mechanisms. IA models consider masked priming a result of activation of the prime persisting to the target, raising its level of activation above the normal resting level and thereby reducing the time for the target to reach the criterion for word recognition. The reduction in time as a result of this persisting activation leads to a priming effect. It is believed that the priming effect is a function of the prime duration as well as the degree of orthographic match between the prime and the target. The corollary is that a form prime is necessarily less effective than an identity prime in terms of generating a priming effect, and that the longer the prime duration is, the greater the priming effect should be (other things being equal).

By comparison, a search model maintains that masked priming is a savings effect. The prime opens the entry for the target when the prime is an exact or close match with the target, thus saving time for the target to open the entry when the target is presented and tries to open the entry. The entry opening time that has been saved contributes to a priming effect. As a savings effect, priming is necessarily limited by the EOT and the SOA. Since form priming and identity priming result from two different kinds of entry opening, they are subject to restrictions defined by their own EOT. Within the set limits, masked priming is believed to be a linear function of the SOA, not the prime duration per se.

1.4 The Relationship between Masked Priming and SOA.

As can be seen from the previous discussion, the theoretical debate over the mechanisms of masked priming centers upon the relationship between masked priming and the SOA. It is therefore worthwhile to review the amount of masked priming as a function of the SOA reported in the previous studies. Included in the review are only studies of form and identity priming employing the regular masked priming technique with a prime duration of up to 60 ms. It is generally believed that a prime presented for 60 ms or less time, when effectively masked by a forward and a backward mask, is not available for conscious perception or recall to most people (Forster & Davis, 1984). The results of these studies are summarized in the two separate tables below, Table 1.1 for identity priming and Table 1.2 for form priming.

Table 1.1 Amount of Identity Priming (IP, in milliseconds) as a function of prime duration (in milliseconds) and the characteristics of words such as word frequency (per million), word length and number of neighbors (N) in Previous Studies

			Word Characteristics		
Source	IP	Duration	Frequency	Length	N
Forster & Davis (1984), Experiment 1					
	45	60	HF 40-60 (K&F)	4-6	
	38	60	LF 1-2 (K&F)	4-6	
Forster, Davis, Schoknecht & Carter (1987), Experiment 1					
	61	60	HF >60	6-10 (M=7.5)	
	66	60	LF 6-9	6-10 (M=7.5)	
Forster et al. (1987), Experiment 2					
	38	60	MF 30-75	4-letter	
	56	60	MF 30-75	8-letter	
Forster et al. (1987), Experiment 4					

34	60	HF >200	4-letter	
25	60	LF <11	4-letter	
Forster et al. (1987), Experiment 5				
43	60	Mixed	4-letter	M=2.86
Forster & Davis (1991), Experiment 5				
54	60	HF >100 (M=234.4)	5-6	M=1.75
72	60	LF <10 (M=5.7)	5-6	M=1.94
Rajaram & Neely (1992), Experiment 1 (“nonstudied items)				
30	50	HF 40-69 (K&F)	3-9	
37	50	LF 1-2 (K&F)	3-9	
Sereno (1991), Experiment 1 (“different” control- word)				
40	60	HF M=175 (K&F)	4-6	
64	60	LF M=7 (K&F)	4-6	
Sereno (1991), Experiment 1 (“opposite” control-nonword)				
42	60	HF M=175	4-6	
72	60	LF M=7	4-6	
Bodner & Masson (1997), Experiment 1				
29	60	HF 40-60 (K&F)	4-6	
45	60	LF 1-2 (K&F)	4-6	
Bodner & Masson (2001), Experiment 2A				
39	60	HF 100-1000 (K&F)	4-6	
71	60	LF 1-10 (K&F)	4-6	
Forster, Mohan & Hector (2003) Experiment 2.1				
29	20		5-8	
39	30		5-8	
66	50		5-8	
74	60		5-8	
Forster, Mohan & Hector (2003) Experiment 2.2				
48	40		5-8	
54	50		5-8	
65	60		5-8	
Kinoshita (2006) Experiment 1				
32	53	HF 103-665 (K&F)	5 letter	0-13 M=4.77
38	53	LF 1-7 (K&F)	5 letter	0-8 M=3.02
Kinoshita (2006), Experiment 2 (LF but familiar)				
29	53	HF 103-665 (K&F) M=233	5 letter	0-13 M=4.77
59	53	LF 1-20 (K&F) M=7.81	5 letter	0-8 M=3.9
Segui & Grainger (1990), Experiment 4 (French)				
42	60	HF targets w/o HigherF neighbors, 4-letter French		
45	60	LF targets w/ HigherF neighbors, 4-letter French		

Table 1.2 Amount of Masked Form Priming (FP, in milliseconds) as a function of prime duration (in milliseconds) and the characteristics of words such as word frequency (per million), word length and number of neighbors (N) in Previous Studies

			Word Characteristics		
Source	FP	Duration	Frequency	Length	N
Forster, Davis, Schoknecht & Carter (1987), Experiment 1					
	50	60	HF >60	6-10 (M=7.5)	
	49	60	LF 6-9	6-10 (M=7.5)	
Forster et al. (1987), Experiment 2					
	8	60	30-75	4-letter	
	32	60	30-75	8-letter	
Forster et al. (1987), Experiment 4					
	-7	60	HF >200	4-letter	
	12	60	LF <11	4-letter	
Forster et al. (1987), Experiment 5					
	22	60	Mixed	4-letter	M=2.86
Forster et al. (1987), Experiment 6					
	-16	60	mixed	4-letter	>7
	18	60	mixed	4-letter	<3
Sereno (1991), Experiment 1					
	14	60	HF M=175 (K&F)	4-6	
	28	60	LF M=7 (K&F)	4-6	
Forster & Davis (1991), Experiment 5					
	28	60	HF >100 (M=234.4)	5-6	M=1.75
	32	60	LF <10 (M=5.7)	5-6	M=1.94
Forster & Taft (1994), Experiment 1a (Body frequency(BF): Shared bodies)					
	4	50	M=11.75 (High BF)		>5 M=7
	37	50	M=9.39 (Low BF)		>5 M=7
Forster & Taft (1994), Experiment 1b: (BF: Non-shared bodies)					
	1	50	M=11.75 (High BF)		>5 M=7
	-4	50	M=9.39 (Low BF)		>5 M=7
Forster & Taft (1994), Experiment 2a (BF: Shared bodies)					
	3	50	M=17.8 (High BF)		<=2 M=1.2
	25	50	M=17.52 (Low BF)		<=2 M=1.2
Forster & Taft (1994), Experiment 2b (BF: Non-shared bodies)					
	20	50	M=17.8 (High BF)		<=2 M=1.2

20	50	M=17.52 (Low BF)		<=2 M=1.2
Forster & Taft (1994), Experiment 3 (Antibody frequency-ABF)				
4	50	M=5.3 (High ABF)		M=2.1
46	50	M=4.5 (Low ABF)		M=1.8
29	50	M=4.8 (Low BF)		M=1.9
Forster & Taft (1994), Experiment 4 (Torso Frequency-TF)				
17	50	M=3.7 (High TF)		M=2.4
12	50	M=3.9 (Low TF)		M=2.5
43	50	M=4.5 (Low ABF)		M=1.8
Forster & Taft (1994), Experiment 5				
6	50			High N
31	50			Low N
Forster, Mohan & Hector (2003) Experiment 2.3				
21	20		5-8	
33	30		5-8	
33	50		5-8	
42	60		5-8	
Forster, Mohan & Hector (2003) Experiment 2.4				
17	28.4		5-8	
35	42.6		5-8	
35	56.8		5-8	
Castles, Davis, Cavalot & Forster (2007)				
7	57	5-877 (K&F) M=132	4-5	0-17 (M=6.1)
Van Heuven, Dijkstra, Grainger & Schriefers (2001):				
27	30	M=4.1	4-letter Dutch	M=4.2 w/o shared neighbors
12	30	M=4.1	4-letter Dutch	M=4.2 w shared neighbors
30	60	M=4.1	4-letter Dutch	M=4.2 w/o shared neighbors
13	60	M=4.1	4-letter Dutch	M=4.2 w shared neighbors
Ziegler et al. (2000):				
4	14	1.5-5168 pm M=93	4-letter French	M=5.9
36	29	1.5-5168 pm M=93	4-letter French	M=5.9
30	43	1.5-5168 pm M=93	4-letter French	M=5.9
30	57	1.5-5168 pm M=93	4-letter French	M=5.9

A total of 15 experiments in 10 studies reported on masked identity priming effects (See Table 1.1). A number of word characteristics were included in these studies, for instance, word frequency, word length, and the number of neighbors, but frequency was the only property of words that has been specifically investigated as to how it affects identity priming. The results were mixed. As shown in Table 1.1, there was a numerical difference between priming for HF and LF words, but it is clearly NOT the case that LF words show much weaker priming effects than HF words. If anything, they show more, suggesting that the search continues when the prime is replaced. It is also important to note that the difference of priming was not significant in most studies except when some other properties of the targets or proportion of identity primes were further manipulated (e.g. Bodner & Masson, 1997, 2001; Kinoshita, 2006). It is nevertheless safe to state that identity priming is not particularly sensitive to frequency. Although not specifically tested, word length also seems to have some influence on the amount of identity priming, with shorter words showing less priming than longer words.

Despite these variables, it is rather evident that the identity priming effects were generally contained within the limits predicted by a savings model: rarely did they get much higher than the upper limit set by the prime duration or SOA. There were a few cases in which LF words showed a bigger effect than the SOA, but whether this difference was significant is not known. If this so-called hyperpriming effect is reliable, it could perhaps be attributed to a failed first search, which probably happens more often when the lexical processor attempts to access LF words (Forster et al., 2003). In the case of an identity prime, the chances for a failed first search may be reduced, thus producing additional savings in time.

The picture for form priming looks rather different. As can be seen from the results of 18 experiments in 7 studies summarized in Table 1.2, form priming is not as robust as identity priming. It has been found to be subject to a number of constraints, e.g. word length, neighborhood density, body frequency, antibody frequency, and prime lexicality, etc. (Forster et al, 1987; Forster & Taft, 1994; Segui & Grainger, 1990). Despite the apparent variability in form priming due to these constraints, it is nevertheless evident that form priming appears to reach a plateau at around 30-40 ms irrespective of the prime duration, long or short (e.g. 60 ms as well as 30 ms). This ceiling effect was made very clear in Forster et. al (2003), which showed that form priming hovered at about 30-40 ms as the prime duration was increased from 30 to 60 ms. Forster et al. (2003) reported on both form and identity priming at a series of prime durations of 20, 30, 50 and 60 ms. Whereas form priming showed a clear ceiling effect of 21, 33, 33, 42 ms as prime duration increased (as pointed out earlier), Similar finding was reported in Ziegler et al. (2000), which tested three forms of priming, i.e. orthographic, phonological, and orthographic-phonological, at four different prime durations of 14, 29, 43, and 57 ms in two tasks, lexical decision and naming. The results showed that form priming, irrespective of phonological similarity, did not exceed 30 ms by very much at any of the prime durations[2]. .

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[2] A 14-ms backward mask consisting of hash marks was inserted between the prime and the target, so the actual SOA in this experiment was longer than the prime duration. The effect of this variation between the SOA and prime duration, however, was not the focus of the study and therefore did not bear much on this debate.

Of all the experiments cited here, only the first experiment in Forster et al. (1987) reported more than 40 ms of form priming. In this experiment, the form priming was found to be unusually large, around 50 ms with a prime duration of 60 ms. The reasons for this unusually large form priming were made clear in the study itself. The items tested were very long, 6-10 letter with an average length of 7.5 letters, and the primes were judged to be as similar to the targets as possible and highly confusable with correctly spelled words. This ceiling effect was clearly absent for identity priming, suggesting that form and identity priming are subject to different limitations by EOT at different levels. Such limits on priming, however, have not yet been directly tested.

Similarly, there is not much evidence regarding the effect of varying the prime duration on the amount of priming. Most of the previous studies tested prime durations of about 50 or 60 ms except for Forster et al. (2003) and Ziegler et al. (2000), which addressed this issue in particular. As pointed out earlier, both studies showed a ceiling effect for form priming, so increasing the prime duration above 30 ms did not seem to influence form priming appreciably. Identity priming, however, revealed a steady increase from 29 ms to 39, 66, and 74 ms corresponding to the increase of the prime duration from 20 ms to 30, 50, and 60 ms as reported in Forster et al. (2003), supporting the prediction of a linear function between masked priming and the SOA from the savings model.

It must be noted here that the SOA was equal to prime duration in all but one of the studies reviewed here, as was the case in most of the previous studies of masked priming. However, the SOA can be manipulated independently from prime duration by inserting a neutral stimulus such as a blank gap or a mask of non-alphabetic signs, etc. between the prime and the target. For an activation model which interprets masked priming as persisting activation, it is imperative that the prime stimulus be physically present to generate activation, so the prime duration is the key factor that determines the amount of priming. The longer the prime duration is, the greater the priming. When the prime stimulus disappears, activation stops increasing or even starts to decay. The scenario in the EOM is quite different. As a savings effect, masked priming is only limited by the smaller of the EOT or the SOA. Whether the prime is physically present or not should not affect priming in any significant way, and extending the SOA by inserting a neutral stimulus should add to the "head-start" and thus enhance priming. Therefore, it should be the SOA that determines priming, not the prime duration per se.

There has not been any study that is specifically designed to test this debate over prime duration and SOA, but there are studies demonstrating the importance of extending the SOA by inserting a gap between the prime and the target. For example, in a study of masked translation priming, Finkbeiner, Forster, Nicol, and Nakamura (2004) showed that a 150-ms interpolated backward mask between the L2 English prime and the L1 Japanese target was necessary to produce L2-L1 translation priming in a semantic categorization task. Similar findings are also reported in Jiang (1999) and Witzel (2010), suggesting that a longer SOA is important for ensuring adequate time for prime processing and effective masking of the prime. It remains to be tested how repetition priming will be affected by extending the SOA with a neutral stimulus inserted between the prime and the target.

1.5 Research Questions

The main purpose of this dissertation is to reveal some of the properties of the underlying mechanisms of masked priming, the most widely adopted technique in research on word recognition. Specifically, it will test two critical predictions from the Entry Opening Model that contrast with those from the persisting activation account: limits on priming and the SOA and prime duration debate. The corresponding research questions in this dissertation are as follows:

1) Given the prime duration, is masked priming merely a function of the degree of orthographic match between the prime and the target? Or is it subject to some other limitations, such as the EOT and the SOA as suggested in the Entry Opening Model?

2) What is the major determinant of how much priming can be obtained? Is it the SOA or the prime duration per se that determines the amount of priming?

Chapter 2 tests the EOM prediction about the limits on priming, comparing the effect of reducing the prime duration on form priming and identity priming. If the reduction in prime duration produces drastic reduction of priming in one form of priming but not the other, it would suggest that there are other limiting factors on priming. In particular, two experiments are reported testing two different groups of participants, i.e.

L1 and L2 English speakers. L2 speakers are tested to see whether and to what extent the results can be replicated across speakers with differing degrees of English proficiency.

Chapter 3 provides a direct test of the prime duration and SOA debate. Three experiments are carried out. Experiment 3 examines identity priming at two SOA conditions. In one condition, a 40-ms prime duration is immediately followed by the target; in the other, a 40-ms prime is followed by a 20-ms blank interval, thus introducing a gap between the prime and the target. The EOM predicts that the inserted 20-ms gap should increase identity priming by roughly the same amount of time, i.e. 20 ms, compared with the standard 40-ms SOA condition. An IA model would not predict any gap advantage in the 40/20 condition because it believes that it is the prime duration that determines priming. Activation builds up only when the prime stimulus is physically present. When it disappears, activation stops increasing or even starts to decay. The results of Experiment 3 are further explored in two more experiments.

Finally, the last chapter provides a summary of the dissertation and discusses possible directions for future research.

1.6 Statistical Analysis

Rather than carrying out a conventional F1.F2 analysis in which either items or subjects are treated as fixed effects, the results were analyzed using linear mixed-effects modeling in R (Baayen, 2008; Baayen, Davidson, & Bates, 2008; Pinheiro & Bates, 2000). This method allows for two crossed random effects (subjects and items), and analyzes the reaction times (RTs) for each trial, without aggregating over items or subjects. Before attempting to fit a mixed-effects model to the data, the RTs were transformed using the log transformation in order to eliminate the marked positive skew typical of data from reaction time studies. This procedure was considered necessary because the distribution of raw RTs is more heavily skewed than the distribution of subject or item mean RTs used in conventional F1.F2 analyses. Outliers were eliminated using the model-based trimming procedure recommended by Baayen (2008), in which individual RTs that were more than 2.5 SD units away from the value predicted by the model were discarded. The lmer function from the lmer4 package in R was used (version 2.11.1; CRAN project; The R Foundation for Statistical Computing, 2008). The probability of the resulting *t* value was estimated using a Markov Chain Monte Carlo procedure (MCMC) using 10,000 iterations. Unless otherwise noted, all effects with a *p* value less than .05 are deemed significant.

CHAPTER 2

LIMITS ON MASKED PRIMING

There are several factors that have been found to limit masked priming. These are degree of orthographic overlap, prime duration, SOA, target neighborhood density, and prime lexicality. The focus of attention in this chapter will be on the degree of orthographic overlap (identity vs. form priming) and prime duration. As discussed earlier, the persisting activation account posits that masked priming is solely determined by the number of matching letters between the prime and the target at any given prime duration, so form priming should always be weaker than identity priming. Additionally, since form priming is considered to be essentially the same process as identity priming, only weaker, then in effect, anything that reduces identity priming such as shortening the prime duration should also decrease form priming to roughly the same degree. For instance, an activation model would predict that a 60-ms prime produces greater priming than a 30-ms prime because activation builds up slowly over time. Hence, 60 ms of activation will be greater than 30 ms of activation for both form priming and identity priming. In other words, one would expect a parallel reduction in priming for both form and identity priming as the prime duration is reduced from 60 to 30 ms.

By contrast, the Entry Opening Model suggests a fundamental difference between the two forms of priming and predicts a more nuanced difference in the priming effect. Specifically, as discussed at length in Chapter One, the central argument of the EOM is that masked priming is a savings effect and that the amount of savings is determined by the smaller of the EOT and the SOA. It is further suggested that the entry opening process may occur at two different levels: a form prime opens the entry at the level of form only, and an identity prime opens the entry at both levels of form and meaning. If opening the entry at the level of form takes about 30 ms as assumed in Forster (2008) and Forster, Mohan & Hector (2003), then form priming should show a ceiling effect at around 30 ms despite longer SOAs. Identity priming is different. Since an identity prime opens the entry at both levels of form and meaning, which takes roughly around 60 ms or longer (Forster et al., 2003), it should be able to reap the full benefit of the "head-start." Therefore, a 60-ms identity prime can produce as much as 60 ms of priming, but a 60-ms form prime can only produce up to 30 ms of priming, nothing greater, being limited by the EOT at the level of form. However, when the prime duration is reduced from 60 ms to 30 ms, identity priming will be reduced accordingly to 30 ms, but form priming should be maintained at about the same level of 30 ms as it is at 60 ms of prime duration. That is, shortening the SOA imposes an upper limit on how much identity priming can be obtained, but since form priming does not get higher than 30 ms even with longer prime durations, it should not be affected by the reduction in prime duration. If the 30-ms estimate of the entry opening time at the level of form is correct, form priming should stay at around 30 ms. If so, there should be a much more dramatic drop in identity priming than in form priming as the prime duration is reduced from 60 ms to 30 ms. Additionally, there should be little or no difference between identity and form priming at 30-ms prime duration but a much greater difference at 60-ms prime duration.

Experiment 1 was designed to test these predictions from the EOM, investigating the effect of reducing prime duration on form and identity priming. The results were compared to the simulation results from Colin Davis's Spatial Coding Model (2010), using the same materials. The Spatial Coding Model (SCM) is an extension of the IA model designed by Colin Davis (2010), with an improved method of assessing orthographic overlap. The SCM simulator was selected for comparison because it is readily available online and has successfully simulated the results from a variety of masked priming experiments, including the subtle effect of sandwich priming (Lupker & Davis, 2009).

2.1 Experiment 1. Limits on Priming in L1 Readers

In this experiment, form priming and identity priming were tested at the prime durations of 30 ms and 60 ms. If masked priming is solely a function of orthographic overlap at any given prime duration, there should be a parallel reduction in both form priming and identity priming when the prime duration is shortened from 60 ms to 30 ms. However, if masked priming is subject to other limiting factors, decreasing the prime duration by half may produce a radical reduction of priming in identity priming but not form priming.

2.1.1 Method

Participants

A total of 24 undergraduate students, all native speakers of English, enrolled in an introductory Psychology course participated in the experiment, for which they received course credit.

Materials and design

A total of 48 pairs of words were chosen as word targets. In order to maximize the chances of obtaining 1-LD form priming effects, these were all 7 letters in length. They were all nouns, their frequencies ranged from 20 to 300 per million (based on Celex database; Baayen, Piepenbrock, & van Rijn, 1995), the number of neighbors (based on N-Watch; Davis, 2005) was no more than 1, and their imageability scores ranged from 150 to 650 ((based on MRC Psycholinguistics Database; Coltheart, 1981). These pairs were matched for frequency, number of neighbors (N) and imageability, as illustrated in Table 2.1. One member of each pair was randomly assigned to either the 30 ms or the 60 ms prime duration condition, and they were tested in blocks in two different orders, 30-ms prime items first and the reverse. A total of 96 orthographically legal nonwords were selected as distracters. Like the word targets, they were all 7 letters in length and had no more than 1 neighbor. These nonwords were constructed by changing two letters of a real word, replacing a vowel for a vowel and a consonant for a consonant. They were designed to have no close resemblance to words (e.g., *gelrare*, *carmick*, *stantis*). For each target, three different primes were constructed: (1) an identity prime, (2) a one-letter-different (1-LD) nonword form prime made by systematically changing one letter of the target word so the changed letter is equally distributed among all 7 letter positions, and (3) an unrelated control prime of the same length. The unrelated primes were other items from the same set, so that each target was paired with an unrelated prime of the same lexical class, word length, frequency range, and number of neighbors as the target. The prime was a word in the case of word targets and a nonword in the case of nonword targets. For each order of testing, three counterbalanced lists of items were prepared so that across all lists, each target word and nonword was primed by an identity prime, a 1-LD prime, and a control prime such that no target appeared more than once in each list. That is, each target was paired with a repetition prime, form prime or an unrelated prime so that each target was seen by a subject only once, and across every 3 subjects it was paired once with a repetition prime, once with a form prime, and once with an unrelated prime. The complete list of word targets can be found in Appendix A.

Table 2.1. Comparison of mean frequency (per million in Celex), N and imageability of items used in the 30-ms and 60-ms prime duration conditions

Prime Duration	Frequency	N	Imageability
30 ms	67.5	0.31	450.3
60 ms	67.4	0.33	441.8

Procedure

The experiment was controlled by a Pentium PC, using the Windows DMDX software developed by J.C. Forster at the University of Arizona (Forster & Forster, 2003).

Items were presented as black letters on a white background using a color monitor with a refresh cycle of 10 ms. The forward mask which began each trial was a row of hash marks (########), presented for 500 ms. It was then replaced by the prime which was presented in lower case letters for 30 ms in half of the trials and 60 ms in the other half. The prime was then replaced by the target in upper case letters, also presented for 500 ms. The combination of the forward and backward masks effectively prevented the conscious detection of the prime and no participant reported being aware of it (for details of prime visibility determined under similar conditions, see Forster, Davis, Schoknecht, & Carter, 1987).

The task was lexical decision. Participants were instructed to respond as quickly as possible without making an excessive number of errors by pressing one of two keys marked ‘‘Yes” and ‘‘No”. Feedback after each trial informed the participants of the speed and accuracy of their response. Items were presented in a different pseudorandom order for each participant. To eliminate the possible confounding of order of presentation of items for 30-ms and 60-ms prime duration, half of the participants were tested with a block of 30-ms items first, followed by a block of 60-ms items, and half were tested in the reverse order. Prior to each block, 12 practice items were included.

2.1.2 Results

In this experiment, the fixed effect factors were Prime (whether the prime was an identity prime, a 1-LD form prime, or a control prime) and Prime Duration (30 ms vs. 60 ms), with subjects and items as crossed random effects. Both fixed-effect factors were repeated measures factors. Thus, the general mixed-effects model used for trimming was as follows: RT = lmer (log(rt) ~ Prime + Prime_Duration + (1|subject) + (1|item)). After the model-based trimming, 2.7% of the observations were excluded from analysis. The mean reaction times and error rates are presented in Table 2.2.

Table 2.2. Mean lexical decision times (in milliseconds) and percent error rates (in parentheses) for word targets as a function of prime duration (ms) and prime type (Experiment 1)

	Prime type			Priming	
	Identity	1-LD	Control	Identity	1-LD
Target: *PROBLEM*	*problem*	*croblem*	*contact*		
30 ms	484(7.8)	485(6.5)	504(12.2)	20	19
60 ms	475(3.1)	497(8.6)	525(10.4)	50	28

Since the purpose of the experiment is to test whether reduction in prime duration leads to parallel or dissociated reduction in identity and form priming, namely, whether there is an interaction between prime type and prime duration, the mixed-effects model applied was as follows: RT = lmer (log(rt) ~ Prime * Prime_Duration + (1|subject) + (1|item)), the asterisk denoting an assumed interaction between the two factors.

The results showed a significant main effect of identity priming ($t = 3.40$, $p < .01$), form priming ($t = 2.80$, $p < .01$), and prime duration ($t = 2.66$, $p < .01$). More importantly, the results showed a significant interaction between prime duration and identity priming ($t = 3.84$, $p < .001$), but not between prime duration and form priming ($t = 1.16$, $p > .05$), suggesting that the two forms of priming behave rather differently when the prime duration is reduced from 60 ms to 30 ms. Identity priming showed a significant 60% drop from 50 ms to 20 ms, but form priming stayed at about the same level, showing a much smaller drop of 32.1% from 28 ms to 19 ms, which was not significant.

Further analysis was made to compare the two forms of priming at 30-ms and 60-ms prime durations separately, and the pattern of dissociation between form and identity priming became more obvious. At 30-ms prime duration, the effects of form and identity priming were almost equal (19 and 20 ms, $t < 1$), but at 60 ms, the identity priming effect was significantly greater than that of form priming (50 and 28 ms, $t = 4.43$, $p < .001$). If form priming is merely a weaker form of identity priming, one would expect form priming to be weaker at any given prime duration. The present experiment clearly shows otherwise.

Analysis of the error rates was carried out using the following mixed-effect model: Error = lmer (error ~ Prime + Prime_Duration + (1|subj) + (1|itemN), family = binomial), because the effect of Prime did not interact with that of prime duration. The results revealed a significant effect of prime type, with both the identity and form conditions showing a significant reduction in error rate ($z = 4.26$, $p < .001$ and $z = 2.70$, $p < .01$ respectively). The main effect of prime duration was not significant ($z = 0.66$, $p > .05$).

2.1.3 SCM Simulation results

The same materials from Experiment 1 were fed into the online simulator of the Spatial Coding Model (Davis, 2010), the prime durations were set at 30 cycles and 60 cycles correspondingly (based on various simulations, Davis assumes that one cycle is equivalent to one millisecond), and the results were shown in Table 2.3 below. There is a drastic drop of 55% for identity priming from 60 to 27 cycles, and a matching 54.3% drop for form priming from 35 to 16 cycles. Moreover, form priming is significantly smaller than identity priming at both prime durations ($p < 0.01$ in both cases), just as an activation model predicts.

Table 2.3. Mean number of cycles for word targets to reach .68 as a function of prime duration (ms) and prime type (SCM Simulation Results)

	Prime type			Priming	
	Identity	1-LD	Control	Identity	1-LD
Target: *PROBLEM*	*problem*	*croblem*	*contact*		
30 ms	74	85	101	27	16
60 ms	46	71	106	60	35

2.1.4 Discussion

The overall pattern of the behavioral results in Experiment 1 forms a striking contrast with the simulation results from the SCM, as illustrated in Figure 2.1 below, a side by side graphic comparison of the results. The behavioral data showed a significant interaction between prime type and prime duration, suggesting that reducing the prime duration exerted a differential effect on the two forms of priming. The drastic 60% drop of identity priming was by no means comparable to the 32% drop of form priming. By contrast, the SCM simulation results showed a corresponding decrease of both identity and form priming to virtually the same degree, 55% vs. 54.3%. Furthermore, the behavioral data showed that identity and form priming were almost identical at 30-ms prime duration (20 ms and 19 ms respectively), but the SCM simulator predicted a significant difference between the two forms of priming at both prime durations.

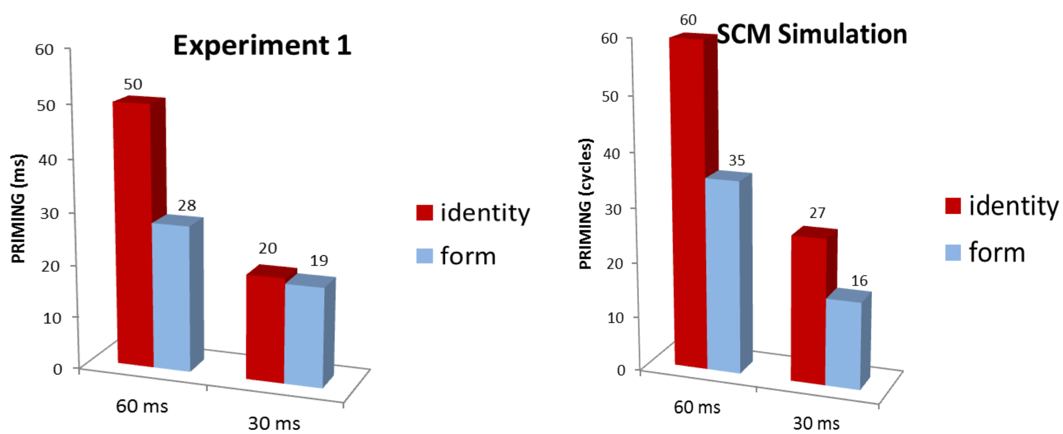

Figure 2.1. Comparison of Experiment 1 results (on the left) and SCM simulation results (on the right).

These behavioral results present a challenge to the persisting activation account of the masked priming effect. If the persisting activation account is correct in assuming that form priming is the same process as identity priming, only weaker, it would be difficult to explain why the same reduction in prime duration produced significant decrease in identity priming but not in form priming. It would be equally perplexing why equivalent effect was obtained for form and identity priming at 30-ms prime duration. If masked priming is merely a function of prime duration and the orthographic match between the prime and the target, one would expect form priming to be weaker than identity priming at any given prime duration, as illustrated in the simulation results in Figure 2.1. Evidently, the behavioral data showed a different picture. To accommodate these results, the persisting activation account may need to be modified.

On the contrary, these behavioral results lend a strong support to the EOM. The differential effect of reducing the prime duration on form and identity priming is expected in the EOM because form priming is limited by the EOT at the level of form, which is estimated to be around 30 ms, and therefore cannot be any higher than 30 ms even with a 60-ms prime or be reduced any further by a 30-ms prime. Additionally, the EOM does not preclude the possibility of form priming being equal to identity priming. In fact, if the EOT at the level of form is 30 ms as assumed in Forster (2008), both form priming and identity priming should be roughly equal at 30 ms of prime duration because both are limited to around 30 ms, form priming by the EOT and identity priming by the prime duration. The normal superiority of identity priming over form priming should therefore be minimized or even eliminated.

It must be noted, however, that the EOM predictions are based on estimates of the EOT, i.e. 30 ms at the level of form and 60 ms at both levels of form and meaning. These specific estimates were not totally confirmed in the first experiment. According to the EOM, with a 60-ms prime, identity priming should be roughly equal to 60 ms but form priming should maintain at the level of 30 ms due to the limitation of the EOT at the level of form. The 28-ms form priming obtained was commensurate with the EOM prediction, but the 50-ms identity priming was 10 ms short of what is predicted. Similarly, with a 30-ms prime, both identity and form priming are predicted to be 30 ms, but the results showed that both were around 20 ms only, also 10 ms short. One might wonder why identity and form priming turned out to be roughly equal when both were weaker than predicted in the EOM. If opening the entry at the level of form is shorter than assumed, for instance, 20 ms instead of 30 ms to accommodate the behavioral results, form priming would be 20 ms but identity priming should still be 30ms, being restricted by the prime duration. Then there should still be a real difference between the two forms of priming with a 30-ms prime.

Despite the 10-ms discrepancy, one essential aspect of the EOM was confirmed, namely that identity priming would be a linear function of prime duration. An increase in the prime duration should lead to a corresponding increase in the amount of priming. Such was the case in Experiment 1– increasing the prime duration by 30 ms led to a 30-ms increase in identity priming from 20 ms to 50 ms. So the question is: can this discrepancy of 10 ms be accounted for in the EOM? One possibility is that the EOT may vary. The first experiment seems to suggest that opening the entry at both levels of form and meaning may take less time than assumed, e.g. around 50 instead of 60 ms, for some words or some participants. If so, identity priming should be limited to 50 ms even if the prime duration is 60 ms. It is also possible that the EOT at the level of form is shorter than 30 ms, but it is not clear from Experiment 1 because form priming was found to be 19 ms with a 30-ms prime but 28 ms with a 60-ms prime. This possibility of a variable entry opening time was explored in the following experiment.

2.2 Experiment 2. Limits on Priming in L2 Readers

If the entry opening time is variable, a reasonable assumption is that it varies for different people, between L1 and L2 readers in particular. As reported in previous research, L2 readers are generally considered to be slower in lexical processing than their L1 counterparts (Gollan, Forster & Frost, 1997). Of all the differences and similarities studied between L1 and L2 readers, slower processing speed is probably one of the few facts that have not provoked much disagreement, although there is much less consensus as to why they are slower. According to the EOM, L2 readers may be slower in two respects, namely in search speed and/or in the entry opening process. If the entry opening time in L2 is longer than in L1, the question is whether or not the savings model of the EOM applies in L2.

To further explore the effect of the EOT on priming, this experiment tested L2 readers of English, using the same design and materials from Experiment 1. Replicating the first experiment with L2 readers will shed light on how the speed of lexical processing, and particularly a longer EOT, may affect the amount of masked priming. A comparison between L1 and L2 readers in Experiment 1 and 2 will also provide an alternative angle for interpreting the mechanisms of masked priming. Additionally, if L2 lexicon is stored in a totally different memory system than L1 lexicon as Jiang (1999) and Jiang and Forster (2001) argued, this experiment will also provide insight into how the mechanisms of masked priming relate to the different memory systems.

2.2.1 Method

Participants

A total of 18 second language speakers of English, who were either enrolled students or visiting scholars in the University of Arizona, volunteered to participate in the experiment.

Materials and design

The design and items were as in Experiment 1. See Appendix A for a complete list of the items.

Procedure

As in Experiment 1, except that the inter-trial interval was increased by 200 ms to allow for extra processing time that was considered necessary for L2 speakers (Jiang, 1999).

2.2.2 Results

As in Experiment 1, the fixed effect factors were Prime and Prime Duration, with subjects and items as random effects. Both fixed-effect factors were repeated measures factors. The same general mixed-effects model as in Experiment 1 was used for data trimming: RT = lmer (log(rt) ~ Prime + Prime_Duration + (1|subject) + (1|item). After the model-based trimming, 1.8% of the observations were excluded from analysis. The mean reaction times and error rates are reported in Table 2.4.

Table 2.4 Mean lexical decision times (ms) and percent error rates (in parentheses) for word targets as a function of prime duration (ms) and prime type (Experiment 2)

	Prime type			Priming	
	Identity	1-LD	Control	Identity	1-LD
Target: *PROBLEM*	*problem*	*croblem*	*contact*		
30 ms	688(10.4)	687(12.5)	724(14.6)	36	37
60 ms	668(9.4)	699(10.4)	745(13.9)	77	46

To test whether there was an interaction between prime type and prime duration, the same mixed-effects model in Experiment 1 was used: RT = lmer (log(rt) ~ Prime * Prime_Duration + (1|subject) + (1|item). The results showed a very similar pattern as in Experiment 1. There was a significant main effect of priming for both form and identity primes (t = 3.4, p < .001 and t = 3.49, p < .001 respectively), although the main effect of prime duration was not significant (t < 1). The pattern of interaction between priming and duration was exactly the same as in Experiment 1: the interaction was significant in the identity condition (t = 2.50, p < .05), but not in the 1-LD form condition (t < 1).

A separate analysis was conducted for the two prime durations of 30 and 60 ms, comparing the two forms of priming at each of the individual prime durations. Again, L2 readers showed the same pattern of priming effect as their L1 counterparts. At 30 ms, the effects of identity and form priming were equivalent (36 ms and 37 ms, t <1), but at 60 ms, identity priming was significantly greater than form priming (77 and 46 ms, t = 3.05, $p < .001$). However, the amount of priming in L2 seemed to be consistently greater than the L1 priming effect observed in Experiment 1 for both form and identity priming at both prime durations. In addition, the priming effect in L2 seemed to be slightly longer than what EOM predicts, contrary to the L1 results where the priming effect was consistently shorter than expected.

Analysis of the error rates was carried out using the following mixed-effect model: Error = lmer (error ~ Prime + Prime_Duration + (1|subj) + (1|itemN), family = binomial). Results showed a significant effect of priming in the identity condition only, indicating a significant reduction in error rate (z = 2.52, p < .05). The priming effect in the 1-LD form condition was not significant (z = 1.55, $p > .05$), nor was the effect of prime duration ($z < 1$).

To make a direct comparison between L1 and L2 results, the data in the first two experiments were combined. For this analysis, the fixed effect factors were Language, Prime and Prime Duration, with subjects and items as crossed random effects. Of the three fixed-effect factors, prime and prime duration were repeated measures factors, and language was a between-subjects factor. The same general mixed-effects model was used for data trimming: RT = lmer (log(rt) ~ Prime + Prime_Duration + (1|subject) + (1|item). After the model-based trimming, 2.3% of the observations were discarded. The priming effects in L1 and L2 are reported in Table 2.5 below.

Table 2.5 Comparison of the 1-LD form and identity priming effects (ms) in L1 and L2 English readers as a function of prime duration (ms) and prime type (Experiment 1 & 2)

	L1 Priming		L2 Priming	
	Identity	1-LD	Identity	1-LD
30 ms	20	17	36	35
60 ms	50	28	78	48

To test whether language interacts with the other two factors, the following mixed-effects model which assumes a three-way interaction was used: RT = lmer(log(rt) ~ Language * Prime_Duration * Prime + (1 | subj) + (1 | itemN)). The results showed a significant main effect of all three factors, language ($t = 5.28$, $p < .001$), prime ($t = 2.35$, $p < .05$ for form priming and $t = 3.08$, $p < .01$ for identity priming respectively), and prime duration ($t = 2.24$, $p < .05$). Also significant was the interaction between identity prime and prime duration ($t = 3.10$, $p < .01$), but none of the other two-way interactions or the three-way interactions were significant (either $t < 1$, or $p > .05$).

Separate analyses for the two prime durations were conducted, using the following mixed-effects model assuming a two-way interaction: RT = lmer (log(rt) ~ Language * Prime + (1| subj) + (1 | itemN). The results confirmed that L1 and L2 priming effect did not differ significantly at either prime duration. At both the 30-ms and 60-ms prime durations, all three main effects of language, form priming and identity priming were significant (all $p < .05$), but neither of the interactions between language and the two forms of prime was significant ($p > .05$). These results suggest that although L2 readers are significantly slower in reaction time overall, they do not differ from L1 readers significantly in terms of the effect of priming at different prime durations.

Since language did not interact with the other two factors, the following mixed-effects model was applied in the error analysis: Error = lmer (error ~language + Prime * Prime_Duration + (1|subj) + (1|itemN), family = binomial). The main effects of language and both forms of priming were significant, suggesting that L2 readers made significantly more errors ($z = 2.31$, $p < .05$), and that both L1 and L2 participants made more errors in the control condition as compared in the related conditions where form and identity primes were used ($t = 2.58$, $p < .01$ for form priming and $t = 2.73$, $p < .01$ for identity priming respectively).

2.2.3 Discussion

The overall pattern of results in Experiment 1 was fully replicated in Experiment 2, as illustrated in Figure 2.2 below. There was no difference at all between identity and form priming at 30-ms prime duration for both L1 and L2 readers of English. That is, form priming was not always weaker than identity priming, which was equally true to both groups of participants.

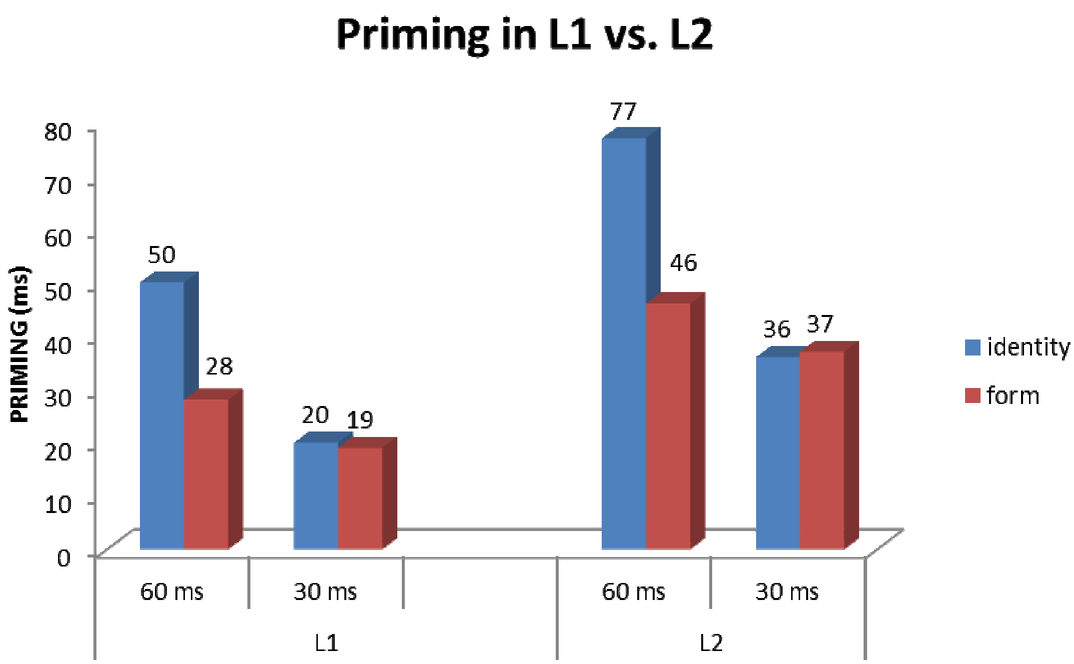

Figure 2.2. Comparison of priming results of Experiment 1 for L1 readers (on the left) and Experiment 2 for L2 readers (on the right) at prime durations of 30 ms and 60 ms.

In terms of the amount of priming observed in relation to the SOA, however, the two groups were exactly the opposite. L1 participants produced less savings than the SOA while L2 participants produced more. As explained in Chapter 1, the EOM predicts that the priming effect should be less than the SOA if the EOT is shorter than the SOA, so it can be argued that the EOT is shorter for the L1 participants in Experiment 1, thus less savings than the SOA. For the hyper-priming effect observed in L2, the same argument from Forster et al. (2003) is applicable. As shown in the results of the first two experiments, there was a significant reduction in errors with a related prime in both L1 and L2. Suppose that the lexical processor may fail to find a matching entry during the first search attempt and that if the first attempt fails, it will launch a second search. A related prime boosts the chance for the lexical processor to locate the matching entry for the target during the first search and therefore reduces the need for a second search, thus leading to extra savings. Assuming that the L2 lexical processor is more likely to miss a matching entry and therefore has to resort to a second search more frequently than the L1 lexical processor, the priming effects in L2 may be inflated, namely, greater than the SOA.

Overall, both the L1 and L2 results supported the EOM predictions. Form priming is not merely a weaker type of identity priming. Rather, it is limited by the entry opening time at the level of form, so reducing the prime duration from 60 ms to 30 ms does not reduce the amount of form priming to the same degree as it does to identity priming.

CHAPTER 3

THE EFFECT OF PRIME DURATION VS. SOA

The first two experiments focused on the EOM predictions concerning the amount of priming as a function of prime type and prime duration. It was shown that form priming and identity priming were subject to different limits determined by the SOA together with the EOT at two different levels, supporting the EOM predictions. However, since the SOA was equal to the prime duration in both experiments, it is not clear whether it is the SOA or the prime duration that determines the amount of priming.

According to the EOM, masked priming is a savings effect. A related prime opens the entry for the target, so when the target is presented, its entry is already opened, thus saving time. In effect, the prime provides a “head-start” for the target, so processing of the target is started before it is even presented. The “head-start,” namely the SOA, then leads to a priming effect. The longer the “head-start” is, the greater the priming effect should be. It is therefore predicted in the EOM that it is the SOA that determines priming, not the prime duration per se. It is worthy of note here that this prediction only applies when the SOA is very short. If the SOA is very long, for example 500 ms, then the priming effect may decay, and the nature of the priming effect will be different because the prime becomes visible.

If the EOM prediction is correct, inserting a short delay between the prime and the target, consisting of a neutral stimulus, ought to increase the amount of masked priming. For instance, if a 40-ms prime is followed by 20 ms of an interpolated mask or a blank frame, then the “head-start” provided by the prime would be 60 ms, not 40 ms. This should produce 60 ms of priming, provided that an identity prime is used. By contrast, an activation account would make a different prediction. Since it is assumed that activation in word units is only generated while the stimulus is present, extending the SOA by inserting a 20-ms blank gap after a 40-ms prime might not be any more effective than the 40-ms prime alone. It might even be less effective, due to decay of activation over the inserted 20-ms gap.

However, the results of a pilot study conducted by Lisa Eliot at the University of Arizona suggested rather different results. In some conditions, priming was increased by a delay of the target, but the opposite result was obtained in other conditions. For example, a 40-ms prime followed by a 10-ms hash mask produced 50 ms of priming, but a 20-ms hash mask dramatically reduced priming to 22 ms. However, the design of this pilot study used different targets in each priming condition, so the conditions were not really comparable. A more rigorous design needs to counterbalance targets across the different priming conditions to remove the possible confounding effect of targets being different. Such was the design in Experiment 3.

It must be noted here that an iconic storage view would make the same predictions as the EOM. That is, iconic memory might extend the apparent duration of the prime, so that a 40-ms prime followed by a 20-ms blank is effectively available for 60 ms, thus producing the same amount of priming as a 60-ms prime (Coltheart, 1980). It is therefore especially relevant to make a note here that all of the experiments reported here were done using black letters on a white background, so if there was any iconic trace, it should be washed out by the white background. Then if more priming is observed for a 40-ms prime followed by a gap, one can be sure that it is not due to iconic storage.

3.1 Experiment 3. The Effects of Prime Duration vs. SOA.

This experiment was specifically designed to investigate the prime duration and SOA debate outlined at the beginning of this chapter.

3.1.1 Method

Participants

A total of 24 undergraduate students enrolled in an introductory Psychology course participated in the experiment, for which they received course credit.

Materials and design

A total of 96 words were chosen as word targets. They were all 7 letters in length, their frequencies ranged from 40 to 160 per million (Celex, Mean = 75.1), and the number of neighbors (N) was no more than 3 (Mean N = .40). A total of 96 orthographically legal nonwords were selected as distracters. Like the word targets, they were all 7 letters in length and had no more than 1 neighbor (Mean N = .43). These nonwords were constructed by changing either one or two letters of a real word, a vowel being replaced for a vowel and a consonant for a consonant. For each target, two different primes were constructed: an identity prime and an unrelated control prime of the same length with no more than 1 shared letter in the same position as the target. This prime was a word in the case of word targets and a nonword in the case of nonword targets. The complete list of word targets and control primes can be found in Appendix B.

These targets were randomly divided into two groups and tested at two different SOAs, 40 ms and 60 ms. The 40 ms of SOA consists of a 40ms prime, and the 60 ms of SOA consists of a 40 ms prime and a 20 ms blank frame inserted between the prime and the target. All of the targets were tested at both SOAs across conditions so that if one group of targets were tested at 40/20 ms in one condition, they would be tested at 40/0 ms in another. In each testing condition, however, half of the targets were tested at 40/0 ms and half at 40/20 ms, and the items were tested in blocks for each SOA. To control for the possible order effect, two different orders of SOA were tested, 40-ms items followed by 60-ms items first and the reverse. For each order of testing, four counterbalanced lists of items were prepared so that across all lists, each target word and nonword was primed by an identity prime and a control prime and tested with an SOA of 40/0 ms and 40/20 ms such that no target appeared more than once in each list.

Procedure

The procedure was the same as in the first two experiments, except that different SOAs were used. In this experiment, the prime was presented for 40 ms and then immediately replaced by the target in half of the trials in each testing condition. In the other half, the prime was presented for the same period of 40 ms, but it was then followed by a blank frame of 20 ms before it was replaced by the target, as shown in Figure 3.1.

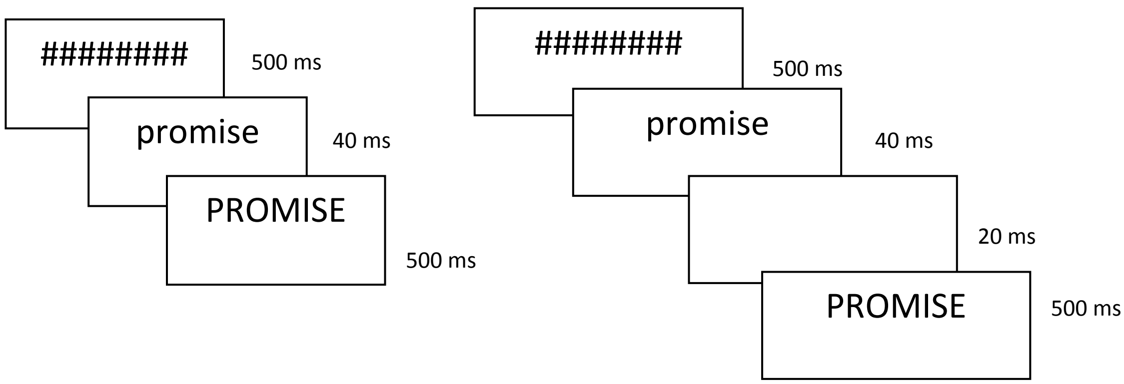

Figure 3.1. Sequence of stimuli in Experiment 3. In the 40-ms SOA (No-Blank) condition (on the left), a 40-ms prime is replaced by the target immediately. In the 60-ms SOA (Blank) condition (on the right), a 20-ms interpolated blank frame is inserted between the 40-ms prime and the target.

As in the first two experiments, the task was lexical decision. At the beginning of the experiment, 20 practice items were included. To eliminate the possible confounding of order of presentation of items for the 40-ms and 60-ms SOAs, half of the participants were tested with a block of 40-ms items first, followed by a block of 60 ms items, and half were tested in the reverse order. Prior to each block, 20 warm-up filler items were included. These practice and filler items were all constructed according to the same criteria as the test stimuli.

3.1.2 Results

In this experiment, there were three fixed-effect factors, Prime (related vs. unrelated), SOA (40/20 vs. 40/0 ms, or Blank vs. No-Blank), and Order (40-60 vs. 60-40), the first two being repeated measures factors, and Order being a between-subjects factor. Subjects and items were two crossed random effects. Thus, the following general mixed-effects model was used for data trimming: RT = lmer (log(rt) ~ Prime + SOA + Order + (1|subject) + (1|item)). After the model-based trimming, 2.4% of the observations were excluded from analysis. Since it was found that Order did not have a significant main effect, nor did it interact with prime or SOA, Order was dropped from all the following analyses of both error and reaction time in the experiment. The mean reaction times and error rates are presented in Table 3.1.

Table 3.1 Mean reaction times (ms) and percent error rates (in parentheses) for word targets as a function of SOA (ms) and prime type (Experiment 3)

	SOA	
	No-Blank (40/0 ms)	Blank(40/20 ms)
Identity	446(6.1)	448(5.9)
Control	489(12.2)	484(11.5)
Priming	43	36

To investigate whether or not there is an interaction between prime and SOA, the following mixed-effects model was applied: RT = lmer (log(rt) ~ Prime * SOA + (1|subject) + (1|item)). Only the main effect of prime type was significant (t = 7.22, p

< .001). The main effect of SOA was not significant (*t* = 1.10, *p* > .05), nor was the interaction between SOA and Prime (*t* = 1.16, *p* > .05). Since it has been reported that the reaction time (RT) on a given trial is correlated with the RT on the previous trial (due to serial effects, such as fatigue or practice), it is sometimes worthwhile to remove the influence of this variable by including it as a covariate in the regression model. This was done using the following mixed-effects model: RT = lmer (log(rt) ~ Prime * SOA + Order + PrevRT + (1|subject) + (1|item). The effect of previous RT was significant (*t* = 7.75, *p* < .05), but extracting its influence from the analysis did not change the results in any important way. The main effect of prime type was still significant (*t* = 6.70, *p* < .001), the main effect of SOA and the interaction between prime and SOA remained to be insignificant (*t* = 1.58 and *t* = 1.11 respectively). It is very clear that the amount of priming was not significantly different between the Blank and No-Blank conditions (36 ms and 43 ms respectively). If anything, the blank gap slightly reduced the amount of priming. This result was contrary to the EOM prediction; rather, it suggested that the priming effect was influenced to a greater degree by the prime duration than by the SOA.

In the error analysis, the same pattern was obtained: only the main effect of prime type was significant (*z* = 5.00, p < .001), demonstrating that significantly fewer errors were made in the identity condition relative to the control condition.

3.1.3 Discussion

The result of equivalent identity priming at different SOAs supports an activation model rather than a savings model. The fact that an identity prime produced about 43 ms of priming when the prime duration was 40 ms is roughly in line with the EOM prediction. However, a savings model also predicts that the amount of priming should be equivalent to the “head-start” provided by the prime. That is, in the inserted gap condition, the gap increases the “head-start” or the SOA by 20 ms, so the amount of priming should also increase by approximately the same amount. The result was quite the opposite. There was no significant boost of the priming effect at all when a 20-ms gap was inserted; if anything, priming was slightly reduced in the gap condition.

Such a result could be interpreted by the persisting activation account based on the Interactive Activation model. Since priming is considered a function of the prime duration, the amount of activation which the prime receives is determined by how long it is present, which in turn determines how much persisting activation will be transferred to the target. When the prime disappears, no further activation takes place. Thus, the priming effect is equal for both conditions with or without the inserted 20-ms gap. Furthermore, since it is assumed that activation may decay over time, the inserted gap may even diminish priming in proportion to the degree of decay that has occurred.

This result also fits in with what Bloch’s Law would predict (Tzur & Frost, 2007). According to this law, it is mistaken to consider brief visual stimuli to be spread out in time and therefore to have instantaneous values of intensity. Such a stimulus does not have an intensity nor a duration. It just has an energy. At a very early stage of visual processing the energy accumulates until it reaches some critical value, and the visual system then delivers exactly the same information to the next level regardless of whether the stimulus was very short but intense or a lot longer but much less intense. Namely, the energy level of a brief visual stimulus is determined by both its duration and intensity (Tzur & Frost, 2007). According to this model, the 40/0 and 40/20 primes would generate the same energy level, and hence produce equivalent priming, on the assumption that priming depends on the energy level. This argument leads to the same prediction as an activation model.

So can this result be accounted for in the savings model? One possibility is that the inserted gap makes the control condition less interfering, thereby reducing the treatment effect. If this is true, it is possible that a 40/20ms SOA will not produce more priming than a 40ms SOA alone. However, it does not seem to be the case in this experiment. There is virtually no difference in the reaction times of the control conditions at the two different SOAs (489 and 484 ms).

Another possibility is that the search for the prime is not always reliable when it is constrained by time. If the prime duration is very brief, e.g. 40 ms as was the case in this experiment, the search for the prime might fail and therefore might not produce any priming. Contrary to the assumption in EOM that once initiated, the search for the prime continues, it is possible that the prime must be physically present when the lexical processor searches for the prime. If so, it is not entirely unreasonable to assume that if the search fails to locate the prime before the prime disappears, no priming will be obtained even with an inserted 20-ms blank. That is, if the search fails to open any entry when the prime is replaced by a blank interval, no entry opening can occur thereafter, hence no priming. Therefore, one would not expect the inserted blank to produce any more priming than in the no-blank condition.

Of course, this assumption only applies to words with certain lexical features. Since previous research has consistently shown a frequency effect (e.g. Scarborough et al. 1977; Forster & Davis, 1984), i.e. low frequency (LF) words take longer to identify than high frequency (HF) words, it can be assumed that the search for a LF prime is more likely to fail at a very brief prime duration. As a consequence, LF words might not benefit from the added 20-ms blank as much as HF words would. If this assumption is true, the priming effect for LF words will be somewhat compromised, predicting an interaction between frequency and priming at a very short prime duration. So far, the current result does not seem to bear out such an assumption very well. For one thing, the items used in the experiment have a relatively medium range of Celex frequencies, 40 to 160 per million (Mean = 75.1). It would be a far stretch to classify them as LF words. To account for the present result, one has to assume that the LF and HF items (relatively speaking) happened to cancel out the differences in priming across the two SOA conditions. For another, it remains to be tested whether LF words produce less priming than HF words at brief prime durations. In fact, there are studies showing that low-frequency words benefit far more from repetition than do high-frequency words when the prime is visible (e.g. Scarborough et al. 1977; Kinoshita, 2006), which results in an attenuated frequency effect for primed words compared to unprimed words.

This frequency attenuation effect, however, is controversial at best, when the prime is masked or presented very briefly. In the original study of repetition priming and frequency attenuation in lexical access, Forster and Davis (1984) found no interaction between repetition priming and frequency, showing that HF and LF words produced equivalent amount of priming with a repetition prime of 60 ms. Rajaram and Neely (1992) reported similar findings with a 50-ms prime. Bodner & Masson (1997, 2001) reported both kinds of results, finding an interaction in some experiments, not in others. Similarly, Kinoshita (2006) found no interaction in one experiment, but a clear interaction when she used a different group of LF words comparable in frequency but much higher in degree of "familiarity." If frequency affects repetition priming in some way, one has to ask whether the results in Experiment 3 can be replicated with HF and LF words. The next experiment was designed to explore this frequency issue.

3.2 Experiment 4. The Effects of Prime Duration vs. SOA in LF Words.

As shown in the previous experiment, inserting a 20-ms gap after a 40-ms prime did not increase priming for words of relatively high frequencies (40 to 160 per million, Mean = 75.1, Celex). Since there are studies suggesting that LF words may produce greater priming than HF words, it is possible that LF words may react differently to an inserted gap. Experiment 5 was designed to test this. If activation models are correct, one would expect the same results as in Experiment 3.

3.2.1 Method

Participants

A total of 38 undergraduate students enrolled in an introductory Psychology course participated in the experiment, for which they received course credit.

Materials and design

The design was exactly the same as in Experiment 3, except that the items tested in this experiment were substantially lower in frequency, and that additional effort was made to ensure that the control primes were matched with the word targets on relevant accounts. As in Experiment 3, a total of 96 words were chosen as word targets, and they were all 5-7 letters long (32 for each length) and had no more than 3 neighbors (Mean N = .68). The Celex frequencies of these words, however, ranged from 3 to 5 per million (Mean = 4.3), substantially lower than the word targets in Experiment 3. To ensure that the control primes were as equivalent to the identity primes as possible, another set of 96 LF words were selected as unrelated control primes, and they were matched with the word targets in length, frequency (Mean = 4.2), and N (Mean N = .77). A total of 96 orthographically legal nonwords were used as distracters. These nonwords were comparable with the word targets in length and N (no more than 2 neighbors, Mean N = .60). Another set of 96 nonwords of matching properties in length and N (Mean N = 0.6) were used as control primes for the nonword targets. The vast majority of these nonwords were made by changing either one or two letters of a real word, vowel for vowel and consonant for consonant. A very small number of them were adapted from a list of nonwords generated by ARC Nonword database (Rastle, Harrington, & Coltheart, M., 2002), available online at *http://www.maccs.mq.edu.au/~nwdb/*. The complete list of word targets and control primes can be found in Appendix C.

As in Experiment 3, two different primes were constructed for each target: an identity prime and an unrelated control prime. These targets were randomly divided into two groups and tested at two different SOAs (40/0 ms and 40/20 ms) in two orders, 40/0-ms items followed by 40/20-ms items first and the reverse. For each order of testing, four counterbalanced lists of items were prepared so that across all lists, each target word and nonword was primed by an identity prime and a control prime and tested with an SOA of 40/0 ms and 40/20 ms such that no target appeared more than once in each list. A total of 60 practice items (20 at the beginning of the experiment, and 20 before the start of each SOA condition) were included. This was designed to familiarize the participant with changes in the timing of the stimuli.

Procedure

The procedure was exactly the same as in Experiment 3.

3.2.2 Results

In this experiment, there were three fixed-effect factors, Prime, SOA (40/0 vs. 40/20 ms, or Blank vs. No-Blank), and Order (40-60 vs. 60-40), the first two being repeated measures factors, and Order being a between-subjects factor. Subjects and items were two crossed random effects. Thus, the following general mixed-effects model was used for data trimming: RT = lmer (log(rt) ~ Prime + SOA + Order +

(1|subject) + (1|item)). After the model-based trimming, 2% of the observations were excluded from analysis. The mean reaction times and error rates are presented in Table 3.2.

Table 3.2 Mean reaction times (ms) and percent error rates (in parentheses) for word targets as a function of SOA and prime type (Experiment 5)

	SOA	
	No-Blank (40/0ms)	Blank(40/20ms)
Identity	505(10.7)	506(7.9)
Control	539(15.8)	551(14.7)
Priming	34	45

Since the effect of order did not interact with Prime or SOA, the following mixed-effects model was applied: RT = lmer (log(rt) ~ Prime * SOA + Order + (1|subject) + (1|item)) in order to investigate whether or not there is an interaction between prime and SOA,. The main effects of prime type and SOA were both significant ($t = 9.69$, $p < .001$ and $t = 2.70$, $p < .01$ respectively). The interaction between SOA and Prime was not significant ($t = 1.53$, $p > .05$). The amount of priming did not appear to be significantly different between the Blank and No-Blank conditions (45 and 34 ms). However, if the effect of previous reaction time was taken into account using the following model, RT = lmer (log(rt) ~ Prime * SOA + Order + PrevRT + (1|subject) + (1|item), the interaction became significant ($t = 2.08$, $p < .05$). The effect of previous reaction time was highly significant (*t* = 9.83, *p* < .001), and the main effects of prime type (*t* = 10.18, *p* < .001) and SOA (*t* = 2.48, *p* < .01) remained significant. Apparently, the reaction time on the previous trial carries a big portion of the variance in the data, and once this variance was extracted from the analysis, the interaction between prime and SOA was boosted to significance.

In the error analysis, the following model was applied: Error = lmer (error ~ Prime * SOA + Order + (1|subject) + (1|item)), family = binomial. Only the main effect of prime type was significant (*z* = 4.64, *p* < .001), demonstrating that significantly fewer errors were made in the identity condition than in the unrelated condition.

3.2.3 Discussion

The results of Experiment 4 were decidedly different from those in Experiment 3, showing that words of different frequencies reacted rather differently to the inserted 20-ms gap. Experiment 3 showed no difference in priming between the two SOA conditions for relatively HF words (40-160 per million based on Celex database, Baayen, Piepenbrock, & van Rijn, 1995), suggesting that it is the prime duration that determines priming. In Experiment 4, however, the inserted 20-ms blank interval led to an 11-ms gap benefit for LF words (3-5 per million, Celex), indicating that it is the SOA that determines priming, not the prime duration per se, lending partial support to the Entry Opening Model. So how can these opposite results be reconciled? Why should frequency matter?

To account for these results, one has to be able to explain how it is possible for word frequency to completely alter the results. As discussed in detail in Chapter 1, the Interactive Activation model considers that the masked priming effect is a result of the persisting activation from the prime, and that the amount of priming is largely dependent on the prime duration. The longer the physical prime is presented, the greater the priming effect should be. Since the physical stimulus must be present to generate activation, the physical presence of the prime is crucial in building up activation and thereby producing a priming effect. Once the prime disappears, no more activation will be produced during the inserted 20-ms blank interval, so no gap benefit should be expected. It is not clear why this argument only applies to HF words, not LF words. According to the IA model, HF words have a higher resting level of activation and therefore take less time than LF words to reach the criterion for lexical access to occur. It is therefore possible that HF words produce less priming than LF words at the same prime duration, but this does not predict that LF words should behave any differently from HF words when a blank gap is inserted between the prime and the target and thereby increase the SOA but not the prime duration. If the IA model is correct, word frequency should not matter.

For the Entry Opening Model, there is a possibility that the contrasting results in the previous two experiments can be accounted for. Since the EOM predicts that the amount of priming is determined by the smaller of the entry opening time or the SOA, it can be assumed that the HF words tested in Experiment 3 have very short entry opening times (shorter than the SOA), thus setting a limit to the amount of priming that could be obtained in both SOA conditions. So, although the SOA was increased by the inserted 20-ms gap, the amount of priming remained the same because it reached a ceiling at the very short entry opening time. However, if the LF words in Experiment 4 have longer entry opening times, say 60 ms or longer, they could benefit from the 20-ms gap. This hypothesis of a variable entry opening time was investigated in the next experiment.

3.3 Experiment 5. The Effects of Prime Duration vs. SOA in HF and LF Words.

To account for the opposite results in the previous two experiments, our hypothesis is that the entry opening time may be variable for different words, HF words having a shorter EOT. If so, HF words would not show a gap benefit (as found in Experiment 3), but LF words should (as found in Experiment 4). To test this hypothesis, we need to compare HF and LF words at two SOA conditions. One of the SOA conditions has to be 40/20, namely a 40-ms prime followed by a 20-ms blank. The other condition must be able to establish a potential ceiling effect in priming for HF words as a result of their brief entry opening time. A regular 60-ms prime condition (60/0) is appropriate because the entry opening time at both levels of form and meaning is estimated to be around 60 ms. If identity priming is found to be less than 60 ms with a regular 60-ms prime, it is very likely that the priming effect is restricted by a shorter EOT. According to the EOM, if HF words show less priming because of a shorter EOT, then one would not expect to see any difference between the two SOA conditions, priming being restricted by the EOT. For LF words, the priming effect should be equal for 40/20 and 60/0 as well, but for a different reason. Namely, if the EOTs of LF words are equal or longer than the SOA, the priming effect should be determined by the SOA. Therefore, a 40-ms prime plus a 20-ms blank gap should produce practically equal priming to a regular 60-ms prime. By contrast, an activation model would predict a difference in priming for both HF and LF words between the two SOA conditions because resting levels of activation should not matter in this activation paradigm.

An important feature of the design of this experiment was that the two SOA conditions were tested separately with different participants. This between-participant design was a special caution taken to avoid the potential influence of temporal attention on masked priming effects. Naccache, Blandin and Dehaene (2002) reported that making the target occurrence unpredictable and thereby shifting the temporal attention via a variable SOA eliminated not only the response congruity priming effect but also the masked repetition priming effect generally considered to be very reliable and robust, suggesting that temporal attention was necessary for cognitive processing of visual stimuli. It is essential that the prime be presented within a certain temporal window close to a predictable target stimulus for it to produce any priming effect. The importance of attention in masked priming experiments was also reported in Lachter, Forster and Ruthruff (2004), showing that masked priming effects depended on whether the prime appeared at spatially attended locations. Having the two SOA conditions tested separately in different sessions will ensure that participants will always know when to expect the target to occur so that the prime is attended to in order to achieve maximum priming effects possible. Although the SOAs tested in this experiment were the same and thus having virtually averted the problem of temporal attention, such special caution was viewed necessary in case the inserted gap might upset the rhythm of testing and thereby affect priming in any significant way.

3.3.1. Method

Participants

A total of 64 undergraduate students enrolled in an introductory Psychology course participated in the experiment, for which they received course credit.

Materials and design

A total of 96 words were selected as word targets. These words were all 5-7 letters in length (32 words for each word length) and had no more than 2 neighbors. Half of these words were high frequency (150-320 per million, Celex), and half were low frequency (3.5-5.0 per million, Celex). These two sets of words of different frequencies were matched on word length and the number of neighbors (N). Another set of 96 words, half HF and half LF, were selected as control primes. They were matched with the HF and LF target words respectively on frequency, word length and number of neighbors. All of the LF word targets and control primes were taken directly from Experiment 4. The HF word targets and control primes were purposefully chosen so that their frequencies are higher than the word targets used in Experiment 3 to ensure a clear frequency effect will be obtained. The item matching details, as well as how they compare with Experiment 3 and 4, are presented in Table 3.3. A total of 96 orthographically legal nonwords were used as distracters, and another set of 96 nonwords of matching properties were used as control primes. All of these nonwords were taken directly from Experiment 4. The complete list of word targets and control primes can be found in Appendix D.

Table 3.3 Comparison of frequency (per million in Celex), mean frequency (reported in parentheses) and mean number of neighbors (N) of items used as word targets and control primes in Experiments 3- 5

		Word Targets		Control Primes	
		Frequency	Mean N	Frequency	Mean N
Exp. 3		40-160 (75.1)	0.40	N/A	N/A
Exp. 4	LF	3.5-5.0 (4.3)	0.68	3.5-5.2 (4.2)	0.77
Exp. 5	HF	150-320 (196)	0.63	130-480 (279)	0.75
	LF	3.5-50 (4.6)	0.58	3.5-5.2 (4.6)	0.75

The experiment used a 2x2x2 mixed design, with frequency and prime type as within-subjects factors and SOA as a between-subjects factor. Specifically, each target was tested in two SOA conditions, 40/20 vs. 60/0, separately with different participants. That is, half of the participants were tested in the 40/20 condition and half in the 60/0 condition. In each condition, each target was paired with an identity prime or a control prime so that each target was seen by a subject only once, and across every 2 subjects it was paired once with an identity prime and once with an unrelated prime, producing two counterbalanced lists of items for each SOA condition. The prime was a word in the case of word targets and a nonword in the case of nonword targets. Both HF and LF words were tested in the same list in a pseudorandom order for each participant. At the beginning of the experiment, the subjects were given 16 practice items, which were selected according to the same criteria as the test stimuli.

Procedure

The same lexical decision task was used. The procedure was similar to Experiment 3, except that the two SOA conditions were tested separately in different sessions using different participants. This between-participants design is a more efficient alternative to a very complicated design with fewer test items in each condition. To ensure equivalent power of the experiment, more than twice the number of participants in Experiment 3 was tested.

3.3.2 Results

There were three fixed-effect factors in this experiment, Prime (whether the prime was an identity prime or a control prime), Frequency (whether the target item was HF or LF), and SOA (whether the SOA was 40/20 or 60/0) with subjects and items as crossed random effects. Prime type and frequency were both repeated measures factors, and SOA was a between subjects factor. The general mixed-effects model used for trimming was as follows: RT = lmer (log(rt) ~ Prime + Frequency + SOA + (1|subject) + (1|item)).

After the model-based trimming, 2.1% of the observations were discarded. The mean reaction times and error rates are presented in Table 3.4.

Table 3.4 Mean reaction times (ms) and percent error rates (in parentheses) for word targets as a function of frequency, prime type and SOA (Experiment 4)

	SOA=40/20		SOA=60/0	
	HF	LF	HF	LF
Identity	459 (3.9)	504 (13.9)	445 (2.2)	497 (11.7)
Control	492 (4.4)	555 (26.0)	476 (4.4)	561 (28.4)
Priming	33	51	31	64

Since the main purpose of the experiment is to test whether priming is different for the two SOA conditions, namely whether there was an interaction between prime type and the SOA, the mixed-effects model applied was as follows: RT = lmer (log(rt) ~ Prime * Frequency * SOA + (1|subject) + (1|item)). The results showed that the main effects of prime type and frequency were significant (t = 8.27, p < .001 and t = 9.22, p < .001 respectively), but the main effect of SOA was not (t < 1). The interaction between SOA and frequency was significant (t = 2.39, p < .05), indicating that the frequency effect was different across the two SOA conditions. More specifically, the frequency effect was bigger in the regular 60-ms prime condition (68 ms) than in the 40/20 condition (54 ms), which may be just due to variance between the participants because SOA was tested between subjects. None of the other interactions was significant. The three-way interaction was not ($t = 1.43$, $p > .05$), neither was the interaction between priming and frequency ($t = 1.78$, $p > .05$) or the interaction between priming and SOA ($t < 1$). These results remained virtually unchanged even after the effect of previous RT was taken into account except that the interaction between priming and frequency became significant ($t = 2.03$, $p < .05$). As illustrated in Figure 3.2 beblow, the amount of priming was not significantly different between 40/20 and 60/0 for both HF and LF word targets (33 vs. 31 ms for HF words and 51 vs. 64 ms for LF words). More importantly, HF words produced less than 40 ms of priming in both SOA conditions, supporting the hypothesis of a shorter EOT for HF words. On the contrary, LF words produced close to 60 ms of priming in both SOA conditions, suggesting that they gained some benefit from the 20-ms gap. Since these LF words were exactly the same as those used in Experiment 4 where they showed 33 ms of priming at 40-ms prime duration, the gap benefit gained was close to 20 ms. This result supports the EOM prediction that increasing the SOA will lead to a corresponding increase of the priming effect by about the same amount provided that the EOT is equal to or longer than the SOA.

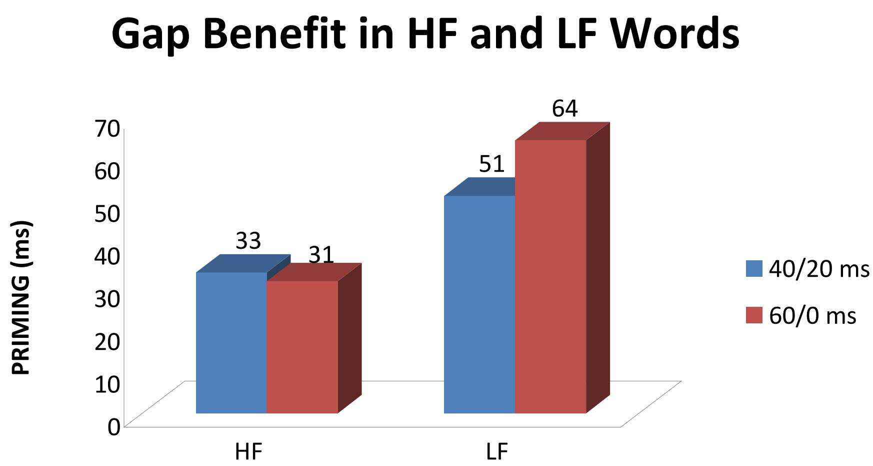

Figure 3.2. Comparison of identity priming for HF and LF words at prime durations of 40/20 and 60/0 ms.

Since SOA did not interact with any of the other two factors, further analysis was made of the interaction between frequency and priming using the following mixed-effects model: RT = lmer (log(rt) ~ Prime * Frequency + SOA + (1|subject) + (1|item)). The frequency by priming interaction was significant (t = 3.93, p < .001). Separate analyses of the two SOA conditions also revealed a significant interaction between frequency and priming (t = 2.05, p < .05 for the 40/20 condition after the previous RT effect was removed and t = 3.66, p < .001 for the 60/0 condition).

Analysis of the error rates was carried out using the following model: Error = lmer (error ~ Prime * Frequency + SOA + (1|subject) + (1|item) because SOA did not interact with the other two factors. Results showed a significant main effect of priming

(z = 1.96, p < .05) and frequency (z = 10.58, p < .001) as well as a significant interaction between prime and frequency (z = 2.96, p < .01.) As shown in Table 3.4, participants in both SOA conditions made fewer errors on HF words than on LF words and in the related condition than in the unrelated condition. The significant interaction showed that there was a bigger improvement of error rates in the related condition over the unrelated condition for LF words than for HF words.

3.3.3 Discussion

It is very clear from the results that the priming effect was almost exactly the same for both HF and LF words at 40/20 and 60/0, thus confirming the EOM prediction that it is the SOA that determines priming, not the prime duration per se. The reasons for such equivalent priming effects, however, must be different for HF and LF words because the priming effect of HF words was only a little over 30 ms for both SOA conditions, much smaller than the predicted 60 ms. One possibility, as suggested earlier in Experiment 4, is that the EOT for these HF words is shorter than the SOA and therefore limited the priming effect to the shorter EOT, so extending the SOA by an inserted 20-ms blank did not produce any additional priming. By contrast, the LF words, presumably having a longer EOT, gained a gap benefit in the 40/20 condition and produced close to 60 ms of priming in both SOA conditions.

It must be noted, however, that this hypothesis of a variable EOT for words of different frequencies is not readily consistent with the EOM assumption of a relatively stable EOT for HF and LF words. Assuming a shorter EOT for HF words would predict a smaller priming effect for HF words than for LF words, thus predicting a significant interaction between priming and frequency. As shown in this experiment, this interaction was significant both in the overall analysis and in the separate analysis of the two SOA conditions. Previous studies, however, have either failed to find any significant interaction completely or were unable to find consistent results. For example, equivalent priming effects were found for HF and LF words in Forster and Davis (1984, 1991), Forster et al. (1987), Rajaram and Neely (1992), and Sereno (1991). Bodner and his colleague reported both equal and significantly different priming effects in a series of studies (e.g. Bodner and Masson, 1997, 2001; Masson and Bodner, 2003), arguing that the masked priming effect depended on experimental contexts such as the nature of surrounding trials or the list of target stimuli, etc. Both kinds of results were also reported by Kinoshita (2006), showing that not all LF words produced greater priming than HF words, but the LF words which were also familiar to the participants did. This result suggests that the essential factor affecting the masked priming effect is the degree of familiarity in combination with word frequency, not frequency by itself. Taken together, the findings from Experiment 5 and previous studies seem to show that word frequency is correlated with some other feature of lexical items that influences priming. For the EOM model, it means that some feature of lexical items may be associated with a shorter EOT. It is very likely, as shown in the results here as well as in Kinoshita (2006), that this feature is correlated with frequency. What it could be calls for further examination.

One concessionary note is in order here before we proceed to the general discussion. The results of this experiment presented compelling evidence against the IA model which predicts a significant difference between the 40/20 and 60/0 conditions on the assumption that priming is determined by the prime duration (i.e. the time when the prime is physically present). For the EOM which predicts equal priming between the two SOAs, however, the results only failed to disprove the null hypothesis. With the main effects of frequency and priming as well as the interaction between SOA and frequency being significant, the null results made a strong case for the EOM nonetheless, but a more powerful direct experiment will further reinforce the findings of this experiment.

CHAPTER 4

GENERAL DISCUSSION AND SUMMARY

This dissertation presents 5 experiments designed to investigate the underlying mechanisms of masked priming during lexical processing. Two lines of argument are at the center of this investigation. The Entry Opening Model (EOM) maintains that masked priming is a savings effect, and that as such, it is determined by the smaller of the EOT or the SOA. By contrast, the Interactive Activation (IA) Model interprets masked priming as persisting activation which is determined solely by the prime duration and the degree of orthographic match between the prime and the target (other things such as prime lexicality being equal). Specifically, two key hypotheses from the EOM were tested and compared with those from the IA Model. One hypothesis has to do with the limitations on form and identity priming, and the other concerns the debate over prime duration and the SOA being the major determinant of the amount of priming.

The first two experiments in Chapter 2 were designed to tackle the first hypothesis, and the results supported the EOM prediction about the limits on priming. Overall, the priming effects observed are within the range of the priming effects reported in previous studies, namely, form priming weaker than identity priming at 60 ms of prime duration in both L1 and L2. The crucial finding is by all means the fact that equivalent priming effects were observed for both form and identity priming at 30 ms of prime duration in both L1 (19 vs. 20 ms) and L2 (36 vs. 37 ms), demonstrating that form priming is not merely a weaker form of identity priming. It is also clear from the results that form priming is subject to a ceiling effect brought about by the EOT at the level of form. Increasing the prime duration from 30 ms to 60 ms did not enhance form priming by any significant amount, showing a non-significant 9-ms increase in both L1 and L2, whereas identity priming was more than doubled in both L1 and L2, registering a significant increase of 30 and 41 ms respectively. Neither of these two results can be readily accounted for in the IA model. As shown by the SCM simulation results, an activation model predicts a matching reduction or increase of the priming effect for both form and identity priming as the prime duration varies. At any fixed prime duration, however, form priming is believed to be weaker than identity priming. To account for equivalent form and identity priming, one must introduce other mechanisms into the persisting activation account.

Although the results of Experiment 1 and 2 supported the EOM’s central prediction about limits on priming, the specifics of this prediction require further experimentation. As pointed out in Chapter 2, the EOM prediction about limits on priming is based on the estimates of the EOT, 30 ms at the level of form and 60 ms at the levels of both form and meaning. The results found were 10 ms short of the estimates, suggesting a shorter EOT, but the essential argument of the EOM remains true. Namely, masked priming is a linear function of the SOA; any increase of the SOA should lead to a matching increase of priming provided that the EOT is as long as or longer than the SOA.

The last three experiments were an attempt to address the SOA and prime duration debate. The results were mixed. Experiment 3 showed no difference in priming between the 40/0 and 40/20 condition, indicating that it was the prime duration that However, when a group of different words of lower frequency were tested in Experiment 4, the results were exactly the opposite. These words showed a clear gap benefit in the 40/20 condition, supporting the EOM prediction of the SOA being the major determinant of the amount of priming. It is therefore imperative that a competent model of masked priming must be able to reconcile these conflicting results.

The last experiment was an attempt towards this end. Since the priming effects reported in Experiment 3 were smaller than the SOA, the expected amount of priming according to the EOM, one possibility is that the test items were subject to the limitation of a shorter EOT. Previous studies showed, although inconsistently, that some HF words produced less priming than LF words, it is thus plausible to assume that HF words as tested in Experiment 3 may have a shorter EOT. If so, they would not show any gap benefit in the 40/20 condition because their priming effect reaches a plateau at the EOT, say 40 ms, so the inserted gap will not produce any additional priming. LF words, presumably having a longer EOT, should gain a gap benefit. The results confirmed this hypothesis very nicely. HF words did not gain any gap benefit, their priming effect being much less than 60 ms in the 40/20 condition, but the priming effect was equal at 40/20 and 60/0, showing a ceiling effect of the EOT in both SOA conditions. LF words showed a definite gap advantage in the 40/20 condition, and therefore produced equivalent priming effect at 40/20 and 60/0. Taken together, it is safe to claim that the findings in these three experiments showed that the physical presence of the prime was not absolutely necessary for generating activation and that an inserted blank gap may produce additional masked priming.

The results in this dissertation seem to show that only LF words will generate more activation during the gap, but not HF words, which is not in any way plausible according to the IA model. If masked priming is whatever is left of the activation from the prime being carried over to the target, the same should be true for both HF and LF words. Once the prime is not present, activation stops increasing or even starts to decay. The contrary results in Experiment 3 and 4 are difficult to interpret in the IA model. More importantly, the equivalent priming effect at 40/20 and 60/0 ms of SOA found in Experiment 5 is problematic for an activation model in every conceivable way.

In conclusion, the Entry Opening Model makes a good prediction about the limits on priming as well as the major determinant of the amount of priming. Masked priming is more like a savings effect than a result of persisting activation. As a savings effect, form priming is different from identity priming in that it reaches a plateau at the EOT at the level of form. The SOA largely determines how much priming can be obtained provided that the EOT does not exert any further upper limits. The EOT, however, does not seem to be as stable as assumed in Forster and Davis (1984), rather, it is variable for different words, so words of very brief EOTs would not show a gap benefit but words of longer EOTs should. It is not clear, however, what contributes to a variable EOT.

The results seem to suggest that the EOT varies with word frequency. HF words in Experiments 3 and 5 did not show any gap advantage, but LF words in Experiments 4 and 5 did. It is rather clear that the HF words tested in Experiment 5 may have a very short EOT, repetition priming being limited to 31 at a regular 60-ms prime duration. However, if the EOTs of HF words are always shorter than that of LF words, the identity priming would never get any greater than what was obtained here, and there would always be an interaction between priming and frequency. As pointed out earlier, the findings in the previous studies were mixed. LF words were observed to produce greater priming than HF words only on some occasions, for example, when other experimental contexts such as the nature of the targets and proportion of repeated trials were manipulated or when the LF words were familiar to the participants. It seems that the LF words tested in this dissertation happen to have a shorter EOT. An important question therefore remains for the Entry Opening Model: if it is not frequency that affects the EOT of a word, what could it be?

APPENDIX A

EXPERIMENTAL ITEMS FROM EXPERIMENTS 1 AND 2

Word Items Used in the 30-ms Prime Duration Condition

problem	student	ability	promise	anxiety	gallery
control	section	message	gesture	illness	partner
support	defence	welfare	cabinet	cottage	nursery
company	officer	captain	comfort	fortune	protein
village	economy	traffic	display	uniform	session
freedom	concern	journey	product	emotion	mystery
attempt	contact	justice	factory	climate	leisure
silence	teacher	library	decline	soldier	payment

Word Items Used in the 60-ms Prime Duration Condition

present	station	respect	address	arrival	cricket
example	purpose	failure	victory	protest	musical
century	benefit	culture	stomach	chicken	servant
history	machine	disease	absence	kingdom	dignity
husband	reality	airport	element	vitamin	expense
capital	opinion	project	article	triumph	shelter
average	pattern	command	chamber	delight	reverse
council	college	plastic	routine	missile	mankind

APPENDIX B

EXPERIMETAL ITEMS FROM EXPERIMENT 3

Word Items

advance	culture	patient	promise	command	forward
airport	variety	careful	reality	contact	library
kitchen	average	husband	concern	discuss	success
totally	capital	theatre	sources	college	account
receive	prevent	western	traffic	plastic	brother
surface	message	colonel	include	express	respect
pension	village	protect	benefit	fifteen	radical
develop	teacher	besides	nervous	tonight	address
mention	chapter	perfect	weather	extreme	central
popular	curious	measure	opinion	quality	freedom
mistake	exactly	writing	failure	content	provide
defence	officer	obvious	holiday	despite	neither
liberal	anybody	explain	similar	silence	achieve
suppose	science	welfare	fashion	council	justice
poverty	disease	attempt	purpose	captain	heavily
balance	concept	strange	picture	suggest	correct

APPENDIX C

EXPERIMENTAL ITEMS FROM EXPERIMENT 4

Word Targets

preach	isolate	swarm	flimsy	glint	analyst
polar	duchess	merge	lantern	quota	mandate
vault	angular	radius	tenor	diploma	homely
robot	reunion	weave	shrine	optimum	salon
sensory	speck	depot	niece	perch	overdue
album	walnut	insert	forbid	parody	ambush
dwell	tremble	contend	utopian	apathy	oblige
dessert	massage	blossom	yacht	satin	expanse
evolve	refrain	chant	presume	mystic	census
shovel	annoy	sloppy	factual	shrug	dodge
quart	kitten	devoid	canopy	troop	groove
melody	offend	robust	bison	choke	perish
evade	prompt	clown	nausea	venue	plaza
tempt	decency	gallon	anarchy	elect	staple
literal	chaotic	aerial	creator	hockey	faction
eyebrow	asthma	turmoil	workmen	gateway	hateful

Unrelated Word Primes

mosaic	coral	abide	pebble	cocoa	premier
groan	tuition	appoint	sneak	birch	chemist
chunk	evoke	serene	pigeon	hygiene	mustard

pyramid	comply	trait	villain	spider	sniff
torrent	booze	rustic	kidney	lunar	dispose
mimic	canoe	casino	shawl	napkin	stuffy
modify	shriek	spinach	quaint	decor	bakery
license	trash	triple	overlap	bulge	console
bouquet	maple	glitter	suffice	siren	defect
banquet	serial	usage	climber	skate	knack
stunt	prelude	hoarse	groom	graph	violin
shiver	referee	forum	humid	badger	mantle
digest	aroma	wrench	premise	confine	aloof
banana	hybrid	blatant	pretext	remorse	soccer
clarify	jaguar	gravy	kneel	dresser	freeway
virtual	behold	variant	compel	bazaar	builder

APPENDIX D

EXPERIMENTAL ITEMS FROM EXPERIMENT 5

High Frequency Words Used as Targets

service	major	company	human	early	beyond
voice	nature	doubt	person	answer	return
friend	floor	support	evening	history	million
above	union	reason	likely	heart	ground
today	church	group	nuclear	third	modern
trade	private	present	finally	result	effect
earth	century	instead	subject	process	among
police	natural	north	further	common	except

High Frequency Words Used as Unrelated Control Primes

usually	south	outside	often	woman	itself
child	office	large	indeed	behind	inside
street	stand	whether	country	certain	control
order	front	labour	number	study	change
until	within	along	several	young	either
cause	example	morning	general	anyone	family
money	problem	society	brought	someone	sense
moment	believe	total	herself	future	system

Low Frequency Word Used as Targets

contend	shrine	gallon	salon	album	groove

dessert	duchess	parody	troop	offend	literal
isolate	robot	decency	canopy	flimsy	yacht
eyebrow	elect	depot	polar	turmoil	dwell
angular	chaotic	radius	sensory	census	prompt
quota	gateway	satin	perch	mandate	evolve
reunion	weave	refrain	hockey	robust	devoid
niece	forbid	shrug	faction	evade	insert

Low Frequency Words Used as Unrelated Control Primes

dispose	remorse	console	forum	behold	cocoa
bazaar	builder	pretext	spinach	blatant	mustard
triple	lunar	groom	abide	stuffy	shawl
aloof	virtual	napkin	usage	defect	bulge
stunt	trash	compel	hoarse	dresser	serene
shiver	bouquet	tuition	canoe	rustic	pebble
variant	sneak	birch	clarify	referee	jaguar
overlap	gravy	serial	coral	mantle	kidney

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