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Repetition and form priming interact with neighborhood density at a brief stimulus onset asynchrony

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The relationships between repetition- and form-priming effects and neighborhood density were analyzed in two masked priming experiments with the lexical decision task. Given that form-priming effects appear to be influenced by a word's orthographic neighborhood, it is theoretically important to find out whether repetition priming also differs as a function of the word's orthographic neighborhood. Within an activation framework, repetition- and form-priming effects are just quantitatively different phenomena, whereas the two effects are qualitatively different in a serial-ordered model of lexical access (the *entry-opening* model). The results show that repetition- and form-priming effects were stronger for *hermit* words than for words with many neighbors. These results pose some problems for both activation and serial-ordered models. The implications of these results for determining how neighbors affect the identification of a word are discussed.

Investigations of the effects of lexical similarity provide valuable information about the processes underlying word recognition, and a number of papers reporting the results of such investigations have appeared recently (e.g., Andrews, 1989, 1992, 1996; Carreiras, Perea, & Grainger, 1997; Forster & Shen, 1996; Grainger, 1990; Grainger & Jacobs, 1996; Grainger, O'Regan, Jacobs, & Seguí, 1989, 1992; Huntsman & Lima, 1996; Paap & Johansen, 1994; Perea & Pollatsek, 1998; Pollatsek, Perea, & Binder, 1999; Sears, Hino, & Lupker, 1995; Snodgrass & Mintzer, 1993). These data indicate that, upon the visual presentation of a word, similarly spelled words (the so-called *neighbors*) become partially activated and affect the speed of lexical access. Virtually all of these experiments have adopted Coltheart, Davelaar, Jonasson, and Besner's (1977) definition of orthographic neighbor—any word that can be created by changing one letter of the stimulus word, preserving letter positions (e.g., *peace*, *poach*, and *beach* are orthographic neighbors of *peach*)—and have defined the neighborhood of a word to be the set of neighbors of that word (or N).

One interesting way of investigating neighborhood structure is by presenting a prime followed by a neighboring target (or the identical target). In this context, the masked priming technique (Forster, 1987, 1998; Forster & Davis, 1984; Forster, Davis, Schoknecht, & Carter, 1987) has been the most fruitful paradigm with which to study competition processes at the earliest stages of word recognition. The priming stimulus is orthographically and/or phonologically related to the target and is presented briefly (30–66 msec) just prior to the target. The prime is preceded by a forward pattern mask, and under these conditions, the trace of the prime is relatively inaccessible to conscious report. (Obviously, the fact that the prime is replaced by the target at a very short stimulus onset asynchrony [SOA] does not necessarily imply that the prime is no longer processed once the target replaces the prime.)

Masked Priming Effects With Orthographic Neighbors

Prior research with the masked priming technique has found that target words are primed by orthographically similar nonword primes (relative to an unrelated control condition), although these effects are restricted to target words extracted from small neighborhoods (e.g., *album*) in both lexical decision (e.g., Forster, 1987; Forster et al., 1987; Forster & Taft, 1994) and naming tasks (Forster & Davis, 1991). In addition, inhibitory relatedness effects have been obtained with orthographically related word primes that are more frequent than the word target (e.g., *blue*–BLUR; Bijeljac-Babic, Biardeau, & Grainger, 1997; Ferrand & Grainger, 1994; Grainger, Colé, & Seguí, 1991; Perea & Rosa, 1998; Seguí & Grainger, 1990), although this issue remains controversial (see Forster, 1987; Forster & Veres, 1998).[1] Furthermore, associative, morphological, and translation priming effects have also been obtained with the masked priming technique (e.g., de Groot & Nas, 1991; Gollan, Forster, & Frost, 1997; Lukatela & Turvey, 1994; Perea & Gotor, 1997; Williams,

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1994). Taken together, these results strongly suggest that masked priming effects occur at the lexical level, rather than at a sublexical level.

The form-priming effects from the above-cited studies can be readily explained in terms of an interactive activation model (McClelland & Rumelhart, 1981; see also Ferrand & Grainger, 1992; Grainger, 1992). In this model, the lexical entries corresponding to the more frequent words have higher resting levels than do the units corresponding to less frequent words. In addition, there is mutual inhibition among the candidates at the lexical level, and a lexical unit is recognized when its level of activation reaches a prespecified decision criterion or when its level of activation rises significantly above the activation level of the other candidates. The interactive activation (IA) model captures the existence of inhibition when the orthographically related prime is of higher frequency than the target (see Jacobs & Grainger, 1992, Simulation 2): When the prime (e.g., *blue*) is a higher frequency neighbor of the target (*blur*), during the processing of the target, *blur*, the node of *blue* is even more activated than that of *blur*, thus increasing the inhibition on the node for *blur* (as compared with an unrelated control condition).

In addition, the IA model can also capture the facilitative priming effects with nonword primes (via sublexical activation). Activation from the nonword primes at sublexical levels (letters, letter clusters, phonological units, syllabic units) feeds forward to the lexical level, with the consequent top-down feedback. As nonword primes activate lexical representations more and more, as compared with target activation, lexical level competition will appear, canceling out sublexical facilitation (see Ferrand & Grainger, 1994). In the case of target words with many neighbors, the activation from the related nonword primes may have spread along the lexical level, so that inhibition between word units will cancel out sublexical facilitation (see Forster et al., 1987, Experiment 5). In the case of words with no neighbors (*hermit* words; e.g., *typhus*), the amount of lexical inhibition from the target's similar words will be negligible, and only facilitation will be obtained. That is, the density constraint for form primes appears to fall out as a natural consequence of the recognition process in the IA model (see the General Discussion section for the simulations with the IA model).

Given that form-priming effects appear to be influenced by a word's orthographic neighborhood, it is theoretically important to find out whether repetition priming also differs as a function of a word's orthographic neighborhood. In an activation framework, repetition-priming and form-priming effects are just quantitatively different phenomena: If the inhibitory effects of masked primes are indeed preactivation effects, as was suggested by Seguí and Grainger (1990), it might be expected that words with many neighbors would show less masked repetition-priming effects than would words with few or no neighbors. The masked presentation of a word with many neighbors (e.g., *peach*) should produce a significant rise in the activation level of its (high-frequency) neighbors (e.g., *beach*, *peace*, *reach*, etc.). The activation levels of these representations will continue to be (partially) supported by information from the target word. So, these representations that remain in a heightened state of activation during target processing will influence target recognition (via lateral inhibition between word nodes). In contrast, if only one word node is activated (e.g., hermit words), no significant inhibition from the other word nodes will be produced. That result would strengthen the argument that competition among candidates (via lateral inhibition) plays a role in visual word recognition. Of course, specific predictions can only be achieved by running computer simulations (see the General Discussion section for the simulations with the IA model).

In the framework of a serial-ordered model of lexical access (*entry-opening* model), Forster and Davis (1984) suggested that immediately after an entry has been accessed, it is left in a moderately excited state so that information can be extracted from it more rapidly. As a result, the time for other processing systems to extract information from the entry might decrease (see Forster & Davis, 1984). In this model, neighborhood density is relevant only to form-priming effects. Specifically, form priming is considered a special case of repetition priming in which the entry for the target has been previously opened. Given that close matches are ignored in a dense neighborhood (in order to keep the number of candidates to a reasonable number), the model predicts an interaction between neighborhood density and form priming. In contrast, the model clearly predicts additive effects of neighborhood density and repetition priming, since an exact match will always open the entry for the target word.[2] Forster and Taft (1994) claimed that "there is no sign that repetition priming is affected by neighborhood density, as shown by Forster and Davis (1984) and Forster et al. (1987)" (p. 858). However, Forster and colleagues did not systematically investigate that question. It may be important to note that Forster et al. (1987, Experiment 3) reported a 38-msec repetition effect for four-letter words and a 56-msec repetition effect for eight-letter words. Since length is highly correlated with neighborhood density, words with few neighbors yielded more repetition priming than did words with many neighbors. Nonetheless, length was confounded with density there, and hence it could be a length effect.

Masked Repetition-Priming Effects and Neighborhood Density

To our knowledge, only one series of experiments has analyzed the role of neighborhood density and masked repetition priming in the lexical decision task. Perea (1993) carried out a series of lexical decision experiments to test the existence of a significant interaction between neighborhood density and repetition priming at several short SOAs (33, 50, and 67 msec). Although none of the individual experiments showed a significant interaction between these factors, the combined analysis of two of the experiments (Experiments 1 and 2B) revealed a significant interaction between neighborhood density and repetition-priming effects at the 50-msec SOA: Repetition-priming effects were greater for words with few neighbors than for words with many neighbors. Since the mean reaction times in the experiments were far from additive and the number of words per neighborhood category for each priming condition was only five, the lack of a significant interaction term in the individual experiments does not permit a claim of additivity. Furthermore, form-priming effects were not investigated.

As a consequence, a combined study of form-priming effects and repetition-priming effects seems necessary in order to globally assess the role of neighborhood density in the masked priming paradigm. To maximize our chances of obtaining a significant interaction between neighborhood density and repetition/form priming, two sets of words were selected: one with hermit words (i.e., words with no orthographic neighbors)[3] and the other with words with many neighbors (at least nine orthographic neighbors). In Experiment 1, we used a 67-msec SOA with the masked priming technique in a lexical decision task. Experiment 2 was designed to replicate Experiment 1 with a different set of nonword foils.

EXPERIMENT 1

Method

Participants. A total of 33 psychology students from the University of València took part in the experiment to fulfill a course requirement. All of them had either normal or corrected-to-normal vision and were native speakers of Spanish.

Materials. Ninety two-syllable Spanish words, all of them containing five letters, were selected as word targets from the Spanish word pool (Alameda & Cuetos, 1995), which is based on a count of two million Spanish words. Forty-five words had no orthographic neighbors (mean $N = 0$), and the other 45 words had at least nine orthographic neighbors (mean $N = 9.9$; range, 9–15). All the target words were of low frequency, with a mean frequency of 12 (range, 1–28) per two million words for the hermit words and a mean frequency of 12 (range, 1–31) for the words with many neighbors. For each word target, three primes were selected corresponding to the three priming conditions: (1) identity (e.g., *tifus*–TIFUS, the Spanish for *typhus*–TYPHUS); (2) substitution–nonword (e.g., *tigus*–TIFUS); and (3) control–word (e.g., *penco*–TIFUS; *penco* is Spanish for nag). The substitution–nonword condition prime was always a nonword with one letter in a middle position that was different from a letter in the target. The control prime was matched on number of syllables, number of letters, and word frequency with the identity prime. None of the control primes shared any letters in common in the same position with their corresponding target.

In addition, we used 90 disyllabic nonword targets, all of them containing five letters. In all cases, nonwords were orthographically legal and had been constructed by changing one middle letter from a Spanish word other than one in the experimental set. Nonword targets had a mean of 3.2 orthographic neighbors (range, 1–7) and were preceded by related word primes (the ones that were used to create the nonwords), identical primes, or unrelated word primes.

Procedure. The participants were tested individually (or in groups of two) in a quiet room. Presentation of the stimuli and recording of reaction times were controlled by Apple Macintosh Plus microcomputers. The routines for controlling stimulus presentation and reaction time collection were obtained from Lane and Ashby (1987) and from Westall, Perkey, and Chute (1986), respectively. Reaction times were measured from target onset until the participant's response. On each trial, a forward mask consisting of a row of five hash marks (#####) was presented for 500 msec on the center of the screen. Next, a centered lowercase prime was presented for 67 msec. The primes were immediately replaced by an uppercase target item. The participants were instructed to press one of two buttons on the keyboard to indicate whether the uppercase letter string was a legitimate Spanish word or not (";" for yes and "z" for no). The participants were instructed to make this decision as quickly and as accurately as possible. When the participant responded, the target disappeared from the screen. After an intertrial interval of 1.5 sec, the next trial was presented. The participants were not informed of the presence of lowercase words. Prime–target pairs were counterbalanced across three experimental lists so that if the identical pair *tifus*–TIFUS was in the first list, TIFUS would be preceded by its unrelated word prime (*penco*) in the second list and by its form-related prime (*tigus*) in the third list. Stimulus presentation was randomized, with a different order for each participant. Each participant received a total of 20 practice trials (with the same manipulation as that in the experimental trials) prior to the 180 experimental trials. The whole session lasted approximately 14 min.

Results and Discussion

Incorrect responses (7.9% for words and 4.5% for nonwords) were excluded from the latency analysis. To avoid the influence of outliers, all reaction times more than 2.0 standard deviations above or below the mean for that participant in all the conditions were also excluded from the latency analysis. Significance levels were less than .05 unless otherwise noted. (These conventions will be applied throughout the two experiments.) The mean lexical decision time and the error rate on the stimulus words and nonwords in each experimental condition is displayed in Table 1. Since the goal of the study was to test how neighborhood density modulates repetition- and form-priming

Table 1
Mean Lexical Decision Times (in Milliseconds) and Percentage of Errors on Word and Nonword Targets in Experiment 1

	Type of Prime									
	Identical		Related		Unrelated		ID Priming		Form Priming	
Target	*M*	PE	*M*	PE	*M*	PE	*M*	PE	*M*	PE
Words										
Low-*N*	671	7.5	716	11.7	747	10.9	76	3.4	31	−.8
High-*N*	656	4.4	701	5.9	700	7.3	44	2.9	−1	1.4
Nonwords	780	3.7	797	4.1	809	5.7	29	2.0	12	1.6

Note—ID priming refers to the difference between the unrelated and the identical condition, and form priming refers to the difference between the unrelated and the orthographically related condition. *N*, set of neighbors.

effects, separate analysis of latency and error data were conducted for each prime type condition (as compared with the unrelated control condition). To test repetition-priming effects for words, mean reaction times on words were submitted to an analysis of variance (ANOVA), with neighborhood density (hermit words, words with many neighbors), orthographic relatedness (identical, unrelated), and list (List 1, List 2, List 3) as factors. List was included in the ANOVA to extract the variance that was due to the lists (see Pollatsek & Well, 1995). List was a nonrepeated measures factor in the analysis by participants (F_1), whereas neighborhood density and orthographic relatedness were within-subjects factors. In the analysis by items (F_2), list and neighborhood density were the nonrepeated measures factors. Parallel analyses were conducted to test the presence of form-priming effects. The statistical analysis of the nonwords was identical to that of the words, except that neighborhood density was not included as a factor.

Analysis of Words

Repetition-priming effects. The ANOVA on the latency data showed that the effect of repetition priming was statistically significant [$F_1(1,30) = 93.51$; $F_2(1,84) = 93.18$]: On average, targets preceded by identical primes were responded to 60 msec more rapidly than targets preceded by unrelated words. The main effect of neighborhood density was also significant [$F_1(1,30) = 28.27$; $F_2(1,84) = 9.27$]: Words from large neighborhoods were responded to faster than hermit words. The interaction between the two factors was statistically significant [$F_1(1,30) = 5.67$; $F_2(1,84) = 5.66$]: Repetition-priming effects were stronger for hermit words [76 msec; $F_1(1,30) = 76.94$; $F_2(1,84) = 72.39$] than for words with many neighbors [44 msec; $F_1(1,30) = 21.36$; $F_2(1,84) = 26.45$].

The ANOVA on the error data showed a significant effect of repetition priming [$F_1(1,30) = 5.77$; $F_2(1,84) = 8.68$]. The effect of neighborhood density was significant in the analysis by participants [$F_1(1,30) = 6.85$; $F_2(1,84) = 2.05$, $p > .15$]. The interaction between repetition priming and neighborhood density was not significant (both ps > .10).

Form-priming effects. The ANOVA on the latency data showed that the main effect of form priming was statistically significant [$F_1(1,30) = 6.61$; $F_2(1,84) = 6.83$]. The main effect of neighborhood density was also significant [$F_1(1,30) = 5.26$; $F_2(1,84) = 8.44$]. The interaction between the two factors was statistically significant [$F_1(1,30) = 5.67$; $F_2(1,84) = 5.44$]: There were form-priming effects for hermit words (31 msec; $F_1(1,30) = 11.00$; $F_2(1,84) = 12.23$], but not for words with large neighborhoods (−1 msec; both Fs < 1). The ANOVA on the error data only showed a significant effect of neighborhood density in the analysis by participants [$F_1(1,30) = 12.74$; $F_2(1,84) = 2.83$, $p < .10$].

Analysis of Nonwords

In the latency analysis, there was a significant effect of repetition priming [$F_1(1,30) = 23.04$; $F_2(1,87) = 28.58$]: On average, nonwords preceded by identical primes were responded to 29 msec faster than nonwords preceded by unrelated primes. In the ANOVA on the error data, the effect of repetition was significant in the analysis by items [$F_2(1,87) = 13.28$; $F_1(1,30) = 2.69$, $p = .111$].

In addition, the 12-msec effect of form priming was significant in the analysis by items [$F_2(1,87) = 4.97$] and approached significance in the analysis by participants [$F_1(1,30) = 3.97$, $p < .056$]. The 1.6% form-priming effect in the percentage of errors was not statistically significant (both ps > .10).

The results of the present experiment are clear-cut. For words, we replicated Forster et al.'s (1987) finding with respect to the presence of form-priming effects only for target words extracted from small neighborhoods. In addition, the present experiment has shown that repetition-priming effects were stronger for hermit words than for words with many neighbors. Furthermore, form- and repetition-priming effects were also found for nonword stimuli, although the magnitude of these effects was smaller than the priming effects for word stimuli. Within an IA framework, these activated neighbors could feed back and support the early identification of the target letters—and therefore, the effect would be lexical rather than sublexical. (Note that the pseudowords had, on average, 3.2 word neighbors.)

One could argue that we need an unrelated nonword prime as a baseline for form priming for word targets and for identity priming for nonword targets. However, the main focus of interest was the neighborhood density constraint for identity primes for word targets, and therefore, it was better to use words as control primes to avoid any possible mismatch for this condition. In any case, the lexical status of the unrelated priming condition does not appear to influence the results with the masked priming technique (see, e.g., Bourassa & Besner, 1998; Perea, Fernández, & Rosa, 1998). Even if such a bias might have somehow affected response latencies, it could not explain the neighborhood density constraint for the identity condition that occurred within the word targets. Instead, it seems more reasonable that such a bias could influence priming results with longer, visible primes under specific circumstances (see, e.g., Zeelenberg, Pecher, de Kok, & Raaijmakers, 1998).

EXPERIMENT 2

The main goal of Experiment 2 was to test the reliability of the priming results obtained in Experiment 1. Also, in order to examine the robustness of the findings of Experiment 1, we used two types of nonwords: nonwords with several word neighbors and hermit nonwords (i.e., nonwords with no word neighbors). In the framework of the entry-opening model, Forster (1998) suggested that masked priming effects for nonword stimuli arise when the nonwords are designed to closely resemble a word and differ from that word by only one letter. In fact, this was the case with the nonwords used by Sereno (1991) and the nonwords used in this experiment. Since there are many published studies that failed to obtain priming effects for nonwords (see Forster, 1998, for an extensive review), it seems that we are dealing with a special kind of effect.[4] Specifically, the entry-opening model predicts that priming could be obtained for any nonword that resembles a word closely enough to require a detailed orthographic check (see Forster, 1998). In this way, the entry for that word would already be an in open state when the target nonword is presented, and hence, the content of the lexical entry would be available sooner. This would imply a faster rejection time of the nonword as a satisfactory match and, consequently, a priming effect relative to an unrelated control condition (Forster, 1998). However, if no close-matching candidates are opened by the prime, there is no way that priming for the target could be obtained.

Method

Participants. A total of 33 psychology students from the University of València took part in the experiment to fulfill a course requirement. All of them had either normal or corrected-to-normal vision and were native speakers of Spanish. None of them had participated in the previous experiment.

Materials. For word trials, we used the same materials as those in Experiment 1. For nonword trials, we selected 45 two-syllable nonword targets from those used in Experiment 1. These nonword targets had a mean of 3.1 orthographic neighbors (range, 2–7). Forty-five two-syllable nonword targets with no orthographic word neighbors (i.e., hermit nonwords)—which were orthographically and phonologically legal in Spanish—were also created. Nonword targets were preceded by identical primes, form-related nonword primes, or unrelated word primes.

Procedure. The procedure was the same as that in Experiment 1.

Results and Discussion

Incorrect responses (9.6% for words and 4.2% for nonwords) were excluded from the latency analysis. The statistical analysis of the nonwords was identical to that of the words. The mean lexical decision times and the error rates on the stimulus words and nonwords in each experimental condition are displayed in Table 2.

Analysis of Words

Repetition-priming effects. The ANOVA on the latency data showed that the effect of repetition priming was statistically significant [$F_1(1,30) = 78.92$; $F_2(1,84) = 57.13$]: On average, targets preceded by identical primes were responded to 45 msec more rapidly than targets preceded by unrelated words. The main effect of neighborhood density was also significant [$F_1(1,30) = 45.38$; $F_2(1,84) = 11.31$]: Words from large neighborhoods were responded to faster than hermit words. The interaction between the two factors was statistically significant [$F_1(1,30) = 5.76$; $F_2(1,84) = 8.72$]: Repetition-priming effects were stronger for hermit words [52 msec; $F_1(1,30) = 66.75$; $F_2(1,84) = 55.24$] than for words from large neighborhoods [37 msec; $F_1(1,30) = 23.39$; $F_2(1,84) = 10.61$].

The ANOVA on the error data showed a significant effect of repetition priming [$F_1(1,30) = 10.53$; $F_2(1,84) = 7.72$]. The effect of neighborhood density was also significant [$F_1(1,30) = 20.86$; $F_2(1,84) = 4.52$]. The interaction between repetition priming and neighborhood density was not significant (both Fs < 1).

Form-priming effects. The ANOVA on the latency data showed that the main effect of form priming was statistically significant [$F_1(1,30) = 9.36$; $F_2(1,84) = 8.60$]. The main effect of neighborhood density was also significant [$F_1(1,30) = 35.45$; $F_2(1,84) = 12.66$]. The interaction between the two factors was statistically significant [$F_1(1,30) = 9.07$; $F_2(1,84) = 11.13$]: There were form-priming effects for hermit words [33 msec; $F_1(1,30) = 16.17$; $F_2(1,84) = 19.65$], but not for words with many neighbors (−3 msec; both Fs < 1). The only significant effect in the error data was that of neighborhood density [$F_1(1,30) = 17.18$; $F_2(1,84) = 4.08$].

Analysis of Nonwords

Repetition-priming effects. In the latency analysis, there was a significant effect of repetition priming [$F_1(1,30) = 14.83$; $F_2(1,84) = 18.80$]: On average, nonwords preceded by identical primes were responded to 23 msec faster than nonwords preceded by unrelated primes. The main effect of neighborhood density was also significant [$F_1(1,30) = 18.55$; $F_2(1,84) = 11.13$]. There were no signs of an interaction between the two factors (both Fs < 1).

In the ANOVA on the error data, the only significant effect was that of neighborhood density [$F_1(1,30) = 19.38$; $F_2(1,84) = 7.26$].

Form-priming effects. The 21-msec effect of form priming was statistically significant [$F_1(1,30) = 9.70$;

Table 2
Mean Lexical Decision Times (in Milliseconds) and Percentage of Errors on Word and Nonword Targets in Experiment 2

	Type of Prime									
	Identical		Related		Unrelated		ID Priming		Form Priming	
Target	*M*	PE	*M*	PE	*M*	PE	*M*	PE	*M*	PE
Words										
Low-*N*	667	10.3	686	12.3	719	14.7	52	4.4	33	2.4
High-*N*	638	5.1	672	7.3	675	7.7	37	2.6	−3	0.4
Nonwords										
Hermits	742	1.8	743	2.6	762	2.6	20	0.8	19	0.0
With neighbors	766	5.5	770	6.7	792	6.1	26	0.6	22	−0.6

Note—ID priming refers to the difference between the unrelated and the identical condition, and form priming refers to the difference between the unrelated and the orthographically related condition. *N*, set of neighbors.

$F_2(1,84) = 12.18$]. The main effect of neighborhood density was also significant [$F_1(1,30) = 12.26$; $F_2(1,84) = 18.93$]. The interaction between these two factors did not approach significance (both Fs < 1).

The error data showed a significant effect only of neighborhood density [$F_1(1,30) = 25.63$; $F_2(1,84) = 7.49$].

The results of the present experiment are again clear-cut. The overall pattern of priming effects was similar in the two experiments. For words, we replicated the results of Experiment 1: Repetition- and form-priming effects were greater for hermit words. Furthermore, an inhibitory effect of neighborhood density for the nonword stimuli was also obtained (see, e.g., Andrews, 1989; Carreiras et al., 1997; Coltheart et al., 1977; Sears et al., 1995).

Finally, form- and repetition-priming effects were similar in size for wordlike nonwords and for hermit nonwords. To accommodate the observed priming effects for hermit nonwords in the entry-opening model, one could argue that the lexical entries from a number of close-matching candidates had been opened by these hermit nonwords (e.g., via the first syllable; see Perea & Carreiras, 1998, for evidence of syllabic effects in Spanish).

GENERAL DISCUSSION

The present results strengthen the view that orthographic structure plays an important role in visual word recognition: Not only do form-priming effects differ as a function of neighborhood density (see Forster et al., 1987), but so do repetition-priming effects.

In the introduction, we suggested that an IA model could predict an interaction between neighborhood density and form/repetition priming. However, specific predictions from an IA model can only be generated by running computer simulations. To test the predictions of the IA (McClelland & Rumelhart, 1981) with the empirical data, we decided to run simulations with this model. The model was implemented with a Spanish lexicon of 3,885 five-letter words in a way that was identical to the implementation made by Jacobs and Grainger (1992). As in previous work by Jacobs and Grainger (1992; see also Grainger, 1990), the threshold for word node activation levels was set to .70 to obtain an approximate measure of identification latencies. The parameters used were the ones given as defaults by Rumelhart and McClelland (1982; McClelland & Rumelhart, 1981), except that the letter-word excitation parameter was set to .06 (see Grainger & Jacobs, 1996, for a similar adjustment for five-letter words). As in the study of Jacobs and Grainger (1992), prime duration was two cycles, which is supposed to simulate an SOA of about 60 msec. Because no lowercase alphabet is available in the model, prime and target were both presented in uppercase. (Given that it seems reasonable that the lowercase and the uppercase letters are converted to a neutral, abstract letter code before any lexical activation takes place, the simulations would not be affected by the case of the primes and targets.) All the word trials tested in the present experiments were presented to the model, and the number of cycles to reach a prespecified decision criterion (.70) was recorded. The mean number of processing cycles for target words in each experimental condition is presented in Figure 1.

The IA model captures the density constraint for form primes, although the model incorrectly predicts some form-priming effects for words with many neighbors: Specifically, the form-priming effect for low-N targets is 2.9 cycles, whereas it is 1.6 cycles for the high-N targets (it should really be zero). In addition, the model fails to capture the interaction between repetition priming and neighborhood density: The repetition-priming effect for low-N targets is 3.8, whereas it is 4.1 cycles for the high-N targets. More important, the IA model also fails to capture the facilitative main effect of neighborhood density (see also Jacobs & Grainger, 1992). This is not surprising, since competition between candidates means that words with many neighbors will be harder to discriminate than words with few neighbors. Nevertheless, it could be argued that the lexical decision task is probably outside the domain of the IA model described by McClelland and Rumelhart (1981), because lexical decisions may also be made on the basis of overall activation in the lexicon (see Balota & Chumbley, 1984; Grainger

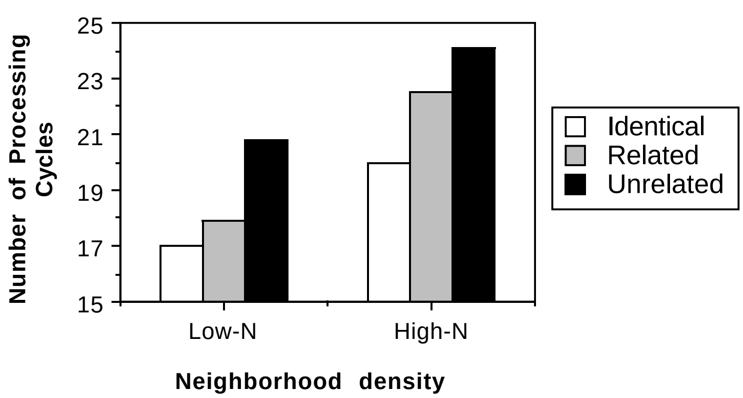

Figure 1. Simulated mean response times with the interactive activation model for the word targets primed for two cycles with an identical prime, a form-related nonword prime, and an unrelated word control.

& Jacobs, 1996; Paap & Johansen, 1994; Snodgrass & Mintzer, 1993). As was suggested by one reviewer,[5] participants could use the strategy of selecting a rapid *yes* response whenever the overall lexical activity is high. This would facilitate the processing of words with many neighbors, but it would not affect the hermits, because they would never trigger a fast *yes* response. This way, a facilitative main effect of neighborhood density would be expected. More important, if this strategy can be applied to the words with many neighbors across the three prime types, it might serve to attenuate any priming effects associated with the recognition of a specific word.

Recently, an extension of the IA model has been proposed that incorporates the possibility of making decisions on the basis of summed lexical activity (the multiple read-out model; Grainger & Jacobs, 1996).[6] The multiple read-out model implements noisy response criteria set on individual word unit activity (the so-called M criterion, as in the IA model) and summed lexical activity (the sum of activations of all word detectors activated above zero; the so-called Σ criterion) to generate quantitative predictions concerning reaction times to word stimuli in the lexical decision task. The latency of the decision will depend on which criterion is reached first. Specifically, the multiple read-out model uses the summed lexical activity computed after seven cycles of processing to adjust the Σ criterion on each trial. This value can be thought of as an index of the wordlikeness of the stimulus. If a given stimulus generates lexical activity that lies above certain critical values, the Σ decision criterion is consequently lowered. This way, high-density words (but not low-density words) can give rise to fast positive responses generated by the Σ criterion. In other words, the multiple read-out model explains the increase in facilitative effects of neighborhood density on correct reaction times to word stimuli as the result of increased use of the Σ criterion, as compared with the M criterion.

If lexical decisions are based on the summed lexical activity (the Σ criterion), the relevant activation function would be given in Figure 2. These functions were obtained by plotting the summed activation over all lexical units for the target words in the experiment (see Forster & Veres, 1998, for a similar procedure). The overall level of activation after 10 processing cycles indicates that the level of summed lexical activity at the early stages of word recognition is relatively high (greater than .4), except for the unrelated words with no neighbors, which suggests that a Σ threshold might have been triggered for all the conditions except for the unrelated low-*N* word targets. This would explain why the results show a facilitative main effect of number of neighbors. However, such an account does have some difficulty in accounting for the form-priming effects: If lexical decisions involving words with many neighbors are based on the summed lexical activity, the model incorrectly predicts a robust form-priming effect, similar in size to the repetition effect (see Figure 2). Of course, it could be argued that another set of parameters (e.g., lower mutual competition among lexical candidates, etc.) might simulate the obtained pattern of results. Alternatively, it could be argued that participants might lower the M threshold (instead of, or in addition to, the Σ threshold) when the summed lexical activity is relatively high at the early stages of word processing. But the problem is that these parameter changes might harm the model's ability to account for other word recognition phenomena. In fairness to Grainger and Jacobs (1996), however, we should note that they did not try to simulate any masked priming experiments in their 1996 paper and did not discuss additional assumptions that may be necessary to model masked priming data.

In addition, is not clear to us how an activation-based model can explain a variety of findings relative to masked priming effects. Both morphological and associative priming effects have been found with the masked priming technique (e.g., de Groot & Nas, 1991; Forster et al., 1987; Lukatela & Turvey, 1994; Perea & Gotor, 1997; Williams, 1994), which implies that the processing of the prime reaches a very advanced level before the target is presented (clearly more than two processing cycles) or that processing of the prime continues on after the target has

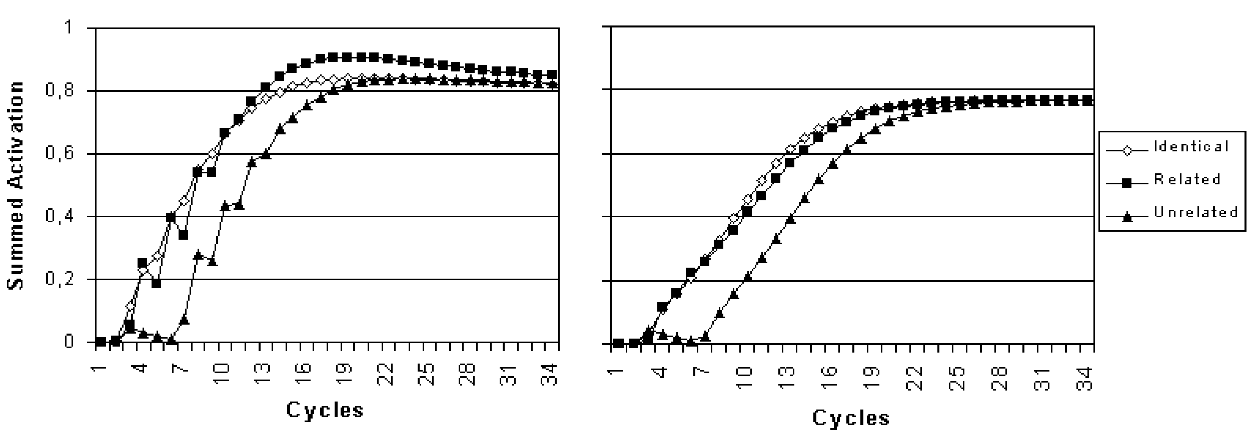

Figure 2. Simulation results with the interactive activation model showing summed activation levels over all word units for the word targets primed for two cycles with an identical prime, a form-related nonword prime, and an unrelated word control. The left panel presents the results for the high-*N* words, and the right panel presents the results for the low-*N* words.

replaced it. Since the processing of the prime is probably guided by a nonsensory representation of the input, there seems to be no reason why the processing of the prime should not continue after termination of the prime, perhaps even overlapping the lexical processing of the target to an appreciable degree (see Forster et al., 1987). For instance, Kiger and Glass (1983) found that an associatively related prime presented immediately after the target can facilitate responses to the target. The question at this point would be how an activation-based model can analyze more than a word at a time. Mozer (1987) proposed a model (BLIRNET) that is able to process several words simultaneously. Interestingly, in the BLIRNET model, only one word at a time is allowed to reach awareness, which may explain why the briefly presented prime is usually ignored with the masked priming technique. Perhaps, a more damaging criticism of an activation-based model is that it is target neighborhood density, and not prime neighborhood density, that appears to determine the prime effectiveness of form primes (Veres, 1986; cited by Forster et al., 1987): Lateral inhibitory connections between word nodes in an activation-based model will damp any activation that is spread widely across a number of word nodes. Nonetheless, recent evidence suggests that the neighborhood characteristics of the prime can also play a role in the effectiveness of form primes (see, e.g., Hinton, Liversedge, & Underwood, 1998; van Heuven, Dijkstra, Grainger, & Schriefers, 1999).

As for the entry-opening model (Forster, 1989; Forster & Davis, 1984; Forster & Taft, 1994), although it can explain the interaction between density and form priming, it cannot explain the interaction between density and repetition priming. Repetition-priming effects should be similar in size for high-*N* and low-*N* words, since the lexical entry of the target will always be opened by a previous presentation of the same word (i.e., an exact match). To accommodate the present results, one could argue that the recognition process of a masked prime is somewhat noisy and the prime does not always open the correct lexical entry (i.e., there would be a higher match criterion for both exact matches, or for very close matches), especially when the item has many visually similar competitors. This assumption seems reasonable, given that the effect of the number of neighbors is usually inhibitory in identification tasks (see, e.g., Carreiras et al., 1997; Snodgrass & Mintzer, 1992; van Heuven, Dijkstra, & Grainger, 1998). This (admittedly post hoc) account would predict greater form- and repetition-priming effects for hermit words than for words with many neighbors.

Finally, it should be stressed that the effects of target neighborhood characteristics might reflect different mechanisms in the single-word paradigm and in the priming paradigm (see, e.g., Andrews, 1996, 1997). In the single-word paradigm, the issue concerns whether partial activation of neighboring words that were never presented influences responses to the target word. In the priming paradigm, an item is explicitly activated, and the effect on target performance is measured. Obviously, the fact that neighborhood density modulates the strength of priming between similarly spelled words does not necessarily imply that neighborhood density modulates the time taken to access those words (see Andrews, 1996; Forster & Shen, 1996).

SUMMARY

To conclude, the present experiments have shown that neighborhood density interacts not only with form priming (Forster et al., 1987), but also with repetition priming at a very short SOA (67 msec). (We should note that on-going research in our laboratory has also found an interaction between form/repetition priming and neighborhood density at other brief SOAs.) The present results can be taken as strong evidence of inhibition in the selection process in visual word recognition (e.g., there is less reprocessing benefit from the identical primes for words with many neighbors, because of inhibition among lexical units), but alternative explanations are also possible (in terms of the entry-opening model). Although the neighborhood density constraint (i.e., smaller form- and repetition-priming effects for words with many neighbors) seems to fall out as a natural consequence of the recognition process in an activation model (via lateral inhibition), implemented versions of activation-based models of visual word recognition do not appear to capture that effect. Part of the problem might well be due to the lack of a clear specification of how masked priming effects are simulated with an activation-based model. The entry-opening model (Forster & Davis, 1984; Forster et al., 1987; Forster & Taft, 1994) readily accommodates the neighborhood density constraint for form priming; however, the model needs to be slightly modified to cope with the fact that the magnitude of the repetition priming effect depends on neighborhood density. We believe that further research on the neighborhood density constraint might be used to discriminate between the different types of selection mechanisms postulated in models of visual word recognition.

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NOTES

1. Perhaps the density of the target words might play a role with word primes as well, given that Forster used long words, whereas Grainger and colleagues used short words that, in general, had many neighbors.

2. Forster and Taft (1994) also developed an alternative explanation—based on a codification system into onsets and bodies that would operate in dense neighborhoods—in which form-related primes may actually have little overlap with the targets. For instance, *fact* and *face* have only the onset in common if *fact* is recoded as *f+act* and *face* is recoded as *f+ace*. However, this recoding would have no effect on identity priming.

3. Although one could argue that this difference (zero neighbors vs. nine or more neighbors) is qualitative rather than quantitative, we would like to note that there is evidence in Spanish that not only are orthographic neighbors (i.e., words that share all letters but one; e.g., Spanish: *casta–caspa*) being activated in the process of visual word recognition—as is usually supposed—but also syllabic neighbors (i.e., words that share a syllable with the target word, especially the first syllable). For instance, the Spanish word *carpa* would be partially activated (or accessible) when the word *cardo* is presented. All the stimuli in our experiments had two syllables, so it is likely that even lexical hermits had some competitors in the set of candidates.

4. Recently, Bodner and Masson (1997) reported very large priming effects (93 msec) for nonword targets in lexical decision when the target was presented in mixed case (e.g., *bReAk*). However, more research needs to be conducted to understand how this masked priming effect occurs (see Forster, 1998).

5. We thank Ken Paap for this suggestion.

6. We should note that the facilitative main effect of neighborhood density can also be simulated with a different set of parameters (most notably, lower mutual competition among lexical candidates; see, e.g., Andrews, 1997; Coltheart & Rastle, 1994) without relying on the overall level of activation in the lexicon. However, we failed to simulate the present masked priming results when the parameter controlling word-to-word inhibition was reduced from .21 (the value by default) to .05 (see Forster & Veres, 1998, for a similar manipulation).

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