

Masked partial priming of letter perception

Jean-Philippe Petit and Jonathan Grainger

CNRS and University of Provence, Marseille, France

In three experiments testing 178 subjects, letter targets were preceded by briefly presented, pattern-masked primes formed by deleting pixels in a larger or smaller version of the target stimulus. In Experiment 1A (alphabetic decision) and Experiment 1B (letter naming) a slight advantage was observed for global primes (alternate pixels deleted) compared with junction primes (midsegment information removed). This advantage was stronger at 50 ms prime exposures than at 30 ms exposures in the naming task. In Experiment 2 (letter naming), midsegment primes (with junction information removed) produced faster latencies than did junction primes. This result was replicated in a third experiment and was shown to be independent of target letter case and the relative size of prime and target stimuli. The same midsegment and junction primes did not facilitate performance compared to neutral primes in the alphabetic decision task. These results suggest that masked partial priming of letter naming can be usefully applied to the study of basic processes in letter perception.

The present study applies the masked prime paradigm with partial letter primes in an attempt to elucidate the early perceptual processes that operate during letter identification. This paradigm has already proved useful in uncovering early orthographic and phonological coding involved in printed word perception (e.g., Evett & Humphreys, 1981; Ferrand & Grainger, 1992, 1994; Peressotti & Grainger, 1999; Perfetti & Bell, 1991). It typically involves the presentation of the following sequence of events: A pattern mask for 500 ms, a briefly presented (< 100 ms) prime stimulus, and the target stimulus for a duration determined by the task to be performed (and possibly followed by a masking stimulus). Very little conscious information is available from prime stimuli in these presentation conditions, thus excluding the use of predictive strategies that subjects might attempt to apply on discovering the prime–target relationship manipulated by the experimenter (Forster, 1993).

Please address all correspondence to J.-P. Petit, Laboratoire de Psychologie Cognitive, Université de Provence, 3 place Victor Hugo, 13311 Marseille, France.

Email: jphpetit@up.univ-mrs.fr

The first author was supported by a grant from the French Ministry of Education.

A number of studies have applied the masked prime paradigm to the study of letter perception (Arguin & Bub, 1995; Bowers, Vigliocco, & Haan, 1998; Jacobs & Grainger, 1991; Jacobs, Grainger, & Ferrand, 1995; Peressotti & Grainger, 1995; Ziegler, Ferrand, Jacobs, Rey, & Grainger, 2000). In all these studies, primes were complete letters that varied in terms of their visual similarity with the target and whether or not they were nominally identical to the target. Variations in visual similarity across prime and target have been shown to influence response latencies in the alphabetic decision task (Bowers et al., 1998; Jacobs & Grainger, 1991; Jacobs et al., 1995; Ziegler et al., 2000), while having little or no influence on letter naming responses (Arguin & Bub, 1995; Bowers et al., 1998; Ziegler et al., 2000). On the other hand, nominally identical but visually dissimilar primes (e.g., a–A) have little influence on alphabetic decision latencies compared to different letter primes (e.g., c–A) but facilitate letter naming responses (Bowers et al., 1998; Ziegler et al., 2000).

The observed absence of effects of prime–target visual similarity in letter naming latencies led Arguin and Bub (1995) to suggest that unique letter identification, necessary for generating a naming response, operates at the level of abstract letter representations (letter types) that disregard shape information. An alternative interpretation (one offered by Bowers et al., 1998), however, is that in the naming task different letter primes lead to the preparation of the wrong articulatory response, thus delaying the computation of an articulatory output for the target letter. Furthermore, Arguin and Bub's failure to find a phonological priming effect in letter naming could be simply due to the fact that they manipulated rime overlap (e.g., B–C). Research has shown that naming latencies in the masked prime paradigm are highly sensitive to shared onsets (Forster & Davis, 1991; Grainger & Ferrand, 1996), and these onset priming effects tend to hide the more subtle influence of shared rimes. In other words, prime–target visual similarity should influence performance in the naming task when possible interference from different onsets is eliminated.

According to this account, when primes are not complete letters, but parts of letters, then form similarity priming should be observable in both the alphabetic decision and letter naming tasks. Contrary to when prime–target visual similarity is manipulated across different letters, visually similar primes that are formed by parts of the target letter should, if anything, lead to the generation of an appropriate rather than an inappropriate articulatory response.¹

Some related work by Sanocki (1991) provides evidence for form priming effects in letter perception. Sanocki used a variant of the masked prime paradigm, called integration priming, where targets are also briefly presented

¹The ambiguity of partial letter primes was not manipulated in the present study, and practically all the partial primes were only compatible with a single letter. Manipulating prime ambiguity is obviously one interesting avenue for future research using the partial letter priming paradigm.

and followed by a pattern mask. He reported facilitatory effects of shape primes (e.g., a cross pattern as a prime for the letter “t”) in a letter discrimination task (two alternative forced choice), even when the alternative letter was compatible with the shape prime (e.g., “t” vs “f”). Facilitation was observed relative to both a no-prime condition and an inconsistent (different shape) prime condition. The fact that very similar shape priming effects were also obtained to pseudoletter targets implies that they are the result of general processes involved in form perception before learned representations have been activated. Sanocki (1997) has argued that with brief prime exposure durations (< 150 ms) these effects are related to the structure of the retinal image. Indeed the work of Davis and Forster (1994) suggests that form priming effects obtained with the integration priming paradigm (i.e., when targets are briefly exposed) may be entirely due to variations in target legibility given a fused image of prime and target stimuli. Davis and Forster also demonstrated that the masked prime paradigm with long target exposures is not sensitive to these low-level physical summation effects.

Given the evidence for effects of visual similarity in masked priming with the alphabetic decision task (Bowers et al., 1998; Jacobs & Grainger, 1991; Jacobs et al., 1995; Ziegler et al., 2000), it appears that the masked prime paradigm could be usefully applied to examine exactly which parts of letters play a critical role in the process of letter perception. In the present study, related primes were created by deleting parts of the target letter to create a partial prime. In Experiment 1, these partial primes either maintained the target letter’s global shape or maintained the junctions (points where two line segments meet). This experiment was therefore designed to determine the relative weight assigned to global shape information and more local segmental information in letter perception. Also, by using two prime exposure durations (30 ms and 50 ms) we test the hypothesis that global information is extracted before more local information (e.g., Lupker, 1979; Sanocki, 1993). Finally, although the results of Davis and Forster (1994) suggest that the masked prime paradigm to be used in the present study is not sensitive to low-level physical overlap between prime and target, we present primes and targets in different sizes to minimize any physical overlap in the related conditions. The alphabetic decision task is used in Experiment 1A and the naming task in Experiment 1B.

EXPERIMENT 1A

Method

Subjects. Sixty students of the University of Provence, thirty for each prime exposure duration, participated in this experiment as volunteers. All reported normal or corrected-to-normal vision.

Design and stimuli. The target letters were 18 letters of the roman alphabet in uppercase format (A, B, E, F, H, I, K, L, M, N, P, R, T, V, W, X, Y, Z) and the target nonletters were 18 new signs designed especially for the experiment (examples are given in Figure 1). Target letters and nonletters were preceded by three different types of prime: Junction, global, or neutral primes (see Figure 1). Junction primes were composed of the pixels concentrated around the points where two lines meet (i.e., where there is a change in orientation), plus pixels situated at the ends of lines. Global primes were composed of the same number of pixels as the junction prime for a given target, but regularly distributed across the entire target letter. Finally, a neutral prime was constructed with 17 pixels (the mean number of pixels in the other types of prime) randomly distributed across the rectangular space that a complete version of the prime would occupy. Each of the targets was presented once in each of the three prime type conditions at each of the two prime durations. The prime-type factor was varied within subjects whereas the prime duration factor was varied between subjects. Thus each subject saw each target three times giving a total of 108 trials. The stimuli were randomly presented.

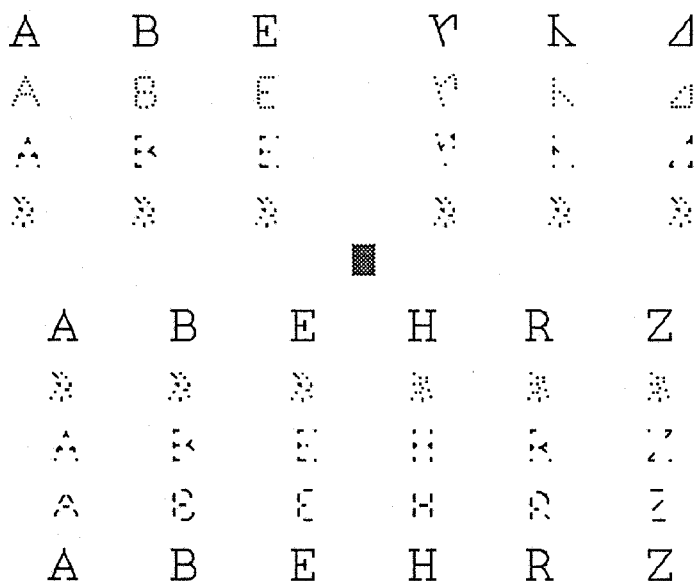


Figure 1. Examples of target letters and nonletters (first row) with the three types of prime tested in Experiment 1 (global, junction, and neutral primes), and target letters with the four types of prime tested in Experiments 2 and 3 (neutral, junction, midsegment, and complete primes). The pattern mask is shown in the middle. Note that primes were twice the size of target stimuli, except in Experiment 3 where the reverse was true.

Apparatus and procedure. Stimulus presentation and response measurements were controlled by a Macintosh microcomputer with a 70 Hz monitor. The experiment was run on PsyScope software (Cohen, MacWhinney, Flatt, & Provost, 1993). The letters corresponded to the type font "courier-24" of the computer. Each letter was about 0.5 cm (0.57°) high and 0.45 cm (0.52°) wide. The prime size was twice the target size so that each prime was about 1 cm (1.15°) high and 0.9 cm (1.03°) wide. Primes and targets were presented on the centre of the screen but with different sizes to minimize the possibility of any purely physical brightness summation contributing to priming effects. Viewing distance was maintained constant at approximately 50 cm and stimuli were presented at high contrast in black on a white background. The sequence of events on each trial was as follows. A rectangular checkerboard mask, filling the rectangular space occupied by the prime stimuli was presented on the centre of the screen for 500 ms. This was immediately replaced in the same position by the prime stimulus, which remained on the screen for approximately 30 or 50 ms depending on the prime duration condition. Immediately after that, the target letter or nonletter appeared in the same position. The target remained on the screen until subjects responded by pressing one of two keys on a button box with the index finger of the left or right hand to indicate if the target was a letter or not. Half of the subjects were asked to respond with the right key for letter targets and with the left key for nonletter targets while the other half were asked to do the opposite. The next trial started after a 1 s blank interval. Subjects were instructed to fixate the checkerboard mask each time it appeared and then to respond as quickly as possible to the target. RT was measured from target onset to subject's response. Subjects first saw 10 practice trials before beginning the main experiment.

Results

Mean correct RT and errors for each experimental condition are given in Table 1. RTs less than 300 ms, or greater than 1000 ms were excluded from analysis (2.4% of the data). There was a reliable main effect of prime type on RT to letter targets, $F(2, 116) = 5.66, p < .01$, but no main effect of prime duration, $F(1, 58) = 0.03$. The interaction between the two factors was not significant, $F(2, 116) = 0.16$. Planned comparisons showed that RT was shorter when target letters were preceded by global primes compared to neutral primes, $F(1, 58) = 10.51, p < .01$. Neither the difference between junction primes and neutral primes, $F(1, 58) = 3.55$ nor the difference between junction primes and global primes, $F(1, 58) = 2.48$, were significant.

There was no reliable main effect of prime type nor prime duration on error rate to letter targets, respectively $F(2, 16) = 1.40$, and $F(1, 58) = 3.21$. The interaction between the two factors was not significant, $F(2, 116) = 2.27$, and no

TABLE 1
Mean alphabetic decision latency (RT in ms) and percentage of error (PE) by prime type and prime duration for letter and nonletter targets in Experiment 1A (standard errors in parentheses)

Prime type	Prime duration			
	30 ms		50 ms	
	RT	PE	RT	PE
Letter targets				
global	485 (13)	2.3 (0.8)	480 (11)	1.3 (0.5)
junctions	491 (14)	4.1 (0.9)	488 (9)	1.7 (0.5)
neutral	497 (12)	2.1 (0.9)	497 (11)	2.4 (0.7)
Nonletter targets				
global	519 (12)	4.3 (1.2)	492 (9)	2.2 (0.7)
junctions	517 (12)	5.4 (1.3)	502 (9)	0.9 (0.4)
neutral	519 (12)	3.2 (1.4)	494 (9)	1.3 (0.6)

contrast in a planned-comparisons analysis was shown to be significant (all $F_s < 1$).

There was no reliable main effect of prime type nor prime duration on RT to nonletter targets, respectively $F(2, 116) = 0.45$, and $F(1, 58) = 2.48$. The interaction between the two factors was not significant, $F(2, 116) = 1.25$. Prime type did not influence error rate to nonletter targets, $F(2, 116) = 1.14$, but there was a reliable main effect of prime duration, $F(1, 58) = 6.75$, $p < .05$. Error rate was lower for nonletters at 50 ms prime exposures than at a 30 ms exposures. The interaction between the two factors was not significant, $F(2, 116) = 1.91$.

EXPERIMENT 1B

Method

Subjects. Sixty students of the University of Provence participated in this experiment as volunteers, thirty at each prime exposure duration. All reported normal or corrected-to-normal vision, and none had participated in the previous experiment.

Design and stimuli. These were the same as for Experiment 1A except that there were no nonletter stimuli.

Apparatus and procedure. These were the same as for Experiment 1A except that the button box was replaced by a headset microphone and voice-key. Letter targets remained on the screen until subjects responded by reading

TABLE 2
Mean letter naming latency (in
ms) by prime type and prime
duration in Experiment 1B
(standard errors in parentheses)

<i>Prime type</i>	<i>Prime duration (ms)</i>	
	<i>30</i>	<i>50</i>
Global	470 (9)	466 (12)
Junctions	473 (8)	478 (10)
Neutral	480 (8)	488 (10)

them aloud into the microphone. RT was measured from target onset to the subject's vocal response detected by a voice-key connected to the microphone and the computer that controlled stimulus presentation.

Results

Mean RTs for each experimental condition are given in Table 2. RTs less than 300 ms or greater than 1000 ms were excluded before analysis (6.6% of the data, the majority resulting from voice-key failures).

There was a main effect of prime type on RT, $F(2, 116) = 18.7, p < .01$, but no reliable main effect of prime duration, $F(1, 58) = 0.07$. The interaction between the two factors was significant, $F(2, 116) = 3.23, p < .05$, reflecting the greater priming effects obtained at 50 ms prime exposures than at 30 ms exposures. The effect of prime type was significant at both the 50 ms, $F(2, 58) = 14.19, p < .01$, and the 30 ms prime exposure duration, $F(2, 58) = 5.13, p < .01$. Planned-comparisons revealed significant differences between RTs following global primes compared to neutral primes, $F(1, 58) = 35.89, p < .01$, between junction primes and neutral primes, $F(1, 58) = 15.18, p < .01$, and also between the junction and global prime conditions, $F(1, 58) = 5.94, p < .05$.

Discussion

The results of Experiment 1 show that very briefly presented masked prime stimuli formed by parts of a letter target influence the processing of letter targets in alphabetic decision and letter naming. On the other hand, no partial priming effects were obtained with nonletter targets in the alphabetic decision task. With letter targets, global primes produced numerically larger effects than junction primes in both tasks, but this advantage was only statistically robust in letter naming.

The letter naming data showed an interaction between prime type and prime duration reflecting stronger priming effects at the longest prime duration. The advantage of global primes over junction primes increased with an increase in

prime exposure duration, from 3 ms at 30 ms prime exposures to 12 ms at 50 ms exposures. Contrary to the predictions of the global precedence hypothesis of Sanocki (1993), it appears that global and local (i.e., junction) primes have similar effects at the shortest prime exposure, with an advantage for global primes appearing at longer exposure durations.

The results of Experiment 1B suggest that prime–target visual similarity does influence letter naming latencies. Indeed, it appears from this experiment that letter naming may be more sensitive to such partial priming effects than the alphabetic decision task. Possible task differences will be further explored in Experiment 3. The following experiment provides a further examination of the type of visual similarity across prime and target that is necessary to obtain priming effects in letter naming. This experiment compares the efficiency of junction primes (as used in Experiment 1) to midsegment (junctionless) primes having similar physical properties in terms of the distribution of pixels across the prime (see Figure 1). A complete prime condition is also included to provide an upper baseline for priming effects, the neutral prime providing the lower baseline.

EXPERIMENT 2

Method

Subjects. Thirty students of the University of Provence participated in this experiment as volunteers. All reported normal or corrected-to-normal vision, and none had participated in the previous experiments.

Design and stimuli. The targets were 14 letters of the alphabet in their uppercase format (A, B, E, F, H, I, K, L, M, N, P, R, T, Z). Four types of prime were tested: complete, junction, midsegment, and neutral. Junction and neutral primes were the same as in the previous experiments. Midsegment primes were composed of the same number of pixels as the junction primes. The midsegment primes were formed by grouping pixels at regions between junctions. Complete primes were the entire letters (examples of prime types are shown in Figure 1). Each of the targets was presented once in each of the four prime conditions, giving a total of 56 trials per subject and per session. Subjects were presented with these 56 trials in random order in two consecutive sessions giving a total of 28 data points per priming condition per subject. Thus, the prime-type factor was varied within subjects and within sessions.

Apparatus and procedure. These were the same as in Experiment 1B except that prime exposure duration was fixed at 50 ms and that subjects were tested in two consecutive sessions with a short break in between.

TABLE 3
Mean letter naming latency (RT in ms) by
prime type and session in Experiment 2
(standard errors in parentheses)

<i>Prime type</i>	<i>Session</i>		
	<i>1</i>	<i>2</i>	<i>Mean</i>
Midsegment	434 (10)	424 (9)	429
Junction	440 (10)	429 (10)	435
Neutral	461 (9)	451 (9)	456
Repetition	413 (10)	404 (10)	408

Results

Mean RTs for each experimental condition are given in Table 3. RTs less than 300 ms or greater than 1000 ms were excluded from analysis (2.3% of the data). There was a main effect of prime type on RT, $F(3, 87) = 122.09$, $p < .0001$, and a main effect of session, $F(1, 29) = 6.48$, $p < .05$, but no Prime type \times Session interaction, $F(3, 87) = 0.03$. Planned-comparisons showed an RT advantage for complete primes compared to midsegment primes, junction primes, and neutral primes, respectively, $F(1, 29) = 67.67$, $p < .0001$; $F(1, 29) = 110.35$, $p < .0001$; and $F(1, 29) = 361.03$, $p < .0001$. There was an RT advantage for midsegment primes compared to junction primes and compared to neutral primes, respectively, $F(1, 29) = 5.19$, $p < .05$, and $F(1, 29) = 116.09$, $p < .0001$. Finally, RTs following junction primes were significantly faster than RTs following neutral primes, $F(1, 29) = 72.18$, $p < .0001$.

Discussion

The results of Experiment 2 show significant partial priming of letter naming from primes sharing junctions and primes sharing midsegments with the target, with a numerically small but statistically significant advantage for the latter. Complete primes were about twice as effective as either midsegment or junction primes. Experiment 2 demonstrated that these masked form priming effects obtained with letter targets are not affected by target stimulus repetition (subjects saw all target letters eight times and priming effects were just as strong averaging over the last four presentations compared to the first four presentations). This has also been shown to be true concerning orthographic and phonological priming effects obtained with word targets (Ferrand & Grainger, 1994). This is an important methodological observation that suggests profitable application of the masked prime paradigm to psychophysical style experimentation, where stimulus repetition helps improve measurement sensitivity.

Experiment 3 provides a further test of masked partial letter priming using the same set of primes and targets as in Experiment 2, except that target stimuli

are now twice the size of prime stimuli (the size of primes and targets being reversed compared to Experiment 2). Increasing target size was designed to ensure better post-masking of the prime stimulus and therefore reduced visibility of primes. Furthermore, prime visibility was measured for each subject after running the main experiment. Experiment 3 also examines whether case compatibility across prime and target influences the priming effects observed in Experiment 2. Primes were always derived from the upper case forms of targets, whereas targets were presented in either upper or lower case format. Priming effects that are independent of case compatibility would suggest that abstract (i.e., case-independent) letter representations are involved. In such a situation, variations in the size of priming effects would reflect differences in the degree with which different prime stimuli can activate such abstract letter identities. Finally, a within-subject manipulation of task (letter naming vs. alphabetic decision) should help clarify task differences in partial letter priming effects.

EXPERIMENT 3

Method

Subjects. The participants were 28 University of Provence undergraduate students. All reported normal or corrected-to-normal vision.

Design and stimuli. The 14 target letters were the same as in Experiment 2 and the 14 target nonletters a subset of those used in Experiment 1. The four types of prime (midsegment, junction, complete, and neutral) were the same as in Experiment 2 for letter targets. For nonletter targets, the junction primes were the same as in Experiment 1A and the midsegment primes were designed in the same way as the midsegment primes for letter targets. Number of pixels was equated across the junction and midsegment primes. Compared to the previous experiments the sizes of prime and target stimuli were reversed so that target stimuli were now twice the size of prime stimuli. Target letters were presented in both lower case and upper case format once in each of the four prime conditions, giving a total of 112 trials per subject in letter naming and 224 trials in alphabetic decision. Since there was no case manipulation for nonletter targets, these were presented twice in each prime condition. Thus, prime type and target format were varied within items and within subjects.

Apparatus and procedure. These were the same as in Experiment 1A for the alphabetic decision task and as in Experiment 1B for the letter naming task, except for the following points. Target stimuli were twice as big as prime stimuli, and were therefore approximately 2 cm (2.3°) high by 1.8 cm (2.06°) wide in both upper case and lower case format. Prime exposure duration was fixed at

50 ms. Subjects first saw 12 practice trials before running each task. Half of the subjects performed the letter naming task before the alphabetic decision task with a short break in between, while the other half did the opposite. All subjects finally performed a prime reportability test in which they were asked to report any prime they could identify as a letter. Presentation conditions for the prime reportability task were identical to the main experiments except that targets were replaced by the letter "X", which remained on the screen until subjects responded by pressing the space key or the key corresponding to the letter they had identified. Thus, a free report procedure was used and subjects were requested to refrain from pure guessing.

Results

Mean letter naming RTs for each experimental condition are given in Table 4. Mean correct alphabetic decision RTs and percentage errors are given in Table 5. RTs less than 300 ms or greater than 1000 ms were excluded from analysis (respectively 2.9% and 0.4% of the data for letter naming and alphabetic decision). The overall analysis confirmed that there were significant main effects of prime type and target format on RT, respectively, $F(3, 78) = 16.5, p < .01$, and $F(1, 26) = 22.77, p < .01$, and no significant interaction between these two factors, $F(3, 78) = 1.16$. The main effect of task failed to reach statistical significance, $F(1, 26) = 3.87$. The interaction between task and order was not significant, $F(1, 26) = 1$. Since there was, however, a trend to an interaction between target format and task, $F(1, 26) = 3.12, p < .10$, the results for each task were analysed separately.

Letter naming. There was a reliable main effect of prime type on RT, $F(3, 81) = 24.05, p < .01$, but no main effect of target format, $F(1, 27) = 2.88$. The interaction between the two factors was not significant, $F(3, 81) = 1.76$. Planned-comparisons showed an RT advantage for complete primes compared to midsegment primes, junction primes, and neutral primes, respectively,

TABLE 4
Mean letter naming latency (RT in ms) by
prime type and target format in
Experiment 3 (primes are in uppercase,
standard errors in parentheses)

Prime type	Target format	
	Uppercase	Lowercase
Midsegment	445 (8)	442 (9)
Junction	446 (9)	454 (8)
Neutral	452 (10)	453 (9)
Repetition	427 (9)	432 (9)

TABLE 5
Mean alphabetic decision latency (RT in ms) and percentage of error (PE) by prime type and target format for letter and nonletter targets in Experiment 3 (primes are in uppercase, standard errors in parentheses)

Prime type	Target format			
	Uppercase		Lowercase	
	RT	PE	RT	PE
Letter targets				
midsegment	460 (9)	2.8 (0.7)	470 (9)	3.3 (0.9)
junction	460 (11)	2.3 (0.7)	465 (10)	3.3 (1)
neutral	460 (9)	2.8 (0.8)	468 (10)	3.5 (1)
repetition	441 (10)	2.3 (0.8)	459 (9)	2.8 (0.8)
Nonletter targets				
midsegment	506 (11)	6.4 (1.2)		
junction	502 (10)	6.5 (1.3)		
neutral	509 (12)	8.7 (1.6)		
repetition	491 (13)	6.3 (1.2)		

$F(1, 27) = 35.88, p < .01$; $F(1, 27) = 50.54, p < .01$; and $F(1, 27) = 35.54, p < .01$. There was an RT advantage for midsegment primes compared to junction primes and neutral primes, respectively, $F(1, 27) = 6.19, p < .025$, and $F(1, 27) = 7.64, p < .025$. Finally, RTs following junction primes did not differ significantly from RTs following neutral primes, $F(1, 27) = 1$.

Alphabetic decision. There were reliable main effects of prime type and target format on RT to letter targets, respectively, $F(3, 81) = 4.18, p < .01$, and $F(1, 27) = 10.83, p < .01$. Target letters in upper case were responded to 10 ms more rapidly than lower case targets. The interaction between the two factors was not significant, $F(3, 81) < 1$. Planned-comparisons showed an RT advantage for complete primes compared to midsegment primes, junction primes, and neutral primes, respectively, $F(1, 27) = 9.97, p < .01$; $F(1, 27) = 6.58, p < .025$; and $F(1, 27) = 8.27, p < .01$. No other contrast was shown to be significant (all F s < 1).

There was no reliable main effect of prime type nor target format on error rate to letter targets, respectively, $F(3, 81) < 1$ and $F(1, 27) = 2.06$, and the interaction between the two factors was not significant, $F(3, 81) < 1$. There was a main effect of prime type on RT to nonletter targets, $F(3, 81) = 6.36, p < .01$. Planned-comparisons showed an RT advantage for complete primes compared to midsegment primes, junction primes, and neutral primes, respectively, $F(1, 27) = 11.21, p < .01$; $F(1, 27) = 4.94, p < .05$; and $F(1, 27) = 15.71, p < .01$. No other contrast was shown to be significant. There was no main effect of prime type on error rate to nonletter targets, $F(3, 81) = 2.48$.

Prime reportability. Subjects who produced more than 10% false reports were excluded from the calculation of prime reportability (6/28 subjects). Report rates were respectively 1.3%, 4.7%, and 38.8% for junction, midsegment, and repetition primes. There was no reliable correlation between prime reportability and amount of priming (average of midsegment, junction, and repetition prime conditions compared to the neutral condition) across subjects for upper case letter targets nor for lower case letter targets, respectively, $r = .12$ and $r = -.05$ in letter naming, and $r = -.33$ and $r = .05$ in alphabetic decision (all $ps > .1$). A split-half analysis on the data for all 28 subjects using report rate level (low vs. high report rate groups) showed no interaction with priming effects or effects of target format, respectively, $F(3, 78) = 1.29$ and $F(1, 26) < 1$ in letter naming, and $F(3, 78) = 1.56$ and $F(1, 26) < 1$ in alphabetic decision. For letter naming, additional analyses performed on the data for the low-report rate subjects showed a reliable effect of prime type, $F(3, 39) = 18.57$, $p < .01$, and planned-comparisons showed an RT advantage for junction primes, midsegment primes, and complete primes compared to neutral primes, respectively, $F(1, 13) = 6.84$, $p < .025$; $F(1, 13) = 10.55$, $p < .01$; and $F(1, 13) = 29.22$, $p < .01$. However, these effects failed to reach significance for the low-report rate subjects in the alphabetic decision task. Report rates were respectively 0.3%, 0.8%, and 19.1 % for junction, midsegment, and repetition primes in the low-report group of subjects.

Discussion

The results of Experiment 3 corroborate those of the previous experiments showing significant priming of letter naming and alphabetic decision. The letter naming data replicate the advantage of midsegment primes compared to both junction and neutral primes observed in Experiment 2, and show that this is not affected by prime-target case compatibility. This important result implies that prime stimuli are affecting processing at the level of case-independent letter representations, and that priming obtained with this task is not just the result of summation of activation across shared subletter features. Furthermore, the prime reportability data suggest that these priming effects are not significantly influenced by the overall reportability level of prime stimuli in the present study.

Unlike letter naming, priming effects in alphabetic decision only arise with complete versions of the target letter (i.e., repetition priming). Neither midsegment primes nor junction primes facilitated alphabetic decision performance relative to a neutral prime condition. In line with the results of Experiment 1, no partial priming effect was obtained with nonletter targets in alphabetic decision. However, in Experiment 3 decisions to nonletter targets were facilitated by complete primes relative to neutral primes. This latter result

suggests that the priming effects obtained with this task, contrary to letter naming, reflect processes operating at the level of subletter features.

GENERAL DISCUSSION

The present experiments provide an initial attempt at applying the masked prime paradigm to the study of early visual processes in letter perception. Primes that share visual information with target letters were shown to facilitate target letter processing compared to neutral primes. However, the two tasks used in the present study, alphabetic decision and letter naming, differed in terms of their sensitivity to the varying levels of prime–target form overlap. Both tasks showed significant priming from global primes (Experiment 1) and complete primes (Experiments 2 and 3), whereas only letter naming showed statistically robust priming from junction and midsegment primes, with a systematic advantage for the latter. These task differences shed some light on the possible mechanisms underlying priming effects with partial letter primes, to be discussed later.

Another result that constrains possible interpretations of these partial letter priming effects is the absence of an interaction between prime–target case compatibility and priming effects. This result suggests that priming effects are subtended by abstract letter identities that are independent of case and font (Arguin & Bub, 1995). Processing of the prime stimulus would lead to growth in activation of units coding the appropriate abstract letter identity, and this would lead to faster target letter recognition when the same abstract letter identity is involved.

According to this account, response generation in the present alphabetic decision experiments would not be based on activity in abstract letter representations. The alphabetic decision task does not logically require unique letter identification for response generation. Any information that allows subjects to successfully discriminate letter targets from nonletter targets is a potential basis for response generation in this task. For example, following the same reasoning developed for the lexical decision task used with printed word stimuli (e.g., Grainger & Jacobs, 1996), a positive alphabetic decision response could be generated on the basis of global letter activity defined as the summed activation across all letter representations.² This type of response strategy may have been exaggerated in the present study by the type of unfamiliar nonletter stimulus that was used. Future work with the alphabetic decision task should examine the influence of different types of nonletter stimulus (e.g., familiar nonletter characters versus unfamiliar letter-like patterns) on response generation in this task.

²See Arguin and Bub (1995) for a similar account of task differences in letter priming.

Effects of visual similarity across primes and targets observed in prior studies using the alphabetic decision task (Bowers et al., 1998; Jacobs & Grainger, 1991; Jacobs et al., 1995; Ziegler et al., 2000) stand in contrast to the absence of priming effects for midsegment and junction primes in the alphabetic decision experiments of the present study. Other than the different type of nonletter stimulus employed in the present study, one critical difference relative to prior work is that primes and targets had different sizes in the present experiments. This was done to reduce any possible influence of low-level summation of visual information. Although all the previously mentioned studies used a briefly exposed pattern mask intervening between prime and target, it remains to be seen whether the effects of visual similarity reported in these studies will be resistant to changes in size across prime and target stimuli.

Given the different size of prime and target stimuli in the present study, the absence of an effect of midsegment and junction primes in the alphabetic decision task could be due to the relatively low degree of visual overlap in these conditions. The effects of global primes (Experiment 1) and identity primes (Experiment 3) in alphabetic decision would then be attributed to an increase in prime–target visual overlap in these precise conditions. Although there was no interaction between priming effects and prime–target case compatibility in the alphabetic decision task of Experiment 3, limiting the analysis to repetition priming effects shows a different picture. Repetition priming effects were more than twice as big when primes and targets were in the same case compared to different case (19 ms vs. 9 ms). The fact that nonletter targets benefited from identity priming in Experiment 3 further suggests that visual processes unrelated to specific letter representations may be the basis of priming effects in the alphabetic decision experiments of the present study.

Contrary to alphabetic decision, response generation in the letter naming task is necessarily based on activity in one specific letter representation. Thus, the observed pattern of data must reflect the different degrees to which a given prime stimulus can generate activation in the appropriate letter representation. The generation of an articulatory code depends on this preliminary letter identification phase, without requiring that this be completed before generation of the articulatory code can begin. These data should therefore shed light on the type of shape information that is critical in the process of letter recognition. In the letter naming tasks of Experiments 2 and 3, midsegment primes significantly facilitated letter naming compared to both neutral primes and junction primes. The slight advantage for the midsegment primes in Experiment 2 may imply that information concerning line orientation plays a greater role than information concerning line intersections (junctions) in the process of letter perception. It should be noted, however, that Boucart, Grainger, and Ferrand (1995) observed a significant advantage for three-dimensional junction primes in an object naming experiment using the masked prime paradigm. Primes containing Y, T, and arrow-like intersections produced faster object naming responses

than primes containing only midsegment information. This advantage for junction primes in object naming could either be due to their having higher local densities than the other types of prime, or it could reflect the possibility that objects are stored as a set of volumetric components (Biederman, 1987; Hummel & Biederman, 1992). In the latter case, the junction primes would facilitate segmentation of the target object into its different components. Since junction primes were actually inferior to midsegment primes in the present study, it would seem that two-dimensional letter shapes are not segmented in a manner analogous to three-dimensional objects.

The procedure used in the present study was chosen to be minimally sensitive to low-level physical summation across prime and target stimuli (what Sanocki, 1997, refers to as integration priming). First, the work of Davis and Forster (1994) has shown that long target exposures impede such low-level integration processes with printed word stimuli, while allowing priming effects to emerge at a more abstract level of representation. Second, primes and targets had different sizes in the present study, thus minimizing the influence of pure physical overlap across prime and target. The priming effects obtained in the present research are therefore likely to reflect a mechanism of the extraction of feature information from letter stimuli that is robust to variations in size and position (Fukushima, 1992).

Finally, it should be noted that the main advantage of the masked prime paradigm compared to a paradigm where subjects are invited to directly identify incomplete versions of letter stimuli, is that highly degraded non-identifiable stimuli can be used. This represents the logical follow-up of the present study. Prime stimuli will be formed of combinations of segments that are not clearly identifiable as any particular letter, thus allowing us to provide a more detailed specification of the early perceptual processes involved in recognizing letters. Thus, the present study provides an initial attempt at applying masked priming to the study of visual processes involved in letter perception, and opens the way for more sophisticated manipulations of prime–target visual similarity in future experimentation.

REFERENCES

- Arguin, M., & Bub, D. (1995). Priming and response selection processes in letter classification and identification tasks. *Journal of Experimental Psychology: Human Perception and Performance*, 21, 1199–1219.
- Biederman, I. (1987). Recognition-by-components : A theory of human image understanding. *Psychological Review*, 94, 115–147.
- Boucart, M., Grainger, J., & Ferrand, L. (1995). Three-dimensional features facilitate object recognition. *Visual Cognition*, 2, 451–478.
- Bowers, J.S., Vigliocco, G., & Haan, R. (1998). Orthographic, phonological, and articulatory contributions to masked letter and word priming. *Journal of Experimental Psychology: Human Perception and Performance*, 24, 1705–1719.

- Cohen, J., MacWhinney, B., Flatt, M., & Provost, J. (1993). PsyScope: An interactive graphic system for designing and controlling experiments in the psychology laboratory using Macintosh computers. *Behavior Research Methods, Instruments and Computers*, 25, 257–271.
- Davis, C., & Forster, K.I. (1994). Masked orthographic priming: The effect of prime-target legibility. *Quarterly Journal of Experimental Psychology*, 47A, 673–698.
- Evett, L.J., & Humphreys, G.W. (1981). The use of abstract graphemic information in lexical access. *Quarterly Journal of Experimental Psychology*, 33A, 325–350.
- Ferrand, L., & Grainger, J. (1992). Phonology and orthography in visual word recognition: Evidence from masked nonword priming. *Quarterly Journal of Experimental Psychology*, 42A, 353–372.
- Ferrand, L., & Grainger, J. (1994). Effects of orthography are independent of phonology in masked form priming. *Quarterly Journal of Experimental Psychology*, 47A, 365–382.
- Forster, K.I. (1993). Form-priming and temporal integration in word recognition. In G.T.M. Altmann & R. Shillcock (Eds.), *Cognitive models of speech processing: The second Sperlonga meeting*. Hillsdale, NJ: Lawrence Erlbaum Associates Inc.
- Forster, K.I., & Davis, C. (1991). The density constraint on form-priming in the naming task: Interference effects from a masked prime. *Journal of Memory and Language*, 30, 1–25.
- Fukushima, K. (1992). Character recognition with neural networks. *Neurocomputing*, 4, 221–223.
- Grainger, J., & Ferrand, L. (1996). Masked orthographic and phonological priming in visual word recognition and naming: Cross-task comparisons. *Journal of Memory and Language*, 35, 623–647.
- Grainger, J., & Jacobs, A.M. (1996). Orthographic processing in visual word recognition: A multiple read-out model. *Psychological Review*, 103, 518–565.
- Hummel, J.E., & Biederman, I. (1992). Dynamic binding in a neural network for shape recognition. *Psychological Review*, 99, 480–517.
- Jacobs, A.M., & Grainger, J. (1991). Automatic letter priming in an alphabetic decision task. *Perception and Psychophysics*, 49, 43–52.
- Jacobs, A.M., Grainger, J., & Ferrand, L. (1995). The incremental priming technique: A method for determining within-condition priming effects. *Perception and Psychophysics*, 57, 1101–1110.
- Lupker, S.J. (1979). On the nature of perceptual information during letter perception. *Perception and Psychophysics*, 25, 303–312.
- Peressotti, F., & Grainger, J. (1995). Letter-position coding in random consonant arrays. *Perception and Psychophysics*, 57, 875–890.
- Peressotti, F., & Grainger, J. (1999). The role of letter identity and letter position in orthographic priming. *Perception and Psychophysics*, 61, 691–706.
- Perfetti, C.A., & Bell, L. (1991). Phonemic activation during the first 40 ms of word identification: Evidence from backward masking and priming. *Journal of Memory and Language*, 30, 473–485.
- Sanocki, T. (1991). Effects of early common features on form recognition. *Perception and Psychophysics*, 50, 490–497.
- Sanocki, T. (1993). Time-course of object recognition: Evidence for a global-to-local contingency. *Journal of Experimental Psychology: Human Perception and Performance*, 19, 878–898.
- Sanocki, T. (1997). Structural contingencies and object-based shifts of attention during object recognition. *Journal of Experimental Psychology: Human Perception and Performance*, 23, 780–807.
- Ziegler, J.C., Ferrand, L., Jacobs, A.M., Rey, A., & Grainger, J. (2000). Visual and phonological codes in letter and word recognition: Evidence from incremental priming. *Quarterly Journal of Experimental Psychology*, 53A, 671–692.