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Semantic Priming From Crowded Words

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Abstract

Vision in a cluttered scene is extremely inefficient. This damaging effect of clutter, known as *crowding*, affects many aspects of visual processing (e.g., reading speed). We examined observers' processing of crowded targets in a lexical decision task, using single-character Chinese words that are compact but carry semantic meaning. Despite being unrecognizable and indistinguishable from matched nonwords, crowded prime words still generated robust semantic-priming effects on lexical decisions for test words presented in isolation. Indeed, the semantic-priming effect of crowded primes was similar to that of uncrowded primes. These findings show that the meanings of words survive crowding even when the identities of the words do not, suggesting that crowding does not prevent semantic activation, a process that may have evolved in the context of a cluttered visual environment.

Keywords

visual perception, consciousness, subliminal perception, reading, lexical decision

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In the visual world, objects do not appear in isolation. Typically, a flower is surrounded by leaves, a cup is surrounded by other dishes, and a word is surrounded by other words. The items surrounding a visual target pose a significant challenge to the ability to see, attend to, and act upon that target, especially if it is in the peripheral visual field. This *crowding* effect influences various aspects of visual processing (Andriessen & Bouma, 1976; Bouma, 1973; Westheimer, Shimamura, & McKee, 1976). Researchers have found, for example, that in the reading of normally spaced text, crowding limits the size of the visual span and constrains reading speed (Legge, Mansfield, & Chung, 2001; Pelli et al., 2007). Outside the fovea, the spatial range over which targets and flankers interact is surprisingly large—typically equal to about one third to one half of retinal eccentricity (Bouma, 1970; Huckauf, Knops, Nuerk, & Willmes, 2008; Toet & Levi, 1992; Tripathy & Cavanagh, 2002).

Some properties of unidentifiable crowded targets are still processed. For example, studies have demonstrated a robust orientation-specific adaptation effect even without observers' conscious access to a crowded grating's orientation (Bi, Cai, Zhou, & Fang, 2009; He, Cavanagh, & Intriligator, 1996). Motion direction (Aghdaee, 2005; Rajimehr, Vaziri-Pashkam, Afraz, & Esteky, 2004), image statistics (Parkes, Lund, Angelucci, Solomon, & Morgan, 2001), and configuration (Livne & Sagi, 2007; Louie, Bressler, & Whitney, 2007) are further examples of properties whose processing survives crowding.

The central questions in research on crowding have been how and where in the brain crowding occurs. Past studies have shown that crowding effects occur when a target and flankers are presented dichoptically, a pattern of results indicating a cortical locus (Flom, Heath, & Takahashi, 1963; Tripathy & Levi, 1994). The findings that adaptation effects for crowded targets are orientation-specific (He et al., 1996) and that crowding is reduced when the target and flankers are presented in locations that are spatially adjacent but cortically remote (Liu, Jiang, Sun, & He, 2009) indicate that the locus of crowding must lie beyond early retinotopic areas (see also Greenwood, Bex, & Dakin, 2010). The observation that the crowding effect is significantly diminished when physically present flankers are rendered invisible (Chakravarthi & Cavanagh, 2009; Wallis & Bex, 2011) also suggests a high-level mechanism for crowding.

A dominant model of crowding posits that crowding results from the integration of features from the target and its neighbors at a stage beyond feature detection (Pelli, Palomares, & Majaj, 2004). Although the target and its neighbors have distinct features, the large integration area makes these stimuli

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indistinguishable from each other. The integration region may be either preattentive (Pelli et al., 2004) or the area of attentional selection itself (He et al., 1996). Other models attribute crowding to the loss of positional information as a result of noisy inputs (Popple & Levi, 2005) or to a combination of observers' uncertainty about the position of the target and the mixing of features from adjacent stimuli (Nandy & Tjan, 2007).

Given that crowding impairs target recognition and that word recognition presumably precedes semantic processing, a natural prediction is that crowded words should have no semantic-priming effect. In fact, as yet, no studies have demonstrated semantic-priming effects for crowded words; this lack of effects is consistent with the absence of semantic extraction from parafoveal words in the reading of English (Rayner, Balota, & Pollatsek, 1986). However, the recent finding of a semantic preview benefit from parafoveal words (i.e., increased reading speed due to semantic extraction from parafoveal lexical primes) in reading Chinese (Yan, Richter, Shu, & Kliegl, 2009) is consistent with an earlier report that prime words that are masked or suppressed from awareness nevertheless influence lexical decisions (Marcel, 1983). Together, these results have established that semantic networks can be activated by primes that are not consciously identified. Unlike masking, crowding is a natural corollary of an observer's lifelong experience with the visual environment; therefore, it is plausible that people have special adaptations for the semantic processing of crowded targets. Indeed, in this article, we show that the semantic-priming effects of Chinese characters are undiminished by severe crowding.

Experiment 1

In our first experiment, we examined the effects of crowding on semantic priming using a primed lexical decision task (LDT). We used single-character Chinese words as stimuli because they are compact enough to be placed in typical crowding arrays with adjacent flankers and yet may still convey specific meanings. Stimuli were presented in the upper visual field, either in isolation (*isolated* condition) or at the center of a crowding array (*crowded* condition; Fig. 1). Following the presentation of a prime, a target was presented at the same location, and participants reported whether the target was a word or a nonword. We expected that if crowding does not prevent semantic activation, reaction times (RTs) would be shorter for primes that were semantically related to targets than for primes that were semantically unrelated to targets, even if the primes were crowded and unrecognized. RTs from the isolated condition provided a baseline index of the effect of semantic priming on lexical decisions. To ensure that primes were unrecognizable in the crowded condition, we followed the primed LDT with an identification task in which participants had to identify the prime words (presented in isolation or crowded by flankers).

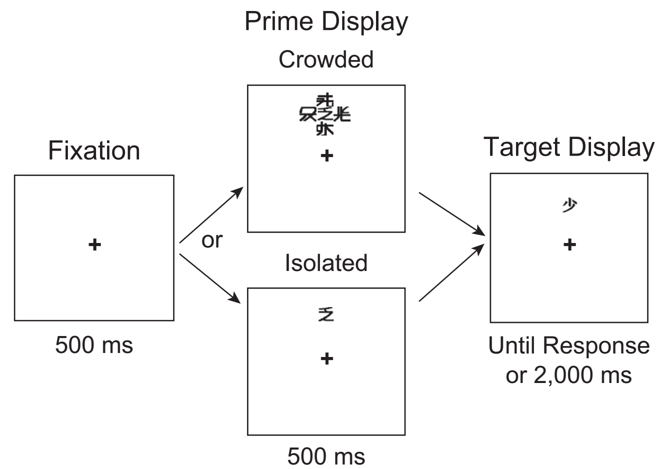

Fig. 1. Examples of stimuli and the time course of trials in the primed lexical decision task. A fixation cross (0.9° × 0.9°) was shown in each display. Participants were first shown a display containing only the fixation cross. In the subsequent prime display, a one-character Chinese word was presented either alone (*isolated* condition) or with four surrounding flankers (*crowded* condition). The flankers were nonwords consisting of five to six strokes similar to those used to write Chinese characters. The center-to-center distance between the prime and the flankers was 2°, and the center-to-center distance between the prime and the fixation cross was 5°. In the subsequent target display, either a one-character Chinese word or a nonword was shown (the word and nonword that could follow a given prime were matched in their number of strokes on a trial-by-trial basis). The prime, flankers, and target were roughly the same size (2° × 2°). All stimuli were white on a black background.

Method

Participants. Sixteen undergraduates at National Taiwan University participated in this experiment. All participants were native Chinese speakers and had normal or corrected-to-normal vision.

Apparatus and stimuli. Stimuli were displayed on a 21-in. CRT monitor with a spatial resolution of 1,024 × 768 pixels and a refresh rate of 60 Hz. Each participant sat in a quiet and dimly lit room with his or her head positioned on a chin rest located 57 cm in front of the CRT monitor. Gaze position of the participant's right eye was monitored using an EyeLink 2000 eye tracker (SR Research, Mississauga, Ontario, Canada) with a sampling rate of 1000 Hz. The experiment was programmed with Experiment Builder software (SR Research). The experimenter sat beside the participant and recorded his or her manual responses using a standard keyboard.

In a pretest, another group of 32 participants rated the semantic relatedness of 72 prime-target pairs we selected from Chou, Chen, Wu, and Booth's (2009) stimuli, using 9-point scales (from 1, *completely unrelated*, to 9, *highly related*). On the basis of these ratings, we selected 24 *semantically related* pairs (pairs with relatedness scores higher than 7.5) and 24 *semantically unrelated* pairs (pairs with relatedness scores lower than 4.5). There were no differences in average lexical frequency or number of strokes between semantically related and semantically unrelated primes or between semantically related and semantically unrelated targets (*t*s < 1). None of the prime-target pairs formed a two-character word or shared a common semantic radical.

Design. Experiment 1 consisted of two tasks: a primed LDT followed by a prime-identification task. For the primed LDT, we used a 2 (crowding: isolated, crowded) × 2 (priming: semantically related, semantically unrelated) factorial design. There were 48 trials for each trial type—24 trials on which the target was a word and 24 trials on which it was a nonword—for a total of 192 trials. For the identification task, we used a one-factor (crowding: isolated, crowded) within-subjects design. The identification task consisted of 96 trials (48 trials in the isolated condition and 48 trials in the crowded condition).

Procedure. Throughout the experiment, if the eye tracker detected that a participant's gaze was directed above a horizontal (invisible) boundary 1.5° above the fixation cross, a warning display was presented, asking the participant to return his or her gaze to the fixation cross. If this happened during a trial, the data for that trial were excluded from analysis, and the trial was rerun later. The warning display remained on screen until the participant's gaze returned to the fixation cross and he or she pressed the space bar to continue the experiment.

Participants completed a practice session before each task, so that they would be familiarized with the tasks. Each practice session was preceded by a gaze-calibration procedure. In the practice sessions, participants completed multiple repetitions of 10 trials (with stimuli different from those used in the formal experiment) until they could maintain fixation in at least 6 trials.

Before the first practice session, participants received instructions for the primed LDT. They were told that their task was to indicate whether each target was a word or a nonword as quickly and as accurately as possible by pressing one of two keys on a computer keyboard. The response keys for words and nonwords were counterbalanced across participants. Participants were also informed that the prime word would be presented in isolation on some trials and with flankers on others, and that they should attend to the location of the prime, where the target would subsequently appear. On each trial of the LDT, a central fixation cross was presented for 500 ms, followed by the presentation of the prime display for another 500 ms. The target display was then presented until the participant responded or 2,000 ms elapsed (Fig. 1). The intertrial interval was 250 ms. After participants completed the practice session, the experimental trials of the LDT were presented.

The second practice session took place after participants completed the primed LDT. They were told that their next task was to identify words that would be presented either in isolation or with flankers. Words were identified by oral report; because homophones are prevalent in Chinese, participants were encouraged to both name the prime words and create phrases with the prime words in them. The experimenter verified each response on-line. The time course of trials in the identification task was the same as that of trials in the primed LDT except that the target display was replaced by a random-dot mask display, which remained on screen until the participant pressed the space bar to start the next trial. After participants completed the practice session, the experimental trials of the identification task were presented.

Results and discussion

Results for the identification task indicated that the prime words were almost always identified correctly when they were presented without flankers (M = 92%, SEM = 4%), but prime words in the crowded condition were identified correctly much less frequently (M = 12%, SEM = 1%). Despite this severe crowding effect, performance on the primed LDT showed robust semantic priming that was as strong in the crowded condition as in the uncrowded condition (Fig. 2a), as indicated by the following analyses. RTs shorter than 300 ms or longer than 1,500 ms (2.9% of trials) were treated as outliers and excluded from analysis; RTs for incorrect responses (5.8% of trials) were also excluded from analysis. Analyses of variance (ANOVAs) on the RTs, with subjects (F_1) and items (F_2) treated as random variables, revealed a main effect of crowding, $F_1(1, 15) = 13.838$, $p < .01$, $\eta_p^2 = .480$; $F_2(1, 46) = 7.695$, $p < .01$, $\eta_p^2 = .143$, and a main effect of priming, $F_1(1, 15) = 86.214$, $p < .001$, $\eta_p^2 = .852$; $F_2(1, 46) = 22.671$, $p < .0001$, $\eta_p^2 = .330$. There was no interaction between crowding and priming, $F_1(1, 15) = 1.61$, $p = .225$, $\eta_p^2 = .097$; $F_2(1, 46) = 3.125$, $p = .083$, $\eta_p^2 = .064$; thus, the semantic-priming effects of crowded and uncrowded primes did not differ.

In the crowded condition, participants were largely unable to identify the primes, but a few primes were nevertheless correctly identified. Could this small number of identified primes have been responsible for the observed semantic-priming effect? Although this was unlikely, given the small proportion of primes that were identified, we reanalyzed the primed-LDT results using a stringent criterion to exclude, for each participant individually, any primes that had been identified in the crowded condition. Specifically, for each participant, the data for a given prime were included only if the participant had correctly identified the prime when it was presented in isolation but had not correctly identified the prime when it was presented with flankers (19.4% of trials removed). Analysis of the individually screened data (Fig. 2b) revealed semantic-priming effects that were just as strong as those revealed by our analysis of the unscreened data. ANOVAs revealed main effects of crowding, $F_1(1, 15) = 10.505$, $p < .01$, $\eta_p^2 = .412$; $F_2(1, 46) = 5.770$, $p < .05$, $\eta_p^2 = .111$, and priming, $F_1(1, 15) = 47.510$, $p < .001$, $\eta_p^2 = .760$; $F_2(1, 46) = 17.890$, $p = .0001$, $\eta_p^2 = .280$. However, there was no interaction between crowding and priming, $F_1(1, 15) = 0.764$, $p = .396$, $\eta_p^2 = .048$; $F_2(1, 46) = 0.319$, $p = .575$, $\eta_p^2 = .007$.

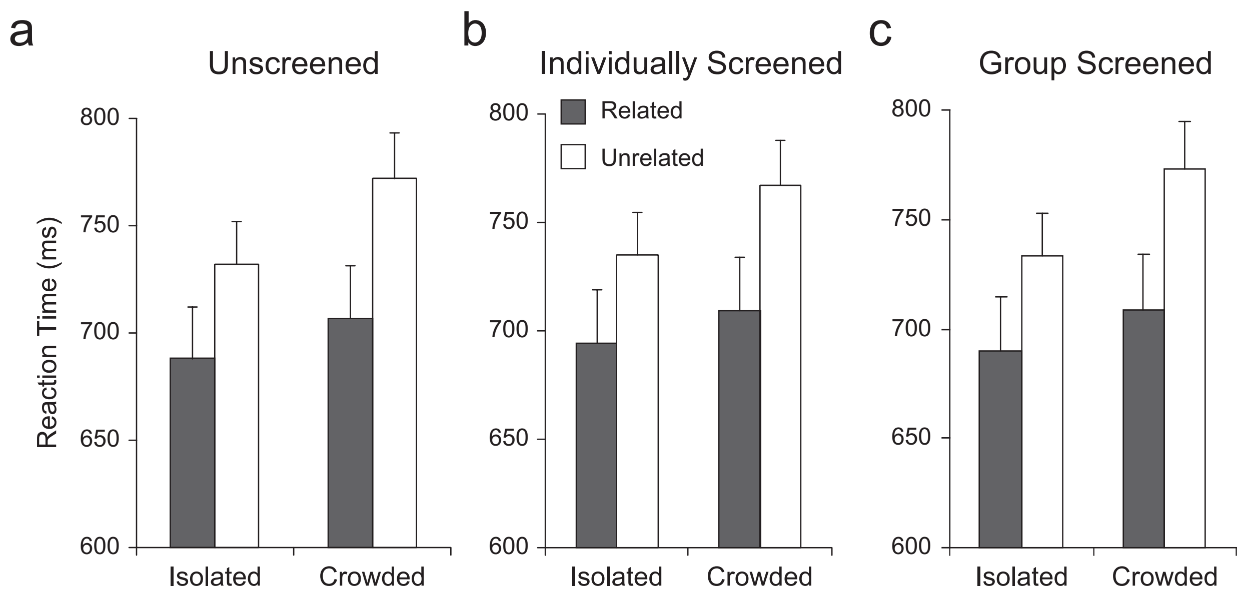

Fig. 2. Results of the primed lexical decision task in Experiment 1. The three graphs show mean reaction times as a function of crowding (isolated vs. crowded) and priming (semantically related vs. semantically unrelated). Means were calculated using (a) unscreened data, (b) individually screened data, and (c) group-screened data (see the text for an explanation of the screening procedures). Error bars represent standard errors of the mean.

Because our individual-level screening procedure unavoidably excluded different trials for different participants, we also conducted a group-screened analysis in which the same trials were included for all participants. For each prime, we calculated the proportion of participants who correctly identified the prime in isolation but failed to identify it when it was crowded; we included data only for trials with primes for which more than half the participants met this criterion (three semantically related prime-target pairs, 6.25% of trials, were removed). The semantic-priming effects revealed by this analysis were just as strong as those revealed by our analyses of individually screened and unscreened data (Fig. 2c). Again, there were main effects of crowding, $F_1(1, 15) = 13.486$, $p < .005$, $\eta_p^2 = .473$; $F_2(1, 43) = 6.685$, $p < .05$, $\eta_p^2 = .135$, and priming, $F_1(1, 15) = 78.725$, $p < .0001$, $\eta_p^2 = .840$; $F_2(1, 43) = 19.060$, $p < .0001$, $\eta_p^2 = .307$. There was no interaction between crowding and priming, $F_1(1, 15) = 1.256$, $p = .281$, $\eta_p^2 = .077$; $F_2(1, 43) = 2.904$, $p = .096$, $\eta_p^2 = .063$.

We also examined accuracy on the primed LDT (Table 1). ANOVAs on the unscreened accuracy data revealed that only priming had a significant main effect, $F_1(1, 15) = 9.243$, $p < .01$, $\eta_p^2 = .385$; $F_2(1, 46) = 4.967$, $p < .05$, $\eta_p^2 = .097$. ANOVAs on the group-screened accuracy data likewise revealed that only priming had a significant main effect, $F_1(1, 15) = 7.511$, $p < .05$, $\eta_p^2 = .340$; $F_2(1, 43) = 3.513$, $p < .0001$, $\eta_p^2 = .077$. For the individually screened data, there were no significant main effects of priming or crowding, and no significant interaction, ps > .05. In all cases, the lack of interaction between crowding and priming indicated that the effect of priming on accuracy, when present, did not differ between crowded and uncrowded primes. Critically, none of our analyses revealed a trade-off between speed and accuracy.

In summary, we found significant effects of semantic priming in the LDT regardless of whether or not a given prime was crowded. The priming effect of crowded primes remained significant and essentially unchanged when we screened the data, either on a subject-by-subject basis or on a group basis, so that analyses included data only for primes that were recognized when presented alone and not recognized when crowded.

Experiment 2

We used the identification task in Experiment 1 to test whether the crowded primes in the LDT were recognizable. However, semantic activation is thought to require only partial awareness of the prime (Kouider & Dupoux, 2004), and the identification test may have been too demanding to reveal such a marginal conscious representation. Therefore, in Experiment 2, we repeated the primed-LDT experiment but replaced the identification task with a classification task (word vs. nonword) in order to assess whether participants could classify the crowded primes even if they could not explicitly identify them. If participants could classify certain primes as words despite crowding, this would indicate that participants had some minimal level of awareness of the lexical properties of those primes. We could then exclude from analysis the data for all LDT trials on which these primes appeared. The procedure for the classification task was the same as that for the

Table 1. Mean Accuracy (Percentage Correct) in the Primed Lexical Decision Task in Experiments 1 and 2

	Raw (unscreened) data		Individually screened data		Group-screened data	
Experiment and condition	Isolated condition	Crowded condition	Isolated condition	Crowded condition	Isolated condition	Crowded condition
Experiment 1						
Semantically related	97 (1)	95 (1)	97 (1)	95 (1)	96 (1)	95 (1)
Semantically unrelated	91 (2)	93 (2)	94 (2)	94 (1)	91 (2)	93 (2)
Experiment 2						
Semantically related	86 (2)	85 (3)	87 (3)	85 (3)	88 (2)	88 (2)
Semantically unrelated	78 (3)	80 (4)	80 (3)	80 (5)	79 (3)	82 (4)

Note: Means in the "individually screened" columns were calculated using only data for primes that a given participant had correctly identified in the isolated condition but had incorrectly identified in the crowded condition. Means in the "group-screened" columns were calculated using only data for primes that more than half of the participants had correctly identified in the isolated condition but had incorrectly identified in the crowded condition. Standard errors are shown in parentheses.

identification task in Experiment 1, except that participants had to report whether each target (in isolation or crowded) was a word or not.

Method

Participants. Another group of 18 undergraduates at National Taiwan University participated in this experiment. All participants were native Chinese speakers and had normal or corrected-to-normal vision.

Procedure. The primed LDT task in Experiment 2 was identical to that of Experiment 1; however, rather than being followed by a prime-identification task, it was followed by a classification task in which participants judged whether primes were words or nonwords. Half of the primes were words (the same words used as primes in the primed LDT task in Experiment 1), and the other half were nonwords. The response keys for words and nonwords were counterbalanced across participants; the assignment of the two keys in the classification task always matched that in the preceding primed LDT. The random-dot mask was a square (6° × 6°) covering a slightly larger area than the total areas of the prime and flankers. Within each task, trials were presented in a random order.

Results and discussion

Participants' accuracy in the classification task was high when the primes were presented in isolation (M = 86%, SEM = 3%;[1] d' = 2.51); however, participants were essentially unable to perform this task when the primes were crowded (M = 55%, SEM = 5%, d' = 0.39).

We again excluded data for primed-LDT trials on which RTs were shorter than 300 ms or longer than 1,500 ms (2.4% of trials) and for trials on which the participant's response was incorrect (16.7% of trials). When we did not screen the data on the basis of classification-task responses, our analysis revealed a clear semantic-priming effect in both the isolated and the crowded conditions (Fig. 3a). A 2 (crowding: isolated, crowded) × 2 (priming: semantically related, semantically unrelated) ANOVA on the RTs revealed a significant main effect of priming, $F_1(1, 17) = 14.172$, $p < .01$, $\eta_p^2 = .455$; $F_2(1, 46) = 6.358$, $p < .05$, $\eta_p^2 = .121$, but no significant main effect of crowding, $F_1(1, 17) = 0.945$, $p = .345$, $\eta_p^2 = .053$; $F_2(1, 46) = 2.391$, $p = .139$, $\eta_p^2 = .049$. Critically, there was again no interaction between crowding and priming, $F_1(1, 17) = 0.116$, $p = .738$, $\eta_p^2 = .007$; $F_2(1, 46) = 0.001$, $p = 1.000$, $\eta_p^2 < .001$.

We next examined the results of the classification task to determine which primes had been so severely crowded that participants could not consciously access their lexical category (word vs. nonword). We again screened the RT data from the primed LDT on an individual basis, excluding primes for which responses had been incorrect in the isolated condition or correct in the crowded condition (39.5% of trials). Analysis of the remaining RTs (Fig. 3b) revealed a significant main effect of priming, $F_1(1, 17) = 11.932$, $p < .01$, $\eta_p^2 = .412$; $F_2(1, 46) = 4.806$, $p < .05$, $\eta_p^2 = .095$, but no main effect of crowding, $F_1(1, 17) = 0.073$, $p = .79$, $\eta_p^2 = .004$; $F_2(1, 46) = 0.012$, $p = .914$, $\eta_p^2 < .001$. There was no interaction between crowding and priming, $F_1(1, 17) = 1.419$, $p = .251$, $\eta_p^2 = .077$; $F_2(1, 46) = 0.079$, $p = .780$, $\eta_p^2 = .002$.

We also performed the group-level screening used in Experiment 1 (eight related and four unrelated prime-target pairs, 25% of trials, were removed) and submitted the remaining RT data (Fig. 3c) to analysis. This analysis revealed that the main effect of priming was significant, $F_1(1, 17) = 16.177$, $p < .001$, $\eta_p^2 = .488$; $F_2(1, 34) = 10.780$, $p < .01$, $\eta_p^2 = .241$, but there was no significant main effect of crowding, $F_1(1, 17) = 0.622$, $p = .441$, $\eta_p^2 = .035$; $F_2(1, 34) = 1.364$, $p = .251$, $\eta_p^2 = .039$. There was also no interaction between crowding and priming, $F_1(1, 17) = 0.056$, $p = .816$, $\eta_p^2 = .003$; $F_2(1, 34) = 0.004$, $p = .95$, $\eta_p^2 < .001$. Again, the analysis of group-screened data

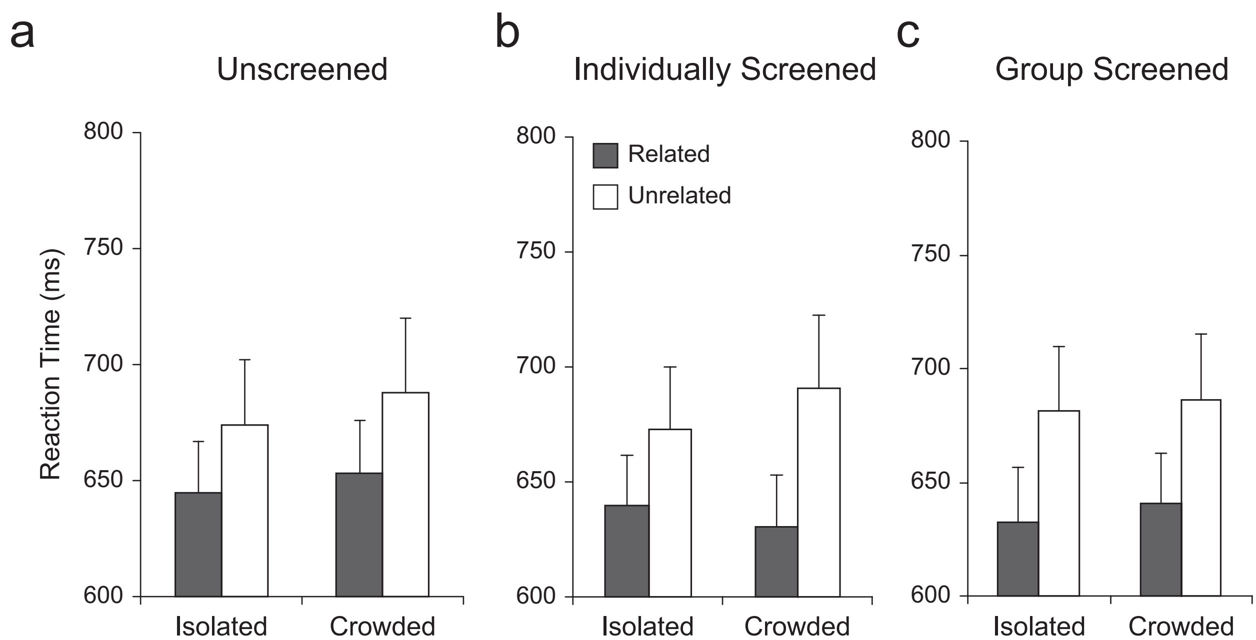

Fig. 3. Results of the primed lexical decision task in Experiment 2. The three graphs show mean reaction times as a function of crowding (isolated vs. crowded) and priming (semantically related vs. semantically unrelated). Means were calculated using (a) unscreened data, (b) individually screened data, and (c) group-screened data (see the text for an explanation of the screening procedures). Error bars represent standard errors of the mean.

revealed a semantic-priming effect just as strong as that revealed by our analyses of individually screened and unscreened data.

We also examined accuracy on the LDT (Table 1). ANOVAs with subjects entered as a random variable revealed that the main effect of priming was significant for unscreened accuracy data, $F_1(1, 17) = 13.138$, $p < .01$, $\eta_p^2 = .436$, and group-screened accuracy data, $F_1(1, 17) = 8.119$, $p < .05$, $\eta_p^2 = .322$. No other effects were significant, *p*s > .05. ANOVAs on the three sets of data with items entered as a random variable revealed no significant main effects of priming or crowding, and no significant interaction, *p*s > .05. The lack of an interaction between crowding and priming indicates that the observed effects of priming on accuracy did not differ between crowded and uncrowded primes. As is typically done in interpreting LDT results, we based our conclusions on the analyses of RTs, and accuracy data were analyzed to ensure that there was no trade-off between speed and accuracy. Given that there were no significant effects of crowding on accuracy and that the effects of priming on accuracy were either absent or in the same direction as those on RTs, there was no evidence for a speed-accuracy trade-off.

The fact that there was a significant effect of priming on RTs, but no interactive effect of priming and crowding, shows that semantic information for crowded primes was activated even when these primes were so severely crowded that participants could not tell whether they were words in the classification task. The same pattern of results held when we used individual-level and group-level screening to exclude data for crowded primes that were classified correctly. This replication of the semantic-priming effect observed in Experiment 1 indicates its robustness.

General Discussion

Understanding the mechanism of crowding is important, given that crowding is a ubiquitous factor impairing object recognition (Levi, 2008). A central question in research on crowding concerns the nature of processing for crowded targets, because uncovering when and how such processing occurs will reveal where in the brain and how the crowding limit is imposed (He et al., 1996; Liu et al., 2009; Pelli, 2008). Taking advantage of the compactness of single-character Chinese words, we demonstrated that crowded words produce a semantic-priming effect equal to that of uncrowded words.

This finding poses serious challenges to present models of crowding. If crowding were due to incorrect feature integration (Pelli et al., 2004), compulsory averaging (Parkes et al., 2001), position uncertainty (Popple & Levi, 2005), or feature mixing (Nandy & Tjan, 2007), and if identification and semantic activation rely on the same information, no semantic-priming effects should have been observed. Our finding that semantic priming was unaffected by crowding indicates that it is possible for spatially noisy input that cannot support identification to give rise to semantic activation. This would imply that semantic processing and identification involve different neural circuits at stages beyond early visual processing.

In the absence of clear identification of crowded stimuli, it may well be that attention is crucial for semantic activation.

Our participants were required to pay attention to the prime and the target, which may have been critical: In a pilot study, we found no semantic-priming effect when the attentional requirement was not enforced or when the processing time was insufficient for attentional deployment (e.g., 150 ms). This pattern of results suggests that the integration field that underlies crowding—that is, the region within which features are pooled, mixed, or confused—is not set preattentively (Pelli et al., 2004) but is rather the area of attentional selection itself (He et al., 1996). Note that an account of a high-level mechanism for the crowding effect does not presuppose sequential processing whereby identification is followed by semantic extraction; the two processes may rely, as we have suggested, on different neural circuits.

A recent study by Huckauf et al. (2008) showed that crowded stimuli can give rise to semantic activation, but the researchers found semantic activation only for stimuli that were consciously identified. To our knowledge, our study is the first to demonstrate robust semantic activation for word primes that are so severely crowded that they cannot be consciously identified. Most earlier studies showing semantic priming by unreportable primes used backward masking to block conscious access to the primes (Cheesman & Merikle, 1984; Marcel, 1983; Ortells, Vellido, Daza, & Noguera, 2006); our work extends this result to crowding. Earlier studies of crowded priming did not test semantic information but did show preserved information about identity and emotion (Faivre & Kouider, 2011a, 2011b; Kouider, Berthet, & Faivre, 2011). These studies did not compare priming strength of crowded and uncrowded primes.

The semantic-priming effects observed in our experiments are consistent with the preconscious preview benefits from parafoveal words discovered in research on reading (Yan et al., 2009) and with an account of a word-shape-based reading process that survives crowding (Pelli & Tillman, 2007). Our results indicate that crowding does not prevent the activation of semantic information, which may be processed by a semantic network such as the left inferior frontal gyrus and posterior middle temporal gyrus (Booth et al., 2002; Chou et al., 2009). Indeed, our data show that there is no significant difference in the semantic-priming effects of isolated and crowded words. In addition, the magnitude of the priming effects in the crowded condition did not correlate with participants' accuracy in identifying primes ($r = -.263$, $p = .324$) or classifying them ($r = .034$, $p = .894$), a pattern of results suggesting similar levels of processing for the semantics of the primes, regardless of observers' degree of awareness of those primes under conditions of crowding. Priming of lexical decisions has been found to be more effective for suprathreshold primes than for masked primes (Carr & Dagenbach, 1990), yet in our experiments with crowded primes, we found no difference in priming strengths between identifiable and unidentifiable (even unclassifiable) primes. This suggests that a lifetime of experience in a cluttered visual environment leads to special adaptations that allow semantic activation for parafoveal targets that are unidentifiable.

Although we made every effort to ensure that the crowded primes in our experiments were unrecognizable and unclassifiable, the identification and classification tasks were conducted after the primed LDT. This allowed for random variation between performance on primed-LDT trials and performance on the subsequent identification and classification trials: A prime that was unrecognized in the LDT might have been recognized in the identification or classification tasks, and vice versa. It would be ideal to use an on-line measure to assess the status of the prime on each trial. There are, nevertheless, drawbacks to using such a dual-response paradigm, because the increase in task demands would dilute participants' attention to the target characters. Overall, our results indicated that semantic priming was robust, regardless of how data were screened, and was not correlated, on an item-by-item basis, with performance on the identification or classification task: Priming was as strong for consciously identifiable or classifiable primes as it was for unidentifiable or unclassifiable primes.

We therefore conclude that semantic priming is possible under conditions of crowding. Whether a similar priming effect could be demonstrated with other scripts is an interesting and important question, but the answer to that question does not affect our primary conclusion. Further studies may reveal special semantic properties of Chinese characters, as suggested by the fact that a semantic parafoveal preview benefit, which is typically not found for English words (e.g., Rayner et al., 1986), has been reported for Chinese characters (Yan et al., 2009). Whatever the case, the especially compact nature of Chinese characters does allow us to suggest that the priming effects observed in our experiments were not due to partial processing of words (e.g., the processing of strokes). Kouider and Dupoux (2004) have shown that partial processing of words (e.g., processing of individual letters) can be sufficient for priming despite being insufficient for conscious recognition of the words. In Chinese, small differences in strokes that fall below the threshold of feature detection and attentional resolution can signify very different meanings (e.g., 已 means "already," whereas 己 means "self"); it is therefore unlikely that the strong semantic priming from crowded primes in our experiments can be attributed to participants' recognition of individual strokes and subsequent reconstruction of these partial words into words.

With carefully controlled crowding and careful screening of data to ensure the effectiveness of the crowding, we have shown that semantic activation does occur for severely crowded words. Our findings suggest that semantic activation relies on a different encoding of stimulus information than identification does. They also demonstrate that subliminal semantic priming is real and not, as Kouider and Dupoux (2004) have suggested, an illusion.

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Declaration of Conflicting Interests

The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

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Note

1. The less-than-perfect performance in the isolated condition is a result of the eccentricity at which it was necessary to present the stimuli in the crowded condition of the main experiment and not of the legibility of the stimuli we used. In a control experiment ($N = 6$), participants' mean level of accuracy on the same classification task was 99.13% when the same set of stimuli were presented one at a time at fixation.

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