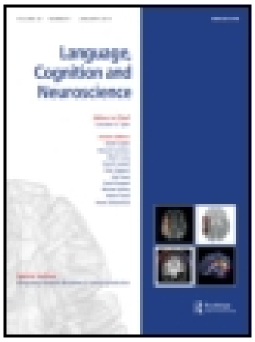

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Jifan Zhou, Chia-Lin Lee & Su-Ling Yeh

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Word meanings survive visual crowding: evidence from ERPs

Jifan Zhou[a,b], Chia-Lin Lee[a,c,d,e] and Su-Ling Yeh[a,c,d]

[a]Department of Psychology, National Taiwan University, Taipei, Taiwan; [b]Department of Psychology and Behavioral Sciences, Zhejiang University, Hangzhou, People's Republic of China; [c]Graduate Institute of Brain and Mind Sciences, National Taiwan University, Taipei, Taiwan; [d]Neurobiology and Cognitive Science Center, National Taiwan University, Taipei, Taiwan; [e]Graduate Institute of Linguistics, National Taiwan University, Taipei, Taiwan

ABSTRACT
Conscious identification of an object in the periphery is drastically impaired when it is surrounded by flankers as opposed to when presented in isolation; this is known as visual crowding. However, one previous behavioural study has shown that semantic priming can actually occur from a crowded stimulus [Yeh, He, & Cavanagh, 2012. Semantic priming from crowded words. *Psychological Science*, *23*(6), 608–616. doi:10.1177/0956797611434746]. Based on this finding, the current study used event-related potentials (ERPs; N400 component) to verify that the response facilitation seen in Yeh et al. [2012. Semantic priming from crowded words. *Psychological Science*, 23(6), 608–616. doi:10.1177/0956797611434746] indeed occurs at the semantic level. We confirmed that the crowded words do produce semantic-level priming. That is, crowded words led to N400 reduction on subsequent targets: the semantically related target elicited a smaller N400 component than did the unrelated targets. And both crowded and isolated primes elicited the same amount of N400 reduction, consistent with the previous behavioural result. Several models on crowding and word processing are discussed and an alternative word processing theory is proposed to explain our results.

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Visual perception; consciousness; word processing; lexical decision; visual crowding

1. Introduction

When an object in peripheral visual field is closely surrounded by other distractors also known as flankers, its perception will be drastically impaired. This phenomenon is referred to as visual crowding, and has been studied extensively before (Bouma, 1970; Flom, Weymouth, & Kahneman, 1963; Stuart & Burian, 1962. For a review on the history of crowding, see Strasburger, Harvey, & Rentschler, 1991; Strasburger & Wade, 2015). Considered as a bottleneck for object perception (Levi, 2008; Pelli, 2008), visual crowding has been shown to impact various visual tasks including face recognition (Farzin, Rivera, & Whitney, 2009), letter recognition (Pelli, Palomares, & Majaj, 2004), and numeral identification (Strasburger et al., 1991). However, despite impaired conscious identification, some properties of crowded objects are still processed; the ones discovered include 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). In addition, and very surprisingly, semantic information also survives crowding (Yeh, He, & Cavanagh, 2012).

The precise mechanisms behind visual crowding still remain unclear, but there appears to be an increasing consensus in the literature that adhere to spatial feature degradation or misintegration due to larger integration fields in the periphery (e.g. Levi, 2008; Pelli & Tillman, 2008) as the main cause behind visual crowding. Lately two models have been increasingly popular: the averaging/pooling model (Balas, Nakano, & Rosenholtz, 2009; Levi, Klein, & Hariharan, 2002; Parkes et al., 2001; Pelli et al., 2004; Pelli & Tillman, 2008) which attributes crowding to the incorrect integration or mixing of visual features as the distance between crowded object and flankers decreases; and the substitution model (Ester, Klee, & Awh, 2014; Nandy & Tjan, 2007; Strasburger, 2005) which proposes the occurrence of crowding as a result of both positional information loss of displayed items, and subjects' confusion between crowded objects and flankers. However, the distinction between these two models may not be so clear-cut, as there have been attempts to integrate these models into a unifying one (Strasburger & Malania, 2013; Strasburger, 2014). Nevertheless, though both models are capable of explaining many findings in the literature including the survival of several simple features (e.g. orientation; Bi et al., 2009; He et al., 1996), they cannot

CONTACT Su-Ling Yeh suling@ntu.edu.tw

easily account for the bypass of higher level information in crowding such as semantic information (Yeh et al. 2012), illusory contour (Lau & Cheung, 2012), and emotional cues (Kouider, Berthet, & Faivre, 2011). Generally, these bypasses cannot be easily explained by pooling or substituting mechanisms since the higher level messages are uniquely represented only by the crowded objects and not by any of the flankers; therefore the messages would be severely degraded in both the averaged version suggested by the first model and/or the flanker substituted version by the latter one. For instance, the emotional bias from the observers in Kouider et al.'s (2011) manipulations would not have manifested if the crowded object (an emotional face) was averaged or substituted with its flankers (noninformative patterns) because the unique emotional cue embedded within the crowded object would have been damaged or lost in the process. Since recent findings do not seem to reconcile with the models, we set out to explore these issues using disparate methods.

As a precursor leading to the current study, Yeh et al.'s (2012) study was the first to demonstrate a strong behavioural semantic priming under the effects of visual crowding. Their methods revolved around a 3-frame task (fixation frame, prime frame, and target frame) in which primes and targets in their respective frames were presented sequentially in that order, with a required lexicality decision (i.e. a decision about whether the target is a word or non-word) in the target frame. To summarise their results, an unrecognisable word within flankers was shown to facilitate the semantic processing of subsequent isolated word, as indexed by shorter reaction times to correct lexicality judgement. Specifically, crowded primes facilitated that judgement to the following targets when they were semantically related, but the same facilitation was not observed when they were unrelated. The magnitude of this priming effect was also equivalent to that elicited by isolated primes. From this it can be concluded that semantic information can be extracted from crowded words. However, it is still unclear at which processing stage this priming occurs: perceptual processing, semantic processing, decision-making, or even response execution. Facilitation at any or several of these stages could have led to the behavioural priming effect reported in that study.

To pinpoint the occurrence stage of the priming effect induced by crowded words, we adopted event-related brain potentials (ERPs) to explore the neural mechanisms underlying the priming effect in visual crowding. In particular, the current study focused on the N400 ERP component. N400 is a negative-going component with a broad, centrally maximal distribution that peaks at around 400 ms (Kutas & Hillyard, 1980). N400 has been shown to be elicited by a wide range of potentially meaningful stimuli including words, pictures, gestures, or even smells, and has been considered a reflection of more implicit aspects of the initial access to the long-term memory. The amplitude of N400 has been shown to be sensitive to a variety of item-level or context-level semantic factors, with observed reduction in the amplitude being interpreted as evidence for facilitated semantic processing (see Kutas & Federmeier, 2000; Kutas & Federmeier, 2011 for comprehensive reviews on N400). These characteristics make N400 a suitable index to investigate semantic priming. Typically, the N400 is reduced in amplitude for words in presence of preceding congruent semantic context. Hence, if word meaning could be extracted in visual crowding and remain active for a period of time to form a semantic context for the subsequent word, the N400 to the subsequent word should vary according to the semantic relatedness between the two words. More specifically, the N400 amplitudes to the target words should be reduced in the related condition but not in the unrelated condition. Hence, if the behavioural facilitation from crowded primes to isolated targets observed in Yeh et al. (2012) indeed occurred at the semantic level, then the N400 reduction should also be observed from the related condition regardless of whether primes were crowded.

In another ERP experiment using N400, Peng, Zhang, Chen, and Zhang (2013) found an N400-reduction priming effect in the situation where the crowding manipulation was applied to the target (crowded/isolated target), instead of to the prime (crowded/isolated prime) as in Yeh et al. (2012). However, as pointed out by Faivre, Berthet, and Kouider (2014), the discriminability of crowded targets was slightly above chance-level in Peng et al. (2013), which brings the unconscious origin of these effects into question. Even in the case when the crowded target words were truly unrecognisable, when isolated words appeared first, word meanings can be consciously processed and then encoded into working memory; thus the priming effect in Peng et al.'s (2013) study primarily reflects the influence from a well-processed word on a subsequent crowded word and does not imply semantic facilitation by crowded words per se. In the current study, as in Yeh et al. (2012), we manipulated the crowded/isolated condition to the prime. This test is stronger than Peng et al.'s (2013), since it requires not only extracting meaning from the unrecognisable word, but also producing semantic activation strong enough to survive the prime-target interval and exert influence on the following target. Therefore, it would be a much stronger evidence if the semantic priming effect is still observed from a crowded word as in our design. Specifically, if an N400 reduction would also be observed from a crowded word in our study, it would be a powerful support to Yeh et al.'s (2012) previous behavioural finding that unconscious semantic processing exists for the visually crowded words. Moreover, the nature of our design would yield more definite clues about the spatial distribution and the occurring stage of this unconscious processing.

2. Materials and methods

2.1. Participants

Twenty-one native speakers of Chinese in Taiwan participated in this study and received financial compensation for their participation. Participants were all right-handed with normal or corrected-to-normal vision and no history of neurological/psychiatric disorders or brain damage. The study was approved by the Research Ethics Committee at the National Taiwan University.

The sample size was determined by a power analysis based on predicted effect size, using G*Power 3 (Faul, Erdfelder, Buchner, & Lang, 2009; Faul, Erdfelder, Lang, & Buchner, 2007). Given an expected effect size of $f =$ 0.6 (according to our pilot N400 study with a small sample size) and with α set to .01, the analysis gave a suggested sample size of 21 subjects.

2.2. Apparatus and stimuli

All stimuli were presented with a black background on an "ASUS 22" LED monitor with a spatial resolution of 1920×1080 pixels at 60 Hz refresh rate (mean background luminance = .097 cd/m^2; mean stimulus luminance = 69.3 cd/m^2). Participants performed the task individually in a dimly lit room, seated about 50 cm from the computer screen.

The primes and targets were identical to those used in Yeh et al. (2012), which consisted of 24 semantically related prime-target pairs and 24 semantically unrelated pairs, yielding a total of 48 pairs. Separately, 48 non-words made from the same stroke features as words but without semantic meaning were created as targets. Thus there was a total of 96 possible targets. To provide context for non-Chinese readers, Figure 1(a) shows some examples of Chinese words with basic character configurations, while Figure 1(b) also offers cases of non-word targets. For fluent Chinese readers, distinguishing real words from the non-words we have used here is an easy task. Seven additional non-words were created as flankers, among which four flankers were chosen randomly to present in each crowded trial. Each word or non-word occupied $2° \times 2°$ in visual angle. The centre-to-centre distance of each flanker and the crowded stimulus was 2°. The experiment was written in MATLAB (The MathWorks, Natick, MA), using the Psychophysics Toolbox extensions (Brainard, 1997; Kleiner, Brainard, & Pelli, 2007; Pelli, 1997).

2.3. Design and procedure

A $2 \times 2 \times 2$ within-subject design with factors *crowding* (isolated/crowded), *semantics* (related/unrelated), and *target type* (word/non-word) was adopted, rendering eight conditions. Each condition comprised 48 trials, resulting in a total of 384 trials. All trials were presented in random order.

Figure 1(b) shows the procedure of this experiment, which was generally identical to that used in Yeh et al. (2012), except that an inter-stimulus interval (ISI) was inserted between the prime and target and the task was changed from a lexical-decision task (LDT) to a go–nogo LDT. Each trial began with presenting a 500 ms cross as a fixation point, and then a peripheral prime (a word or a non-word) in the upper visual field (5° above the fixation). In the isolated condition, primes were presented alone and could be easily identified. In the crowded condition, primes were at the centre of the crowded array, which rendered them difficult to identify. The prime was presented for 500 ms, followed by a variable blank-screen prime-target ISI that ranged from 100 to 300 ms to reduce brain potentials associated with anticipation of the upcoming stimuli. The target was then presented at the same location as the prime until the participant responded or 2000 ms elapsed. The target could be a word (in the word target condition) or a non-word (in the non-word target condition); the task, referred to as a LDT, was to judge the lexicality of the target. In the word target condition, the target was semantically related to the prime in half of the trials, and unrelated in the other half. The requirement of a binary decision in the LDT has been shown to elicit decision-related P300 responses (see Donchin & Coles, 2010 for a review) that overlap with N400s in time and complicate the interpretation of the N400 effects. In view of that, a go/no-go LDT was adopted here. In this task, participants were required to only press a key (the left-arrow key on a standard keyboard) when the target was *not* a word. As this task required no overt responses to, and hence less attentional processing of, the experimental stimuli in question (i.e. the "words" here), it has been adopted in the literature to attenuate the late positivity in order to better focus on the N400 effect (Holcomb, Grainger, & O'Rourke, 2002; Kellenbach & Michie, 1996). Another advantage of this task is that

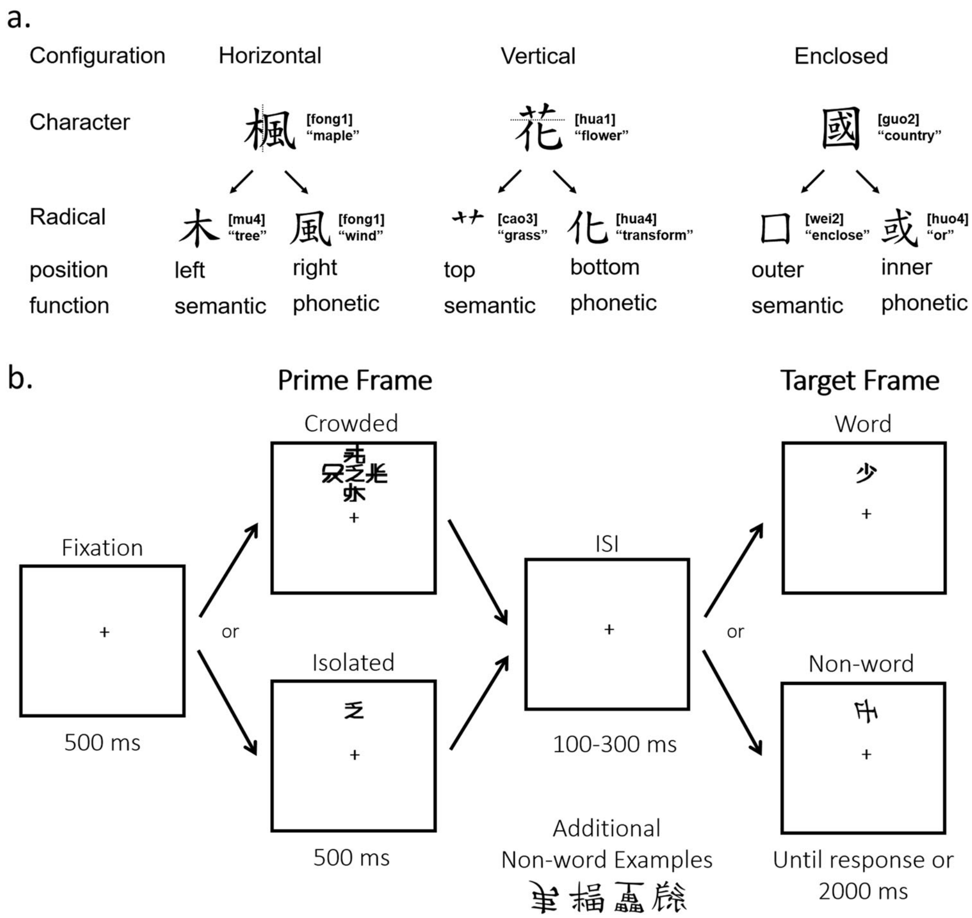

Figure 1. Stimuli and Procedures. (a) Examples of Chinese characters and some basic character configurations (horizontal/vertical/enclosed) as used by Yeh and Li (2002). In these configurations, each word can be dissected into radicals, which cue the meaning (semantic radical) and the pronunciation (phonetic radical) of the character; some radicals can also be standalone characters. Though there are many other types of configurations not demonstrated, these represent the more common types. (b) Examples of stimuli and the time course of one experimental trial. After presenting a 500 ms fixation cross, a one-character Chinese word appeared in the upper visual field as a prime. The prime word was presented either alone (isolated condition) or with four surrounding flankers (crowded condition). With an ISI varying randomly from 100 to 300 ms, a one-character Chinese word or a non-word was shown as target. Participants were instructed to judge the lexicality of the target within 2 s.

the electroencephalograms (EEGs) recorded from the word target condition would be free from the influence of overt behavioural responses.

2.4. Electrophysiological recording and preprocessing

EEGs was recorded using the Neuroscan system with a 32-channel Quick-cap. All recordings were initially referenced to a central vertex reference electrode, and re-referenced offline to the average of the left and right mastoids. To control for artefacts from eye movements, vertical electro-oculograms (vEOGs) and horizontal electrooculograms (hEOGs) were recorded with two pairs of electrodes: one pair placed above and below the left eye, and the other pair placed at the external ocular canthi. All interelectrode impedances were maintained below 5 KΩ. The EEG and EOG were amplified by the SynAmps using a 0.05–100 Hz bandpass filter and were continuously sampled at 1000 Hz/channel for off-line analysis.

EEG preprocessing was performed with the Neuroscan SCAN Edit software. EEGs were corrected for ocular artefacts. To ensure that participants did not divert their gaze to the target, the trials in which the vEOG exceeded ± 50 μV during the target display were excluded from the data analysis. Additional artefact rejection was applied to other electrode sites when epochs with EEG amplitude exceeded ± 75 μV. Taken together, 15.9 ± 3.6% of trials were excluded from further ERP analysis. The EEGs and EOGs were digitally filtered offline with a 0.05–30 Hz bandpass filter. ERPs were time-locked to the onset of the target. Epochs of EEG data were taken from 150 ms before stimulus onset to 1000 ms after.

2.5. Eye movement monitoring

To ensure that participants were fixating at the centre of the screen at all times during a trial such that the manipulation of crowding was valid, participants' eye movements were also monitored by an EYELINK 2000 eye tracker (SR Research, Mississauga, Ontario, Canada) with a sampling rate of 1000 Hz. Throughout the experiment, if the eye tracker detected that a participant's gaze was directed beyond a horizontal boundary 1.5° above the fixation cross, the current trial would be skipped and all stimuli except the fixation would be removed. The next trial would not start until the gaze returned to the fixation cross, and the skipped trial would be re-tested before the end of the experiment. The participants were well informed about the eye-movement controlling requirements and monitoring procedure.

3. Results

The accuracy of the go–nogo task was 92%, indicating that participants performed well in the LDT. Data of incorrect trials were excluded from further analysis. Grand average ERP data from correct trials plotted in Figure 2(a) showed that the N400 reduction was observed in both the isolated and crowded conditions, with semantically related targets eliciting less negative N400s than did semantically unrelated targets. As shown in Figure 2(b), the N400 priming effects in both isolated and crowded conditions had a central-posterior distribution, typical for N400 effects to visually presented language materials (Kutas & Federmeier, 2011). The mean amplitude of the N400 component measured between 300 and 600 ms was submitted to a 2 (Crowding: uncrowded, crowded) × 2 (Semantic relatedness: related, unrelated) × 3 (Anteriority: anterior, central and posterior) repeated-measure ANOVA. Fifteen electrodes from the international 10-20 system were chosen as representative sites, among which F7, F3, Fz, F4, F8 represent the anterior region; T7, C3, Cz, C4, T8 represent the central region; and P7, P3, Pz, P4, P8 represent the posterior region. Greenhouse-Geisser corrections were adopted to correct for violations of sphericity associated with repeated measures when necessary. Results revealed significant main effects of Crowding ($F(1,20) = 5.10$, $p < .05$, $\eta_p^2 = .20$), Semantic relatedness ($F(1,20) = 9.56$, $p < .01$, $\eta_p^2 = .32$), and Anteriority ($F(2,40) = 12.71$, $p < .001$, $\eta_p^2 = .39$). The Semantic relatedness × Anteriority interaction reached marginal significance ($F(2,40) = 2.84$, $p = .09$, $\eta_p^2 = .12$). LSD post-hoc tests showed that the N400 reduction was significant in the isolated condition in the central ($p < .05$) and posterior ($p < .01$) regions, and in the crowded condition in the central ($p < .05$) and posterior ($p < .01$) regions (see Figure 2(b)). These results suggested that the N400 reduction (As shown by the difference in µV between related/unrelated groups in each condition) occurred in both the isolated and crowded conditions. There was no significant Crowding × Semantic-relatedness interaction ($F(1,20) = 0.25$, $p = .63$, $\eta_p^2 = .01$), nor three-way interaction ($F(2,40) = 0.88$, $p = .39$, $\eta_p^2 = .04$); thus the magnitude and distribution of the N400 reduction was not different between crowded and isolated conditions[1].

4. Discussion

Surprised by the survival of semantic information in visual crowding, we set out to investigate the semantic priming effect reported in Yeh et al.'s (2012) behavioural study. By using the ERP technique, we replicated semantic priming effects induced by unrecognisable words due to visual crowding. In particular, when the prime word and the target word were semantically related, a reduced N400 response to the LDT associated with the target was observed regardless of whether the prime was crowded or isolated. The effect did not occur when primes and targets were semantically unrelated. This result provides strong support for the previous behavioural finding in Yeh et al. (2012) by confirming that semantic information does indeed survive visual crowding as evidenced by an ERP response. More importantly, to answer the question about at which stage this priming effect occurs, the N400 reduction suggests that the priming effect of crowded words occurs at a semantic processing stage.

Converging evidence of semantic priming has been reported by recent publications; for example, Peng et al. (2013) demonstrated an N400-reduction priming effect on crowded targets preceded by semantically related isolated primes. N400 effects have also been reported under conditions with limited level of awareness, for example, under attentional-blink (Luck, Vogel, & Shapiro, 1996) or visual-masking conditions (Coulson & Brang, 2010). In addition, an fMRI study showed that crowded words, when presented out of context, also activated brain regions related to semantic processing (Yeh, Lee et al., 2012). Particularly the activated regions include the left Fusiform Gyrus (FG) for orthographic processing, the left Middle Temporal Gyrus (MTG) for semantic representation and the left Inferior Frontal Gyrus (IFG) for controlled retrieval and selection of semantic knowledge. These studies also support the idea that semantic information is activated even with unrecognisable crowded words, and the induction of the priming effect occurs at a semantic level.

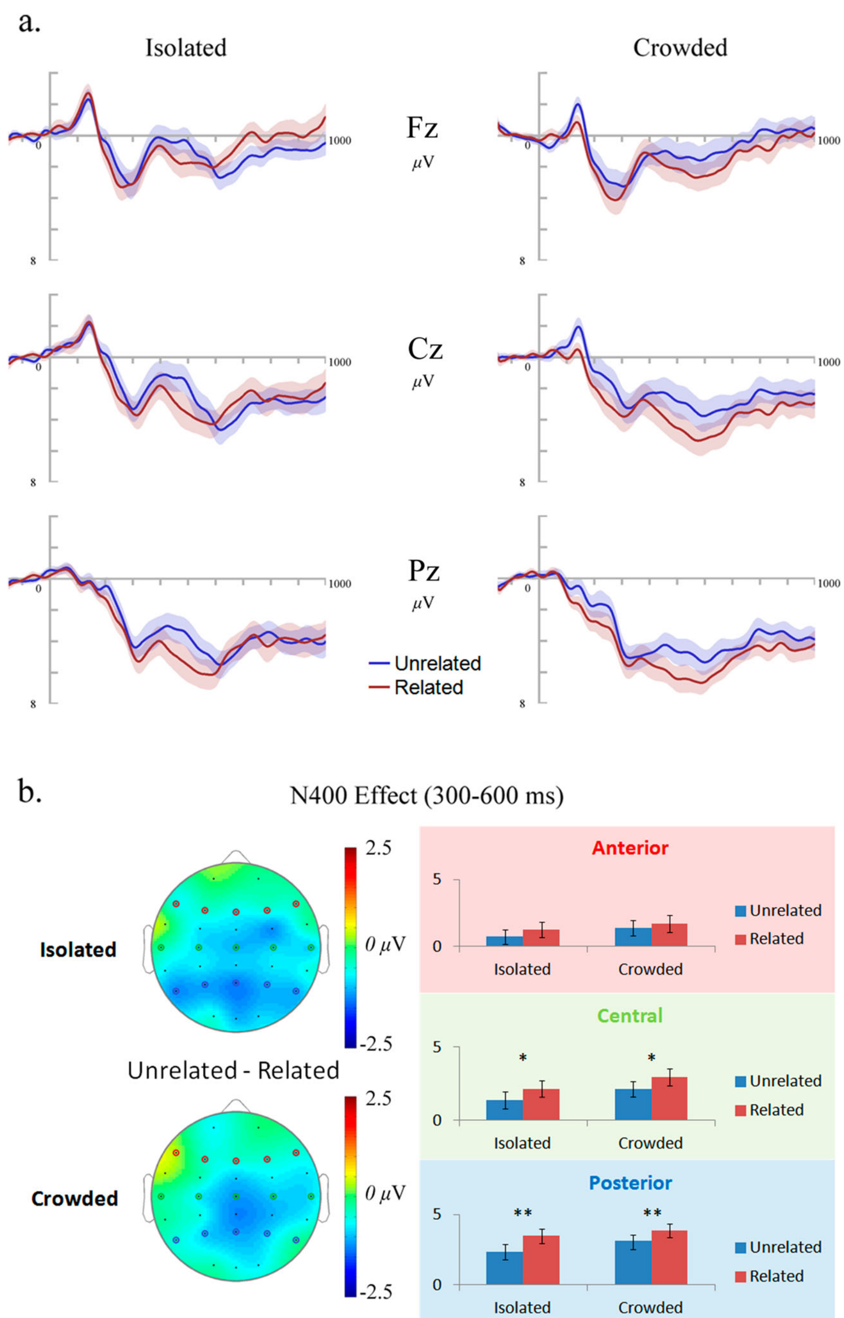

Figure 2. (a) ERPs for the related (red) and unrelated (blue) targets at the representative electrodes (for N400) Fz, Cz and Pz in the isolated and crowded conditions. The shaded regions of matching colour indicate the ±1 SE interval between participants. (b) The N400 reduction (the difference in μV between related and unrelated groups in each condition from 300 to 600 ms) in the anterior, central, and posterior regions (averaged across representative electrodes, anterior: F7, F3, Fz, F4, F8; central: T7, C3, Cz, C4, T8; posterior: P7, P3, Pz, P4, P8) in the isolated and crowded conditions. The symbols (* $p < .05$, ** $p < .01$) indicate the significance level of the difference between the related and unrelated conditions. The topographic maps of the N400 reduction are shown in the left panel.

Another important implication from our result is that semantically related crowded primes elicited the same level of the N400 reduction on isolated targets as did semantically related isolated primes. In agreement with the behavioural results in Yeh et al. (2012), this suggests that the semantic meaning of crowded primes not only survive visual crowding, but also produce the same level of impact as isolated primes on ensuing semantic facilitation. Thus, though quite surprising and counterintuitive, the semantic processing of crowded words is not a weaker version of isolated ones. This is different from the findings of Peng et al. (2013), who showed a smaller N400 priming effect in the crowded than in the uncrowded condition. However, Peng et al.'s design might have introduced several complications. First of all, Peng et al. analysed ERPs with the time window locked to the crowded and uncrowded target words, which inevitably superimposed the semantic priming effect with the low-level differences (i.e. stimulus size) between crowded and uncrowded words. This may also have been the primary reason for the different scalp distributions of the N400 semantic priming effect across conditions (central-posterior for uncrowded condition, but anterior for crowded condition). Critically, Peng et al. adopted a speeded semantic relatedness judgement task. As a consequence, the ERP responses in the uncrowded condition were dominated by a decision-related late positivity (Donchin & Coles, 2010). The larger N400 priming effect in the uncrowded compared to the crowded condition could have been caused by the differences in the late positivity in these two conditions. Perhaps due to these concerns, Peng et al. (2013) did not make a strong claim about the different effect sizes across crowding conditions.

In terms of crowding theories, our results are not accounted for by the two well-known models on crowding that focus on spatial feature degradation or assimilation in the visual periphery, which includes the averaging/pooling model (Balas et al., 2009; Levi et al., 2002; Parkes et al., 2001; Pelli et al., 2004; Pelli & Tillman, 2008) and the substitution model (Ester et al., 2014; Nandy & Tjan, 2007; Strasburger, 2005). Our reasoning is that both accounts assume loss of crowded object signal integrity during visual processing which cannot happen to the signal from which semantic information is obtained. To further clarify, the flankers used in our study, though created to mimic actual Chinese words, do not carry any semantic meaning by themselves under any circumstances; consequently, if the flankers are averaged or substituted even partially with the prime word, the semantic meaning behind the word would have been lost. Although our findings are not covered by these models, we are not the first to report conflicting evidence. As presented in the Introduction, studies of other higher level information including illusory contour (Lau & Cheung, 2012), and emotional bias (Kouider et al., 2011) can survive crowding as well. Since these reports cannot be satisfactorily described by the aforementioned models, a new model compatible with the survival of certain high-level visual features in crowding is needed.

Chaney, Fischer, and Whitney (2014) recently proposed the "hierarchical sparse selection" (HSS) model that may be able to solve the puzzle. It asserts two principles, the first of which states that large receptive or integration fields do not necessarily lead to a loss of visual features. The argument is that even though individually each receptive or integration field may carry ambiguous information, the combination of overlapping signals from many receptive fields should be able to convey enough information for decoding stimuli smaller than each receptive field. The second principle states that even though signals might maintain their integrity within the feed-forward visual system, the operation that analyses and sends the visual signal to perception might not. Hence, unambiguous perception of an object is possible only when the top of the hierarchy "sparsely selects" just the neuronal inputs that carry relevant information for decoding, yet this is impossible in the presence of irrelevant flanker features. In addition, there may be competition between different brain areas in sampling the neuronal outputs, as the decoding by the output layers are said to take place in a winner-take-all fashion according to the model. The HSS model, though not empirically tested with human subjects in that publication, can resolve contradictory findings on the survivability of stimulus details.

By applying the model to our observations, we can explain how a bypass of semantic information is conceivable when visual crowding renders the words unrecognisable. Specifically, suppose the details of the crowded prime are passed-on beyond the detection stage and are individually selected and processed by different cortical areas (e.g. those that perform pattern recognition), it would then be possible to observe semantic activation without orthographic activation (Yeh et al., 2012). Previous Chinese reading models have mostly assumed sequential activations starting with orthographic information processing (e.g. Borowsky & Besner, 1993; Forster & Davis, 1984; Tan & Perfetti, 1998; Taft, 2006) which may contradict our finding here; but if we consider semantic information to be independently processed from orthographical information (i.e. each having its own independent processing routes), then that could explain how semantic processing without word identification is possible.

Taking the HSS model (Chaney et al., 2014) and a recent finding that semantic access and recognition of words can happen simultaneously (Laszlo & Federmeier, 2011) into consideration, our results are in line with the idea that semantic processing does not require conscious word identification. Though possibly counterintuitive, one class of explanation is that separate neural pathways for semantic processing exist, and not all comprise a word identification stage. Peng, Liu, and Chen (1996) proposed one such "radical-processing pathway" model for Chinese words (radicals are components of Chinese characters; they can be arranged horizontally, vertically, or in an enclosed configuration, Yeh & Li, 2002; Refer to Figure 1(a) for examples). In this model, the radicals and their spatial relationship directly activate semantic networks, without forming a whole-word representation in advance; hence the semantic information of crowded words in the present study may take the radical-level meaning-processing pathway (based on radicals and their spatial relationship) that directly links radicals to meaning without leading to word identification (see also Zhou & Marslen-Wilson, 1999). Alternative to Peng's radical-pathway account, another possible mechanism behind our finding would be the "bottom-up/top-down" account. Several models of Chinese-word recognition (e.g. Shen, Li, & Zhu, 1997; Shen, Pan, & Li, 1997; Shen & Zhu, 1995, 1997) proposed two routes[2] in word processing: a bottom-up and a top-down route. The bottom-up route processes information in a feed-forward manner where basic features extracted from visual input are sent to radical detectors in order to activate the radical representations at a higher level; at the whole-word level the word representations are formed from the radical-level output. The top-down route provides a feedback connection with higher level representations (including coarse representations still being processed), to facilitate the processing at lower levels by decreasing thresholds of both feature and radical detectors. Moreover, it is suggested that top-down processing is related to conscious perception, while bottom-up processing is automatic and implicit (Chen & Yeh, 2009; Hochstein & Ahissar, 2002). From that, top-down processing that leads to conscious perception would be only one of the two routes, and not a prerequisite to extracting word meanings.[3] According to the bottom-up/top-down model, semantic activation in crowded words could take merely the bottom-up route and not the top-down one. These models, though disparate in proposing how radicals are processed, are not exclusive to each other; i.e. the radical-level processing of meaning could be one of the many bottom-up processes of Chinese-word recognition while orthographical processing of radical signals could be another. On top of that, based on our preliminary study on phonological priming which showed that phonological activations actually require word identifications in Chinese script (Dong, Chen, & Yeh, 2013), we deduced that orthographical properties of Chinese characters are prerequisites for phonological activations and should be considered together as one pathway. Taking a step further, since precise orthographical information is not accessed in crowding (crowded words are unrecognisable), there has to be another route, potentially similar to the one from the radical-processing pathway model, responsible for semantic activation. With the HSS model (Chaney et al., 2014) in mind, we postulate that, if semantic and orthographic/phonologic routes indeed project to different brain areas, there might be competition for the limited information embedded within the crowded signal. In this light, either semantic activation dominates orthographic activation in terms of signal competition, or signals from non-word flankers distract orthographic activation more profoundly than semantic activation; both explanations can account for the result we observed here.

It should be noted that since we only focused on the N400 component in this study, we do not exclude the possibility that crowded words also affect other processing stages besides semantic processing. We merely draw the conclusion that semantic priming indeed occurs for crowded words while remaining open to other potentially co-existing effects. However, since the go–nogo paradigm was employed, we can effectively rule out response execution as a stage that could confound our results. To wrap up, we have demonstrated here that ERP procedures are robust in locating unconscious processing stages in addition to confirming results for priming effect documented in behavioural studies. Hence, future endeavours may adopt similar methods (i.e. utilizing different ERP components) to explore other potential priming effects or unconscious activations from visually crowded objects.

5. Conclusion

The current study used the ERP technique to demonstrate that crowded words can produce semantic priming on subsequent words. Specifically, when the prime and the target were semantically related, then regardless of whether the prime was crowded or isolated, a smaller N400 response during target presentation was observed, compared to when primes and targets were semantically unrelated. Moreover, we have also observed the effect on the N400 to be equal in magnitude in both crowded and isolated conditions. In line with previous behavioural study (Yeh et al., 2012), our findings suggest that semantic processing indeed occurs for the crowded words that are consciously unrecognisable, and the meanings extracted from crowded words facilitate the semantic processing of the subsequently presented words.

Disclosure Statement

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Notes

1. To confirm that these result patterns were not due to low signal to noise ratio (SNR), we calculated the SNR by dividing the peak amplitude in the N400 time window (300–600 ms) by the amplitude of the background noise represented by the standard deviation of the waveform in the pre-stimulus interval (−150 to 0 ms). The results showed that the SNR values for every condition-anteriority combinations varied from 10 to 35, which are comparable with values reported in prior studies using the same approach (e.g. Debener et al., 2007; Hu, Mouraux, Hu, & Iannetti, 2010; Spencer, 2005).
2. Note that the dual-route model mentioned here is not referring to the well-known phonological model that suggests lexical and non-lexical routes from print to speech (Coltheart, Curtis, Atkins, & Haller, 1993; Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001).
3. As a model of word recognition, it does not specify how meaning is extracted from words. However, given that the whole-word level representation can be completed by the bottom-up route alone (which is implicit without the top-down processing), there is no reason to suspect that word meaning cannot be extracted from the word representation in this case.

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