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Accessing the meaning of invisible words

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ABSTRACT

Previous research has shown implicit semantic processing of faces or pictures, but whether symbolic carriers such as words can be processed this way remains controversial. Here we examine this issue by adopting the continuous flash suppression paradigm to ensure that the processing undergone is indeed unconscious without the involvement of partial awareness. Negative or neutral words projected into one eye were made invisible due to strong suppression induced by dynamic-noise patterns shown in the other eye through binocular rivalry. Inverted and scrambled words were used as controls to provide baselines at orthographic and feature levels, respectively. Compared to neutral words, emotion-described and emotion-induced negative words required longer time to release from suppression, but only for upright words. These results suggest that words can be processed unconsciously up to semantic level since under interocular suppression completely invisible words can lead to different processing speed due to the emotion information they carry.

1. Introduction

Words play an important communicative role in modern societies, allowing abstract concepts and elaborate ideas, in addition to statements about facts and events, to be conveyed in visual form. Through years of experience, skilled readers' word recognition process becomes automatic, as revealed by the Stroop effect (Stroop, 1935): Naming the color in which color words are printed is difficult (slow and error prone) when the color of the ink and the color word itself are not the same (i.e., saying "red" when shown the word "blue" written in red ink). Other researchers have shown that emotion words presented for a very brief period can be processed up to a semantic level (Huang, Baddeley, & Young, 2008; Zeelenberg, Wagenmakers, & Rotteveel, 2006). Nevertheless, the question of whether words' meanings can be accessed implicitly *without any awareness* remains unsettled, and this is the main issue tackled in this study.

From the scandal created by James Vicary's subliminal slogan for Coca Cola (see in Karremans, Stroebe and Claus (2006)) to the rigorous test using the masked priming paradigm for unconscious semantic processing (e.g., Marcel, 1983), the major controversy is about whether the evidence for implicit semantic processing of words is genuine (Abrams & Grinspan, 2007b; Gaillard et al., 2006; Naccache & Dehaene, 2001). Some researchers have questioned that the apparent semantic priming effect might have been obtained through sub-word processing (Abrams, 2005; Abrams & Greenwald, 2000; Kouider & Dehaene, 2007) or partial awareness (Kouider & Dupoux, 2004). In order to solve methodological shortcomings, we used the continuous flash suppression (CFS) paradigm (Fang & He, 2005; Tsuchiya & Koch, 2005) in the current study.

In this paradigm, a critical stimulus is presented to one eye, and constantly changing high-contrast Mondrians (masks) are presented to the other eye. Due to the interocular suppression from the continuous flash masks, the critical stimulus cannot be consciously perceived for quite some time. Compared to other paradigms in studies on implicit processing, this method has several advantages. First, the exposure duration can be extended long enough for full (implicit) processing, and during

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this relatively long duration, the physical properties of the critical stimulus can remain constant while participants' awareness state of the critical stimulus changes (Kim & Blake, 2005). Furthermore, this paradigm offers a clear criterion (e.g., simple detection of any part of the critical stimulus or no response as to the critical stimulus is required), rather than ambiguous or partial rivalry, for the observer. Finally, the critical stimuli always compete with the same Mondrians so as to provide the same baseline for different critical stimuli (Jiang, Costello, & He, 2007).

Several studies using this CFS paradigm have demonstrated that in addition to low-level properties (e.g., Hong & Blake, 2009; Maehara, Huang, & Hess, 2009; Tsuchiya & Koch, 2005) high-level information can also be processed in the interocular suppression phase. This includes facial identity and facial expression (Jiang & He, 2006; Yang, Zald, & Blake, 2007), genders of body images (Jiang, Costello, Fang, Huang, & He, 2006), and tools (Fang & He, 2005). Can the list be extended to include symbolic carriers such as the semantics of words? Using the CFS paradigm to measure the reaction time (RT) for the participants to perceive the critical stimulus (the time to release it from suppression), Jiang et al. (2007) found shorter RTs when the critical stimulus was a recognizable word than when it was an unrecognizable word. These findings imply that familiar stimuli could be processed differently from unfamiliar ones even when the critical stimuli were invisible to the observer. However, it is still unclear whether this difference between familiar and unfamiliar stimuli is due to its form (i.e., a word template) or meaning.

To our knowledge, there has not been any report so far showing genuine and pure semantic processing of invisible words using the CFS paradigm except for a recent study that found semantic priming with a visible prime (e.g., Costello, Jiang, Baartman, McGlennen, & He, 2009, see Section 4), and yet no consensus has been reached in previous studies using other paradigms that have been questioned for their claims about truly implicit semantic processing (Abrams, 2005; Abrams & Greenwald, 2000; Abrams & Grinspan, 2007a; Kouider & Dupoux, 2004, 2007). The main goal of this study was to examine whether word semantics can be processed and accessed implicitly by using emotional words with a negative valence as the critical stimulus in the CFS paradigm and to see whether RTs would be different for negative words than for neutral words in the suppressed phase. If there is a reliable difference between the processing times of the two kinds of invisible words, one can infer that the semantics of words is extracted, even when they are invisible.

2. Experiment 1

We chose Chinese words with a negative valence as the critical stimulus in the CFS paradigm to test whether negative words (e.g., "angry") are processed differently than neutral words in the suppressed phase of binocular rivalry. To prevent any emotional connotation in the neutral-word category, we put functional words (e.g., "however") in this category. In order to provide baselines at the levels of orthography and low-level local features in space domain between negative and neutral words, we also used inverted and scrambled words for comparison at the two levels, respectively.

Following the two most relevant studies using CFS (Costello et al., 2009; Jiang et al., 2007), we also performed a manipulation check to ensure that the result obtained was not caused by response bias – different criteria used for different kinds of critical stimuli *after* but not *during* the interocular suppression phase. In this control experiment, the critical stimulus was superimposed on the Mondrians, and both were projected into two eyes, thus changing the viewing from dichoptic to binocular. This percept mimics the percept in the dichoptic viewing condition but the critical stimulus is not suppressed. If the differential results between negative and neutral words are due to response bias such as different criteria set for the two kinds of words after the release from suppression (i.e., becoming consciously perceived), similar results in the binocular viewing condition and in the dichoptic viewing condition should be obtained.

2.1. Method

2.1.1. Participants

Twelve National Taiwan University undergraduate students participated in this experiment for course credit. They were all skilled readers of Chinese, naïve about the purpose of this experiment, and had normal or corrected-to-normal vision.

2.1.2. Stimulus, materials, and apparatus

Stimuli were displayed on a 22-inch ViewSonic P225f CRT monitor (1024 $\times$ 768 resolution at 60 Hz frame rate) and presented via E-Prime software (Psychological Software Tools, Pittsburgh, PA) and controlled by an IBM compatible personal computer. The participant sat in a dark chamber, with his or her head positioned on a chin-rest at a viewing distance of 60 cm.

In the dichoptic viewing condition, two different images were projected onto each eye through a four-mirror stereoscope, which consisted of two mirrors fixed in the center and angled +/− 45° orthogonally, and two adjustable mirrors mounted on the two sides. The two images included a gray Chinese word presented on a white background and a Mondrian pattern changing at a rate of 10 Hz. The two images were each surrounded by an outer square frame (10.70° $\times$ 10.70° visual angle, with a thickness of 0.2°) to assist the binocular fusion of the two outer frames. The Mondrians (extended 5.50° $\times$ 5.50°, generated by Matlab 7.0) contained small rectangles (randomly chosen with different sizes, having a width and length from 0.02° to 1.07°, and with different colors, having RGB values from 0 to 255). To prevent the possibility that the abrupt onset of a word would cause suppression of the other side and thus make the word suddenly visible (Yang et al., 2007), the contrast of the word was raised gradually from 0% to 50% within 500 ms and was then kept constant at 50% contrast until the end of the trial. The trial also ended automatically if no response was made within 6 s.

In the binocular viewing condition, the word was superimposed on the Mondrians and presented to both eyes. The contrast of the word was raised gradually from 0% to 50% within 3.3 s and kept constant afterwards. The timing was set to obtain RTs similar to those achieved under the dichoptic condition.

We used a set of 24 Chinese two-character words that contained an equal number of negative and neutral words. The negative and neutral words were matched in stroke numbers (mean stroke counts: neutral, 23.08; negative, 23.33) and word frequency (mean frequency per one million words: neutral, 15.11; negative, 15.06) based on the Ministry of Education Word Frequency database in Taiwan. Each two-character word extended $2.68^\circ \times 1.34^\circ$ and was presented 1.27° (center-to-center) above or below fixation (a cross, $0.78^\circ \times 0.78^\circ$) with equal probability. In the scrambled condition, each word was segmented into 5×10 squares that were arrayed randomly to remove the top–down information but preserve the same low-level local features in space domain.

2.1.3. Design

This experiment was a within-subject factorial design in which two factors were manipulated: emotional valence (negative and neutral) and word form (upright, inverted, and scrambled). Each of the six conditions contained 48 trials, and the 288 trials were presented in a random order. In order to control ocular dominance, the eye (left/right) to which the Mondrian or the word was projected in the dichoptical condition was counterbalanced. We also used different stimulus onset asynchronies (SOAs) between the onset time of the first Mondrian and that of the word to prevent any rhythmic expectation of the appearance of the word. The same manipulations were used in the binocular viewing condition as in the dichoptic viewing condition, except that the number of trials was cut in half.

2.1.4. Procedure

At the beginning of each trial, the participant was instructed to fuse the dichoptical images through the stereoscope with the help of the two outer square frames in the display and press the "z" key to start the trial after achieving the binocular fusion of the outer square frames (i.e., when he/she saw only one frame).

Although the word was presented to one eye and the Mondrians to the other eye, the word was not detectable in the beginning of a trial due to the dominance of high-contrast dynamic Mondrians in binocular rivalry. The task was to press the "z" key as soon as any part of the word was detected and the recorded RT served as an index of the time needed to bring the word into conscious perception. After the detection response, the participant was required to make a judgment about the location of the word. If he thought it was above the fixation cross, he pressed the "o" key and if he thought it was below the cross, he pressed the "k" key (see Fig. 1).

2.2. Results

2.2.1. Dichoptic viewing

RTs longer than 6 s (<.06%) and error trials of the location judgment were excluded from further analysis (mean accuracy = 94.39%, *SD* = 3.42%). Results for correct RTs are shown in Fig. 2A. The RT data were submitted to a two-way repeated measure analysis of variance (ANOVA) with the factors of emotional valence (neutral and negative) and word form (upright, inverted, and scrambled).

The main effects of emotional valence [$F(1, 11) = 15.41$, $MSE = 23227.75$, $p < .005$, $\eta_p^2 = .58$] and word from [$F(2, 22) = 45.27$, $MSE = 162177.67$, $p < .0001$, $\eta_p^2 = .80$] were significant, and so was the interaction of emotional valence and word form [$F(2, 22) = 3.96$, $MSE = 23254.77$, $p < .05$, $\eta_p^2 = .26$]. In the upright condition, negative words ($M = 1583$ ms) were detected slower than neutral words ($M = 1305$ ms) [$F(1, 33) = 20.09$, $MSE = 23245.76$, $p < .001$, $\eta_p^2 = .38$]. However, the RTs for the two kinds of words were not different in the inverted and scrambled conditions [$F(1, 33) = 0.40$, $p > .05$, $\eta_p^2 = .01$ and $F(1, 33) = 2.83$, $p > .05$, $\eta_p^2 = .08$, respectively]. In the neutral word condition, RTs varied with the word form [$F(2, 44) = 44.74$, $MSE = 92716.22$, $p < .0001$, $\eta_p^2 = .67$]. The Tukey test showed that upright words ($M = 1305$ ms) were detected faster than the inverted words ($M = 1746$ ms), which were detected faster than the scrambled words ($M = 2469$ ms). In the negative-word condition, the simple main effect of word form was also significant [$F(2, 44) = 35.43$, $MSE = 92716.22$, $p < .0001$, $\eta_p^2 = .62$]; scrambled words ($M = 2574$ ms) were detected slower than upright and inverted words ($M = 1584$ ms and $M = 1786$ ms, respectively), and the latter two were not significantly different.

The accuracy data showed that the main effect of valence was significant [$F(1, 11) = 7.99$, $MSE = 0.001$, $p < .05$, $\eta_p^2 = .42$]; lower accuracy was found for negative words ($M = 93.2\%$) than for neutral words ($M = 95.4\%$). The main effect of word form was also significant [$F(2, 22) = 30.71$, $MSE = 0.001$, $p < .0001$, $\eta_p^2 = .74$]; lower accuracy was found for scramble words ($M = 90.8\%$) than for upright ($M = 97.2\%$) and inverted words ($M = 94.8\%$). There was no response accuracy trade-off.

2.2.2. Binocular viewing

RTs longer than 6 s (<.14%) and error trials of the location judgment were excluded from further analysis (mean accuracy = 98.44%, *SD* = 1.70%). Results for correct RTs are shown in Fig. 2B. Only the main effect of word form was found [$F(2, 22) = 34.59$, $MSE = 36191.67$, $p < .0001$, $\eta_p^2 = .76$]; scrambled words ($M = 2202$ ms) were detected slower than upright words ($M = 1800$ ms) and inverted words ($M = 1813$ ms). There was no main effect of emotional valence [$F(1, 11) = 0.95$,

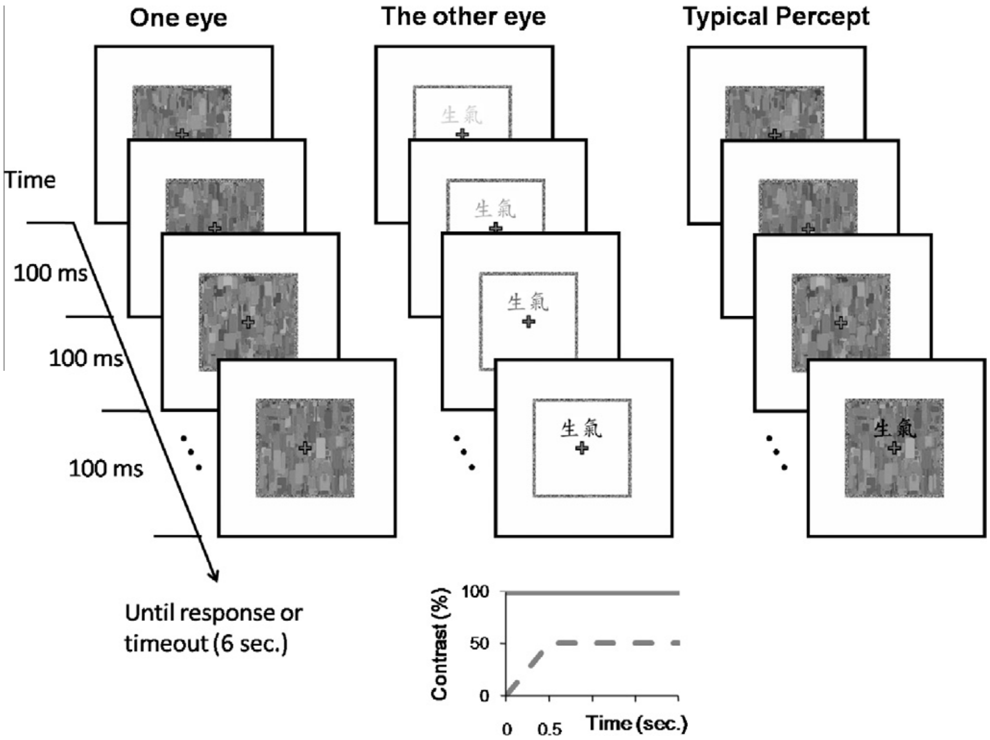

Fig. 1. Stimuli and procedure. The critical stimuli were black Chinese words, and the masks were color Mondrians. They were presented dichoptically for 100 ms per frame as shown in the two left-hand columns. The right-hand column is the schematic representation of the percept seen by the participants (typically, they perceived parts of the word, and then the trial ended by the key press). The contrast of words gradually increased and stayed constant at 50% contrast after 500 ms (the dash line), and the Mondrians were always presented with full contrast (the solid line), as shown in the bottom figure. The sequence of presentation stopped once the observer pressed a key to indicate detection of the word, or after 6 s if no response was made.

$p > .05$, $\eta_p^2 = .08$; $M = 1947$ ms for negative word and $M = 1930$ ms for neutral one], nor was there an interaction of word form and emotional valence [$F(2, 22) = 0.68$, $p > .05$, $\eta_p^2 = .06$]. Accuracy was high overall and no difference was found across different conditions.

2.3. Discussion

The results of this experiment showed a difference in the time it took a participant to release a word from suppression. RT was longer and accuracy lower for the participant to detect negative words than neutral words, and this only occurred when the words were upright but not when they were inverted or scrambled. This indicates that even for symbolic carriers such as words, the meaning that is extracted through normal upright orthography can be accessed even when they were invisible due to strong interocular suppression created by the high-contrast dynamic Mondrians. Such implicit processing of words' meanings should not be attributed to response bias, as indicated by the different result patterns in the dichoptic viewing and binocular viewing conditions. The slower response to negative words than neutral words occurred only during dichoptic viewing but not during binocular viewing when there was no difference between the times it took to detect the two kinds of words.

Negative and neutral words were not detected at different speeds when they were inverted or scrambled, indicating that no meaning can be extracted when a word is in an unfamiliar form and that the equal baselines at the orthography or feature levels ensure that the different results obtained for upright negative and neutral words were not due to orthography or some salient perceptual features. The fact that there was a faster detection time for inverted words than for scrambled words also indicates that perceptual grouping was preserved for inverted words even though the extraction of meaning was disrupted.

3. Experiment 2

In the previous experiment, function words with no concrete meanings were chosen as neutral words to prevent any implied emotional intension. There were thus two differences between the two kinds of words: negative vs. neutral and function vs. content words. Therefore, the different processing times observed in Experiment 1 could have been caused by emotional valence or word role (cf. Guo, Qi, Peng, & Yan, 2008), or both. Although this would not affect our main conclusion

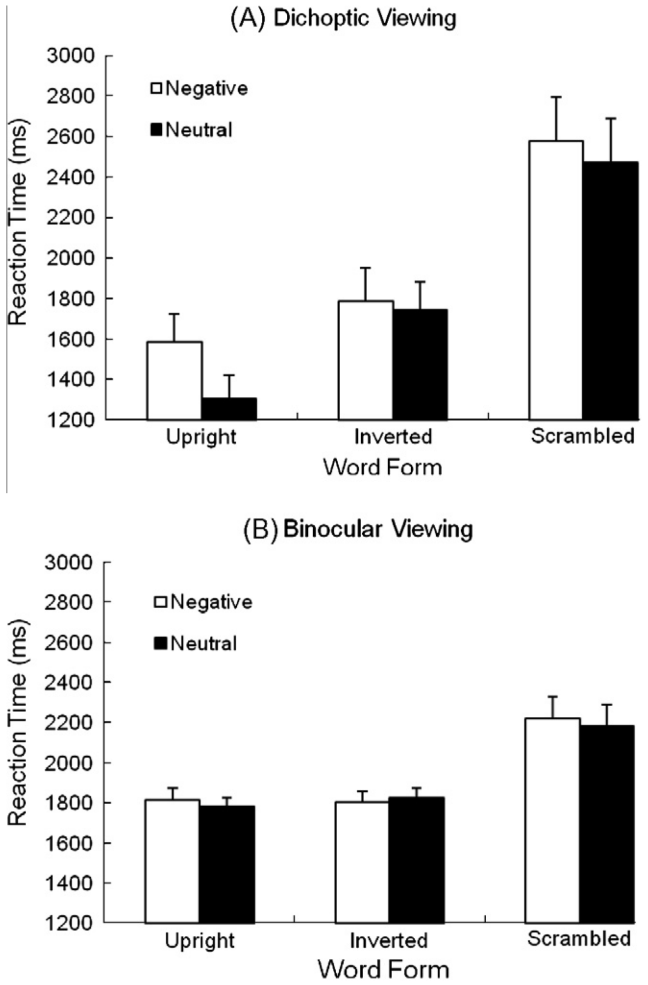

Fig. 2. Mean reaction times under (A) the dichoptic viewing condition and (B) the binocular viewing conditions in Experiment 1.

that words can be processed implicitly, it is desirable to differentiate the two and examine whether emotional information per se can be extracted during the suppressed phase. For this reason, the negative and neutral words were both content words in this experiment.

In addition, the emotion words used in Experiment 1 were those that describe emotion (e.g., "angry", "fear", etc.). In this experiment, we used the emotion words that induce emotions (e.g., "abuse", "murder"), in order to generalize the external validity of emotional words.

3.1. Method

3.1.1. Participants

Another group of 12 undergraduate students at National Taiwan University participated in this experiment.

3.1.2. Materials, procedure, and design

The display, procedure, and design were the same as in Experiment 1 except for the following. In order to control the word role, we selected two new sets of words, each set containing 16 words. Because of the increased number of words, the total number of trials was 384.

3.2. Results

3.2.1. Dichoptic viewing

Response longer than 6 s (mean excluded rate <.69%) and error trials of the location judgment were excluded from further analysis (mean accuracy = 94.79%, *SD* = 3.78%). Results for correct RTs are shown in Fig. 3A. The ANOVA revealed significant main effects of emotional valence [$F(1, 11) = 7.70$, $MSE = 17718.90$, $p < .05$, $\eta_p^2 = .41$ and word form [$F(2, 22) = 28.40$,

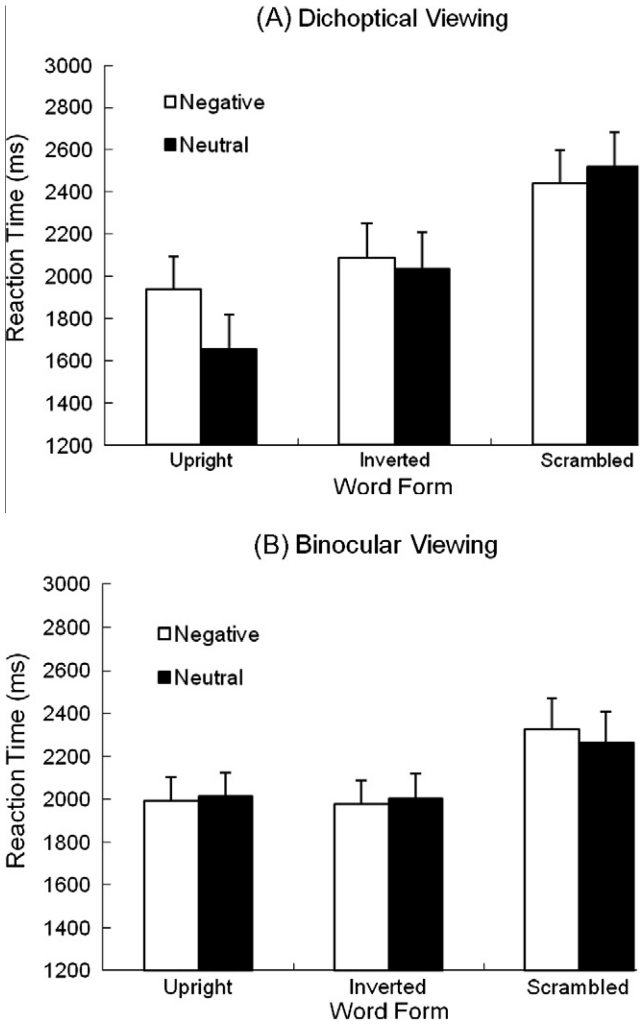

Fig. 3. Mean reaction times under (A) the dichoptic viewing condition and (B) the binocular viewing conditions in Experiment 2.

MSE = 99731.41, $p < .0001$, $\eta_p^2 = .72$] as well as their interaction [$F(2, 22) = 6.55$, *MSE* = 31097.78, $p < .01$, $\eta_p^2 = .37$]. Negative words ($M = 1940$ ms) were detected slower than neutral words ($M = 1655$ ms) when they were upright [$F(1, 33) = 18.35$, *MSE* = 26638.15, $p < 0.001$, $\eta_p^2 = .36$], but not when they were inverted or scrambled [$F(1, 33) = 0.67$, $p > .05$, $\eta_p^2 = .02$; $F(1, 33) = 1.40$, $p > .05$, $\eta_p^2 = .04$, respectively]. The simple main effect of word form in the neutral word condition [$F(2, 44) = 34.36$, *MSE* = 65414.60, $p < .0001$, $\eta_p^2 = .61$] revealed that upright words ($M = 1654$ ms) were detected faster than inverted words ($M = 2035$ ms), which were detected faster than scrambled words ($M = 2518$ ms). The simple main effect of word form in the negative-word condition [$F(2, 44) = 12.05$, *MSE* = 65414.60, $p < .001$, $\eta_p^2 = .35$] showed that scrambled words ($M = 2439$ ms) were detected slower than upright ($M = 1940$ ms) and inverted words ($M = 2089$ ms), and there was no difference between the detection speed of upright and inverted words.

The accuracy data showed that the main effect of valence was significant [$F(1, 11) = 10.709$, *MSE* = 0.001, $p < .01$, $\eta_p^2 = .49$]; lower accuracy was found for negative words ($M = 94.1\%$) than for neutral words ($M = 95.9\%$). The main effect of word form ($M = 96.3\%$ for upright, $M = 94.3\%$ for inverted, and $M = 94.3\%$ for scrambled words) and the interaction of valence and word form were not significant [$F(2, 22) = 2.591$, $p > .05$, $\eta_p^2 = .19$; $F(2, 22) = 1.771$, $p > .05$, $\eta_p^2 = .14$, respectively]. Therefore, similar results as in the first experiment were found: slower detection and lower accuracy for negative words than for neutral words.

3.2.2. Binocular viewing

RTs longer than 6 s (<.06%) and error trials of the location judgment were excluded from further analysis (mean accuracy = 99.05%, $SD = 1.24\%$). Results for correct RTs are shown in Fig. 3B. There was no main effect of emotional valence [$F(1, 11) = 0.03$, $p > .05$, $\eta_p^2 = .003$; $M = 2100$ ms for negative words and $M = 2095$ ms for neutral ones], and there was no interaction of word form and emotional valence [$F(2, 22) = 0.90$, $p > .05$, $\eta_p^2 = .08$]. Nonetheless, word forms affected the detection

RT [$F(2, 11) = 25.96$, $MSE = 27529.14$, $p < .0001$, $\eta_p^2 = .83$]; upright words ($M = 2005$ ms) and inverted words ($M = 1991$ ms) were detected faster than scrambled words ($M = 2297$ ms).

3.3. Comparison of the dichoptic viewing condition in Experiments 1 and 2

In order to confirm that the results of the two experiments were consistent, a three-way ANOVA on RTs with the factors of emotional valence, word form, and experiment was conducted; the first two were within-subject factors, and the last one was a between-subject factor. The main effects of emotional valence [$F(1, 22) = 22.87$, $MSE = 20473.32$, $p < .0005$, $\eta_p^2 = .51$] and word form [$F(2, 44) = 73.487$, $MSE = 130954.54$, $p < .0001$, $\eta_p^2 = .77$] were significant, but the main effect of experiment was not [$F(1, 22) = .80$, $p > .05$, $\eta_p^2 = .04$].

The interaction of emotional valence and word form was significant [$F(2, 44) = 9.49$, $MSE = 27176.27$, $p < .0005$, $\eta_p^2 = .30$], as it had been in each of the previous experiments. In the upright condition, negative words ($M = 1762$ ms) were detected slower than neutral words ($M = 1480$ ms) [$F(1, 66) = 38.31$, $MSE = 24941.96$, $p < 0.0001$, $\eta_p^2 = .37$] but not when they were inverted or scrambled [$F(1, 66) = 1.06$, $p > .05$, $\eta_p^2 = .02$ and $F(1, 66) = .08$, $p > .05$, $\eta_p^2 = .001$, respectively]. The Tukey test for the simple main effect of neutral words [$F(2, 88) = 78.97$, $MSE = 79065.41$, $p < 0.0001$, $\eta_p^2 = .64$] showed that upright words ($M = 1479$ ms) were detected faster than the inverted words ($M = 1890$ ms), which were detected faster than the scrambled words ($M = 2493$ ms). In the negative-word condition, the simple main effect of word form was also significant [$F(2, 88) = 46.01$, $MSE = 79065.41$, $p < .0001$, $\eta_p^2 = .51$]; scrambled words ($M = 2507$ ms) were detected slower than upright and inverted words ($M = 1762$ ms and $M = 1937$ ms, respectively), and the latter two were not significantly different.

The interaction of word form and experiment was also significant [$F(2,44) = 4.20$, $MSE = 130954.54$, $p < .05$, $\eta_p^2 = .16$]. However, the simple main effect was found only within each experiment but not across experiments; that is, the effect of word form was significant in Experiment 1 [$F(2, 44) = 56.06$, $MSE = 130954.54$, $p < .0001$, $\eta_p^2 = .72$] and Experiment 2 [$F(2, 44) = 21.63$, $MSE = 130954.54$, $p < .0001$, $\eta_p^2 = .50$]. The results of the two experiments were not different when words were in the upright [$F(1, 66) = 2.14$, $p > .05$, $\eta_p^2 = .03$], inverted [$F(1, 66) = 1.5$, $p > .05$, $\eta_p^2 = .02$], and scrambled [$F(1, 66) = .03$, $p > .05$, $\eta_p^2 = .0005$] conditions. The interaction of emotional valence and experiment was not significant [$F(1, 22) = 1.28$, $p > .05$, $\eta_p^2 = .05$], and neither was the interaction between emotional valence, word form, and experiment [$F(2, 44) = 1.39$, $p > .05$, $\eta_p^2 = .06$].

The accuracy data showed that the main effect of word form was significant [$F(2, 44) = 20.965$, $MSE = 0.001$, $p < .0001$, $\eta_p^2 = .48$]; Upright words ($M = 96.8\%$) led to higher accuracy than inverted words ($M = 94.6\%$), which led to higher accuracy than scrambled words ($M = 92.5\%$). The main effect of emotional valence [$F(1, 22) = 17.668$, $MSE = 0.001$, $p < .001$, $\eta_p^2 = .45$] was significant; lower accuracy was found for negative words ($M = 93.6\%$) than for neutral words ($M = 95.6\%$). The interaction of experiment and word form was also significant [$F(2, 44) = 6.873$, $MSE = 0.001$, $p < .01$, $\eta_p^2 = .24$]; the accuracies of word forms were significantly different in Experiment 1 [$F(2, 44) = 24.744$, $MSE = .001$, $p < .0001$, $\eta_p^2 = .56$], the Tukey test showed that upright words ($M = 97.2\%$) led to higher accuracy than inverted words ($M = 94.8\%$), which led to higher than scramble words ($M = 90.8\%$). The accuracies of scrambled words between the two experiments were also different [$F(1, 66) = 4.257$, $MSE = .003$, $p < .05$, $\eta_p^2 = .06$]; it was higher in Experiment 2 ($M = 94.3\%$) than in Experiment 1 ($M = 90.8\%$).

There was no significant difference between experiments [$F(1, 22) = .213$, $p > .05$, $\eta_p^2 = .01$], nor was there interaction between experiment and valence [$F(1, 22) = .155$, $p > .05$, $\eta_p^2 = .01$] or between valence and word form [$F(2, 44) = .474$, $p > .05$, $\eta_p^2 = .02$]. Neither was there a three-way interaction [$F(2, 44) = .831$, $p > .05$, $\eta_p^2 = .04$].

3.4. Auxiliary experiment

For both Experiments 1 and 2, we found differences in accuracy between the dichoptic and binocular viewing conditions. In Experiment 1, the mean accuracy was 94.39% for dichoptic viewing and 98.44% for binocular viewing [$F(1, 11) = 20.309$, $MSE = 0.000$, $p < .001$, $\eta_p^2 = .64$]; in Experiment 2, it was 94.79% for dichoptic viewing and 99.05% for binocular viewing [$F(1, 11) = 10.74$, $MSE = 0.001$, $p < .001$, $\eta_p^2 = .49$]. This result may imply a different uncertainty for the observer under these two viewing conditions. To approximate the level of uncertainty between the two viewing conditions, we ran an additional experiment similar to the second experiment in procedure and stimuli; however, we mixed the two viewing conditions within a block and compared negative and neutral words in the upright condition only. Six participants from the same subject pool participated in this auxiliary experiment. Results showed similar accuracy levels between the two viewing conditions [$M = 99.3\%$ for binocular and 97.8% for dichoptic viewing; $F(1, 5) = 4.084$, $p > .05$, $\eta_p^2 = .44$]. The main effect of emotion valence was significant [$F(1, 5) = 16.99$, $MSE = 2806.50$, $p < .001$, $\eta_p^2 = .77$]; a planned comparison still showed that negative words were detected slower ($M = 1655$ ms) than neutral ones ($M = 1495$ ms) in dichoptic viewing [$F(1, 10) = 13.27$, $MSE = 5802.03$, $p < .01$, $\eta_p^2 = .57$] but not in binocular viewing ($F(1, 10) = .169$, $p > .05$, $\eta_p^2 = .02$; $M = 1368$ ms for negative word and $M = 1350$ ms for neutral one). Therefore, the difference in the uncertainty level should not be the cause for the results of a slower response for negative words than for the neutral ones found only in the dichoptic but not in the binocular viewing conditions.

3.5. Discussion

In this second experiment, both neutral and negative words were content words, and the emotion words – those that induce emotions rather than those that describe emotions – were like those used in the first experiment. Nonetheless, the results were similar to those found in Experiment 1: RTs were slower for negative words than for neutral words in the interocular suppression phase – but only for upright words. The cross-experiment analysis revealed that the effects did not differ between experiments, which indicate that the RT difference obtained was not affected by the different manipulations in these two experiments. Furthermore, the result of no RT difference found between negative and neutral words under the binocular viewing condition excludes the possibility of a response bias to explain the RT difference in the dichoptic viewing condition. Further, the results from the auxiliary experiment in which the two viewing conditions were mixed in a block exclude the possibility that uncertainty plays a role. The reliable results obtained from both experiments support the view that even when words are not consciously perceived during the suppression phase, their emotional meanings can still affect the processing time for them to emerge in the viewer's consciousness.

4. General discussion

This study examined whether words' meanings can be processed implicitly *without any awareness* by adopting the CFS paradigm. Results from two experiments clearly demonstrate that words can be processed up to the semantic level even though they are invisible; this is possible due to strong ocular suppression in binocular rivalry, which is reflected by the RT difference for processing words that carry emotional information than for words that do not have emotional information. This was true when the emotion words were those that described emotion (Experiment 1) or those that induced emotion (Experiment 2) and when the neutral words were function words (Experiment 1) or when they were content words (Experiment 2). The possibility of response bias was excluded since no RT difference was observed in the binocular viewing condition; even the uncertainty between two viewing conditions was made more similar by mixing the two conditions within a single block (auxiliary experiment). Using the CFS paradigm has the advantage of presenting the critical stimulus under implicit processing for a long time before it emerges to form conscious perception. In this way, the semantic information can be fully processed without involving partial awareness, which has been an issue in previous studies (Abrams & Grinspan, 2007a, 2007b; Kouider & Dupoux, 2004, 2007).

Except for a study by Costello et al. (2009) that used the aid of a visible prime presented for 2 s, existing studies have not yet demonstrated semantic processing in the suppressed phase during binocular rivalry. Zimba and Blake (1983) presented the prime word during suppression or during dominance and found shorter lexical decision RTs for semantically related words (i.e., a semantic priming effect) only during dominance phases of rivalry. Thus, they concluded that no semantic processing is possible during suppression. However, notice in their second auxiliary experiment that they also show that under the suppression phase, the magnitude of semantic priming was increased with increasing prime duration, as was the identification accuracy (accuracy was 58% for 66 ms, 78% for 126 ms, and 100% for 186 ms prime duration). That is, in their study, processing time correlates with the probability for the prime to break into consciousness. The advantage of using the CFS paradigm is that we can lengthen the duration of the emotional words to increase the processing time in the suppression state; this still ensures that these words are invisible before the response. In other words, the CFS paradigm suppresses the stimulus from awareness better than the conventional binocular rivalry paradigm used in Zimba and Blake (1983), even with the stimulus duration much longer than the longest one they used. The absence of semantic access during suppression in their study and the presence in ours suggest that sufficient processing time is needed for suppressed words to be processed up to the semantic level while remaining suppressed from conscious perception. Along the same line of reasoning, Lo and Yeh (2008) demonstrated the dissociation of processing time and consciousness and showed that some processes – such as texture segregation – require sufficient processing time to be accomplished under the unconscious state.

On the other hand, the semantic priming effect observed in Costello et al. (2009) may have been manifested by activation between the connections of a prime word's node to a semantically relevant target's node due to the closely interconnected semantically relevant nodes (Collins & Loftus, 1975; McNamara, 1992). In other words, the visible prime word may have paved the way for the invisible target through activation of the semantic nodes, making the semantically related target become perceptually more fluent. We went one step further in this study by demonstrating that emotional words, per se – without any aid from a preceding prime – can be processed differently from neutral words in the suppression phase in binocular rivalry. Taken together with previous studies using the binocular rivalry paradigm (e.g., Costello et al., 2009; Zimba and Blake,1983), the current study provides further evidence that binocular rivalry is a multistage competition processing (Blake & Logothetis, 2002; Costello et al., 2009; Freeman, 2005; Walker,1978) and, most importantly, could be at or beyond semantic access.

Why can invisible words' meanings be accessed implicitly? Three possibilities can be provided here: first, Chinese is considered a logographic writing system, which has a closer orthographic–semantic relationship than alphabetic systems (Wang, 1973). Given the closer shape-meaning relationship inherent in the Chinese writing system, it is possible that it will affect the neural coding and, thus, the rules of identification under CFS.[1] For example, the strokes in each Chinese character may undergo an "unconscious binding" process (Lin & He, 2009) that not only encodes individual features but also combines different features in a hierarchical way (Yeh, Li, Takeuchi, Sun, & Liu, 2003), forming higher-level representations such as word form and meaning. This could be further enhanced by the functional significance of the emotional valence embedded in words. Alternatively, according to the hierarchy and reverse hierarchy model (Hochstein & Ahissar, 2002), the feed-for-

[1] We thank Bruce Bridgeman for suggesting this possibility.

ward hierarchy pathway processes stimulus properties from low-level to high-level brain areas implicitly without consciousness, and the high-level area – such as the inferotemporal area – is the first stage of explicit processing to represent different objects and categories in gist. From this perspective, it seems possible that we know the emotional valence from words before we identify what the words are. Finally, emotional information seems robust in the implicit processing pathway when explicit information and implicit information are separately processed in different streams (Lo & Yeh, 2008). Previous studies have demonstrated automatic/unattended/unconscious processing of emotional pictures or faces (e.g., Anderson & Phelps, 2001; Jiang & He, 2006; Most, Chun, Widders, & Zald, 2005; Vuilleumier, Armony, Driver, & Dolan, 2001), and anatomical studies also indicate that the amygdala plays an important role in emotional processing (Costafreda, Brammer, David, & Fu, 2008; Phelps & LeDoux, 2005; Sergerie, Chochol, & Armony, 2008; but see Tsuchiya, Moradi, Felsen, Yamazaki and Adolphs (2009)). Using emotional words as the index of semantic information extraction in the current study thus provides the advantage that the emotional information carried might cause higher cortical and subcortical activation, regardless of whether the carriers are faces, pictures, or words.

Our finding that there is a slower response and lower accuracy to release from interocular suppression for negative words than neutral words is attributed to the semantic difference between the types of words. Particularly, accessing the meaning of negative emotions implicitly may have retarded the response because of the difficulty in *dis*engaging from negative emotional information. According to the automatic vigilance hypothesis (Estes & Adelman, 2008; Pratto & John, 1991), negative information would attract attention automatically and be rapidly evaluated. However, the slower disengagement of attention from negative stimuli would cause a retarded response to consequence stimuli (e.g., Huang et al., 2008; Most et al., 2005) or negative stimuli per se (Algom, Chajut, & Lev, 2004).

Yang et al. (2007) used the CFS paradigm and found *shorter* RTs for invisible fearful *faces* than for neutral ones, whereas we found *longer* RTs for negative *words* than for neutral ones. The major difference between their study and the current one lies in the emotionally laden stimuli used in the two studies: faces vs. words. As a result, the perceptual salient features embedded in fearful faces may have contributed to the faster detection rate in their study. Indeed, Yang et al. (2007) found similar advantage for fearful faces when the faces were inverted, and even when only the areas of the eyes were presented. Furthermore, the fearful face advantage was also found in the amygdala-impaired patient (Tsuchiya et al., 2009). These all suggest that perceptually salient features such as large white eyes may contribute to the faster detection rate of fearful faces. When words were used, as in the current study, it is the difference in emotion valence (negative vs. neutral), rather than any perceptual features, that contributes to the difference in results between negative and neutral words, as revealed by the similar detection rate in our inverted condition. This may imply that without any contribution from perceptual features, the pure negative valence effect on CFS may be possibly really slowing down the detection.[2] This is an interesting question worthy of further investigation.

Alternatively, faces and words may trigger distinct processing pathways in the brain (i.e., *the dual-route hypothesis* of emotion evaluation, LeDoux, 2000; Phelps & LeDoux, 2005). Processing of faces may take a direct pathway from thalamus to amygdala, whereas processing of words may take the indirect pathway from the occipitotemporal area and the visual word form area (Cohen et al., 2000) and then to the amygdala. Much evidence from fMRI studies have supported distinctly different brain pathways for faces and words (e.g., Costafreda et al., 2008; Gaillard & Naccache, 2005), and behavioral studies also indicate a different processing of emotional faces and words (e.g., Raccuglia & Phaf, 1997). One caveat derived from the current study is that future studies should take into consideration this stimulus-specific effect in emotion processing.

Finally, arousal level may modulate the processing speed of negative stimuli. Larsena, Mercera, Balotaa and Strubea (2008) conducted a meta-analysis and showed that the slower lexical decision response to negative words was obtained only for low-arousal but *not* for high-arousal words. This modulation effect of arousal level in emotion processing also affects the dominance duration and the first percept in binocular rivalry (Sheth & Pham, 2008): negative pictures are more dominant than positive ones at the high-arousal level but less dominant at the low-arousal level. It is possible that the lower the arousal level, the less dominant the negative stimulus. This may provide some hint as to the discrepancy in results: better performance for negative stimuli (Yang et al., 2007) or worse (the current study) than neutral ones. Compared to studies using faces or pictures as emotional-laden stimuli, the slower response to negative words found in the current study may be due to their lower arousal level in general.

Our results also show that for both dichoptic and binocular viewing conditions, inverted words are detected faster than scrambled words. This suggests that even for unfamiliar forms, such as inverted words, the holistic form has preserved some kind of perceptual grouping advantage (i.e., orthography) not found when one is presented with scrambled words. This finding is consistent with previous studies showing that contour integration affects the switch in binocular rivalry (Alais & Blake, 1999; Alais, Lorenceau, Arrighi, & Cass, 2006; Silver & Logothetis, 2004). Furthermore, the similar detection rate for negative and neutral words when inverted and scrambled indicates identical baselines at the orthographic or local features in space domain, respectively. Compared to earlier findings, the current study provides clear evidence that during the implicit semantic processing of symbolic carriers such as words, the emotional information carried can be extracted without the involvement of salient perceptual features or forms, as discussed above.

In conclusion, by demonstrating genuine semantic processing under interocular suppression, this study provides significant insights into specific visual processing such as reading. Although acquiring reading skills takes effortful learning that

[2] We thank Naotsugu Tsuchiya for pointing out this.

involves intention and consciousness, once the skill is learned, a skilled reader can extract the meaning of words without any conscious effort after all.

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