

Depth of facial expression processing depends on stimulus visibility: Behavioral and electrophysiological evidence of priming effects

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Participants performed a priming task during which emotional faces served as prime stimuli and emotional words served as targets. Prime–target pairs were congruent or incongruent, and two levels of prime visibility were obtained by varying the duration of the masked primes. To probe a neural signature of the impact of the masked primes, lateralized readiness potentials (LRPs) were recorded over motor cortex. In the high-visibility condition, responses to word targets were faster when the prime–target pairs were congruent than when they were incongruent, providing evidence of priming effects. In line with the behavioral results, the electrophysiological data showed that high-visibility face primes resulted in LRP differences between congruent and incongruent trials, suggesting that prime stimuli initiated motor preparation. Contrary to the above pattern, no evidence for reaction time or LRP differences was observed in the low-visibility condition, revealing that the depth of facial expression processing is dependent on stimulus visibility.

Facial expression serves as a major source of nonverbal information in social interactions (Adolphs, 2002). Consistent with such social significance, previous research has suggested that facial expression processing is privileged and may take place independent of awareness. For example, it has been reported that reaction to a target is influenced by a facial expression *prime* stimulus preceding it, even when the prime was briefly presented and masked so that participants were unaware of its occurrence (Murphy & Zajonc, 1993; Neidenthal, 1990). In line with these behavioral results, neuroimaging studies have reported that the amygdala, a subcortical brain region believed to be important for emotional processing, evokes responses to emotion-laden faces when they are presented in backward masking conditions (Morris, Öhman, & Dolan, 1998; Whalen et al., 2004; Whalen et al., 1998). In addition, event-related potential (ERP) studies have reported that unconsciously processed facial expressions may exhibit differential P1 (90–140 msec) and N2 (150–200 msec) component responses, suggesting that unaware facial information can be registered at early visual processing stages (Kiss & Eimer, 2008; Li, Zinbarg, Boehm, & Paller, 2008; Liddell, Williams, Rathjen, Shevrin, & Gordon, 2004; Williams et al., 2004). Despite evidence supporting unaware perception of facial expressions, contrasting results have been presented recently. These studies have reported differential amygdala responses to fearful faces in aware conditions, but not in unaware conditions (Pessoa, Japee, Sturman, & Ungerleider, 2006; Phillips et al., 2004), and have suggested that many participants are able

to detect briefly presented and masked face stimuli (Pessoa, 2005; Szczepanowski & Pessoa, 2007).

Although a vast literature has addressed the challenging question of visual awareness, relatively little is known about how different *levels* of stimulus visibility affect behavior and the brain, especially in the domain of facial expression processing (Wiens & Öhman, 2007). Indeed, much of the work on visual awareness has focused on establishing the types of processing that do or do not occur in *unaware* conditions. This emphasis is present, we believe, given the overall tendency of researchers to view awareness as a binary phenomenon—for instance, a participant is either *aware* or *unaware* of a stimulus. Here, we reasoned that if perception is not all or none, and instead is more gradual (Cleeremans & Dienes, 2008), facial expression processing should vary as a function of stimulus visibility.

Studies supporting the notion that unaware processes may involve higher levels (e.g., semantic) of processing have capitalized on the *congruency priming paradigm*, in which priming effects are obtained when prime and target stimuli are congruent (Dehaene et al., 1998; Greenwald, Draine, & Abrams, 1996; Greenwald, Klinger, & Liu, 1989). For instance, when affective word primes were masked, the semantic classification of affective word targets was faster when the prime and target were congruent—that is, when both prime and target denoted positive or negative emotion—than when they were incongruent—that is, when the prime–target pair was positive–negative or negative–positive (Greenwald et al., 1996; Greenwald et al., 1989). In the present study, we were interested in

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testing whether priming effects could be modulated by the visibility of face prime stimuli—in other words, testing whether low-visibility facial expression primes (like affective word primes) also have an impact on a semantic word classification task. Since semantic priming effects between facial expressions and words have been reported (Carroll & Young, 2005), we reasoned that if facial expression processing is strongly privileged, priming should be observed in *both* low- and high-visibility conditions. Our study utilized facial expressions as primes and emotional words as targets. On half of the trials, the prime was congruent with the target (both were positive or negative), and on the other half, it was incongruent with the target. Participants were instructed to make semantic decisions of whether words belonged to the category “happy” or “fearful.” Two levels of face prime visibility were obtained by varying the durations of the backward-masked faces (Figure 1A).

The lateralized readiness potential (LRP) is an ERP that is maximally generated at scalp sites over motor cortex, contralateral to the responding hand (Coles, Gratton, & Donchin, 1988; De Jong, Wierda, Mulder, & Mulder, 1988). Because LRPs can occur in the *absence* of an overt response (and thereby reflect motor preparation), they provide a powerful method for probing whether specific perceptual or cognitive information is available for the motor system before an actual motor response. In fact, previous studies have exploited this property in order to investigate the impact of briefly presented and masked primes (Dehaene et al., 1998; Eimer & Schlaghecken, 1998). The

logic behind these studies is that if primes are processed and, in turn, influence participants’ task execution, those primes should trigger LRP-related activity *before* overt responses to the targets are made. Thus, in contrast to reaction time (RT) data, which reflect cumulative effects derived from prime and target stimuli, the LRP measure provides a strategy for gauging prime-related activity as the trial temporally unfolds (see Figure 2 and Method). To examine the role of stimulus visibility in facial expression perception, in the present study, we used a combination of behavioral and electrophysiological techniques. As in previous studies (Dehaene et al., 1998; Eimer & Schlaghecken, 1998), we recorded ERPs over motor cortex while participants performed the priming task. In general, our study investigated two types of markers of the impact of the prime stimuli. First, behaviorally, if effectively processed, the primes would be expected to lead to RT effects when congruent and incongruent trials were compared (Dehaene et al., 1998; Greenwald et al., 1996; Greenwald et al., 1989). Second, the LRP waveform provided a neural signature of the impact of the prime per se, since differences in motor potentials between trial types could be used for determining whether face primes initiated motor preparation before actual motor response (Dehaene et al., 1998).

A potential explanation for the discrepancy of results concerning unaware perception of facial expressions relates to how awareness is operationally characterized (Hannula, Simons, & Cohen, 2005; Pessoa, 2005; Pessoa, Japee, & Ungerleider, 2005; Szczepanowski & Pes-

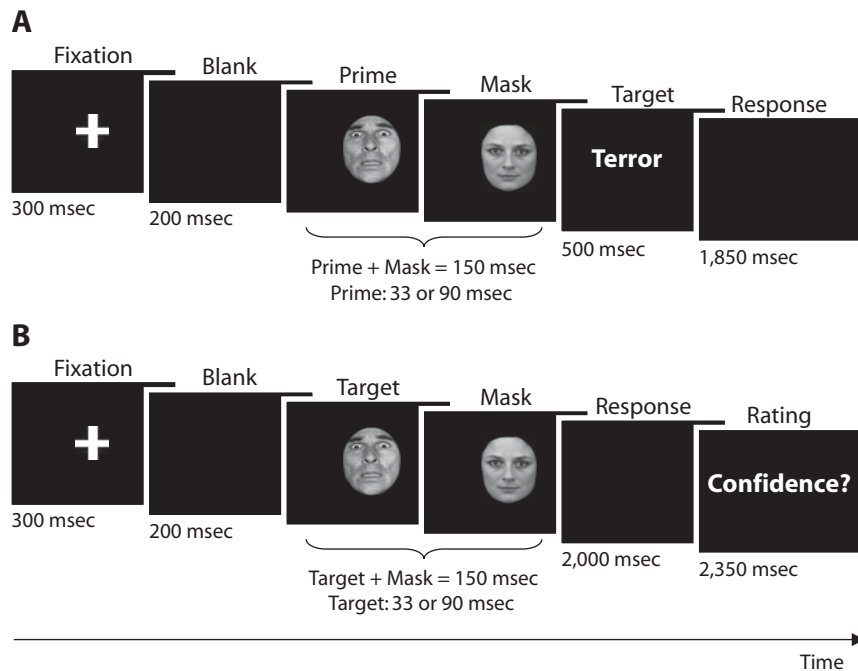


Figure 1. (A) Priming paradigm. Fearful, happy, or neutral face primes were displayed for 33 or 90 msec and were immediately followed by a neutral face mask. Participants were requested to make a semantic classification (“fearful” or “happy”) on a word target that was presented immediately after the prime–mask pair. (B) Awareness paradigm. Following the faces, participants were requested to discriminate whether the first face was a fearful or a happy face. Next, they rated the confidence (low, high) in their previous response.

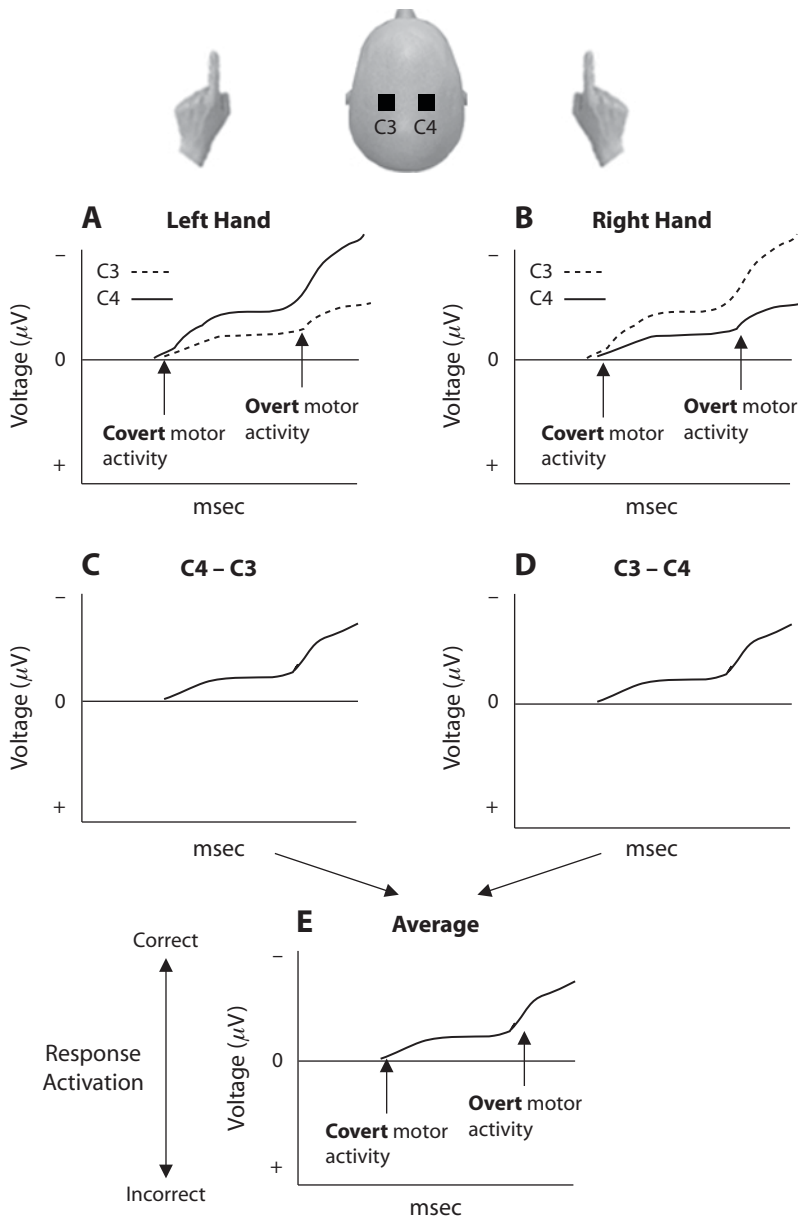


Figure 2. Derivation of the lateralized readiness potential (LRP). The top panels show idealized ERPs recorded from C3 and C4 electrodes over the left and right motor cortex. (A) The potentials associated with the left-hand movements. (B) The potentials associated with the right-hand movements. When a stimulus, such as a prime, conveys response-related information, stronger covert motor activation at scalp sites contralateral to the responding hand may develop before an actual movement is executed. Likewise, an overt movement leads to strong differential scalp-related signals. Differences between scalp sites can then be captured by calculating the differences of the potentials recorded from the C3 and C4 electrodes: C4 – C3 for the left-hand movements (panel C) and C3 – C4 for the right-hand movements (panel D). Next, the difference potentials for left- and right-hand movements are averaged to form the LRP (panel E). An upward LRP deflection reflects activation of a correct response, and a downward LRP deflection (not shown) indicates activation of an incorrect response, such as that primed by an incongruent stimulus in the present experiment. This figure was inspired by Coles (1989).

soa, 2007)—namely, via subjective or objective methods (Merikle, Smilek, & Eastwood, 2001; Snodgrass, Bernat, & Shevrin, 2004). According to subjective criteria, the assessment of awareness should be based on participants' self-reports, whereas objective measurements propose to use participants' performance levels as indications of awareness, typically during forced-choice tasks. The studies reporting unaware perception of facial expressions have often evaluated awareness according to the subjective method, which usually has a lower threshold than that of the objective method (Szczepanowski & Pessoa, 2007). By contrast, the studies that have failed to find unaware perception have often evaluated awareness via the objective method. In the present study, we employed both methods to assess participants' awareness of the masked primes as a function of prime duration. During a separate behavioral session, subjective and objective awareness measures were estimated within the same task through the use of signal detection theory (SDT) methods (Green & Swets, 1966; Macmillan & Creelman, 2005; Szczepanowski & Pessoa, 2007).

We believe that face processing should influence the LRP in our paradigm. The congruency priming effect has long been attributed to the results of response competition between primes and targets, indicating that *prime*-related information is transmitted to the response system, thereby potentially interfering with *target*-related responses (Dehaene et al., 1998; Greenwald et al., 1996; Greenwald et al., 1989). In particular, we do not hypothesize the involvement of direct projections from the amygdala to primary motor cortex. Instead, we hypothesize that face processing activates semantic representations that prime motor responses (see also the Discussion).

METHOD

Participants

Fifteen right-handed participants (8 males; mean age = 22 years, range = 19–31) without past neurological or psychiatric history took part in the study. All had normal or corrected-to-normal vision and gave informed consent according to procedures approved by the Institutional Review Board of Indiana University, Bloomington.

Priming experiment. As shown in Figure 1A, each trial began with a fixation duration of 300 msec, followed by a blank stimulus of 200 msec, followed by a happy or a fearful face prime, which was immediately masked by a neutral face. The prime and the mask involved different identities. The visibility of the face prime was manipulated by presenting it for 33 or 90 msec. The total duration of the prime–mask pair was fixed at 150 msec. Following the faces, a happy or a fearful word target stimulus was displayed for 500 msec. Participants were instructed to attend to the stimuli throughout the entire trial and to make a happy or fearful judgment on the target word as quickly and as accurately as possible. A right-hand buttonpress was required for a happy word, whereas a left-hand buttonpress was required for a fearful word. The assignment of response hands was reversed for the second half of each participant's session. To rule out the possibility that different prime durations would contribute to any confounding effects, additional conditions with neutral face primes were introduced. Overall, the priming experiment was a 3 (*congruency*: *congruent*, fear–fear and happy–happy prime–target stimuli; *incongruent*, fear–happy and happy–fear; *neutral*, neutral–fear and neutral–happy) × 2 (*visibility*: *low*, 33-msec prime duration; *high*, 90-msec prime duration) design. Participants completed 10 runs, each consisting of 120 tri-

als, with 200 trials for each condition. The order of the trials within each run was randomized.

Awareness experiment. Before performing the priming experiment, participants participated in a separate behavioral session that assessed visual awareness. The awareness paradigm was similar to the one used during the priming experiment, except that the faces were not followed by word targets, and neutral face primes were not included (Figure 1B). Participants were instructed to discriminate whether masked faces exhibited a fearful or a happy expression, in addition to rating their confidence in the response (low or high confidence). Details of a similar experimental procedure and further rationale can be found in a recent study by Szczepanowski and Pessoa (2007).

Stimuli

Face stimuli used in the present study were obtained from the Ekman series (Ekman & Friesen, 1976), subtending a visual angle of 3° × 4°. Five instances of identity-matched fearful, happy, and neutral faces were adopted. Most of the hair and nonfacial contours were excluded from the faces. Word stimuli were adapted from Carroll and Young's (2005) study. The happy words were *pleasure*, *ecstasy*, *happiness*, *cheer*, and *delight*; the fearful words were *dread*, *terror*, *fright*, *fear*, and *scare*. In Carroll (2004), all words (1° × 2° to 4°) received high ratings for the corresponding emotional category.

Data Analysis of the Awareness Experiment

The aim of the awareness experiment was to evaluate participants' subjective and objective awareness of the 33- and 90-msec faces used as the primes in the priming experiment. To obtain an index of *objective* awareness, a standard sensitivity measure (d') was computed using SDT methods. We refer to this measure as $d'_{\text{objective}}$. As an index of *subjective* awareness, we estimated participants' ability to discriminate between correct and incorrect responses, on the basis of their confidence ratings (Kolb & Braun, 1995; Kunimoto, Miller, & Pashler, 2001). To do so, we partitioned trials in the following manner: A "hit" corresponded to a correct trial with high confidence; a "miss" corresponded to a correct trial with low confidence; a "false alarm" corresponded to an incorrect trial with high confidence; and a "correct rejection" corresponded to an incorrect trial with low confidence. Thus, *correct* trials the participant rated with high confidence were hit trials, whether or not the masked face was fearful or happy. *Incorrect* trials the participant rated with high confidence were false alarm trials, irrespective of the type of target face. These definitions follow those employed in Type 2 SDT analyses (Galvin, Podd, Drga, & Whitmore, 2003; Pollack & Decker, 1958). As a result, an SDT-like measure of sensitivity reflecting *subjective* perception could be derived: $d'_{\text{subjective}}$. As argued by Kunimoto et al. (2001), the present measure of subjective perception is phenomenologically valid because it depends crucially on the participant's own introspective assessment of his or her performance. According to this view, the participants' confidence *cannot reflect accuracy* unless they are partially aware of the information on which they based their discriminative responses—that is, high versus low confidence (Kunimoto et al., 2001). Under conditions in which participants have no awareness of the stimuli, their confidence ratings should be *unrelated to accuracy*. (See also Szczepanowski & Pessoa, 2007, for further discussion.)

Electrophysiological Recording and Analysis

During the priming experiment, electrophysiological data were recorded continuously using an EPA-6 Sensorium bioamplifier (1000-Hz A/D rate; 0.02-Hz high pass; 300-Hz low pass; gain = 10K). Recordings were made at the C3 and C4 sites using an extended International 10–20 cap system with Ag/AgCl-sintered electrodes referenced to the tip of the nose. Vertical electrooculogram (VEOG) was recorded from bipolar electrodes placed above and below the left eye. All electrode impedances were kept below 10 kΩ.

For ERP analysis, the continuous data (including VEOG) were first resampled at 125 Hz and digitally filtered with a 20-Hz low-pass filter. (The same pattern of results was obtained when no low-

pass filtering was employed.) Next, the filtered data were segmented into 1,300-msec epochs starting 200 msec before the onset of fixation. Trials were rejected according to the following criteria: incorrect behavioral responses; RTs longer than the mean plus or minus four standard deviations; VEOG exceeding $\pm 75 \mu\text{V}$ (peak to peak); or voltages exceeding $\pm 100 \mu\text{V}$ (peak to peak). As a result, 62% to 96% of the trials were considered artifact-free. The remaining trials were baseline corrected with respect to a 200-msec prestimulus time window. EEGLAB (www.sccn.ucsd.edu/eeglab/) and MATLAB (MathWorks, Natick, MA) were used for data preprocessing, analysis, and visualization.

The LRP was computed according to standard procedures (Coles et al., 1988) (Figure 2). For each condition, activity at the C3 and C4 electrode sites was first averaged separately for congruent and incongruent trials according to prime duration (33 or 90 msec). For the neutral prime condition, activity was averaged separately for the two durations. Next, the averaged ERP activity was sorted according to the hand of response. The LRP for each of the six conditions ($3 \text{ congruency} \times 2 \text{ visibility}$) was then defined according to the formula $\text{LRP} = [(C4 - C3)_{\text{left hand}} + (C3 - C4)_{\text{right hand}}] / 2$. This formula computes the average of the difference potentials between the C3 and C4 sites for trials with left-hand responses and the difference potentials for trials with right-hand responses. The LRP makes explicit the lateralized negativity (upward, in our figures) that precedes a movement in a way that is hemisphere independent (given the averaging) and that subtracts away any nonmotor asymmetrical activity (Coles et al., 1988). Critically, note that the initial preparation of an *incorrect* movement on an *incongruent* trial will give rise to an initial positive (downward) LRP deflection (not shown in Figure 2; see Figures 5 and 8; see also Dehaene et al., 1998), even when the initially incorrect plan is canceled and only the correct movement is actually executed (on the basis of the target information). In other words, on trials in which the *prime* stimulus is processed at the motor level (i.e., affects motor preparation), LRP activity on a *congruent* trial should exhibit a negativity following the prime and a stronger negativity following the target, the latter reflecting the eventual motor response. LRP activity on an *incongruent* trial should exhibit a positivity following the prime (i.e., the prime signals a response that is opposite to that signaled by the target) and, again, a stronger negativity following the target.

Critically, LRP difference waveforms between congruent and incongruent trials provide an index of the extent to which *prime* stimuli affect response-related processes; this procedure effectively “subtracts away” covert LRP-related activity potentially contaminated by the *targets*. In other words, because subtractions that involve comparing *all* congruent to *all* incongruent conditions involve the same target stimuli (i.e., fearful and happy words), any resulting LRP differences before actual motor execution must have originated from the processing of the *prime* stimulus. For the statistical analyses below, condition-related LRPs were averaged within specific temporal windows (e.g., average LRP signal from 600–900 msec) and then tested via repeated measures ANOVAs or *t* tests.

RESULTS

Awareness Experiment

Objective ($d'_{\text{objective}}$) and subjective ($d'_{\text{subjective}}$) awareness values for low- and high-visibility conditions are displayed in Figure 3. As expected, participants exhibited increased sensitivity in high- relative to low-visibility conditions, in terms of both objective [$t(14) = 4.97, p < .001$] and subjective [$t(14) = 3.77, p < .01$] measures. Although sensitivity values for both measures were significantly lower in the low-visibility condition, participants' performance was still better than chance ($d' = 0$), as confirmed by one-sample *t* tests [$d'_{\text{objective}}, t(14) = 7.85, p < .001$; $d'_{\text{subjective}}, t(14) =$

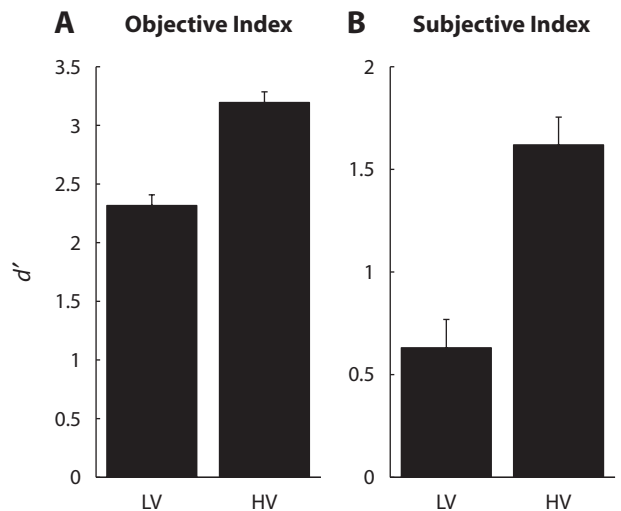


Figure 3. Values of awareness sensitivity (d') as a function of low or high visibility, according to (A) objective and (B) subjective measures. Error bars indicate 95% within-participants confidence intervals (Loftus & Masson, 1994).

3.48, $p < .01$]. We further examined participants' awareness of masked faces at the individual level by testing the significance of d' for each individual (Macmillan & Creelman, 2005); a p value of .05 was employed as the statistical threshold. The results showed that in the low-visibility condition, a total of 14 participants were able to reliably detect fearful faces according to the objective measure, and a total of 5 participants exhibited subjective awareness; with Bonferroni correction for multiple comparisons, 12 were objectively aware and 2 were subjectively aware. Note that all participants exhibited $d'_{\text{objective}}$ and $d'_{\text{subjective}}$ values significantly greater than zero in the high-visibility condition.

Priming Experiment

Behavioral performance. RTs and accuracy for congruent (fearful prime–fearful target/happy prime–happy target) and incongruent (fearful prime–happy target/happy prime–fearful target) trials were computed separately for low- and high-visibility conditions. A two-way repeated measures ANOVA was conducted on the RTs and, separately, on accuracy, with the factors of *congruency* (congruent, incongruent) and *visibility* (low, high); neutral trials were analyzed separately as a control condition. For RTs, the analyses showed a significant main effect of *congruency* [$F(1,14) = 8.13, p < .05$], but no main effect of *visibility* [$F(1,14) = 1.19, p = .3$], and a significant *visibility* \times *congruency* statistical interaction [$F(1,14) = 7.55, p < .05$], revealing that the RT pattern differed for the low- and high-visibility conditions (Figure 4). No significant effects were observed for accuracy [for the interaction, $F(1,14) = 2.67, p = .12$]. To examine the interaction effect further, additional *t* tests were conducted on the RTs for each visibility condition. RTs were significantly faster on congruent than on incongruent trials in the high-visibility condition [$t(14) = 4.6, p < .001$], but not in the low-visibility condition [$t(14) = 0.62,$

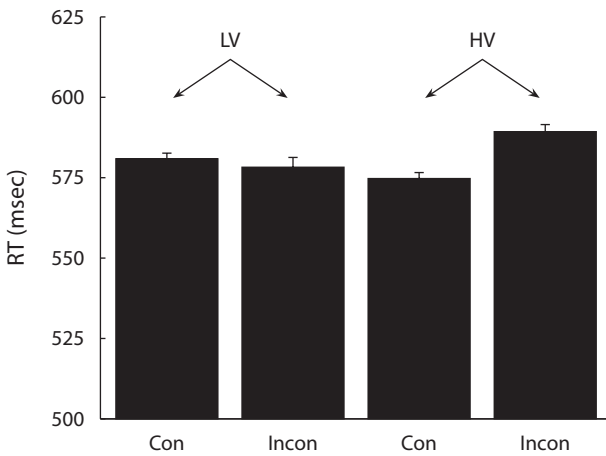


Figure 4. Mean reaction times (RTs) as a function of visibility (high, low) and congruity (congruent, incongruent). Error bars indicate 95% within-participants confidence intervals.

$p = .55$]. These findings indicate that priming effects were only evident in the high-visibility condition.

Electrophysiological data. Figure 5 shows the LRP waveforms obtained for congruent and incongruent trials for each prime visibility. A two-way repeated measures ANOVA was performed first to examine the relationship between *congruency* and *visibility* on the LRPs. Because we were interested in the potential effects of the prime stimuli, averaged LRP amplitudes in the interval between 600 and 900 msec were entered into the analysis (see the shaded region in Figure 5; prime onset occurred at 500 msec). The analysis revealed a significant main effect of *congruency* [$F(1,14) = 9.57, p < .01$], but no main effect of *visibility* [$F(1,14) = 0.64, p = .4$], and a significant *visibility* \times *congruency* interaction [$F(1,14) = 4.80, p < .05$], indicating that prime visibility affected the LRP waveforms differently for congruent and incongruent trials. Note that these interaction results effectively “subtract

away” target effects, since the results involved comparing *all* congruent to *all* incongruent conditions, and thus contained the same target stimuli.

To further investigate the time course of LRP differences, we analyzed the waveforms for consecutive 100-msec temporal windows in the 400- to 1,000-msec interval (the 400- to 500-msec window preceding prime onset and the 900- to 1,000-msec window were included as controls). As revealed by Bonferroni-corrected *t* tests, LRP differences between congruent and incongruent trials were observed during the 600- to 700-msec, 700- to 800-msec, and 800- to 900-msec intervals (all $ps < .05$) in the high-visibility condition. No significant differences were observed in the low-visibility condition, even when not Bonferroni corrected. The latter result provides further evidence that the differences observed in the high-visibility condition in the 600- to 900-msec time window were not confounded by *target*-related processing. If that were the case, differential covert target-related signals should have been observed in the low-visibility condition, too.

Subsequent one-sample *t* tests confirmed that in the high-visibility condition, during the three consecutive temporal windows from 600 to 900 msec, LRP waveforms exhibited significant positive deflections (i.e., > 0) for congruent trials and negative deflections (i.e., < 0) for incongruent trials (all $ps < .05$). These deflections may be further interpreted by referring to the derivation of the LRP in Figure 2, which illustrates that, on congruent trials, the prime stimulus signals the correct motor response (as prime and target are congruent), leading to an upward LRP deflection. On incongruent trials (not shown in Figure 2), the prime signals the incorrect response mapping, leading to a downward LRP deflection. Note that the 600- to 700-msec window provides further strong corroborating evidence of *prime*-related motor activation, because in the high-visibility condition, the *target* stimulus was shown at 650 msec from trial onset. No target-related motor signals would have been expected between 600 and

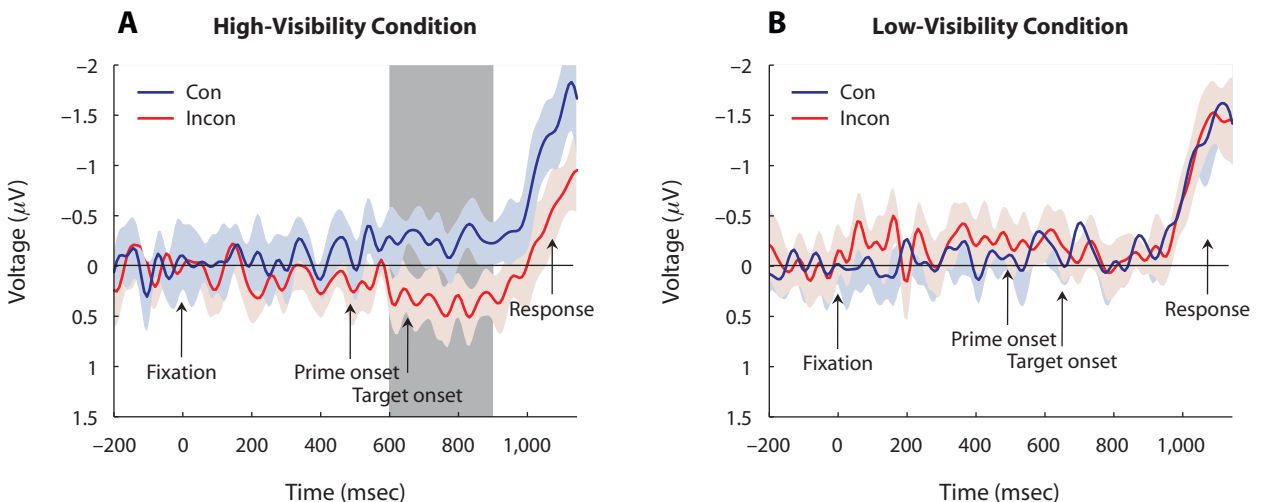


Figure 5. Time course of mean LRP waveforms on congruent and incongruent trials in (A) the high-visibility condition and (B) the low-visibility condition. The darker and lighter shaded regions are 95% confidence intervals for congruent and incongruent conditions, respectively. The gray shaded area (600–900 msec) indicates a significant difference between the two conditions ($p < .05$).

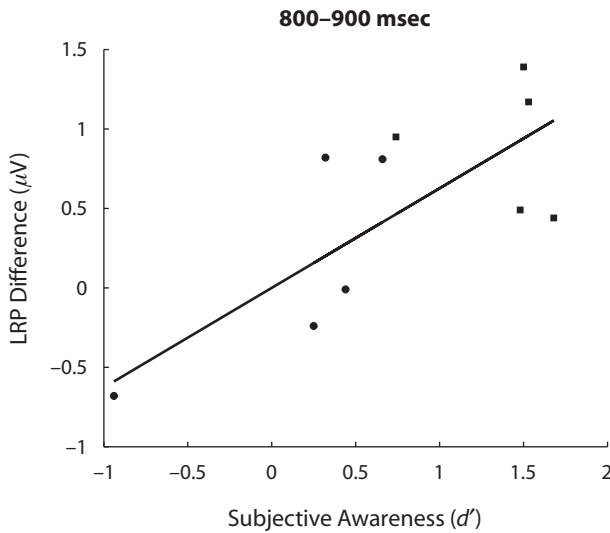


Figure 6. Correlation between subjective awareness and priming effects. LRP-related priming (LRP differences during the 600- to 900-msec interval) was significantly correlated with subjective awareness during the 800- to 900-msec window. Filled squares indicate a participant with a $d'_{\text{objective}}$ value significantly greater than zero (i.e., subjectively aware), whereas filled circles indicate a participant whose $d'_{\text{subjective}}$ did not exceed zero (i.e., subjectively unaware). The black line corresponds to the best linear fit to the data.

700 msec. In summary, consistent with the RT data above, the LRP waveforms also exhibited priming-related effects for congruent trials in the high-visibility condition, but not in the low-visibility condition.

Relationship Between Priming Effects and Subjective Awareness in the Low-Visibility Condition

In the low-visibility condition, participants demonstrated a range of *subjective* awareness values (ranging from unaware to aware), so we further investigated the

relationship between awareness and priming effects for this condition. To probe this relationship, we considered 10 participants for whom the LRP differences indicated evidence of a priming effect (positive LRP differences between congruent and incongruent trials between 600 and 900 msec). LRP differences within consecutive 100-msec time windows in the interval between 400 and 1,000 msec were correlated with subjective awareness values. As illustrated in Figure 6, the data revealed that LRP priming-related differences were significantly correlated with subjective awareness values during the 800- to 900-msec time window ($r = .73, p < .05$). This is consistent with properties of the temporal evolution of the LRP waveform, such as reaching a peak around 300 msec poststimulus on no-go trials (Miller & Hackley, 1992). Note that a Bonferroni correction was not applied here, given that the results of the previous section provide a type of a priori hypothesis concerning the 600- to 900-msec interval. In addition, the correlation approached significance for the 600- to 700-msec ($r = .57, p = .09$) and 700- to 800-msec ($r = .52, p = .12$) intervals. Also, the correlation for the 600- to 900-msec interval was significant if all participants were considered ($r = .60, p = .02$). Finally, note that we did not calculate the correlation between subjective awareness and RTs, since RT-related priming effects were observed in only 6 participants in the low-visibility condition.

For completeness, we also determined correlations between *objective* awareness and LRP differences. For the critical 600- to 900-msec time window, the results were, for 600 to 700 msec, $r = .55, p = .09$; for 700 to 800 msec, $r = .52, p = .12$; for 800 to 900 msec, $r = .46, p = .18$. Thus, for objective awareness, only the early 600- to 700-msec interval approached statistical significance.

Neutral Face Control Condition

We used different prime durations in the priming experiment to manipulate prime visibility, and we performed additional analyses on the neutral-face prime condition in order to assess the impact of the durations on RTs

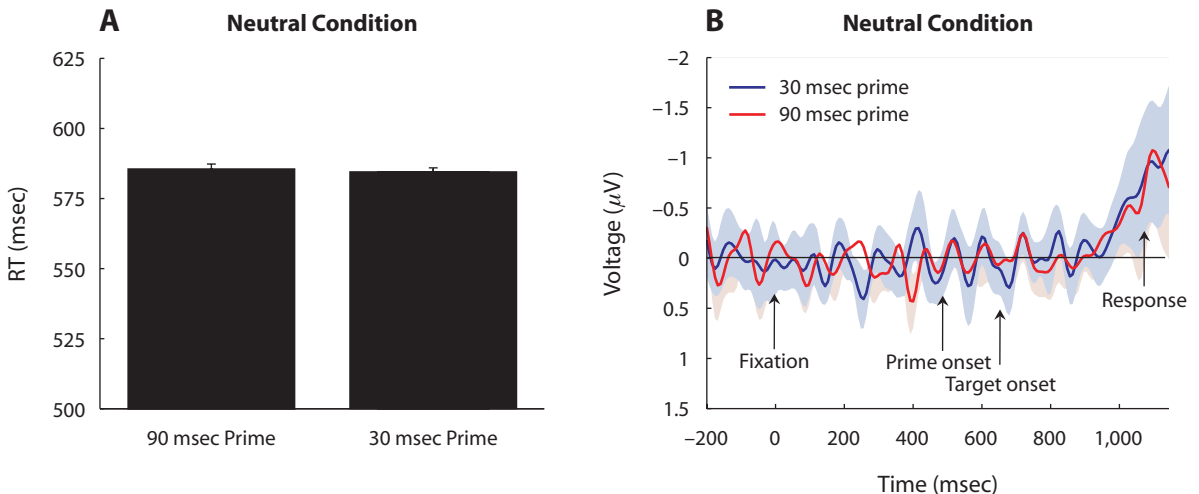


Figure 7. (A) Mean reaction times (RTs) and (B) time course of LRP waveforms for the 33- and 90-msec neutral-prime conditions.

(Figure 7A) and LRPs (Figure 7B). The comparisons of data from the 33- and 90-msec neutral-prime conditions revealed no significant RT differences ($p > .7$) and no LRP differences within the three consecutive 100-msec time windows between 600 and 900 msec (all $ps > .3$). In addition, LRPs generated in the 33- and 90-msec neutral-prime conditions did not exhibit significant positive or negative deflections from zero (all $ps > .2$).

Effects of the Valence of Face Primes

In an additional analysis, we investigated whether congruency effects varied according to the valence of the facial expression of prime stimuli. To compute the LRPs associated with fearful and happy primes, we determined the LRPs on low- and high-visibility trials for the following conditions: fearful face/fearful word, fearful face/happy word, happy face/happy word, and happy face/fearful word (Figure 8). First, a three-way repeated measures ANOVA was performed to examine the relationship among *prime type* (happy, fearful), *target type* (happy, fearful), and *vis-*

ibility (low, high) on the averaged LRPs between 600 and 900 msec. Although only a near-significant interaction was found during this time window [$F(1,14) = 3.38, p = .087$], further analyses revealed a significant three-way interaction during the 700- to 800-msec interval [$F(1,14) = 4.80, p < .05$]. To understand this three-way interaction further, two-way repeated measures ANOVAs were performed as before to examine the effects of *congruency* and *visibility* on the averaged LRPs between 600 and 900 msec for each prime type. For fearful primes, the analyses revealed a significant *visibility* \times *congruency* interaction [$F(1,14) = 12.84, p < .005$], indicating that prime visibility affected the LRP waveforms differently, as a function of trial type. By contrast, for happy primes, no significant interaction effect was observed ($p = .8$).

For fearful primes, subsequent *t* tests revealed that in the high-visibility condition, significant LRP differences between congruent and incongruent trials were observed during the 600- to 700-msec and 700- to 800-msec intervals (all $ps < .05$); a near-significant difference was

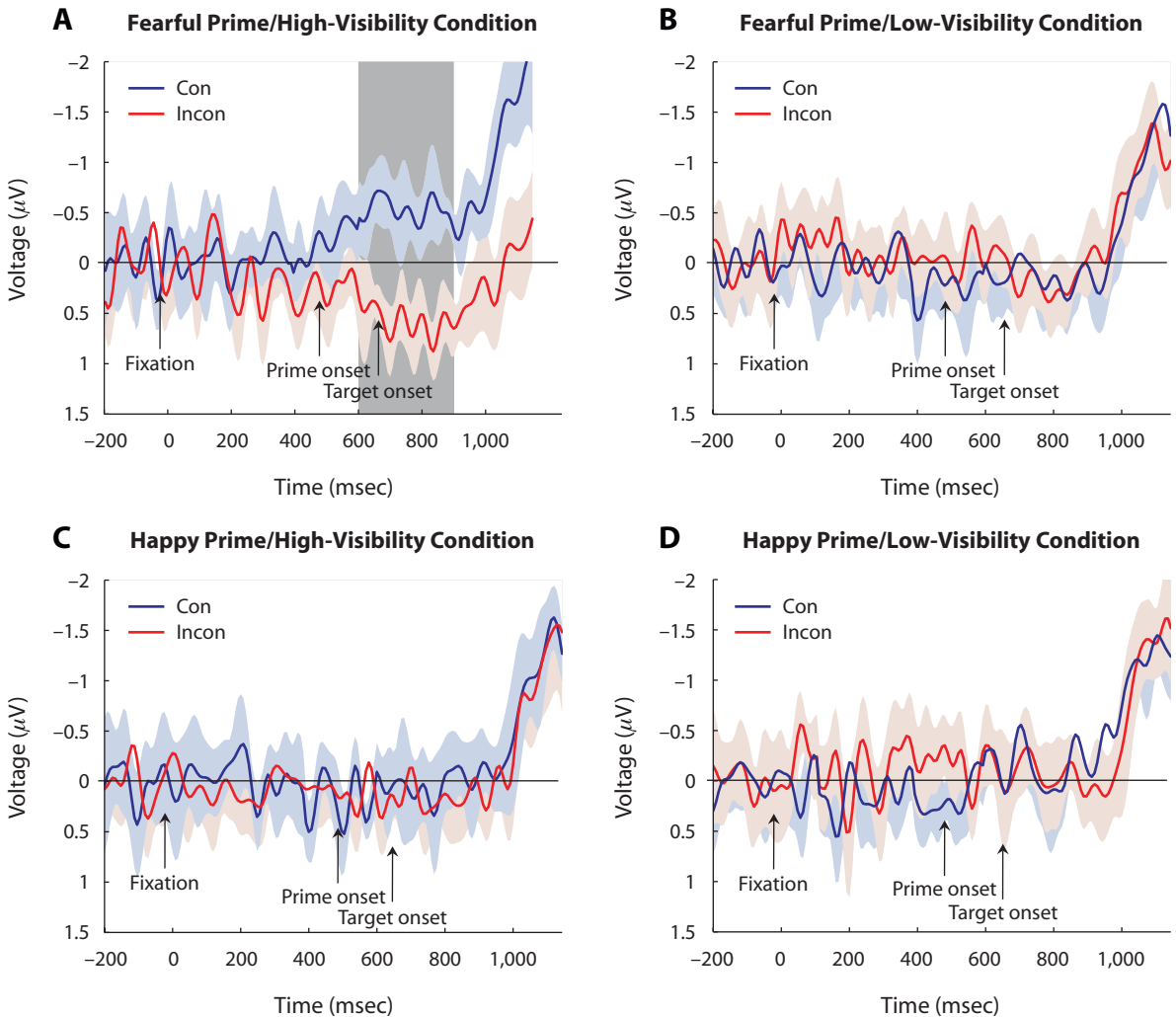


Figure 8. Mean LRP waveforms for (A, B) fearful face primes, and (C, D) happy face primes as a function of visibility. The darker and lighter shaded regions are 95% confidence intervals for congruent and incongruent conditions, respectively. The gray shaded area (600–900 msec) indicates a significant difference between two conditions ($p < .05$).

observed during the 800- to 900-msec interval ($p = .07$). However, no significant differences were observed in the low-visibility condition. Follow-up one-sample t tests further confirmed that in the high-visibility condition, during the three consecutive temporal windows from 600 to 900 msec, fearful prime LRP waveforms exhibited significant positive deflections (i.e., >0) on congruent trials and negative deflections (i.e., <0) on incongruent trials (all $ps < .05$). For happy primes, however, no significant LRP differences between congruent and incongruent trials were observed. In addition, no significant deflections from zero were observed.

It should be noted that the comparisons between congruent and incongruent trials for the four conditions shown in Figure 8 do not completely eliminate potential differential *target*-related signals (during the 600- to 900-msec window). For instance, in Figure 8A, congruent and incongruent trials differed by involving fearful and happy target words, respectively. However, significant LRP differences were observed only for fearful prime faces in the high-visibility condition; therefore, differential signals between 600 and 900 msec were most likely due to the *prime* stimulus, since any differential *target*-related signals should have been observed in some of the other conditions of Figure 8. Note, in addition, that behavioral RT results are due to the combined effects of prime and target stimuli; an analysis that parallels the one shown in Figure 8 is therefore problematic, because target stimuli are not matched.

Finally, we did not calculate the correlation between subjective awareness and LRP activity for the fearful primes, because our awareness experiment did not assess participants' awareness of fearful faces per se; instead, the experiment assessed their ability to discriminate fearful from happy faces.

DISCUSSION

In the present study, we investigated whether stimulus visibility modulated the depth of facial expression processing in the context of the congruency priming paradigm. Behavioral and electrophysiological findings revealed a consistent pattern of results. In the high-visibility condition, responses to word targets were faster when the primes and the targets were congruent than when they were incongruent. The electrophysiological data for the high-visibility condition showed that face primes triggered a negative LRP on congruent trials but a positive LRP on incongruent trials. Positive and negative LRP deflections were observed 100 to 400 msec following the prime stimulus, and as early as 100 to 200 msec postprime, providing an electrophysiological marker showing that the prime was registered and that motor preparation had been initiated when the prime stimulus was highly visible. Thus, both RT and LRP data provided evidence of priming effects in the high-visibility condition. Contrary to this pattern of results, no evidence for priming was observed in the low-visibility condition; no differences in RT or LRP were observed. Overall, our results provide evidence that stimulus *visibility* plays an important role in the processing of facial expressions.

We related our manipulation of visibility (33- and 90-msec durations) to visual awareness of the masked face primes in a separate session by assessing the participants' awareness of the masked primes according to both subjective and objective awareness measures in the same task through the use of SDT methods. A tremendous amount of energy has been expended in debating the potential merits and shortcomings of different awareness measures (Merikle et al., 2001; Snodgrass et al., 2004). We have recently argued that a potentially useful strategy involves evaluating different measures of awareness and ascertaining how they may be related to physiological measures (Szczepanowski & Pessoa, 2007). Here, we chose to employ a subjective measure that is readily assessed during a forced-choice paradigm by employing an SDT-like analysis that evaluates how well a participant's forced performance (which itself provides an index of objective awareness) is in line with the participant's subjective assessment of their responses, as gauged by confidence ratings (for an extended discussion, see Kunimoto et al., 2001). As expected, both subjective and objective awareness measures revealed that participants exhibited better awareness in the high-visibility than in the low-visibility condition.

No priming effects were observed during the low-visibility condition, even though participants were able to reliably discriminate between fearful and happy faces in a separate experimental session. In fact, we operationally defined awareness as a positive $d'_{\text{objective}}$, and 14 participants *did* exhibit *objective* awareness in the low-visibility condition. These results suggest that objective awareness was *insufficient* for the occurrence of priming effects, at least in the context of the separate experimental sessions employed here. Although our definition of *subjective* awareness is such that subjective values should be lower than objective ones (for technical discussions, see Galvin et al., 2003; Szczepanowski & Pessoa, 2007), it is noteworthy that only 5 participants exhibited above-chance *subjective* awareness in the low-visibility condition. It is thus possible that subjective awareness provided a better estimation of the effects of the prime in our experimental context. Indeed, the correlation between subjective awareness values and priming-related LRP effects (Figure 6) strengthens the notion that subjective awareness may provide an index that better reflects the impact of the prime on behavior and the brain. Furthermore, these findings suggest that even for possibly suprathreshold (but brief) stimuli, a graded amount of processing (indexed by LRP responses) may take place as a function of stimulus visibility (indexed by subjective awareness). Generally, our study supports the notion that it may be profitable to conceptualize visual awareness in a more graded fashion (Cleeremans & Dienes, 2008), as opposed to involving a sharper binary transition between unaware and aware states (Sergent & Dehaene, 2004). See Seth, Dienes, Cleeremans, Overgaard, & Pessoa (in press) for an extended discussion.

Because the visibility of the masked face primes was manipulated by changing prime duration, it is conceivable that differential effects observed when high- and low-visibility conditions were contrasted were due, in part, to physical

differences in the stimuli (i.e., different durations). To control for this possibility, we employed a condition involving neutral face primes and contrasted 33- and 90-msec neutral-prime trials. No significant RT or LRP differences were observed, eliminating stimulus duration as a potential confound in our results. Furthermore, because our critical results involved statistical comparisons involving all congruent and incongruent stimuli, residual differential target effects were effectively eliminated, given that they were common to both low- and high-visibility conditions.

Consistent with prior research (Carroll & Young, 2005), the present study revealed that affective words could be primed by congruent facial expressions (i.e., sharing the same semantic category), at least in high-visibility conditions. Whereas the task was to make overt responses on the basis of the classification of the word targets, the observation of motor-preparation-related LRP activity suggests that face-related—namely, prime-related—information was processed. Indeed, this type of evidence has been commonly taken to suggest semantic influences between prime and target stimuli (see Kouider & Dehaene, 2007, for a review). Also, no priming effects were observed for low-visibility (but *suprathreshold*) primes, indicating that stimulus visibility plays an important role in determining whether facial expression processing reaches semantic levels of representation. It is important to note that some studies have argued that priming effects, such as those observed here, reflect a stimulus–response association, rather than genuine semantic activation (Abrams & Greenwald, 2000; Damian, 2001). Regardless of the ultimate resolution of this debate, our findings suggest that the extent of facial expression processing differs according to stimulus visibility.

Our analyses of the electrophysiological data revealed that LRP-related activity was evident only in the high-visibility condition. Subsequent analysis indicated that such priming-related signals were observed only for fearful face primes. These results are consistent with findings showing that threat-related stimuli may be more easily detected (Fox et al., 2000; Öhman, Flykt, & Esteves, 2001; Öhman, Lundqvist, & Esteves, 2001) and with the notion that the processing of threat-related stimuli is enhanced in comparison with other types of emotional stimuli (Anderson, Christoff, Panitz, De Rosa, & Gabrieli, 2003; Vuilleumier, Armony, Driver, & Dolan, 2001; Whalen et al., 1998). Furthermore, for happy face primes, the results indicated that even longer durations than those used in the high-visibility condition, such as 500 msec (without masking), might be needed to produce more robust priming effects (Carroll & Young, 2005).

Note that although LRP and RT signatures of priming exhibited agreement in the present study, there may be situations in which the two are dissociated. For instance, the initial preparation of an incorrect movement on an incongruent trial will be apparent in the LRP, even though the incorrect plan is canceled, and only the correct movement is performed. However, RT effects may or may not be observed because, in this case, the final “total RT” includes not only elements of incongruency, but also processing stages related to the prime and target stimuli. In this man-

ner, the final RT is a less sensitive measure of the effect of the prime stimulus. And, critically, it lacks the temporal information afforded by the LRP. Thus, we suggest that LRP-related information is valuable, even when RT effects are not observed, as in the case of the low-visibility conditions. A similar rationale can be found in studies of mental chronometry (Coles et al., 1988; De Jong et al., 1988; Miller & Hackley, 1992).

Although our main goal was not to investigate unaware perception, it is natural to wonder whether our design was optimal in terms of detecting subliminal processing of facial expressions. For a stricter test of visual awareness and its neural correlates, it would have been interesting to investigate a situation in which positive behavioral effects were accompanied by a lack of subjective awareness. In our setting, however, congruency effects were not observed in the low-visibility conditions, in which 10 participants were subjectively unaware. In this context, it is interesting that in some cases, subliminal presentation of affective primes may elicit stronger effects than do low-visibility, suprathreshold stimuli (Murphy & Zajonc, 1993; for a related conceptual proposal, see Snodgrass et al., 2004).

The extent of facial expression processing without awareness remains a matter of debate (Kouider & Dehaene, 2007; Pessoa, 2005). The present study sought to investigate, instead, how facial expression processing is modulated by stimulus visibility, by using both behavioral and electrophysiological techniques. When participants performed a semantic classification of word targets, only high-visibility faces, particularly fearful faces, served as effective prime stimuli. Thus, the processing of low-visibility faces may not involve semantic and/or motor levels of representation. Overall, the present study reveals that the depth of facial expression processing is determined by stimulus visibility, despite the social significance of this stimulus class.

AUTHOR NOTE

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