Low-level awareness accompanies "unconscious" high-level processing during continuous flash suppression

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The scope and limits of unconscious processing are a matter of ongoing debate. Lately, continuous flash suppression (CFS), a technique for suppressing visual stimuli, has been widely used to demonstrate surprisingly high-level processing of invisible stimuli. Yet, recent studies showed that CFS might actually allow low-level features of the stimulus to escape suppression and be consciously perceived. The influence of such low-level awareness on high-level processing might easily go unnoticed, as studies usually only probe the visibility of the feature of interest, and not that of lower-level features. For instance, face identity is held to be processed unconsciously since subjects who fail to judge the identity of suppressed faces still show identity priming effects. Here we challenge these results, showing that such high-level priming effects are indeed induced by faces whose identity is invisible, but critically, only when a lower-level feature, such as color or location, is visible. No evidence for identity processing was found when subjects had no conscious access to any feature of the suppressed face. These results suggest that high-level processing of an image might be enabled by—or co-occur with—conscious access to some of its low-level features, even when these features are not relevant to the processed dimension. Accordingly, they call for further investigation of lower-level awareness during CFS, and reevaluation of other unconscious high-level processing findings.

Introduction

In the course of a typical day, humans encounter numerous stimuli that are detected, identified, and put into context within a few hundred of milliseconds. Remarkably, several recent studies demonstrated that many of these high-level processes can take place even when the stimuli are invisible: observers were found to read and process the meaning of words (Abrams, Klinger, & Greenwald, 2002; Armstrong & Dienes,

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2013; Costello, Jiang, Baartman, McGlennen, & He, 2009; Dehaene, Kerszberg, & Changeux, 1998; Lamy, Mudrik, & Deouell, 2008; Reber & Henke, 2012); process semantic incongruencies in written sentences (Sklar et al., 2012) and visual scenes (Mudrik, Breska, Lamy, & Deouell, 2011); perform arithmetic operations (Bahrami et al., 2010; Garcia-Orza, Damas-Lopez, Matas, & Rodriguez, 2009; Ric & Muller, 2012); categorize faces (Barbot & Kouider, 2012; Stein, Senju, Peelen, & Sterzer, 2011b) and other objects (Almeida, Mahon, Nakayama, & Caramazza, 2008; Poscoliero, Marzi, & Girelli, 2013); process emotions (Adams, Gray, Garner, & Graf, 2010; Faivre, Berthet, & Kouider, 2012; Yang, Zald, & Blake, 2007); and exercise executive functions (Capa, Bustin, Cleeremans, & Hansenne, 2011; Lau & Passingham, 2007; van Gaal, Ridderinkhof, Fahrenfort, Scholte, & Lamme, 2008) in the absence of perceptual awareness (for reviews, see Kouider & Dehaene, 2007; Lin & He, 2009; Mudrik, Faivre, & Koch, 2014; van Gaal & Lamme, 2012).

Many of these studies used a technique called continuous flash suppression (CFS; see Tsuchiya & Koch, 2005) to render the critical stimuli invisible. In CFS, a stimulus presented to one eye is suppressed by rapidly changing patterns presented to the other eye. Unconscious processing of the suppressed stimulus is typically demonstrated by either finding an indirect effect of the suppressed stimuli on the processing of a subsequent target (Adams et al., 2010; Bahrami et al., 2010; Barbot & Kouider, 2012; Costello et al., 2009; Faivre et al., 2012; Sklar et al., 2012) or by finding a difference in the time it takes different types of stimuli to break suppression (breaking CFS or b-CFS measure; Jiang, Costello, & He, 2007; Mudrik et al., 2011; Sklar et al., 2012; Yang et al., 2007). Such measures indicate that subjects were indeed able to process the critical feature, despite being unaware of the suppressed stimulus.

Yet, a few recent reports hint that CFS does not prevent awareness in an all-or-none fashion. Instead, some low-level features like color (Hong & Blake, 2009) or location (Zadbood, Lee, & Blake, 2011) can escape suppression and become visible, even when subjects report not seeing the stimulus itself or any part of it and thus, are not attributable to piecemeal rivalry; for example, reporting seeing a "shapeless cloud" of color, which is not perceived as part of a stimulus (Hong & Blake, 2009), or knowing that something was there without knowing what it was (Zadbood, Lee, & Blake, 2011). Such awareness of low-level features during CFS is more likely to occur with small overlaps between the visual features of the suppressing and the suppressed stimuli (Hong & Blake, 2009; Yang & Blake, 2012). Critically, such low-level awareness may not be detected and analyzed by researchers, as most studies control for the visibility of the feature of interest only, rather than the visibility of other, lower-level features. For instance, when investigating unconscious processing of face identity, researchers only showed that subjects were at chance in discriminating their fame or identity (Barbot & Kouider, 2012), and similarly, when probing categorization, researchers only showed that subjects were at chance in discriminating their category (Almeida et al., 2008, experiments 2–6). Notably, controlling for the feature of interest is well accepted in the field, following extensive discussions in the literature of unconscious processing (e.g., Reingold & Merikle, 1988; Snodgrass, Bernat, & Shevrin, 2004). However, it does not exclude the possibility that awareness of low-level features has a role in driving unconscious effects at higher levels.

Only a few CFS studies controlled for lower-level awareness. This was either done by using a detection task, where subjects are not asked about the feature of interest, but are rather prompted to determine whether a stimulus had been presented or not (i.e., stimulus detection, see Almeida et al., 2008, experiment 1; Amihai, Deouell, & Bentin, 2011), or by asking subjects to make a discrimination about a lower level feature than the one being tested (e.g., probing unconscious semantic processing while controlling for chance-level performance on a feature detection task; Kang, Blake, & Woodman, 2011). Interestingly, these studies failed to demonstrate unconscious processing of their feature of interest (i.e., race and gender of faces, see Amihai et al., 2011; meaning of words, see Kang et al., 2011; see also Almeida et al., 2008, experiment 1). Note that among the studies that controlled for the feature of interest rather than low-level awareness, two also failed to find high-level processing (Faivre & Koch, 2014; Ludwig, Sterzer, Kathmann, Franz, & Hesselmann, 2013). Although these studies allude to the possibility that high-level unconscious processing may depend on—or be correlated with—the visibility of low-level features, this interpretation has yet to be tested directly. In this study we therefore set out to examine whether awareness of low-level features serves as a gating mechanism for the processing of higher-level features.

More specifically, we tested whether unconscious processing of invisible high-level facial features can occur when low-level ones are also invisible, following Barbot and Kouider's (2012) findings of unconscious identity processing. To that end, we used a priming paradigm, in which the presentation of a prime stimulus facilitates the processing of a subsequent target stimulus, if the two are related. In two independent experiments, we compared unconscious processing of face identity, as indexed by identity repetition priming, when subjects were either unaware of any stimulus feature (*unconscious trials*), or aware of low-level features like face color in Experiment 1 or location in Experiment 2, but not identity (*low-level* *awareness trials*). In a separate set of experiments we established that subjects can be aware of the color or location of a suppressed face during CFS without consciously perceiving other facial features like face orientation or gender, see Appendix 1 in Supplementary Material.

We hypothesized that if low-level stimulus awareness is indeed required for, or at least co-occurs with, high-level processing, then identity priming effects would be larger or found only in the low-level awareness trials, even though the color or location of a face is not informative about its identity.

Experiment 1: Does seeing the color of suppressed faces modulate identity priming?

Experiment 1 examined the relationship between high-level processing as indexed by repetition priming, and low-level awareness. We probed unconscious processing of face identity following Barbot and Kouider (2012; however, note that the faces were presented in grayscale), while critically adding a trial-by-trial report of color awareness. We then compared identity repetition priming when subjects were either unaware of face color (unconscious trials), or aware of face color but not identity (low-level awareness trials). Priming was assessed by comparing reaction times for categorizing the target face as famous/unknown when it was preceded by either an identical or a different famous/unknown face (prime; primes and targets always belonged to the same fame category. Accordingly, differences in reaction times were compared within each fame category).

Materials and methods

Subjects

Thirty-five healthy subjects with normal or corrected-to-normal vision (22 male, 13 female; 35 right-handed, 23 right eye dominance), aged 18–35 years ($M = 25$) participated in the experiment. Fifteen subjects were excluded due to low performance on target fame discrimination (<85%, implying that they were unable to efficiently categorize the target faces), or high performance on prime fame in confidence levels 1 and 2 in the control prime-visibility session (>70%, implying that they were not following instructions regarding subjective color confidence ratings properly). Akin to the study by Barbot and Kouider (2012), subjects' exclusion was relatively high, mainly due to the challenge of reaching high performance on both target discrimination and color categorization despite CFS. However, it is important to note that criteria for subjects' exclusion were objective, and orthogonal to priming effects. In both Experiment 1 and Experiment 2 we aimed at 20 subjects after exclusion, as done in previous face experiments, and stopped data collection when we reached this number. Of these 20 subjects, 14 had enough trials (>20) in confidence 1, and 18 had enough trials in confidence 2. Twelve had enough trials in both confidence levels.

Stimuli and apparatus

Participants viewed a CRT display (1024 × 768, 100 Hz), through an adjustable mirror stereoscope attached to a chin rest at a distance of 57 cm. MATLAB and Psychtoolbox 3 (Brainard, 1997; Kleiner, Brainard, & Pelli, 2007; Pelli, 1997) were used to control stimuli presentation. A black and white dashed frame (9.75° × 9.75°) was presented on a gray screen to both eyes to facilitate binocular fusion. Each participant selected 18 faces (half male and half female) that he or she could easily recognize from a set of 60 famous faces (actors, politicians, singers). In addition, 18 unknown faces that were famous faces from another country (Israel), were used. Subjects confirmed not recognizing these faces. This constituted a stimuli bank of 18 famous and 18 unknown faces for each subject, based on his or her own preferences. The use of famous yet unknown faces was done to control for differences in facial appearance and picture quality as compared with famous faces. All faces were matched for average luminance using the SHINE toolbox (Willenbockel et al., 2010). Faces were colored blue or green to allow examination of color awareness, and were centrally presented (6.8° × 4.3°) to the nondominant eye (eye dominance was assessed by asking subjects to point at a distant target, cover each one of their eyes and report when they had experienced a stronger visual shift; Miles, 1929). Face edges were blurred by a convolution with a squared Gaussian elliptical mask ($\sigma1 =$ quarter of face width, $\sigma2 =$ half of face height). CFS patterns were grayscale circles of random sizes, locations, and luminance and were presented to the dominant eye at 10 Hz.

A new combined subjective-objective measure of awareness (SOMA)

We devised a new way to measure subjects' objective and subjective level of awareness, so that both measures were combined into one intuitive test. On each trial, an array of eight letters composed of four "B" and four "G" letters at varying sizes was presented after the prime (see Figure 1A). Subjects were asked to give their objective report (select B or G for blue or green color, respectively), combined with the related confidence level. The size of letters represented the

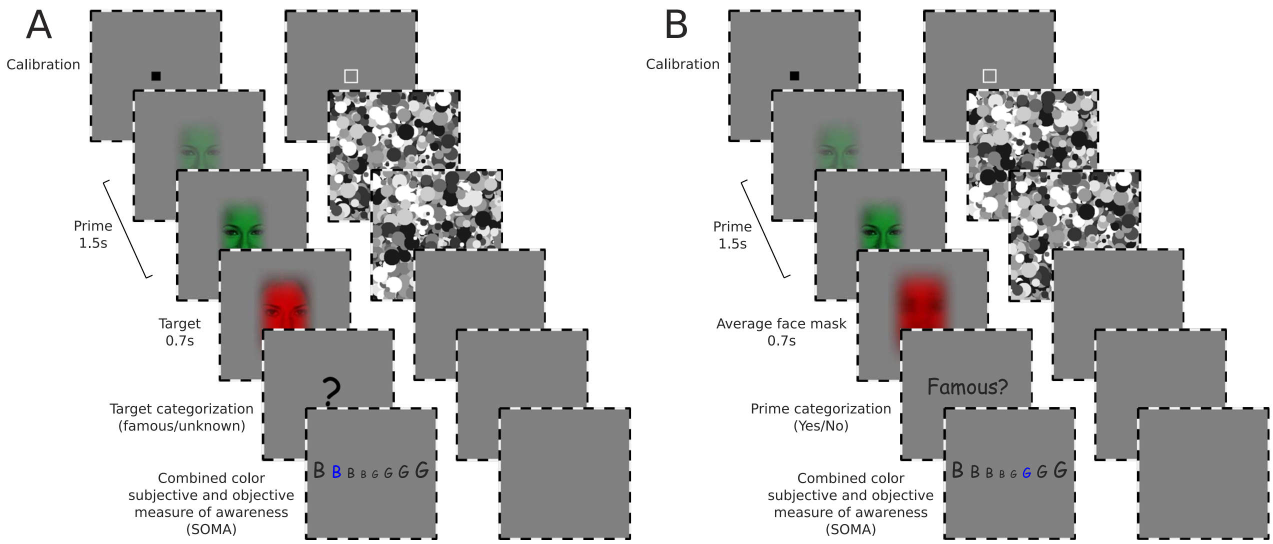

Figure 1. Experimental paradigm. (A) Experiment 1, priming session. A green or blue colored prime face was presented for 1.5 s during CFS (its contrast was ramped up during the first second). A red colored target face was then presented for 0.7 s, followed by a question mark. Subjects indicated as quickly as possible if it was a famous or an unknown face by pressing one of two buttons. Subsequently, subjects reported the color of the prime face and their confidence on a combined scale (SOMA; see Materials and methods) ranging from "pure guess" (smallest letter) to "saw a clear part of the face" (biggest letter). (B) Experiment 1, prime-visibility session. Here a red colored mask (average face) appeared on screen for 0.7 s, followed by a "famous"? or "unknown"? question about the prime face (question was randomly chosen in each trial), for which subjects replied yes or no. Subjects then reported the color of the prime face and their confidence on the same SOMA scale.

degree of confidence, with 1 = "pure guess" (smallest letters), 2 = "I think I know the color," 3 = "I'm sure about the color," and 4 = "I saw a clear part/contour of the face" (largest letters). A random letter was initially colored blue and subjects used the left and right arrows to move the blue coloring to the desired letter, and then confirmed their selection using the space bar. We argue that the use of SOMA allows for an accurate and simultaneous measure of awareness at the subjective and objective levels, as well as type 1 and type 2 measures for signal detection or metacognition purposes (e.g., Jachs, Blanco, Grantham-Hill, & Soto, 2015; Maniscalco & Lau, 2012; Szczepanowski & Pessoa, 2007) without any confounds in terms of task order (i.e., performing the objective measure before or after the subjective one is known to modulate performance; Wierzchon, Siedlecka, & Paulewicz, 2014) or memory failure (i.e., when presenting the objective measure after the subjective one, subjects' awareness might be underestimated in case they consciously perceived some of the stimulus, yet failed to perform the objective task due to forgetting).

Procedure

Experiment 1 included training, priming, and prime-visibility sessions. In all sessions, trials were self-paced, and began with the presentation of a small black square and white frame of matched size to the left and right eye, respectively, at the fovea. Participants moved the frames to reach binocular fusion, so that the black square would fit into the white frame. Then, CFS stimulation started as described below. Prime and CFS patterns contrasts were set individually for each subject based on training performance, with the aim of reaching a maximal and similar number of confidence 1 and confidence 2 trials. After the first block of the priming session, contrast values were reevaluated and changed if necessary, and the session restarted.

Training session: The training session included 1–2 blocks of 36 trials. In each trial, the prime face was presented together with the CFS patterns for 1.5 s, while its contrast was linearly ramped up during the first second. Subjects then reported the prime color and their confidence of that report using the combined objective and subjective measure of awareness (SOMA). Feedback was presented on screen (the chosen letter turned green in correct trials or red in incorrect trials) for 400 ms.

Priming session: The subsequent priming session was aimed at evaluating face identity processing at different levels of stimulus visibility. It included 14 blocks of 36 trials. Half of the trials within each block were repetition trials (identical prime and target) and half were nonrepetition trials (different prime and target of the same fame category and gender). Half were of famous faces, and half of unknown faces. Fame and repetition were pseudorandomized across trials.

In each trial, a prime face was presented together with the CFS patterns for 1.5 s, while its contrast was linearly ramped up during the first second. The prime face was followed by a red target face presented to the nondominant eye for 700 ms (Figure 1A), sized to be 20% bigger than primes (8.2° × 5.2°) to avoid retinotopic overlap between the prime and the target. Similar to the primes, the edges of the targets were blurred using an elliptical mask. Subjects were asked to classify the target as famous or unknown (by pressing the "F" or "V" buttons, respectively; Figure 1A). After the target, a black question mark appeared and turned red after 500 ms. Subjects were encouraged to respond as quickly as possible, preferably before the question mark turned red. After fame categorization, subjects indicated the color of the prime and rated their confidence using the SOMA.

Prime-visibility session: Finally, the prime-visibility session was aimed at assessing subjects' access to fame information at different levels of awareness. It included four blocks of 36 trials. CFS stimulation was now followed by a 700 ms presentation of a red mask composed of the average of the 36 faces used. Then, one of two possible questions randomly appeared: "famous"? or "unknown"? and subjects answered yes or no (up and down arrow keys, respectively; Figure 1B). Question randomization was aimed at minimizing unconscious effects of stimulus-response mapping (Damian, 2001). After fame categorization, subjects reported prime color and their confidence using the SOMA.

Results

Color-fame separation

Subjects classified their categorization of prime color as a "pure guess" (confidence 1; unconscious trials) in 35.0% of the trials, as "I think I saw the color" (confidence 2; low-level awareness trials) in 48.2% of the trials, as "I'm sure about the color" (confidence 3) in 10.8% of the trials, and as "saw a clear part/contour of the face" (confidence 4) in 6.0% of the trials. Given the relatively low number of confidence trials 3 and 4 (our threshold setting procedure was purposely designed to maximize the number of confidence 1 and 2 trials, while ignoring the number of confidence 3 and 4 trials), and, since our experimental question pertained to unconscious (confidence 1) versus low-level awareness (confidence 2), all confidence 3 and 4 trials were discarded from the analysis (16.8% of total trials).

Confidence 1 trials coincided with a low, but significantly higher than chance-level performance for color categorization, $M = 56.2\%$, $SD = 7.6\%$, $t(13) = 3.08$, $p = 0.009$, 95% CI [51.9, 60.6]. To investigate the origins of such performances above chance level, we conducted binomial distribution tests at the individual subject level, using the number of visibility 1 trials for each subject. This showed that only 4 subjects out of 14 were above chance (with $p < 0.05$). In these subjects, better than chance performance might have stemmed from unconscious processes, or from some residual awareness. We further address this possibility below, when describing priming results.

Confidence 2 trials (rated as "I think I know the color") corresponded to a much higher performance for color categorization, $M = 78.9\%$, $SD = 10.0\%$, $t(17) = 12.25$, $p < 0.0001$, 95% CI [73.9, 83.9]. Crucially, prime color categorization was independent from prime fame categorization, tested in the prime visibility session (Figure 2A, inset). Prime fame categorization was at chance for confidence 1 and 2: confidence 1, $M = 48.2\%$, $SD = 7.0\%$, $t(12) = -0.94$, $p = 0.36$, 95% CI [43.9, 52.4]; confidence 2, $M = 52.3\%$, $SD = 6.1\%$, $t(17) = 1.60$, $p = 0.13$, 95% CI [49.3, 55.3]; no significant difference in accuracy at confidence 1 and confidence 2: Welch two sample t test, $t(22.56) = -1.71$, $p = 0.10$. This confirms that at confidence 2, subjects had access to the color of the suppressed faces while having no information about their fame; paired t test between color and fame performance, $t(18) = 11.90$, $p < 0.001$. At confidence 1, the same paired t test yielded no significant difference, $t(12) = 1.82$, $p = 0.09$.

However, one could still argue that our visibility test does not probe the critical feature that drives the priming effect (i.e., repetition between the identity of prime and target), as subjects were asked to judge whether the face was famous or not, rather than to report the face identity. This concern is strengthened by recent findings from our lab, showing that repetition priming may stem from low-level similarities between primes and targets, even when the two differ in size (Faivre & Koch, 2014). To test this claim, we conducted two control studies (one for Experiment 1 and another for Experiment 2) that probed subjects' discrimination of prime identity. Subjects were presented with two faces, and were asked to indicate which of the two was the prime, as done by Barbot and Kouider (2012). In line with the results of Experiments 1 and 2, subjects' performance was at chance (see Appendix 2 in Supplementary Material).

Priming effects for confidence levels 1 and 2

Overall, subjects categorized the target as famous/unknown with high accuracy, $M = 94.1\%$, $SD = 4.0\%$, 95% CI [92.4, 95.9], and an average reaction time of 810 ms, $SD = 110$ ms, 95% CI [762, 858]. Trials in which the target was erroneously categorized, or with a reaction time <300 ms or >2000 ms (Ratcliff, 1993) were excluded (6.8% of total trials). To assess the priming effect, we compared subjects' reaction times in trials in which the target and prime faces were identical with

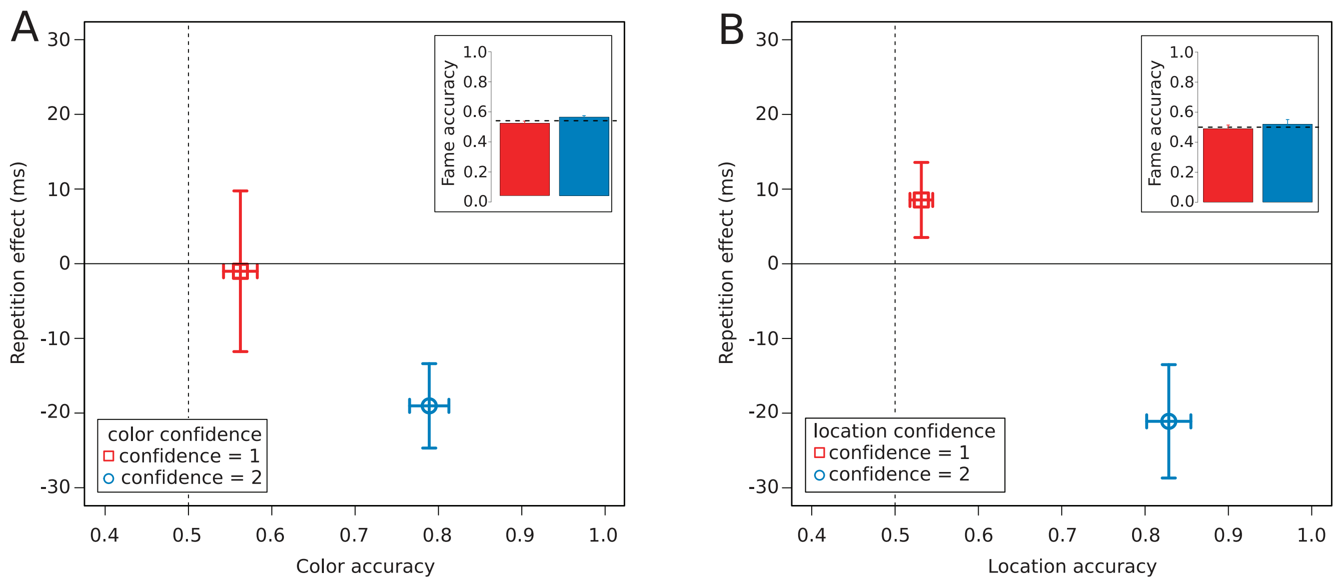

Figure 2. Low-level awareness modulates identity-priming effects during CFS. (A) Low-level awareness of color (Experiment 1; $n = 20$). Average repetition effect for famous faces plotted against the accuracy on color categorization for confidence levels 1 and 2 (red and blue, respectively). Adaptation effects were found only for low-level awareness (confidence 2) trials. Inset depicts average accuracy on prime fame categorization for confidence levels 1 and 2. Note that while in unconscious trials, subjects had access to neither color nor fame information (confidence 1; $n = 14$). In low-level awareness trials (confidence 2; $n = 18$) subjects reported color with high accuracy (approx. 0.8) but were still at chance for fame categorization. (B) Low-level awareness of location (Experiment 2; $n = 20$). Average repetition effect for unknown faces plotted for confidence levels 1 ($n = 10$) and 2 ($n = 14$), red and blue, respectively. Again, adaptation effects were only found for low-level awareness (confidence 2) trials. Error bars denote *SEM*.

trials where they were different, in each fame category (famous or unknown) and for each confidence level. Accordingly, a $2 \times 2 \times 2$ repeated measures ANOVA was run on subjects' reaction times with repetition (same/different prime and target), fame (famous/unknown prime), and confidence about color ("pure guess"/"think") as factors. An inverse transformation of reaction times was performed to respect the normality assumption for analyses of variance (Kolmogorov-Smirnov test, $D = 0.07$, $p = 0.53$). Subjects that had <20 trials at a given confidence level were omitted from the analysis for that confidence level.

Main effects of fame, $F(1, 18) = 13.17$; $p = 0.002$, partial $\eta^2 = 0.42$, and of confidence, $F(1, 11) = 10.1$, $p = 0.009$, partial $\eta^2 = 0.48$, were found, reflecting respectively that participants categorized famous faces, $M = 794$ ms, $SD = 115$ ms, 95% CI [766, 823], more rapidly than unknown ones, $M = 839$ ms, $SD = 111$ ms, 95% CI [812, 866], and that they were faster when their confidence about prime color was 2, $M = 796$ ms, $SD = 119$ ms, 95% CI [769, 825], compared to 1, $M = 842$ ms, $SD = 104$ ms, 95% CI [815, 869]. Most importantly, we found a triple interaction between fame, confidence, and repetition, $F(1, 11) = 6.77$, $p = 0.025$, partial $\eta^2 = 0.38$.

Paired comparisons within subjects who met the selection criteria (>20 trials) for both conditions (confidence 1 and 2) revealed that for famous faces, a prime slowed down subjects' performance on a repeated target only when its color was categorized with a confidence of 2 ($M = -26$ ms, $SD = 25$, $t(11) = -3.57$, $p < 0.001$, but not with a confidence of 1, $M = -4$ ms, $SD = 37$, $t(11) = -0.39$, $p = 0.8$; one-tailed paired t test of the difference, $t(11) = 1.71$, $p = 0.057$. To further assess whether the lack of priming in confidence 1 stemmed from insufficient sensitivity of our experimental design or from a genuine lack of effect, we computed Bayes factors, representing the likelihood ratio of the data under the assumption of the presence or absence of an effect (referred to as B hereafter; see Dienes, 2011; Jeffreys, 1961; $0.33 < B < 3$ suggests insensitivity, and $B < 0.33$ implies no effect). The priming effects were modeled as normally distributed with the mean and standard deviation found in confidence 2. We found that B was equal to 0.22 in confidence 1, which provides substantial evidence for the null hypothesis. The same planned comparisons applied to all subjects (i.e., those who also had trials in confidence 1 or confidence 2 only) yielded similar results: confidence 2, $M = -19$ ms, $SD = 24$ ms, $t(17) = -3.37$, $p = 0.004$, 95% CI [–31, –7]; confidence 1, $M = -1$ ms, $SD = 40$ ms, $t(13) = -0.09$, $p = 0.93$, 95% CI [–24, 22]; Figure 2A).

The lack of priming effect in confidence 1 trials further strengthens our interpretation above that these trials were indeed unconscious, in line with subjects' subjective ratings, and despite their slightly higher than chance performance. Moreover, even if there was some residual awareness in some of the trials classified as confidence 1, this would go against our findings as it would have made it more difficult to find a difference in priming between confidence 1 and 2 trials.

No significant effect was found for unknown faces: confidence 1, $M = -12$ ms, $SD = 52$ ms; $p = 0.47$, 95% CI [–50, 25]; confidence 2, $M = 6$ ms, $SD = 57$ ms; $p = 0.7$, 95% CI [–27, 39]. The same ANOVA was run on accuracies, and yielded no significant effects of repetition (all $p > 0.1$). Our results thus show a repetition habituation effect for famous faces when subjects accessed the color of the face. Such repetition habituation effects are typical of long-lasting stimuli, which are thought to induce an *overstimulation cost* (Barbot & Kouider, 2012; see also Faivre & Kouider, 2011a for similar results in crowding). Note that when visible, such long-lasting stimuli induced strong priming effects in the two aforementioned studies. Unfortunately we were unable to test this hypothesis, as we had a low number of conscious trials (confidence 4; only three subjects had at least 20 trials at that confidence level). In addition, we could not merge trials with confidence ratings of 3 and 4, as they corresponded to distinct conditions of awareness ("sure about the color" and "saw a clear part/contour of the face," respectively).

Discussion

Experiment 1 first verified that low-level awareness of color during CFS exists beyond simple stimuli (Hong & Blake, 2009), and can be found for face stimuli as well. In 45.5% of the trials, subjects were able to detect the color of the suppressed faces at remarkably high accuracy (78.9%), despite being at chance for categorizing the face as famous or not, and despite rating their confidence as relatively low. Most crucially, in Experiment 1 identity priming was only found when subjects were aware of the color of the suppressed faces, even though color and identity are two orthogonal features (i.e., one is not informative for discriminating the other).

The latter finding implies that some conscious access may be needed for high-level processing of suppressed faces, or at least that the two co-occur. Yet it is possible that this co-occurrence stems from the fact that awareness of color pertains to information about the content of the suppressed stimulus, which in turn may require relatively extensive processing. Such extensive processing may also accommodate high-level information, leading to the observed co-occurrence. Moreover, Experiment 1 probed a very specific situation, in which a highly salient feature (i.e., color) was suppressed using black and white Mondrians. It is thus plausible that our findings may not apply to other studies. In addition, it may be that suppressing such a salient feature requires such a high level of suppression that it precludes any unconscious processing. Finally, even though the prime and target stimuli differed in size, the fact that they were presented at the same screen location implies that priming may have been driven by low-level retinotopic similarities rather than the encoding of identity per se (see Faivre & Koch, 2014, for modeling evidence). Hence, the level of processing involved remains unknown. To address these issues, Experiment 2 focused on a lower-level feature (location) that (a) does not require any special type of suppressors; (b) does not involve a salient feature; (c) does not entail any information about the content of the stimulus, but only to its appearance at a specific location; and (d) rules out retinotopic similarities between the prime and the target.

Experiment 2: Does seeing the location of suppressed faces modulate identity priming?

Materials and methods

Subjects

Twenty-seven healthy subjects with normal or corrected-to-normal vision (15 male, 12 female; 26 right-handed, 21 right eye dominance), aged 18–34 years ($M = 25$) participated in the experiment. Seven subjects were excluded due to low performance on target fame discrimination (<85%) or high performance on prime fame in the control prime-visibility session (>70%). Of these 20 subjects, 10 had enough trials (>20) in confidence 1, and 14 had enough trials in confidence 2. Seven had enough trials in both confidence levels.

Stimuli, apparatus, and procedure

The stimuli, apparatus, and procedure of Experiment 2 were identical to those of Experiment 1, except for the following changes: all images (primes and targets) were grayscale, with no blurring of edges, and no resizing of targets, as there was little retinotopic overlap due to the different locations. Thus, size was $4.7° \times 3.1°$ for all stimuli. Primes were presented at either 2.6° to the left or to the right side of a white fixation cross (0.5° overlap of the prime and target images). Target was centrally presented. The SOMA was composed of the letters L (for left) and R (for right). The CFS patterns' contrast in each trial was pseudorandomly assigned to 0.25, 0.5, or 1 to ensure that subjects would have enough trials in each confidence level. The priming session included 15 blocks.

Results

Location-fame separation

About one quarter of the trials were classified as "pure guess" (confidence 1, 27.9%). These trials coincided with a low, but significantly higher than chance-level, performance for locating the face, $M = 53.2\%$, $SD = 4.3\%$, $t(9) = 2.31$, $p = 0.05$, 95% CI [50.0, 56.2]. Here also we conducted binomial distribution tests at the individual subject level, using the number of visibility 1 trials for each subject. This showed that only 2 subjects out of 10 were above chance (with $p < 0.05$). Confidence 2 ("I think I know the location," 39.1% of total trials), confidence 3 ("I'm sure about the location," 16.3%), and confidence 4 ("Sure about the location and saw a part of the face," 16.7%) corresponded with a much higher performance, confidence 2, $M = 82.8\%$, $SD = 9.9\%$, $t(13) = 12.38$, $p < 0.001$, 95% CI [77.1, 88.6]; confidence 3, $M = 98.4\%$, $SD = 0.3\%$, $t(7) = 52.1$, $p < 0.001$, 95% CI [96.2, 100.6]; confidence 4, $M = 99.2\%$, $SD = 0.5\%$, $t(4) = 210.26$, $p < 0.001$, 95% CI [98.6, 99.9]. To comply with Experiment 1, all confidence 3 and 4 trials were discarded from the analysis (33.0% of total trials; here also, only five subjects had >20 confidence 4 trials). Like in Experiment 1, fame discrimination in confidence levels 1 and 2 (tested separately, Figure 1B) was at chance: confidence 1, $M = 48.9\%$, $SD = 7.7\%$, $t(9) = -0.45$, $p = 0.66$, 95% CI [43.4, 54.4]; confidence 2, $M = 51.9\%$, $SD = 11.6\%$, $t(13) = 0.61$, $p = 0.55$, 95% CI [45.2, 58.5]; Figure 2B inset). No difference between confidence levels was found, Welch two sample *t* test, $t(21.93) = -0.76$, $p = 0.46$. At confidence 1, no difference was found between location and fame categorization, paired *t* test: $t(9) = 1.61$, $p = 0.14$, while at confidence 2, performance was higher for the discrimination of location than of fame, $t(13) = 9.87$, $p < 0.001$. An additional prime-visibility control study, like the one that was run for Experiment 1, also showed chance level performance for confidence levels 1 and 2 (see Appendix 2 in Supplementary Material).

Priming effects for confidence levels 1 and 2

Like in Experiment 1, target accuracy was high, $M = 95.0\%$, $SD = 4.6\%$, 95% CI [92.8, 97.1], with similar reaction times, $M = 777$ ms, $SD = 112$ ms, 95% CI [724, 830]. Incorrect trials and outliers were excluded from analysis based on the same criteria (7.7% of total trials). A $2 \times 2 \times 2$ repeated measures ANOVA was run on reaction times with repetition (same/different prime and target), fame (famous/unknown target), and confidence ("pure guess"/"think") as factors. An inverse transformation of reaction times was performed, Kolmogorov-Smirnov test, $D = 0.17$, $p = 0.009$, to reduce deviations from normality observed on the raw data, $D = 0.2$, $p < 0.001$. Here again we found a triple interaction between fame, confidence, and repetition, $F(1, 6) = 11.53$, $p = 0.01$, partial $\eta^2 = 0.66$. No other effects reached significance (all *p* values >0.1). In this experiment, only seven subjects met the selection criteria for both confidence 1 and confidence 2, preventing us from conducting paired comparisons. However, unpaired comparisons between all subjects that met the criteria for each confidence level revealed a significant difference for unknown faces between priming in confidence 1, $M = 9$ ms, $SD = 16$ ms, $t(9) = 1.70$, $p = 0.12$, 95% CI [–3, 20], and confidence 2 trials, $M = -21$ ms, $SD = 28$ ms, $t(13) = -2.78$, $p = 0.02$, 95% CI [–37, –5]; Welch two sample *t* test between confidence levels, $t(21.05) = 3.26$, $p = 0.003$ (see Figure 2B). In addition, the Bayes factor for priming in confidence 1 was equal to 0.01, which provides substantial evidence for the absence of effect in this condition. Importantly however, these results might stem from the different number of subjects in confidence 2 ($n = 14$) and confidence 1 ($n = 10$). It is possible that the lack of priming for confidence 1 trials reflects lack of statistical power rather than the true absence of an effect. To examine this possibility we ran a bootstrap analysis. We conducted a post hoc *t* test for confidence 2 so that in each iteration, only 10 out of the 14 subjects were randomly chosen (performed for all possible combinations of 10 out of 14; $n = 1{,}001$; Figure 3). The distribution of mean effect size varied between –32 ms and –6 ms with a peak around –21 ms, while the actual mean effect value in confidence 1 was 9 ms. No effects were found for famous faces: confidence 1, $M = -11$ ms, $SD = 37$ ms, $p = 0.28$, 95% CI [–31, 10]; confidence 2, $M = 12$ ms, $SD = 39$ ms, $p = 0.2$, 95% CI [–7, 31].

Finally, an ANOVA analysis with contrast values of CFS patterns (i.e., 0.25, 0.5, and 1), and confidence levels (1, 2, and 3) as factors was run on the number of trials, showing that the strength of CFS influenced confidence judgments, $F(4, 36) = 38.24$, $p < 0.001$, partial $\eta^2 = 0.81$, so that weaker CFS protocol led to higher confidence judgments. Therefore, the observed effect is correlated not only with subjects' awareness levels, but also with the difference in the physical properties of the trials. Note, however, that all confidence levels were obtained at each CFS contrast (Figure 4), and that Experiment 1 did not suffer from this confound, since no manipulation of CFS contrast took place.

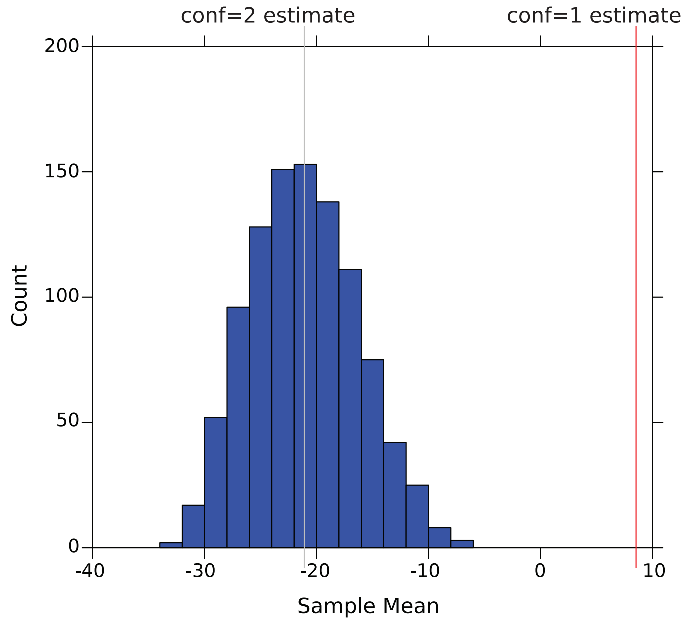

Figure 3. Bootstrapping analysis for Experiment 2. Distribution of the bootstrap analysis results for the mean repetition-effect size for each possible combination of 10 out of 14 (number of subjects included in the analysis for confidence levels 1 and 2, respectively) subjects. Gray and red lines denote the original average effect size for confidence levels 1 and 2, respectively.

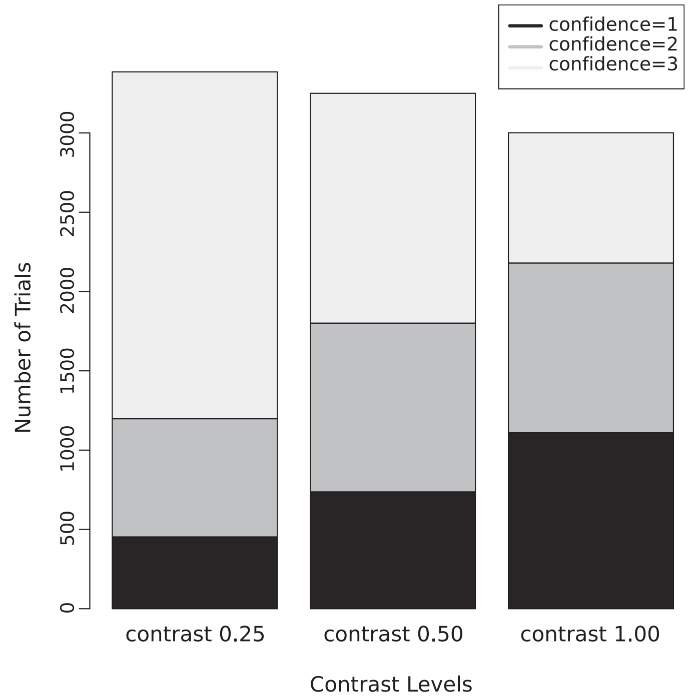

Figure 4. Distribution of number of trials as a function of CFS patterns contrast level in the location priming experiment (Experiment 2). Number of trials in each confidence level plotted against the three different CFS pattern contrast levels. Although there is a correlation between contrast and confidence levels, all three confidence levels trials were obtained in each of the CFS contrast levels.

Discussion

Experiment 2 replicated the findings of Experiment 1, yet with a different low-level feature: location rather than color. This suggests that the co-occurrence of awareness of a low-level feature of suppressed stimuli and the processing of their higher-level features is not specific to a certain low-level feature, but may reflect a more general mechanism. Our results imply that during CFS, high-level processing may co-occur with an explicit awareness of some low-level features (see General discussion for possible explanations). Importantly, the use of location in Experiment 2 further shows that lower-level awareness coincides with higher-level processing even when the lower-level feature does not contain information about the content of the suppressed stimulus, but only regarding its location in space.

It is interesting to note that, in both experiments, subjects performed slightly higher than chance when discriminating faces' color and location, even when they claimed to be completely guessing (confidence 1 trials). This could suggest that they were underestimating their awareness level (i.e., they were aware of the stimuli but failed to report so due to a conservative criterion) in all or some of the trials, or that this low but still higher than chance performance stemmed from unconscious processes (Abrams & Greenwald, 2000; Damian, 2001). Note that the former explanation of residual low-level visibility works against our claim, making it more likely to find an effect in confidence 1 trials than not to find it. Crucially, we found no evidence for high-level processing in confidence 1 trials.

One point that remains unclear though is why the habituation effect found in confidence 2 trials was driven by famous faces in Experiment 1 (in line with most previous studies; Axelrod, Bar, & Rees, 2015), and by unknown faces in Experiment 2. Currently, the role of familiarity during unconscious face processing is still unclear: while most studies found subliminal priming for famous faces only (Barbot & Kouider, 2012; Faivre & Kouider, 2011b; Henson, Mouchlianitis, Matthews, & Kouider, 2008), some others found weaker priming effects for unknown faces as well (Kouider, Eger, Dolan, & Henson, 2009). One possibility is that the pattern of results we obtained stems from the different level of processing probed in each experiment. Indeed, Experiment 1 required subjects to process and become aware of information about the content of the stimulus (i.e., its color), not only of its appearance at one of two possible locations as in Experiment 2. In addition, while primes and targets shared the same retinotopy in Experiment 1, they were presented at different locations in Experiment 2, which rules out the fact that priming stemmed from low-level similarities (Faivre & Koch, 2014). Future research will be needed to clarify the aspect of familiarity in our results, and the potential effects of the task and of retinotopic overlap on familiarity processing.

General discussion

Defining consciousness is considered a hard, if not an impossible task (Crick & Koch, 2003; Edelman, 1989; Searle, 1998; Sutherland, 1989). Yet, it seems that reaching a proper operational definition of unconscious processing is not an easier one (Reingold & Merikle, 1988; Sandberg, Timmermans, Overgaard, & Cleeremans, 2010; Seth, Dienes, Cleeremans, Overgaard, & Pessoa, 2008). The predominant contemporary approach to defining unconscious processing relies on finding a signature of a cognitive process while ruling out that it was consciously accessed. The former typically involves an indirect measure (e.g., in our case, priming), while the latter involves a direct measure, so that conscious access is assessed by asking the observer to directly report on the stimulus of interest. In this study, we showed that during CFS, subjects can be unconscious of a high-level feature of a stimulus (here, the identity of a face), yet still have access to some of its lower-level features such as location or color. This extends the findings of Hong and Blake (2009) and Zadbood et al. (2011), by demonstrating that awareness of low-level and high-level features can be dissociated also for complex stimuli, such as faces. More importantly, we found repetition priming effects—previously reported as evidence for unconscious processing of face identity—only when subjects had conscious access to lower-level features of the suppressed faces (i.e., only when subjects could see the color or location of the face; confidence 2 trials). When subjects had no access to any of the faces' features (confidence 1 trials), no effect was found. Critically, this was found both for color, which relates to the content of the stimulus, and for the location, which bears no information about the content of the stimulus. Moreover, as opposed to color, which is a highly salient feature that is not commonly used in CFS studies, location is not salient and common to every CFS study; that is, every stimulus is displayed at a specific location in space. These results suggest that the processing of facial identity under CFS does not occur unless some visual features are accessed consciously, even though these features do not convey identity cues.

The fact that CFS allows for low-level awareness, which in turn may facilitate high-level processing, is of interest also for those who used CFS as a methodological tool outside the field of consciousness studies. Such disciplines include other fields of psychology and neuroscience including clinical psychology (Sterzer, Hilgenfeldt, Freudenberg, Bermpohl, & Adli, 2011; Yang et al., 2011); clinical psychopharmacology (Hoge et al., 2014); addiction studies (Yan et al., 2009); learning and conditioning (Pearson, 2012; Raio, Carmel, Carrasco, & Phelps, 2012; Seitz, Kim, & Watanabe, 2009); and emotional processing (Almeida, Pajtas, Mahon, Nakayama, & Caramazza, 2013; Vizueta, Patrick, Jiang, Thomas, & He, 2012). Given this wide usage of the CFS paradigm and the considerable scientific attention its findings are receiving, it is crucial to investigate its mechanisms and better understand the depth of visual processing it allows (see Dubois & Faivre, 2014, for a recent special issue on this topic).

An especially surprising aspect of our results is that low-level awareness here pertained to features that are completely irrelevant to the dimension that drove the effect (i.e., face identity). As opposed to previous reports of partial awareness of word parts enhancing word priming (Kouider & Dupoux, 2004), here subjects could not strategically use the information gained by some fleeting conscious experiences of color or location to facilitate identity processing, as these dimensions are orthogonal. What mechanism could then account for this phenomenon?

We present two possible explanations. First, it may be that conscious access to at least some of the features of a stimulus is required for processing its higher-level aspects. This implies that the degree of information processing depends on the degree of conscious access to the stimulus, as suggested by studies showing qualitative or quantitative differences between conscious and unconscious processes: Blake, Tadin, Sobel, Raissian, & Chong (2006); Harris, Schwarzkopf, Song, Bahrami, & Rees (2011); Hesselmann, Hebart, & Malach (2011); and Yang, Hong, & Blake (2010). Presumably, some access to the features of the stimuli (even very low-level ones) is accompanied by global information sharing (Dehaene & Changeux, 2011; Dehaene & Naccache, 2001) that is needed for the mechanisms that encode higher-level features like face identity (Nestor, Plaut, & Behrmann, 2011). In the absence of any conscious processing of the stimulus (i.e., not even of its low-level features), such global information sharing does not take place, and the processing of higher-level mechanisms does not occur. Similarly, it could be that high-level processing requires strong or sustained activation in lower-level stages of the processing, which occurs only when subjects are aware of these low-level aspects of the stimulus. Such a sustained activation could then drive attentional processes that may facilitate high-level unconscious processing of the stimulus. Accordingly, in specific cases where lower-level stages of the processing are subcortical (e.g., in emotional processing; Whalen et al., 2004) and can be activated without awareness, low-level awareness might not be required for high-level processing.

Alternatively, the relation between consciousness and high-level processing may not be one of necessity but of correlation, so that low-level consciousness is not required for high-level processing, but only co-occurs with it. According to hierarchical models of the visual system (Riesenhuber & Poggio, 1999), the perceptual strength required for a feature to become visible increases with its complexity (i.e., along the visual pathways, from face location or color to facial expression or identity; Moutoussis & Zeki, 1997; Zeki & Bartels, 1998). This increase of perceptual strength thresholds with stimulus complexity can explain situations of partial awareness, in which low-level but not high-level features are accessed consciously (Kouider, De Gardelle, & Sackur, 2010). Similarly, it may be that the perceptual strength required for a feature to be unconsciously processed increases with its complexity. This would imply that there are two kinds of thresholds, one for conscious perception of a feature and the other for its unconscious processing, and that these two thresholds may be shifted (i.e., the threshold for consciously perceiving a lower-level feature X coincides or lies close to the threshold for unconsciously processing a higher-level feature Y). Since the quality of stimulus encoding varies between trials due to ongoing state variations (e.g., Busch, Dubois, & VanRullen, 2009), the number and complexity of features that are processed unconsciously or accessed consciously may vary on a trial-by-trial basis: in trials in which the overall stimulus representation is very weak, no threshold will be crossed, so that subjects will report seeing nothing and no priming will be observed. In trials in which the stimulus representation is a bit stronger, the threshold for unconscious (but not for conscious) processing of a low-level feature will be crossed, leading subjects to report seeing nothing, while still showing priming for that low-level feature. In trials in which the stimulus representation is even stronger, the threshold for conscious access of a low-level feature and the threshold for unconscious processing of a high-level feature can be crossed together, leading to the situation we observed here, where subjects report seeing only a low-level feature of the stimulus but show priming for a higher-level feature. Note that, according to this view, high-level priming should not be found without low-level priming, and high-level awareness should not occur without low-level awareness. To our knowledge, no evidence for such situations (i.e., high-level but no low-level priming/awareness) exists in the literature.

Importantly, both accounts seem to imply that high-level processing is tightly bound with at least some level of conscious awareness (Dulany, 1997; Eriksen, 1960; Holender, 1987; Stein, Hebart, & Sterzer, 2011a), either since the latter is necessary for the former, or since it co-occurs with it.

We now discuss two limitations of our study. First, we cannot rule out the possibility that both the invisibility of low-level features and the absence of repetition priming effects co-occurred due to a low signal-to-noise ratio between the prime and the CFS patterns (e.g., stemming from a lack of attentional amplification, ongoing oscillations before stimulus onset, fatigue, or change in response criterion). However, this confound is present in any behavioral study that measures priming without controlling for low-level awareness. Thus, irrespective of its origin, the dissociation between the effect found in confidence 2 trials and the null result in confidence 1 trials should be taken into account when interpreting CFS studies that argued for high-level unconscious processing without controlling for low-level awareness (e.g., Bahrami et al., 2010; Barbot & Kouider, 2012; Sklar et al., 2012). This joins the recent criticism of the breaking-CFS (b-CFS) paradigm (Stein et al., 2011a), which is used by many to demonstrate high-level processing of invisible stimuli (for review, see Gayet, Van der Stigchel, & Paffen, 2014).

Second, the results of our study are not conclusive regarding the validity of other CFS studies. First, because we only focused on one type of unconscious processing (face identity), though with two types of low-level features (color and location). Second, the data entail some intriguing patterns, which still beg an explanation (e.g., the differential role of familiarity in Experiments 1 and 2). Future studies should follow ours in understanding these patterns, exploring the involvement of low-level awareness in other higher-level processes and comparing it to other forms of partial awareness found in other paradigms: visual masking (e.g., Kouider & Dupoux, 2004); crowding (e.g., Freeman & Simoncelli, 2011); attentional blink (e.g., Elliott, Baird, & Giesbrecht, 2013); and visual search (e.g., Greene & Oliva, 2009; Rensink, 2004). Despite these two limitations, the current results suggest that empirical findings of unconscious high-level processing should be more cautiously interpreted. We show that CFS does not necessarily render stimuli "invisible": it sometimes suppresses awareness of high-level features of a stimulus while allowing awareness of lower-level features, and this low-level awareness might have far reaching effects on the processing of the suppressed stimulus. Thus, unless controlled for low-level awareness, previous findings obtained with CFS should be put in the appropriate context, showing that high-level feature processing is possible *without awareness of that feature, not necessarily without any awareness of the stimulus whatsoever*. This, according to some, is a strong enough claim that suffices for the study of conscious versus unconscious processing (Dienes & Seth, 2010; Reingold & Merikle, 1988). Alternatively, stricter measures of awareness can be used in future studies, controlling not only for the visibility of the feature of interest but for the visibility of lower-level features as well, as was indeed done by Hesselmann et al. (2011), Meng, Cui, Zhou, Chen, & Ma (2012), and others. Yet again, this may lead to finding fewer high-level effects during unconscious processing and, accordingly, may be considered by some to be an overly strict approach. This question, which at this point remains open, further stresses the need for assessing the generality of our findings, notably by testing whether other low-level features (e.g., orientation, size, spatial frequency) are involved during unconscious processing of other orthogonal features (e.g., emotional or semantic contents) rendered invisible by different techniques (e.g., masking, crowding).

Conclusions

The current study sheds new light on the graded nature of awareness. While awareness of each feature is probably all-or-none (Del Cul, Baillet, & Dehaene, 2007; Sergent & Dehaene, 2004), we show that different stimulus features can emerge into awareness at different times and are correlated with different levels of stimulus processing. Previous studies that claimed unconscious high-level processing during CFS may accordingly be revisited in search for similar low-level awareness, given the relations we found between such awareness and indirect measures of unconscious processing.

Keywords: continuous flash suppression (CFS), priming, unconscious processing, partial awareness, face processing

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