

# The informational correlates of conscious and nonconscious face-gender perception

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We used a face-gender repetition priming paradigm to precisely map the spatial frequencies (SFs) that influence observers' responses under different prime awareness conditions. A *visible prime* condition was set up by presenting the stimulus sequence mask–blank–prime–blank–mask–target and an *invisible prime* condition by switching the order of the masks and the blanks (see also Dehaene et al., 2001). The prime faces ( $\sim 4.6^\circ \times 3.1^\circ$ ) were randomly filtered trial-by-trial according to the SF bubbles technique (Willenbockel, Fiset et al., 2010). Classification vectors, derived by summing the SF filters from each trial weighted by observers' transformed response times, revealed that SFs around 12 cycles per face width modulated responses in both prime awareness conditions. The significant SFs closely matched those optimal for accurate performance in a direct face-gender classification paradigm. Surprisingly, the significant SFs facilitated observers' responses in the visible prime condition, whereas they slowed responses in the invisible prime condition. Our findings suggest that SF tuning per se remains robust under different prime awareness conditions but that diagnostic visual cues might be utilized in a qualitatively different fashion as a function of awareness.

## Introduction

Only a fraction of the visual input that impinges on our retinas actually enters our awareness, i.e., is perceived consciously. Numerous studies have shown, however, that some stimuli of which we are not aware can still impact our neural activity and behavior in a nonconscious manner (e.g., see Kouider & Dehaene, 2007, for a review). The question remains to know how the visual processes that underlie conscious perception differ from those underlying nonconscious perception.

Many convincing demonstrations of nonconscious perception in neurotypical individuals have involved priming effects: The processing of a visible target stimulus is influenced by a related preceding (prime) stimulus, even when participants are not aware of the prime (e.g., Abrams, Klinger, & Greenwald, 2002; De Gardelle & Kouider, 2010; Dehaene et al., 1998, 2001; Finkbeiner & Palermo, 2009; Naccache, Blandin, & Dehaene, 2002; Naccache & Dehaene, 2001). Typically, a direct measure (e.g., prime detection or discrimination) is employed to demonstrate null sensitivity for the

Citation: Willenbockel, V., Lepore, F., Bacon, B. A., & Gosselin, F. (2013). The informational correlates of conscious and nonconscious face-gender perception. *Journal of Vision*, 13(2):10, 1–14, <http://www.journalofvision.org/content/13/2/10>, doi:10.1167/13.2.10.

prime. An indirect measure (i.e., the effects of the prime on target perception) establishes that the prime information was nonetheless encoded and processed. Many studies reported facilitatory priming effects for nonconsciously perceived primes that were identical or congruent to the target (see Kouider & Dehaene, 2007, for a review). However, negative compatibility effects in which primes that are congruent with the target inhibit observers' responses have also been reported (see, e.g., Eimer & Schlaghecken, 2003, for a review).

A common way of rendering a prime invisible is to present it only briefly and to have it immediately followed by a masking stimulus (Breitmeyer & Ögmen, 2006; Kouider & Dehaene, 2007). Masking is thought to decrease the bottom-up stimulus strength and consequently to help suppress the stimulus from awareness (specifically, to render it subliminal; Dehaene, Changeux, Naccache, Sackur, & Sergent, 2006). An elegant masking paradigm was used by Dehaene et al. (2001) to investigate the neural correlates of word perception under different awareness conditions. In the invisible, nonconscious condition, participants were presented with a stimuli sequence that consisted of a blank screen, followed by a first mask, a word, a second mask, and then another blank. In the visible condition, the masks and the blanks were switched—so that the word was immediately surrounded by blanks. Using these minimally different conditions in combination with functional magnetic resonance imaging (fMRI) and event-related potential (ERP) recordings, Dehaene et al. demonstrated that activation to invisible stimuli was much less than activation to visible stimuli in several brain areas and that some areas only significantly responded to visible stimuli. In a second experiment, they demonstrated that the invisible words, used as primes, led to repetition priming (see also Kouider, Dehaene, Jobert, & Le Bihan, 2007).

Likewise, many other studies have employed masking paradigms to contrast brain activation between minimally different conscious and nonconscious conditions, which have revealed several neural markers of consciousness (see Dehaene & Changeux, 2011, for a recent review). Surprisingly few studies, however, have investigated possible distinctions in the *visual information* that leads to conscious versus nonconscious priming effects. Since typically only a subset of the visual input reaches our awareness while a considerable amount of information remains nonconsciously processed (e.g., Dehaene & Changeux, 2011), it is conceivable that different aspects of a complex visual stimulus lead to priming effects under different awareness conditions. For example, it is possible that different spatial frequencies (SFs) of the words used by Dehaene et al. (2001) were processed as a function of awareness.

It is well established that the human visual system processes input with multiple channels, each tuned to specific SFs (see De Valois & De Valois, 1990, for a review). Low SFs represent coarse information (e.g., the blurred shape of a face) whereas high SFs represent precise, detailed information (e.g., the fine wrinkles in a face). It has been proposed that different SF ranges are processed at different speeds via distinct neuroanatomical pathways (Livingstone & Hubel, 1988), play different functional roles (e.g., Bar, 2003; Bullier, 2001), and possibly interact differently with awareness (De Gardelle & Kouider, 2010; Khalid, Finkbeiner, König, & Ansorge, in press).

To investigate putative interactions between SF processing and awareness, De Gardelle and Kouider (2010) employed a masked priming paradigm with foveally presented hybrid faces as primes (i.e., the low SFs of one face image were combined with the high SFs of another; Schyns & Oliva, 1994). The primes were displayed as briefly as 43 ms and as long as 300 ms to create four visibility conditions. The observers were asked to perform a fame judgment task on visible target faces. Based on the priming effects observed for famous faces, the authors reported two main results: First, they found comparable nonconscious priming effects for low-SF (<12 cycles per face width, cpf) and high-SF information (>12 cpf). Second, they observed that the magnitude of the priming effects increased with prime duration for high-SF and full-bandwidth stimuli, but not for low-SF stimuli. However, in creating the hybrids, the continuous SF spectrum of the face images was divided into two segments by using an arbitrary cutoff of 12 cpf, which falls into the SF band that is diagnostic for recognizing famous faces (Butler, Blais, Gosselin, Bub, & Fiset, 2010). Therefore, it remains possible that qualitative differences (i.e., in terms of optimal SF or SF bandwidth) were present but not revealed given the filtering method and task employed.

In fact, a recent study on nonconscious face-gender priming including low- and high-pass filtered primes provided support for qualitative differences (Khalid et al., in press). In two experiments, the authors measured face-gender priming effects using peripherally presented low-pass or high-pass filtered primes (similar in SF content to those by De Gardelle & Kouider, 2010). The authors found converging evidence that nonconscious priming occurs with low- but not with high-SF primes.

The aim of the present study was to map the SFs that modulate observers' responses in different prime awareness conditions with a higher SF resolution than previous work and independent from any cutoff frequencies. The key aspect of the present demonstration is that we randomly sampled the SFs of the prime faces on a trial-by-trial basis according to the SF bubbles technique (Willenbockel, Fiset, et al., 2010). Sampling SFs over the whole spectrum allowed us to

correlate participants' response times (RTs) with the information that was made available to them and reveal the SF tuning curves for the task at hand. Observers were asked to perform face-gender judgments—a natural two-choice task, for which both low and high SFs have been found to be useful (Schyns & Oliva, 1999) and for which nonconscious priming has been demonstrated (Finkbeiner & Palermo, 2009; Khalid et al., in press). To minimize the difference between our visible prime and invisible<sup>1</sup> prime conditions we employed a masking paradigm adapted from Dehaene et al. (2001) for use with *SF bubbled* face primes. Using this approach, we tested whether the same information is diagnostic for face-gender perception as a function of awareness and whether consciously and nonconsciously processed diagnostic cues lead to the same behavioral effects.

## Methods

### Participants

Twelve adults (seven women; 21–37 years old; *Mdn* = 25.50 years) took part in Experiment 1. Eighteen adults (nine women; 19–30 years old; *Mdn* = 22.00 years) took part in Experiment 2. Four participants completed both experiments. All participants were recruited at the Université de Montréal, reported to have normal or corrected-to-normal vision, and provided written informed consent. The experiments were conducted in accordance with the Declaration of Helsinki and were approved by the CÉRFA (Comité d'éthique de la recherche de la faculté des arts et des sciences) of the Université de Montréal.

### Materials

Twenty grayscale photographs of faces from Schyns and Oliva (1999) were used as base stimuli (see Figure 1 for an example). The images ( $256 \times 256$  pixels) depicted five male and five female faces (width =  $\sim 3.1^\circ$ , height =  $\sim 4.6^\circ$ ), each showing a happy and a neutral expression. The position of the main facial features, hairstyle, orientation, and lighting were normalized, and the faces were equated in mean luminance and contrast (root mean square [RMS] contrast = 0.43) using the SHINE (spectrum, histogram, and intensity normalization and equalization) toolbox (Willenbockel, Sadr, et al., 2010). The targets were constructed by reducing the RMS contrast of the face images to 0.32, and the primes were created by randomly SF filtering the images according to the SF bubbles technique (see Figure 1 for three examples and

Willenbockel, Fiset, et al., 2010, for a detailed description and an illustration of the filtering procedure). On each trial, a given base image was first padded with a uniform gray background and then transformed into the frequency domain using a fast Fourier transform. The amplitude spectrum of the transformed image was multiplied element-wise with a random filter that was constructed in the following way: A vector consisting of randomly distributed binary elements (10,195 zeros and 45 ones) was convolved with a Gaussian kernel (an SF bubble;  $\sigma = 1.8$ ). As a result, a smooth sampling vector was obtained. To account for the finding that the human visual system is more sensitive to low than to high SFs (e.g., see De Valois & De Valois, 1990, for a review), the sampling vector was transformed using a logarithmic function (see Willenbockel, Fiset, et al., 2010, for details). The log-transformed, smoothed sampling vector was then “rotated” about its origin to obtain a two-dimensional (2D) filter. After multiplying this filter element-wise with the base image's amplitude spectrum, we back-transformed the result into the image domain via an inverse fast Fourier transform. The filtered image contained a random subset of the base image's SF information. For the analysis, we essentially used the log-transformed, smoothed sampling vector, henceforth referred to as SF filter.

On average the primes had a mean RMS contrast of 0.16 ( $SD = 0.04$ ). Masks were random noise textures of  $256 \times 256$  pixels generated on each trial (Figure 2).<sup>2</sup> They had a mean RMS contrast of 0.52 ( $SD = 0.03$ ) and subtended a visual angle of  $5.8^\circ \times 5.8^\circ$ . All stimuli were displayed on a  $40.3 \text{ cd/m}^2$  background using a calibrated CRT monitor. The experiment was programmed in MATLAB with the Psychophysics toolbox (Brainard, 1997; Pelli, 1997).

### Procedure

We conducted two experiments, which both consisted of a practice phase, visibility test (pretest), testing phase, and another visibility test (posttest). The experiments differed mainly in the number of conditions and the number of trials per condition in the testing phase. Experiment 1, which was the main experiment, was designed to map SF tuning as a function of prime awareness. It required a large number of trials per condition; therefore, we minimized the number of conditions (visible prime, invisible prime). Experiment 2, which served as a control experiment, included an additional prime-absent condition, but relatively few trials per condition.

During all phases, the participants were seated in a dark room, and a chin rest was used to maintain a viewing distance of 1 m from the screen. The practice

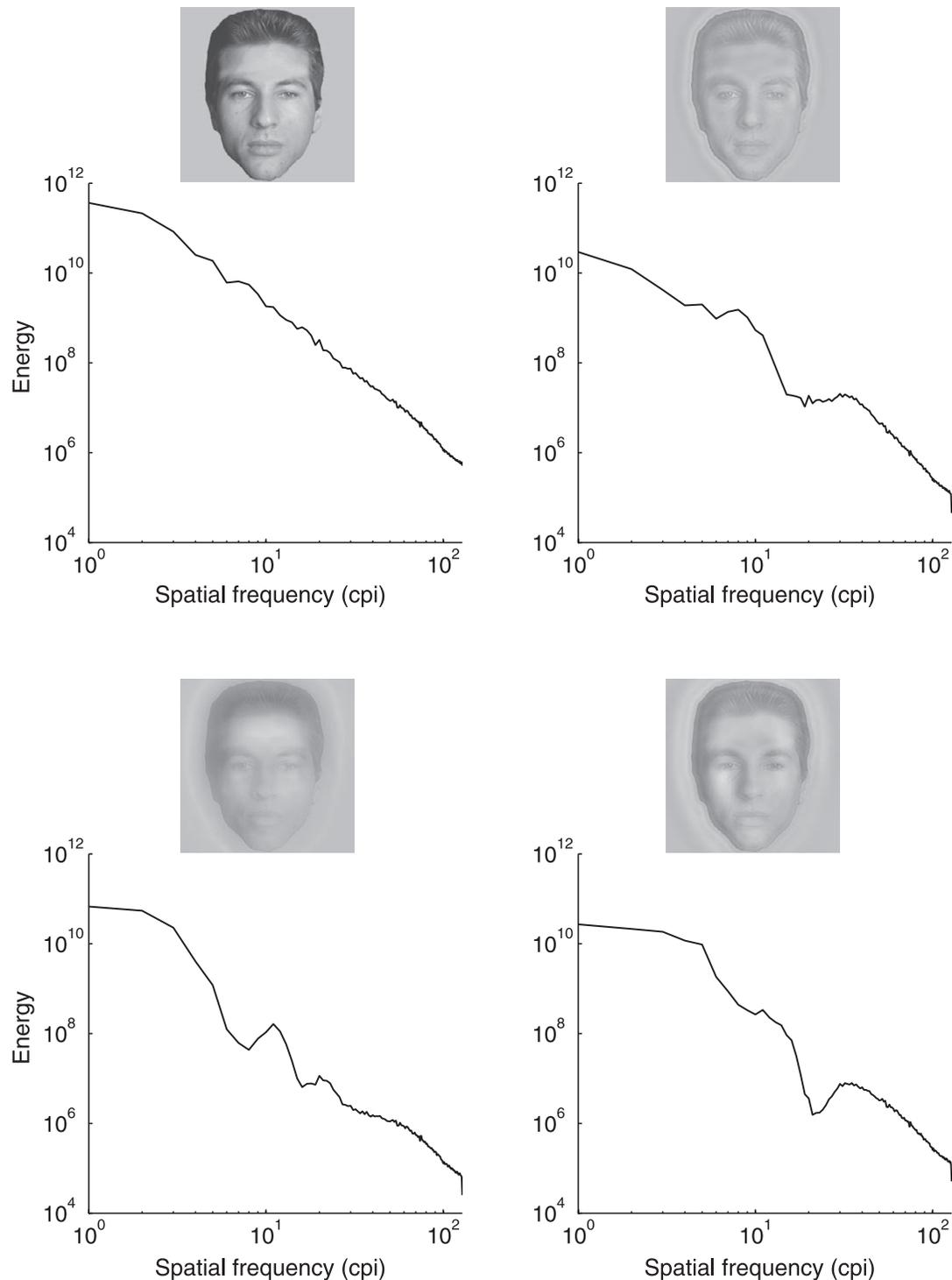


Figure 1. Sample stimuli. The top left panel shows one of the base face images and a plot of its spatial frequency (SF) content (energy plotted as a function of SF in cycles per image, cpi). The other panels show sample results after filtering the base face image with the SF bubbles technique on three hypothetical trials.

phase, which was identical for both experiments, started after the participants had seen all base images. Each practice trial consisted of the presentation of a central fixation cross (500 ms), followed by a mask (50 ms), a uniform gray field (blank; 50 ms), an SF sampled

face (33–142 ms), another blank (33 ms), another mask (17 ms), and phase noise created from the average of all target faces (until a response was made; see Figure 2). The duration of the SF sampled face image was adjusted trial-by-trial using QUEST (Watson & Pelli,

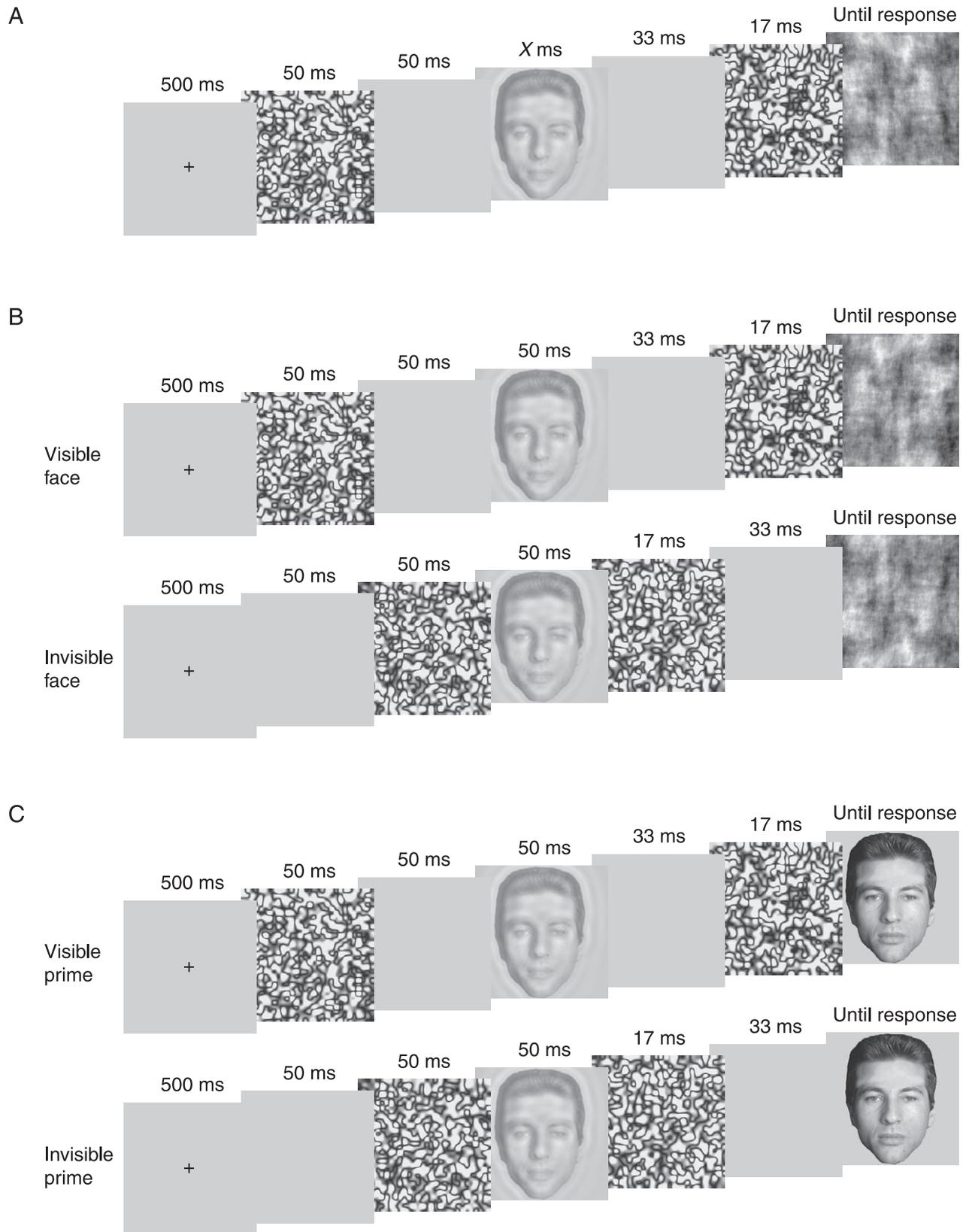


Figure 2. Illustration of the experimental paradigm used in Experiments 1 and 2. (A) Stimuli sequence for the practice phase. The duration of the face image was adjusted trial-by-trial to maintain accuracy at 90%. (B) Stimuli sequence for the pre- and post-visibility tests. The stimuli sequence at the top corresponds to the visible face condition and the stimuli sequence at the bottom to the invisible face condition. The only difference between the two conditions is the temporal order of the masks and blanks. (C) Visible and invisible prime sequences used in the testing phases of both experiments, which included a full-spectrum target face at the end of each trial. Note that in Experiment 2, the prime face was replaced by a blank on 50% of the trials.

1983) to maintain performance at 90% correct. Participants were instructed to accurately identify the gender of the faces by pressing labeled keys, counter-balanced across observers, on a regular computer keyboard. Auditory feedback in the form of a brief 3000-Hz tone was provided when an incorrect response was made. Each observer performed a minimum of three 100-trial blocks. The practice was completed once the face-stimulus duration decreased to 50 ms or less. In Experiment 1, participants completed a total of 17,400 practice trials ( $M = 1,450$  trials per subject,  $\min = 300$  trials,  $\max = 3,100$  trials, 95% confidence interval [1067, 1958]), and in Experiment 2 they completed 19,000 trials ( $M = 1,911$  trials per subject,  $\min = 300$  trials,  $\max = 4,900$  trials, 95% confidence interval [1483, 2508]) (see Table 1).

The pretest included a visible face and an invisible face condition (Figure 2b). The visible face condition was identical to the mask–blank–face–blank–mask–noise sequence of the practice phase, except that the face was presented at a fixed duration of 50 ms (see also, e.g., Finkbeiner & Palermo, 2009; Khalid et al., in press); this resulted in a face–mask stimulus onset asynchrony (SOA) of 83 ms. In the invisible face condition, the masks and the blanks were switched (see also Dehaene et al., 2001) so that the masks immediately surrounded the face image (blank–mask–face–mask–blank–noise; face–mask SOA = 50 ms). The two visibility conditions were interleaved in random order. Observers were asked to accurately identify the gender of the randomly SF filtered faces. In Experiment 1, observers performed the pretest with both original-contrast (80 trials) and contrast-reduced faces (320 trials) that were randomly inter-mixed. It turned out that contrast reduction was not necessary to obtain chance-level performance in the invisible face condition; thus, original-contrast faces were used in the remainder of the study, and only those results will be reported. In Experiment 2, observers completed 200 pretest trials (with original-contrast faces).

The testing phase followed the same basic procedure as the pretest except that (a) a target full-spectrum face replaced the phase noise at the end of each trial, (b) a control condition was added to Experiment 2, and (c) the focus was on RT rather than accuracy. Specifically, in the testing phase of both experiments, the last image in the stimulus sequence always displayed an unfiltered face that remained on the screen until the observer made a response. The target face was identical to the SF filtered face (i.e., the prime) on prime-present trials. In Experiment 1, there was always a prime in the sequence (visible prime, invisible prime). In Experiment 2, the prime faces were replaced by a blank on 50% of the trials, resulting in four conditions (visible blank, visible prime, invisible blank, invisible prime). In both

Experiment	Participant	Number of trials	Peak SF (cpf)	$Z_{\max}$	Cluster size $k$	Significance
1	1	1,600	7.97	3.99	20	*
	2	2,900	14.34	6.32	49	*
	3	1,500	13.28	6.29	29	*
	4	800	10.63	3.22	8	*
	5	300	9.56	3.19	11	*
	6	3,100	10.63	5.96	24	*
	7	600	9.56	2.79	6	*
	8	2,000	12.22	3.51	12	*
	9	1,000	13.28	2.78	10	*
	10	1,100	11.69	3.23	7	*
	11	1,500	11.69	3.76	23	*
	12	1,000	7.97	3.47	9	*
2	1	1,200	17.53	3.03	15	*
	2	3,000	11.16	4.97	23	*
	3	2,800	10.63	5.86	39	*
	4	2,200	7.97	3.17	25	*
	5	1,200	14.88	5.26	25	*
	6	1,300	8.50	2.82	4	n.s.
	7	2,400	11.69	2.32	2	n.s.
	8	3,200	15.94	4.60	37	*
	9	4,900	9.03	8.14	27	*
	10	1,500	8.50	4.25	11	*
	11	1,400	10.63	2.80	7	*
	12	1,900	8.50	4.13	17	*
	13	700	11.16	4.10	14	*
	14	900	14.88	4.26	27	*
	15	700	12.21	3.67	17	*
	16	2,100	13.28	3.90	20	*
	17	300	4.78	1.39	0	n.s.
	18	2,700	17.53	4.42	104	*

Table 1. Spatial frequency (SF) tuning results for individual observers in the practice phases of Experiments 1 and 2. The table gives the number of trials, peak SF in cycles per face width (cpf), maximum Z-score, cluster size, and significance as evaluated using the cluster test (Chauvin et al., 2005). Notes: \*significant using the cluster test ( $k_{crit} = 4.81$  pixels,  $p < .05$ , two-tailed,  $Z_{arbitrary} = \pm 2.3$ ,  $S_r = 128$ ,  $FWHM = 4.24$ ); n.s., not significant.

experiments, observers were instructed to pay attention to the whole stimulus sequence and to identify the gender of the full-spectrum target face as accurately and as quickly as possible. The testing phase of Experiment 1 consisted of 25 blocks of 80 trials, for a total of 1,000 trials per condition per observer; that of Experiment 2 consisted of 10 blocks of 80 trials (200 per condition per observer).

In order to reassess the visibility of the primes after the testing phase, each participant completed a 200-trial posttest that followed the same procedure as the pretest and was identical for both experiments.

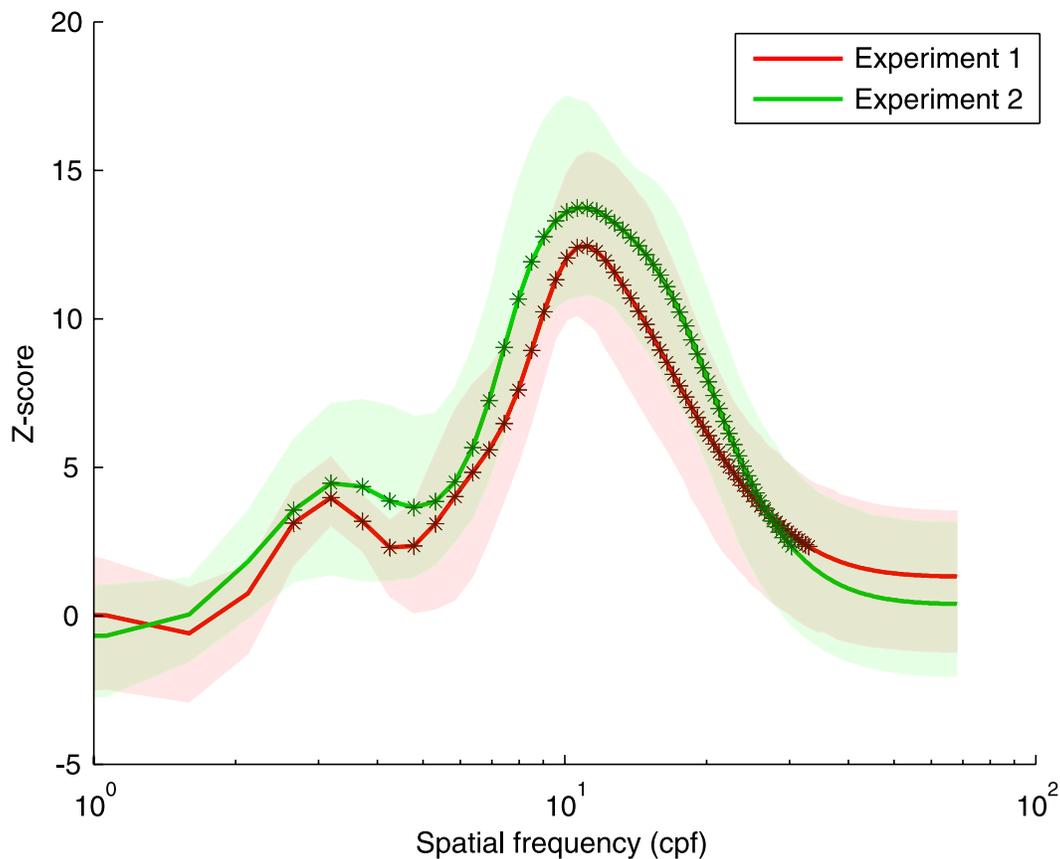


Figure 3. Spatial frequency tuning for direct, accurate face-gender discrimination. The graph depicts the group classification vectors derived from the practice phases of Experiment 1 (red; the pink area shows the 95% confidence interval) and Experiment 2 (green; the light green area shows the 95% confidence interval). Stars mark the significant segments of the classification vectors.

## Analysis and results

### SF usage for direct, accurate face-gender discrimination

First, we analyzed the data from the practice phases of Experiments 1 and 2. This allowed us to see which SFs are optimal for direct, accurate face-gender categorizations and to compare SF tuning for the two groups of participants. We summed the SF filters from each practice trial weighted by the observers' transformed accuracies. The accuracies were transformed as follows: Correct responses were given a value of  $P(\text{incorrect})$ , which denotes the probability of observing an incorrect response—i.e., here 0.1—and incorrect responses a value of  $-P(\text{correct})$ —i.e., here  $-0.9$ . Henceforth, we will call the result of this weighted sum a *classification vector*. One such classification vector was computed per block per participant. One participant classification vector was calculated for each observer by summing all respective block classification vectors. Finally, we derived one group classification vector for Experiment 1 and another for Experiment 2

by summing the appropriate participant classification vectors and transforming the results into  $Z$ -scores (see Willenbockel, Fiset, et al., 2010, for details). Statistical significance was evaluated by applying the cluster test (Chauvin, Worsley, Schyns, Arguin, & Gosselin, 2005): Given the clusters greater than an arbitrary  $Z$ -score threshold,  $Z_{\text{arbitrary}}$ , the test gives a cluster size,  $k_{\text{crit}}$ , above which the specified  $p$ -value is satisfied ( $k_{\text{crit}} = 4.81$  pixels,  $p < .05$ , two-tailed,  $Z_{\text{arbitrary}} = \pm 2.3$ ,  $S_r = 128$ ,  $FWHM = 4.24$ ).

The  $Z$ -transformed group classification vector for Experiment 1 showed a positively significant SF range ( $k_{\text{max}} = 58$ ) with a local maximum at 3.19 cpf ( $Z_{\text{local max}} = 3.98$ ) and a global maximum at 11.16 cpf ( $Z_{\text{max}} = 12.46$ ). Similarly, the group classification vector for Experiment 2 showed a positively significant SF range ( $k_{\text{max}} = 53$ ) with a local maximum at 3.19 cpf ( $Z_{\text{local max}} = 4.47$ ) and a global maximum at 10.63 cpf ( $Z_{\text{max}} = 13.74$ ) (Figure 3). The two classification vectors were highly correlated ( $r = 0.99$ ), suggesting that SF tuning was very consistent across the two groups of participants. The peak SFs for individual participant classification vectors are given in Table 1.

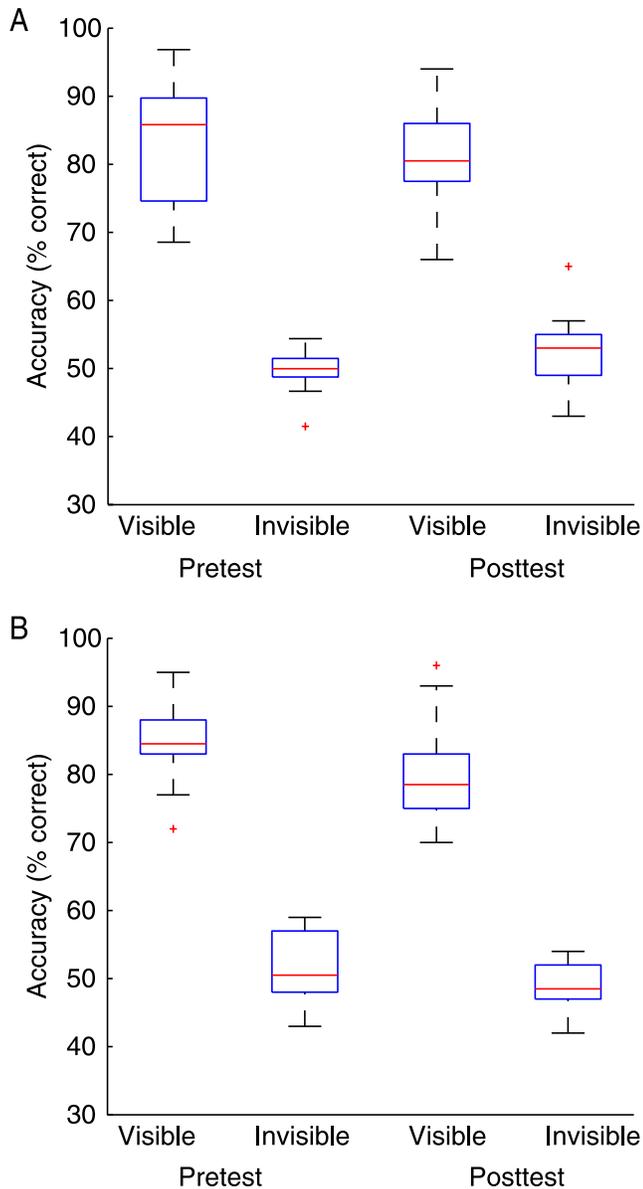


Figure 4. Pre- and posttest results from (A) Experiment 1 and (B) Experiment 2 for the visible and invisible face conditions. Red horizontal lines indicate medians, edges of the blue boxes indicate 25<sup>th</sup> and 75<sup>th</sup> percentiles, black whiskers extend to the extremes not considered outliers, and red crosses mark outliers.

### Prime visibility

Next, we analyzed the pre- and posttest data of both experiments to verify prime visibility (Figure 4). Pretest accuracy in the visible face condition was significantly higher than chance in both Experiment 1 ( $M = 83.14\%$ ,  $SE = 2.63\%$ ,  $t(11) = 12.60$ ,  $p < 0.001$ ), and Experiment 2 ( $M = 84.33\%$ ,  $SE = 1.24\%$ ,  $t(17) = 27.76$ ,  $p < 0.001$ ). In the invisible face condition, pretest accuracy was neither significantly different from chance in Experiment 1 ( $M = 49.83\%$ ,  $SE = 1.00\%$ ,  $t(11) = -0.17$ ,  $p =$

$0.87$ , nor in Experiment 2 ( $M = 51.22\%$ ,  $SE = 1.32\%$ ,  $t(17) = 0.92$ ,  $p = 0.37$ ).

Similarly, posttest accuracy in the visible face condition was significantly above chance in Experiment 1 ( $M = 81.25\%$ ,  $SE = 2.14\%$ ,  $t(11) = 14.58$ ,  $p < 0.001$ ) and in Experiment 2 ( $M = 79.44\%$ ,  $SE = 1.66\%$ ,  $t(17) = 17.75$ ,  $p < 0.001$ ). Posttest accuracy in the invisible face condition did not attain statistical significance, neither in Experiment 1 ( $M = 52.67\%$ ,  $SE = 1.59\%$ ,  $t(11) = 1.68$ ,  $p = 0.12$ ), nor in Experiment 2 ( $M = 48.89\%$ ,  $SE = .86\%$ ,  $t(17) = -1.29$ ,  $p = 0.21$ ). These pre- and posttest results for both experiments also held up when using  $d'$  instead of accuracy. Overall, the visibility tests showed that both groups of participants could reliably identify the gender of the faces in the visible face condition but not in the invisible face condition. As can be seen in Figure 4, however, one participant performed above chance in the invisible face condition of the posttest of Experiment 1 (65% correct). Interestingly, it is the only participant who completed the posttest on a different day than the pretest and the main experiment.

### Which SFs prime?

To examine which SFs within the primes modulate observers' responses to the target, we analyzed the data from the testing phase of Experiment 1 (specifically, Blocks 5 to 25 for each participant; 20,160 trials in total). Trials with incorrect face-gender discrimination responses were excluded. Classification vectors were derived by summing the SF filters of the prime stimuli weighted by the observers' transformed RTs. The RTs were transformed as follows:  $[-\log(\text{RT} + 1) - \text{mean}_{\log(\text{RT}+1)}] / \text{std}_{\log(\text{RT}+1)}$ . One classification vector was computed per condition and per block. One participant classification vector per condition was then calculated for each observer by summing all respective block classification vectors. Group classification vectors were derived for each condition by summing the respective participant classification vectors and transforming the results into Z-scores. To explore the difference in SF tuning between the conditions, we subtracted the group classification vectors for the two awareness conditions and transformed the result into Z-scores. The cluster test was again used to evaluate statistical significance.

Figure 5 depicts the Z-scored classification vectors for the two prime visibility conditions. The classification vector for the visible prime condition showed positive Z-scores across nearly the whole SF spectrum, with a significant peak at 12.22 cpf ( $Z_{\max} = 3.70$ ;  $k_{\max} = 21$ ). The classification vector for the invisible prime condition showed positive Z-scores for a range of low

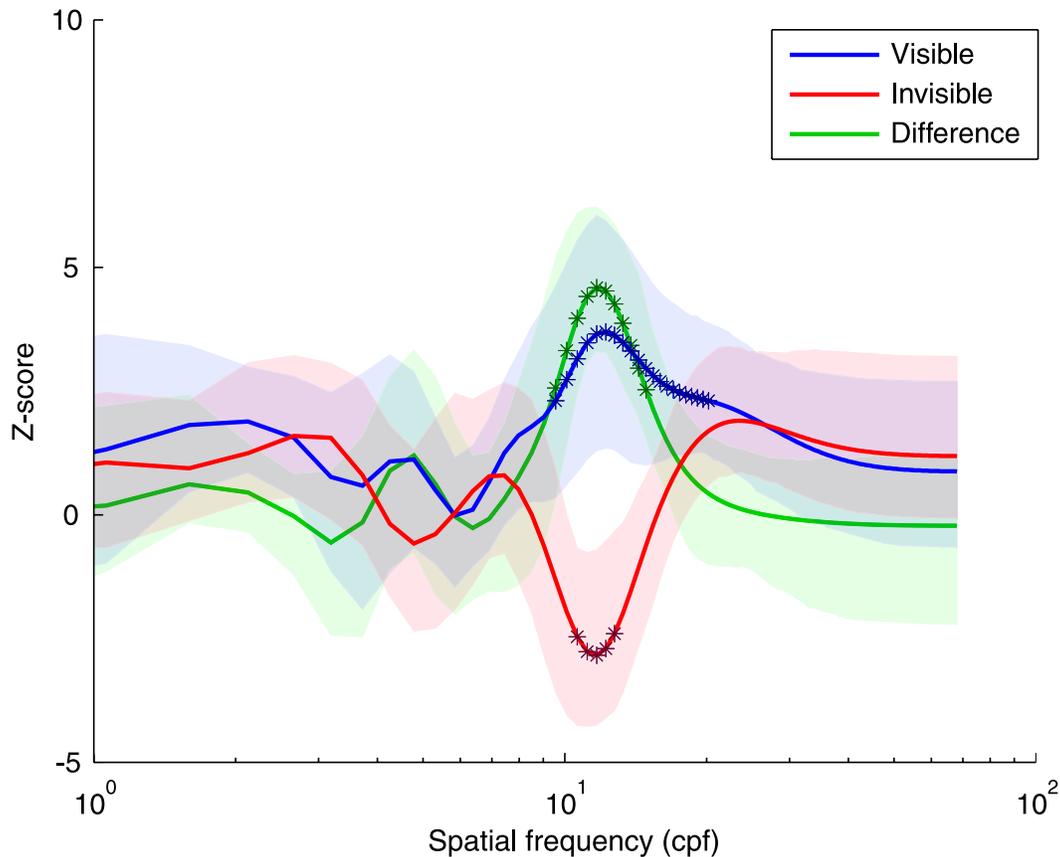


Figure 5. Spatial frequency tuning for conscious and nonconscious face-gender priming. The graph shows the group classification vectors derived from the testing phase of Experiment 1 for the visible prime condition (blue), the invisible prime condition (red), and the normalized difference between the two (green). The light areas show the respective 95% confidence intervals. Stars mark the significant segments of the classification vectors.

and high SFs, but without any significant peaks. Strikingly, for mid-SFs, Z-scores became negative, with a significant dip at 11.69 cpf ( $Z_{min} = -2.84$ ;  $k_{max} = 5$ ). The difference classification vector (visible prime vs. invisible prime) peaked significantly at 11.69 cpf ( $Z_{max} = 4.59$ ;  $k_{max} = 11$ ). We also computed the classification vectors without the outlier participant's data (see the posttest results for Experiment 1)—the difference between our visibility conditions remained significant for basically the same SFs (the peak was at 12.22 cpf;  $Z_{max} = 4.29$ ;  $k_{max} = 10$ ).

In sum, the correlation was maximal for the same mid-SFs in both visibility conditions; however, these SFs were linked with fast responses in the visible prime condition, whereas they were linked with slow responses in the invisible prime condition.

### Priming effects

The sign reversal for the significant Z-scores in Experiment 1 raises the question of the nature of the overall priming effects in the two visibility conditions.

To assess the direction and magnitude of priming, we analyzed the RTs from correct trials in the testing phase of Experiment 2. This was done using a repeated-measures analysis of variance with the factors prime visibility (visible prime, invisible prime) and presence (prime absent, prime present). The results showed that there was no main effect of prime visibility,  $F(1, 17) = .75$ ,  $p = 0.40$ , but a significant main effect of presence,  $F(1, 17) = 83.94$ ,  $p < 0.001$ . The latter reflected faster responses when the primes were present than when they were absent, i.e., facilitatory priming. There was also a significant Visibility  $\times$  Presence interaction,  $F(1, 17) = 19.18$ ,  $p < 0.001$ . The interaction was driven by a larger facilitatory priming effect in the visible prime (28 ms; 95% confidence interval [20, 34]) than in the invisible prime (9 ms; 95% confidence interval [3, 14]) condition. Contrasts for the interaction term revealed that the priming effects were significant in both visibility conditions [visible:  $F(1, 17) = 54.32$ ,  $p < 0.001$ ; invisible:  $F(1, 17) = 10.03$ ,  $p < 0.01$ ]. No significant effects were found in accuracy; see Table 2 for mean accuracy and RTs in Experiments 1 and 2,

Exp.	Condition	Accuracy (% correct)				RT (ms)			
		Mean	Min	Max	95% confidence interval	Mean	Min	Max	95% confidence interval
1	Visible prime	96.09	93.21	98.21	[95.34, 96.83]	500.84	439.22	814.84	[465.68, 620.37]
	Invisible prime	95.70	91.19	98.45	[94.36, 96.65]	521.52	454.27	842.44	[485.55, 618.44]
2	Visible prime	94.25	87.50	99.50	[92.72, 95.33]	578.46	527.60	664.78	[565.16, 595.73]
	Visible blank	94.19	87.00	99.00	[92.53, 95.58]	606.19	564.42	703.36	[593.62, 627.86]
	Invisible prime	94.47	91.50	99.50	[93.49, 95.77]	589.35	538.55	689.55	[574.65, 609.25]
	Invisible blank	94.56	89.00	99.50	[93.22, 95.92]	597.93	549.95	719.75	[581.80, 623.88]

Table 2. Face-gender judgment accuracy and response times (RTs) in the testing phases of Experiments 1 and 2.

and Table 3 for RT priming effects for each observer in Experiment 2.

## Discussion

We examined which SFs modulate observers' responses as a function of prime awareness. A face-gender repetition priming paradigm adapted from Dehaene et al. (2001) allowed us to set up visible and invisible prime conditions that differed solely in the timing of mask onset. By combining this paradigm with the SF bubbles technique (Willenbockel, Fiset, et al., 2010), we were able to map in an unbiased manner which SFs influenced observers' RTs. The present study is one of the first to examine SF tuning as a function of awareness at such a fine SF resolution (see also Willenbockel, Lepore, Nguyen, Bouthillier, & Gosselin, 2012). Our main results show that the same SFs affected RTs in both prime visibility conditions but, surprisingly, in opposite directions.

With regard to SF tuning, we found that information around 12 cpf significantly influenced observers' RTs (given face stimuli subtending a horizontal visual angle of  $\sim 3^\circ$ ). This finding resembles SF tuning results obtained in other face perception tasks. For instance, an SF band centered between 7 and 16 cpf was found to be optimal for the identification of faces subtending visual angles between  $2.3^\circ$  and  $9.5^\circ$  (e.g., Costen, Parker, & Craw, 1994, 1996; Gaspar, Sekuler, & Bennett, 2008; Gold, Bennett, & Sekuler, 1999; Näsänen, 1999; Willenbockel, Fiset, et al., 2010). Moreover, SFs around 11 cpf were maximally correlated with observers' accuracy in the direct face-gender discrimination task of the practice phases of Experiments 1 and 2. This suggests that SF tuning per se is robust across face identification, direct face-gender discrimination, and face-gender priming, even under different prime awareness conditions. It also suggests that the masks we used to manipulate prime visibility did not alter SF tuning.

The present SF results extend the findings of De Gardelle and Kouider (2010) and Khalid et al. (in press) by revealing the precise informational correlates of conscious and nonconscious priming. Both previous studies demonstrated nonconscious face priming effects for low SFs. Additionally, De Gardelle and Kouider, but not Khalid et al., observed nonconscious priming for high SFs. However, the filtering methods employed in those studies are limited in that they rely on a cutoff frequency for low- and high-pass filtering ( $3\text{ c}/^\circ$ , which corresponded to approximately 12 cpf). SF bubbles has the advantage over low-, high-, and band-pass filtering that it is unbiased and can reveal subtle differences in peak SFs or bandwidths (see also Thurman & Grossman, 2011, for a comparison of SF bubbles with band-pass filtering). This way, potential pitfalls related to the largely arbitrary choice of cutoff frequencies can be avoided. For instance, if our experiment was rerun with primes that were low- and high-pass filtered at 12 cpf, one would expect to see low- and high-SF priming independently of awareness; however, if it was rerun with primes that were low- and high-pass filtered at 17 cpf, one would expect to see low- and high-SF priming in the visible prime condition but only low-SF priming in the invisible prime condition. In fact, as we have shown, the same SFs were maximally correlated with observers' responses in both visibility conditions, with slightly greater absolute values in the visible prime condition.

A surprising aspect of our results is that the significant SFs influenced RTs in opposite directions in the two awareness conditions. Whereas in the visible prime condition, the significant SFs led to fast responses, they led to slow responses in the invisible prime condition. Such a reversal was seen neither in De Gardelle and Kouider's (2010) nor in Khalid et al.'s (in press) RT priming effects. This could be due to methodological differences, such as the choice of cutoff frequencies—possibly, the reversal would have been present for a mid-SF band-pass condition containing, e.g., SFs between 8 and 16 cpf.

To shed light on the nature of the overall priming effects in our paradigm, we ran a control experiment

Participant	Priming effect (ms)	
	Visible prime	Invisible prime
1	12	14
2	–11	21
3	27	13
4	29	16
5	27	8
6	20	17
7	45	–2
8	6	4
9	8	0
10	39	30
11	37	–16
12	43	–13
13	29	6
14	28	6
15	26	18
16	42	11
17	51	6
18	40	16

Table 3. Individual priming effects (response times from prime absent trials minus response times from prime present trials) for the two visibility conditions in the testing phase of Experiment 2.

(Experiment 2). It allowed us to compare the RTs from prime-present trials with those from prime-absent trials, separately for the two prime awareness conditions. Priming studies often measure congruence effects (e.g., RTs from same-gender vs. different-gender prime-target trials in Khalid et al., in press). However, the purpose of Experiment 2 was to uncover how the difference we observed in SF tuning (in Experiment 1) translates into overall RT effects, while introducing as few changes with regard to Experiment 1 as possible. Therefore, the prime-present versus prime-absent contrast was more appropriate: First, in Experiment 1, prime and target were always identical. Adding a different-gender condition at this stage would have introduced the potential confound that different gender implies different identities and different photos. Second, a different-gender condition could potentially have led to a change in the observers' strategy, since prime information would not always have been useful (e.g., participants might have paid less attention to the primes overall compared to Experiment 1).

The results of Experiment 2 revealed *facilitatory* priming effects of 9 ms and 28 ms for the invisible and visible prime conditions, respectively. By themselves, these findings appear consistent with previous face-gender priming results (e.g., Finkbeiner & Palermo, 2009; Goshen-Gottstein & Ganel, 2000; Henson et al., 2003; Khalid et al., in press). For instance, Finkbeiner and Palermo (2009) observed faster responses to target faces displaying the same gender as the invisible

(masked) prime faces than to targets of opposite gender (congruence effects of 10 ms, 9 ms, and 8 ms for different SOA conditions in Experiment 3). Khalid et al. found congruence effects of 4–6 ms for invisible low-SF primes. The studies by Goshen-Gottstein and Ganel (2000) and Henson et al. (2003) revealed long-lag repetition priming effects (i.e., shorter RTs to repeated versus unrepeated faces, with repetition lags of ~10 min) of approximately 20–30 ms for consciously perceived familiar and unfamiliar faces. Furthermore, several studies using different tasks demonstrated that priming effects are larger when the primes are consciously perceived than when they are rendered nonconscious (e.g., De Gardelle & Kouider, 2010; Kouider et al., 2007). Thus, the results of Experiment 2 closely replicate classic priming effects, both in terms of the direction of the priming (i.e., facilitatory) and magnitude.

How can these facilitatory priming effects observed in Experiment 2 be reconciled with the SF results obtained in Experiment 1? All blind statistical tests for classification images—including the cluster test (Chauvin et al., 2005) that we employed—assume relatively focal signals. Accordingly, several SFs that show positive Z-scores could have facilitated observers' responses despite being outside of the significant SF band in both classification vectors. In the visible prime condition, the band of SFs that attained statistical significance would also have facilitated observers' responses, resulting in an enhanced facilitatory effect. In the invisible prime condition, in contrast, the same band of SFs would have somewhat hindered observers' responses, resulting overall in a relatively small facilitatory effect.

This does not explain, however, why the influences of the diagnostic SFs are reversed as a function of awareness. This reversal could be related to a number of previous results demonstrating opposite priming influences in contexts of different awareness conditions (e.g., Eimer & Schlaghecken, 2002; Frings & Wentura, 2005; Klapp & Hinkley, 2002; for reviews see Eimer & Schlaghecken, 2003; Sumner, 2007). For example, Eimer and Schlaghecken (2002) found negative compatibility effects when the primes were not consciously perceived but positive compatibility effects when the primes did reach the observers' awareness. The negative compatibility effect was initially demonstrated using a left/right forced choice task with arrows as stimuli (Eimer & Schlaghecken, 1998, 2002) but has now been replicated in other paradigms, for instance, with emotional faces (Bennett, Lleras, Oriet, & Enns, 2007). Possibly, the results in our invisible prime condition reflect signs of a transition from positive to negative priming, with most SFs facilitating responses (hence the overall positive priming effect) but the SF band most systematically facilitating responses in the visible

condition inhibiting responses (hence the local negative priming effect). It is possible that if we had measured gender congruence effects in our control task instead of the prime-present versus prime-absent contrast, we would have observed a negative priming effect.

It is still debated which factors determine the direction of priming effects (e.g., see Sumner, 2007, for a review). It has been suggested that there might be a causal link between prime awareness and the direction of the compatibility effects (see, e.g., Eimer & Schlaghecken, 2002; Klapp & Hinkley, 2002). However, more recent results speak against this possibility (e.g., Schlaghecken, Blagrove, & Maylor, 2008; Verleger, Jaśkowski, Aydemir, Van der Lubbe, & Groen, 2004; see Sumner, 2007, for a review). Alternatively, it has been suggested that interactions between the mask and the prime might play a role (e.g., see Sumner, 2007, for a review). It would be conceivable that the increase in RTs observed in our study is related to interactions between information at  $\sim 12$  cpf in the invisible prime face and the immediately following mask; this interaction might not be present in the visible prime condition due to the inserted blank. In any case, more work will be needed to clarify the links between the direction of priming, masking, and awareness.

Several discussions in the field of nonconscious perception have emphasized the importance of revealing qualitative differences in the effects obtained with visible and invisible stimuli. In fact, reliably demonstrating nonconscious perception has posed many challenges (e.g., for reviews see Holender, 1986; Kouider & Dehaene, 2007), and revealing differences of a qualitative nature has been suggested to be the most convincing way to show that the conscious/nonconscious distinction is meaningful (Cheesman & Merikle, 1986). Here, we examined the possibility that qualitative differences reside in the visual information that is encoded and processed consciously versus nonconsciously. Results showing that, for instance, low SFs are processed nonconsciously whereas high SFs are not available during nonconscious processing would have strongly supported the qualitative views (see also Khalid et al., in press). However, the present results did not reveal differences in SF tuning per se. This could mean that the same underlying process(es) played a role in both awareness conditions (e.g., Holender & Duscherer, 2004; Perruchet & Vinter, 2002). It could also be that the composite RT measure that we employed does not contain enough signal to reveal subtle SF tuning differences in foveal vision. In a number of other recent studies results have been reported that were interpreted as qualitative differences between conscious and nonconscious perception (e.g., Barbot & Kouider, 2012; Eimer & Schlaghecken, 2002; Frings & Wentura, 2005; Snodgrass & Shevrin, 2006); both Willenbockel et al. (2012) and Khalid et al. (in

press) found differences in SF tuning as a function of awareness in face perception. We think that two interesting avenues for future research would be to map SF tuning with a high resolution in peripheral vision (see Khalid et al., in press) and to further investigate the reversal of priming influences we observed specifically for the SFs that are diagnostic for the task at hand.

*Keywords:* consciousness, face perception, priming, spatial frequency

## Acknowledgments

This work was supported by the Natural Sciences and Engineering Research Council (NSERC) for the Canada Research Chair and operating grant to Franco Lepore, and a NSERC Discovery grant to Frédéric Gosselin. We thank Josiane Jauniaux for help with data collection for Experiment 2 and Quoc Vuong and two anonymous reviewers for their helpful comments and suggestions.

Commercial relationships: none.

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## Footnotes

<sup>1</sup> By *invisible* we mean gender-invisible (see also, e.g., Finkbeiner & Palermo, 2009; Khalid et al., in press).

<sup>2</sup> MATLAB code to generate the masks: `mask = abs(imresize(randn(30, 30), [256, 256])); mask(mask > 1) = 1; mask = (mask - 0.5) * 0.85 + 0.5;`

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