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Unconscious semantic priming from pictures under backward masking and continuous flash suppression



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ABSTRACT

It is debated whether the meaning of invisible pictures can be processed unconsciously. We tested whether pictures of animals or objects presented under backward masking or continuous flash suppression could prime the subsequent categorization of target words into animal or non-animal. In Experiment 1, the backward masking part failed to replicate the priming effect reported in two previous studies, despite sufficient statistical power ($N = 59$). Similarly, the continuous flash suppression part provided no evidence for a priming effect. In Experiment 2 ($N = 65$) we shortened the prime-target SOA from 290 ms to 90 ms, but again failed to obtain unconscious semantic priming under backward masking. Thus, our study did not provide evidence for unconscious semantic processing of pictures. These findings support the emerging view that unconscious processing is rather limited in scope.

1. Introduction

Understanding the functional role and neural basis of conscious awareness is one of the central challenges for cognitive psychology and neuroscience. One promising approach consists in mapping out those perceptual and cognitive functions that can take place without conscious awareness, i.e. unconsciously. Ultimately, this research program should not only determine the extent and scope of unconscious processing but also yield a set of functions that cannot occur unconsciously (Baars, 1988; Kouider & Faivre, 2017). However, a consensus on the scope and potential limits of unconscious processing seems currently out of reach, with some concluding that unconscious processing can carry out basically any high-level function (Hassin, 2013; Sklar, Deouell, & Hassin, 2018; Soto & Silvano, 2014; van Gaal & Lamme, 2012), whereas others are more skeptical, proposing that processing without awareness is rather limited (Hesselmann & Moors, 2015; Moors et al., 2019; Moors, Hesselmann, Wagemans, & van Ee, 2017; Newell & Shanks, 2014; Peters & Lau, 2015; Stein, 2019). Part of this disagreement derives from the multitude of experimental approaches to unconscious processing, including various psychophysical techniques used to render stimuli unconscious. Even with the most established approaches, however, providing evidence for genuine high-level processing outside of awareness, while ruling out alternative accounts, has proven challenging.

Unconscious processing has most widely been studied in the visual domain, most commonly by adopting a variant of the subliminal priming paradigm. In subliminal priming an invisible stimulus (the prime) exerts an influence on responses to a subsequent visible stimulus (the target). By manipulating the relationship between prime and target different levels of unconscious visual processing can be targeted. Such priming studies have provided convincing evidence that stimulus analysis at early levels in the

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visual hierarchy, for example those involved in lightness and wavelength processing prior to color and lightness constancy, does not require awareness (e.g. [Breitmeyer, Ro, & Singhal, 2004](#); [Schmidt et al., 2010](#)). However, it is debated whether higher-level processing, including semantic and conceptual analysis, can occur unconsciously. Although many studies provided evidence for unconscious semantic priming (reviewed by [Kouider & Dehaene, 2007](#); [Van den Bussche, van den Noortgate, & Reynvoet, 2009b](#)), several alternative accounts have been put forward, challenging whether the prime was truly unconscious and whether the prime-target association was truly semantic.

To convincingly demonstrate unconscious semantic priming, several requirements need to be fulfilled: First, to rule out weakly conscious perception of the primes an objective awareness check should demonstrate that participants were unable to discriminate the primes ([Schmidt, 2015](#); [Snodgrass, Bernat, & Shevrin, 2004](#)). Second, when primes are also presented as targets or when primes can be expected given the task instructions, priming may reflect unconscious response activation ([Damian, 2001](#)) or activation of prepared “action triggers” for expected stimuli rather than unconscious semantic activation ([Kunde, Kiesel, & Hoffmann, 2003](#); but see [Van Opstal, Reynvoet, & Verguts, 2005a, 2005b](#)). To address these concerns, primes should come from large categories, such as animals ([Pohl, Kiesel, Kunde, & Hoffmann, 2010](#); [Van den Bussche & Reynvoet, 2007](#)), or from a novel set outside of the task set ([Van Opstal, Calderon, Gevers, & Verguts, 2011](#); [Van Opstal, Gevers, Osman, & Verguts, 2010](#)). Third, to eliminate the possibility that visual similarity between primes and targets caused priming effects (e.g. shape similarities or orthographic overlap; e.g., [Abrams and Greenwald \(2000\)](#), [Abrams \(2008\)](#), [Pohl et al., 2010](#); [Sakuraba, Sakai, Yamanaka, Yokosawa, & Hirayama, 2012](#)), primes and targets should be presented in different formats.

Two studies tried to meet these criteria by using pictures as primes (which represent a virtually infinite set) and words as targets, large stimulus sets, and objective awareness checks ([Dell’Acqua & Grainger, 1999](#); [Van den Bussche, Notebaert, & Reynvoet, 2009a](#)). In these studies, masked images of animals or (non-animal) objects primed the subsequent categorization of target words into animal or non-animal. The study by [Van den Bussche et al. \(2009a\)](#) fulfilled all the requirements for demonstrating truly unconscious semantic priming. In this study, stimuli came from large categories, primes never represented the same exemplar as the targets, and targets came from large stimulus pools (in the large target-set condition). This study represents one of the strongest demonstrations for genuine high-level processing outside of conscious awareness.

Here, our first goal was to replicate this study, using identical stimuli, tasks, and procedures. Our second goal was to evaluate the influence of different psychophysical techniques for rendering primes invisible. We compared standard backward masking (BM) as used in the original study to continuous flash suppression (CFS, [Tsuchiya & Koch, 2005](#)). CFS is a strong interocular suppression technique that has recently been widely adopted to study unconscious processing. There is evidence that unconscious processing under CFS is more limited than under BM, with several failures to obtain unconscious semantic effects under CFS ([Kang, Blake, & Woodmann, 2011](#); [Yang, Tien, Yang, & Yeh, 2017](#)). For example, two recent CFS studies failed to obtain evidence for picture priming at the categorical level ([Hesselmann, Darcy, Ludwig, & Sterzer, 2016](#); [Hesselmann, Darcy, Rothkirch, & Sterzer, 2018](#)). Because only few studies directly compared CFS with BM using similar stimuli and tasks ([Almeida, Mahon, Nakayama, & Caramazza, 2008](#); [Faivre, Berthet, & Kouider, 2012](#)), here we tested whether the established unconscious semantic priming effect that had been obtained with BM ([Dell’Acqua & Grainger, 1999](#); [Van den Bussche et al., 2009a](#)) would be similarly present or absent under CFS. Such comparisons are necessary for placing different methods for presenting stimuli unconsciously in a hierarchy according to the extent of unconscious processing they permit ([Breitmeyer, 2015](#)), which will help to guide future work in consciousness research.

2. Experiment 1: Close replication of [Van den Bussche et al. \(2009a\)](#) and extension to continuous flash suppression

Experiment 1 was a close replication and extension of [Van den Bussche et al. \(2009a\)](#). In the backward masking (BM) part we sought to replicate this previous study to compare results to the newly devised continuous flash suppression (CFS) version of this experiment.

2.1. Method

The study’s method, planned sample, exclusion criteria, hypotheses, and analysis pathways were pre-registered (<https://osf.io/y4jkk/>). The BM experiment was a close replication of the large-target set condition by [Van den Bussche et al. \(2009a\)](#). For the CFS experiment, we used the same stimuli as in the BM experiment and presented the primes for a duration similar to previous priming studies using CFS (e.g. [Almeida et al., 2008](#)). Prime-target SOA was identical in the BM and the CFS experiment.

Participants and statistical power. Participants were recruited from the University of Amsterdam subject pool, and received either course credit or a small monetary compensation for their participation. All participants had normal or corrected-to-normal vision, were Dutch native speakers, and were naïve to the purpose of the study.

We planned to include $N = 45$ participants in our main analyses testing for priming effects in the BM and CFS experiments, respectively, providing 95% power to detect a medium effect size ($d_z = 0.5$) at an alpha level of 5% (one-tailed). This sample size provided 99.9% power to detect the effect size reported by [Van den Bussche et al. \(2009a\)](#); for large target set $d_z = 0.86$). Data collection was terminated when this sample size was achieved, after exclusion of participants fulfilling the exclusion criteria related to above-chance prime discrimination (see below).

Fifty-nine participants were tested for this study, out of which 14 were excluded for parts of the analyses as they matched the exclusion criteria related to above-chance prime discrimination. Four participants met the exclusion criteria for the BM experiment, and eleven met the exclusion criteria for the CFS experiment (one participant met the criteria for both experiments). Out of the whole group of 59 participants, 15 were male and the mean age was 23.8 years. In the subgroup of 45 participants that did not fulfill any of

the exclusion criteria for parts of the analyses, twelve were male and the mean age of this group was 24.1 years.

Apparatus and display. Stimuli were displayed on an 19-inch Iiyama Vision Master Pro 510 (A201HT) CRT monitor (resolution 1024×768 pixels). The monitor was set to a refresh rate of 75 Hz and therefore allowed to display priming stimuli for the required 13.3 ms (to replicate Van den Bussche et al.'s (2009a) timing settings; accurate timing of our screen was confirmed with a photodiode). In the BM experiment, participants viewed the screen from a free viewing distance of approximately 60 cm. In the CFS experiment, participants viewed the screen from a viewing position of 48 cm, with their head positioned on a chinrest in front of the monitor. This chinrest had a removable mirror stereoscope attached to it (chinrest and stereoscope were removed for the BM experiment). The mirror stereoscope was adjusted for every participant before the CFS main experiment and before the CFS prime awareness test, in order to ensure complete fusion of the two images. The code for the experiment was written in MATLAB using the Psychtoolbox functions (Brainard, 1997).

Stimuli. Stimuli (kindly provided by Eva van den Bussche) were identical to the ones used by Van den Bussche et al. (2009a). The set of prime images consisted of a total of 50 line drawings (25 animals and 25 non-animal objects) that were originally selected from the set of grayscale images of the “Snodgrass and Vanderwart-like” objects (Van den Bussche et al., 2009a; also see Rossion & Pourtois, 2004). The size of these image primes was set to 140×140 pixels. The set of target words consisted of the Dutch names of the prime images (between three and six letters long). Target words were presented in black Arial font (capital letters, size 20 points) on a white background. Between trials the category (animals vs. non-animal objects) of targets and primes was manipulated, resulting in four conditions, two congruent and two incongruent (conditions presented as prime-TARGET): object-OBJECT, animal-ANIMAL, object-ANIMAL and animal-OBJECT. Identity conditions (e.g. cat-CAT) were never shown. There were 100 prime-target pairs, which were presented twice. All participants were presented with the same prime-target pairs (in randomized order). See the appendix for all prime-target pairs.

BM experiment. The order of the BM and the CFS experiment was counterbalanced between subjects. The setup of the BM experiment closely followed Van den Bussche et al.'s (2009a) original study. Participants were instructed to take part in a task that involved categorizing words as either objects or animals. Initially, participants were not informed of the presence of the primes but were merely asked to respond to the target words as quickly and accurately as possible, using the left and right arrow keys on a standard keyboard. Assignment of buttons to target categories (animal vs. object) was counterbalanced between participants.

See Fig. 1a for a schematic example of a trial from the BM experiment. At the beginning of each trial, a fixation cross was presented for 400 ms, followed by a forward mask consisting of four individual noise patterns (kindly provided by Eva van den Bussche), each presented for 13.3 ms (total duration of mask: 4×13.3 ms = 53 ms). Next, the prime image was shown for 13.3 ms, followed by a blank screen for 26.6 ms. After the blank screen, the backward mask was shown in the same manner as the forward mask (4 individual noise patterns for 13.3 ms each), followed by a second blank screen for 200 ms (all presentations were synchronized with the 13.3-ms vertical refresh cycle of the screen). Lastly, the target word was presented until the subject's response was registered. The inter-trial interval was one second. Participants completed a total of 200 trials: all 50 target words were presented twice on a congruent trial, and twice on an incongruent trial. Combinations of primes and target words (kindly provided by Eva van den Bussche) were identical to the original study.

CFS experiment. After individually calibrating the mirror stereoscope, participants were given the same instructions as in the BM experiment. The general setup slightly differed from the BM setup (see Fig. 1b): Two white frames surrounded by fusion contours (consisting of noise pixels) were presented side-by-side on a black screen, such that one frame was presented to each eye. Stimuli were presented inside these frames. Primes were presented to the participant's non-dominant eye (as determined by a variant of the Miles test). At the beginning of a trial, a fixation cross was presented for 400 ms to both eyes. This was followed by the presentation of a prime image for 200 ms to one eye while two CFS mask images were presented to the participant's dominant eye (for 100 ms each, standard diamond-shaped CFS masks, e.g. Stein & Sterzer, 2011). After the presentation of the prime image and the CFS masks, the blank frames were shown for 90 ms. Finally, the target word was presented to both eyes until the subject's response was registered. The inter-trial interval was one second. As in the BM experiment, 200 trials were completed by the participants, and prime-target combinations were identical to the BM experiment (but trial order was randomized for each experiment separately).

Objective test of prime awareness. After completion of both the BM and the CFS experiment participants completed a BM and a CFS awareness check (in the same order as the main experiments). Here the setup was almost identical to the main experiments, except that subjects were not presented with a target word to categorize. Instead they were informed of the presence of the primes, and ‘XXXXX’ was displayed instead of the target words. Participants were asked to categorize the primes, as accurately as possible, without speed pressure (guessing when necessary). Participants completed 100 trials for each masking technique. Each of the 50 prime images was therefore presented twice with each masking technique.

Exclusion criteria. Participants with median RTs above 700 ms (more than 5 SDs above the mean median RTs reported by Van den Bussche et al. (2009a) for incongruent non-animal object targets) in either experiment would have been excluded. Also participants with error rates above 25% (more than 5 SDs above the mean error rates reported by Van den Bussche et al. (2009a) for incongruent non-animal object targets) in either experiment would have been excluded. None of our participants fulfilled these exclusion criteria.

For part of the analyses, participants with above-chance prime discrimination performance were excluded (see Shanks, 2017, for a discussion of why such post-hoc exclusion of participants is invalid and leads to regression to the mean¹). Prime discrimination

¹ As it was difficult to predict whether CFS would effectively suppress primes for all participants, we nevertheless included this additional analysis in our pre-registration protocol. Had we found significant priming effects in this sub-group analysis with the whole sample showing above-chance

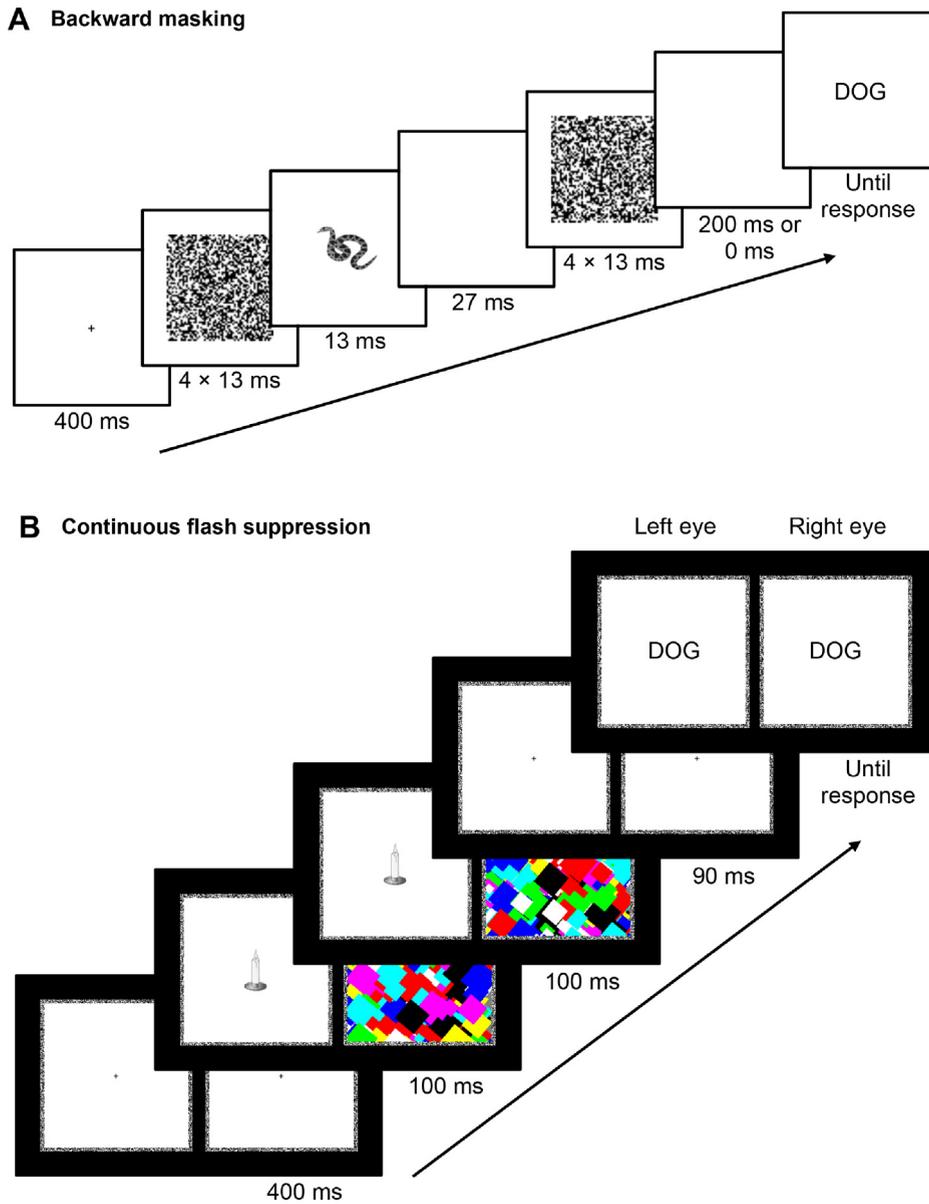


Fig. 1. Schematic illustration of trials in (a) the backward masking (BM) experiment and (b) the continuous flash suppression (CFS) experiment. (a) The BM example shows a congruent trial (prime and target both animals). Note that in Experiment 1 there was a 200-ms blank screen between the final mask and the target word (as in Van den Bussche et al., 2009a), whereas in Experiment 2 the target word followed the final mask with no delay. (b) The CFS example shows an incongruent trial (prime object, target animal).

accuracy was tested against chance using a binomial test: With 100 trials and a chance level of 50% correct, prime discrimination above 58% correct was significantly above chance (one-tailed).

Data pre-processing. For the BM and CFS main experiments, trials with incorrect responses were excluded from the analysis, and for both experiments median RTs (following Van den Bussche et al., 2009a) were calculated separately for congruently and incongruently primed targets.

For the prime awareness tests, the sensitivity index d' was calculated, considering animal primes that were correctly categorized as hits and object primes that were incorrectly categorized as false alarms.

(footnote continued)

prime discriminability, results for this sub-group would have been difficult to interpret, as these results would have been influenced by regression to the mean (Shanks, 2017).

2.2. Results and discussion

Data analyses followed the pre-registered analysis plan (with the exception of the section “additional exploratory analyses” below), first testing priming effects and prime discrimination for the whole sample ($N = 59$) and subsequently separately for those participants who did not discriminate primes with above-chance accuracy in either experiment ($N = 45$). Fig. 2 shows the results for the whole sample, separately for each target category (a factor we did not consider in our main, pre-registered analyses).²

Priming effects for the whole sample. For the BM experiment, the difference between RTs for congruently primed targets ($M = 504$ ms, $SD = 63.9$) and for incongruently primed targets ($M = 505$ ms, $SD = 65.0$) was not significant, $t(58) = -0.34$, $p = .369$ (one-tailed), $d_z = 0.04$. Similarly, for the CFS experiment, the difference between RTs for congruently primed targets ($M = 548$ ms, $SD = 70.7$) and for incongruently primed targets ($M = 551$ ms, $SD = 76.2$) was not significant, $t(58) = -0.98$, $p = .167$ (one-tailed), $d_z = 0.13$. Thus, there was no evidence for priming from backward masked or CF-suppressed prime images, even before considering participants’ prime awareness.

Comparison of priming effects between BM and CFS. A repeated measures ANOVA with the factors experiment (BM, CFS) and prime-target congruency (congruent, incongruent) revealed a significant effect of experiment, $F(1, 58) = 82.08$, $p < .001$, $\eta_p^2 = 0.59$, with overall faster RTs in the BM experiment than in the CFS experiment, but no significant effect of congruency, $F(1, 58) = 1.23$, $p = .273$, $\eta_p^2 = 0.02$, and no significant interaction, $F < 1$.

Prime discrimination sensitivity for the whole sample. For the BM experiment, prime discrimination sensitivity ($M = 0.04$, $SD = 0.26$) did not differ significantly from chance, $t(58) = 1.30$, $p = .100$ (one-tailed), $d_z = 0.17$, demonstrating that in the BM experiment prime images were objectively invisible. For the CFS experiment, prime discrimination sensitivity ($M = 0.24$, $SD = 0.62$) was significantly better than chance, $t(58) = 2.98$, $p = .002$ (one-tailed), $d_z = 0.39$, showing that for the whole sample CFS failed to render prime images objectively invisible.

Results for the reduced sample. Also in the separate analysis, carried out for those participants who did not show above-chance prime discrimination, there were no significant RT differences between congruently and incongruently primed targets, neither in the BM experiment, $t(44) = -0.08$, $p = .469$ (one-tailed), $d_z = 0.01$ (congruently primed targets, $M = 498$ ms, $SD = 55.2$; incongruently primed targets, $M = 499$ ms, $SD = 56.7$), nor in the CFS experiment, $t(44) = -0.06$, $p = .498$ (one-tailed), $d_z < 0.01$ (congruently primed targets, $M = 545$ ms, $SD = 64.5$; incongruently primed targets, $M = 545$ ms, $SD = 65.2$). As expected, prime discrimination sensitivity in this reduced sample was not significantly better than chance, both $p > .145$ (one-tailed), showing that for this sub-sample prime images were indeed objectively invisible in both experiments.

Additional exploratory analyses. We also compared response accuracies between congruent and incongruent trials using Wilcoxon signed rank tests (two-tailed). There were no significant differences, neither for the BM experiment (whole sample, $Z = -0.21$, $p = .834$; reduced sample, $Z = -0.15$, $p = .881$), nor for the CFS experiment (whole sample, $Z = -0.85$, $p = .394$; reduced sample, $Z = -0.03$, $p = .978$).

The RT data were also analyzed with repeated-measures ANOVAs with the factors target category (animal, object) and prime-target congruency (congruent, incongruent). For the whole-sample BM experiment this analysis revealed a significant main effect of target category, $F(1, 58) = 25.69$, $p < .001$, $\eta_p^2 = 0.31$, reflecting faster RTs for animal targets than object targets (Fig. 2). Neither the main effect of prime-target congruency nor the interaction were significant, both $F < 1$. Similarly, for the reduced-sample BM experiment and for the CFS experiment (whole and reduced sample), there were significant main effects of target category, with faster RTs to animal targets (all $p < .001$) but no other significant effects (all $p > .05$).

Finally, priming effects were also analyzed as the difference in mean RTs after removing outlier RTs using Tukey’s (1977) method. In brief, also with this analysis there were no significant priming effects, all $p > .146$, one-tailed.

3. Experiment 2: Backward masking with shorter prime-target SOA

One concern with Experiment 1 is the relatively long prime-target SOA of ~ 290 ms. Although Van den Bussche et al. (2009a) found significant priming effect with this SOA setting, other studies found unconscious priming with SOAs of 67 ms (Ortells, Kiefer, Castillo, Megías, & Morillas, 2016) or 100 ms (Pohl et al., 2010) and a rapid decay of unconscious priming for SOAs longer than 100 ms (Greenwald, Draine, & Abrams, 1996; also see Kiefer & Brendel, 2006; Kiefer & Spitzer, 2000). In Experiment 2 we therefore changed the BM experiment to a prime-target SOA of ~ 90 ms. In addition, we included an unmasked variant of the BM experiment to establish conscious priming effects. The comparably long prime presentation time in CFS (with two flashes, 200 ms) precludes a shortening of prime-target SOA. We therefore did not include a CFS condition in Experiment 2.

3.1. Method

The masked part of Experiment 2 was nearly identical to the BM part of Experiment 1, except that the 200-ms blank screen between the final mask and the target word was removed (see Fig. 1a). The unmasked part of Experiment 2 was the same, except that all masks were removed. The order of the different parts of Experiment 2 was counterbalanced between participants. Half the

² We followed Van den Bussche et al. (2009a) in analyzing priming effects and prime discrimination separately. Had we found significant priming effects it would have been important to additionally compare priming effects and prime discriminability on the same scale (e.g., Franz & von Luxburg, 2015; Schmidt & Vorberg, 2006).

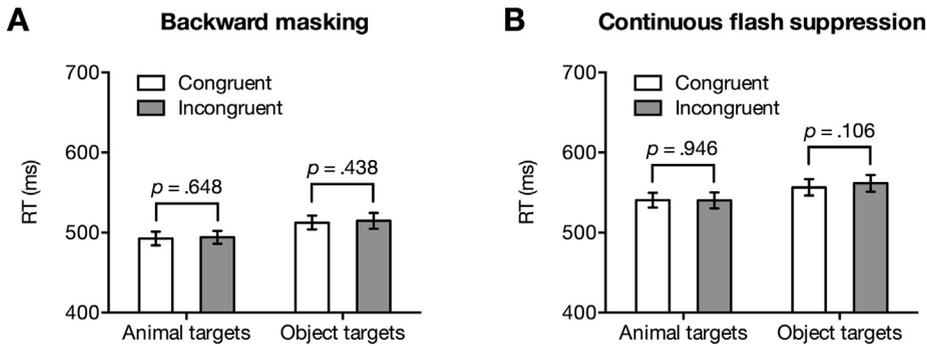


Fig. 2. Results for the whole sample ($N = 59$) from Experiment 1 for (a) the backward masking experiment and (b) the continuous flash suppression experiment. Bar plots show group means of median RTs as a function of target category and prime congruency. Error bars represent SEMs.

participants started with the masked part, then completed the awareness check (identical to Experiment 1, but without the blank screen before the “XXXXX” prompt), and then the unmasked part. The other half started with the unmasked part, then did the masked part, and then the awareness check. Because we again failed to obtain evidence for unconscious priming (see below), we did not further consider the order of the different experimental parts in our analyses.

Participants and participant exclusion. For Experiment 2, we tested as many participants as possible to maximize power. As for Experiment 1, participants were recruited from the University of Amsterdam subject pool, and received either course credit or a small monetary compensation for their participation. All participants had normal or corrected-to-normal vision, were Dutch native speakers, and were naïve to the purpose of the study.

A total of 76 participants completed Experiment 2 out of which 11 had to be excluded as they matched the exclusion criteria (same as for Experiment 1) related to long median RTs (above 700 ms) or to error rates above 25%, in either the masked or unmasked part. Of the remaining 65 participants, 14 were male and the mean age was 24.8 years. Out of these 65 participants, five participants showed above-chance prime discrimination in the awareness check (greater than 58% correct, binomial test, one-tailed) and these were excluded from part of the analyses.

Apparatus, display, stimuli, and data pre-processing. These were identical to the BM part of Experiment 1.

3.2. Results and discussion

Data analyses followed Experiment 1, first testing priming effects and prime discrimination for the whole sample ($N = 65$) and subsequently separately for those participants who did not discriminate primes with above-chance accuracy ($N = 60$). Fig. 3 shows the results for the whole sample, separately for each target category (a factor we again did not consider in our main analyses).

Priming effects for the whole sample. For the masked experiment, the difference between RTs for congruently primed targets ($M = 525$ ms, $SD = 57.9$) and for incongruently primed targets ($M = 525$ ms, $SD = 61.0$) was not significant, $t(64) = -0.10, p = .459$ (one-tailed), $d_z = 0.01$ (Fig. 3). For the unmasked part, the difference between RTs for congruently primed targets ($M = 514$ ms, $SD = 60.9$) and for incongruently primed targets ($M = 557$ ms, $SD = 61.9$) was highly significant, $t(64) = -14.07, p < .001, d_z = 1.74$. Thus, while there was again no evidence for priming from backward masked prime images, unmasked primes evoked very strong effects.

Prime discrimination sensitivity for the whole sample. Prime discrimination sensitivity ($M = -0.02, SD = 0.24$) did not differ significantly from chance, $t(64) = -0.54, p = .295$ (one-tailed), $d_z = -0.07$, again showing that with BM prime images

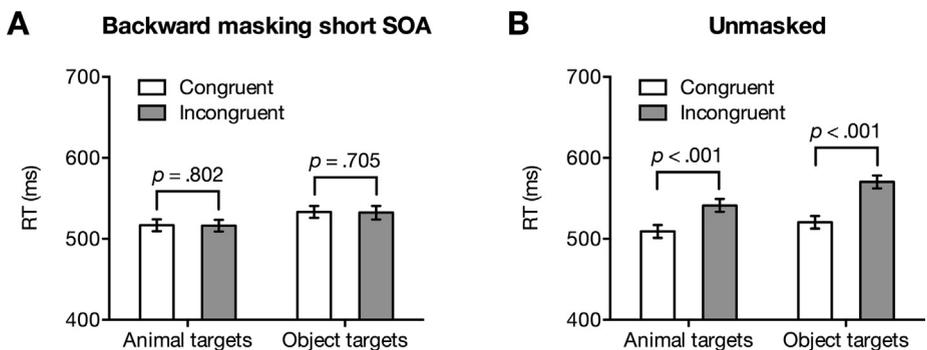


Fig. 3. Results for the whole sample ($N = 65$) from Experiment 2 for (a) the backward masking experiment with shorter prime-target SOA and (b) the unmasked variant of this experiment. Bar plots show group means of median RTs as a function of target category and prime congruency. Error bars represent SEMs.

were objectively invisible.

Results for the reduced sample. Also in the separate analysis including those participants who did not show above-chance prime discrimination, in the masked BM part there were no significant RT differences between congruently and incongruently primed targets, $t(59) = -0.33$, $p = .372$ (one-tailed), $d_z = 0.04$ (congruently primed targets, $M = 527$ ms, $SD = 59.5$; incongruently primed targets, $M = 528$ ms, $SD = 62.5$). Perhaps surprisingly, prime discrimination sensitivity ($M = -0.06$, $SD = 0.18$) in this reduced sample was even significantly worse than chance, $t(59) = -2.80$, $p = .003$ (one-tailed), $d_z = -0.36$. This may either be a false positive, or reflect the exclusion strategy. As prime discriminability for the whole sample was not significantly better than chance, excluding participants with the highest prime discriminability may have artificially pushed performance below chance (and this may be an illustration of known issues with post-hoc subject exclusion, e.g. Schmidt, 2015; Shanks, 2017).

Additional exploratory analyses. In the unmasked part, accuracy in congruent trials ($M = 96.9\%$, $SD 3.1$) was significantly higher than in incongruent trials ($M = 92.7\%$, $SD 6.3$), $Z = -5.96$, $p < .001$. In the masked BM part, however, there were no significant differences (whole sample, $Z = -0.69$, $p = .491$; reduced sample, $Z = -0.83$, $p = .408$).

We also analyzed the RT data with repeated-measures ANOVAs with the factors target category (animal, object) and prime-target congruency (congruent, incongruent). Just as in Experiment 1, for the whole-sample masked BM experiment this analysis revealed a significant main effect of target category, $F(1, 64) = 24.41$, $p < .001$, $\eta_p^2 = 0.28$, with faster RTs for animal targets than object targets (Fig. 3). Again, neither the main effect of prime-target congruency nor the interaction were significant, both $F < 1$. Similarly, for the reduced-sample BM experiment there was a significant main effect of target category ($p < .001$), but no other significant effects ($F_s < 1$). For the unmasked part, all effects were significant (all $p < .001$), reflecting faster RTs for animal targets, faster RTs for congruent trials, and a larger priming effect for object targets (Fig. 3). An additional ANOVA for the whole sample comparing RTs from the masked BM part and the unmasked part revealed a significant interaction between experimental part (masked, unmasked) and congruency, $F(1, 64) = 152.97$, $p < .001$, $\eta_p^2 = 0.71$, reflecting a larger priming effect in the unmasked part.

Finally, priming effects from the masked BM part were again analyzed as the difference in mean RTs after removing outlier RTs using Tukey's (1977) method. Also with this analysis there were no significant priming effects, all $p > .329$, one-tailed.

4. General discussion

The present study tested unconscious semantic priming from pictures rendered invisible through backward masking (BM) and continuous flash suppression (CFS). We adopted the approach by Van den Bussche et al. (2009a), as this study fulfilled the key criteria for demonstrating genuinely semantic and truly unconscious processing of pictures. However, in Experiment 1 our BM condition failed to replicate the significant priming effect reported in this previous study. Similarly, our CFS condition yielded no evidence for a priming effect. In Experiment 2, we used a shorter prime-target SOA of 90 ms, but again failed to obtain evidence for unconscious priming, whereas an unmasked, conscious condition yielded large priming effects. Thus, in contrast to two previously published studies that found priming from unconscious pictures on word targets (Dell'Acqua & Grainger, 1999; Van den Bussche et al., 2009a), our experiments failed to demonstrate unconscious processing of pictures.

The failure to replicate these previous findings is unlikely due to a lack of statistical power. In Experiment 1, with our original sample of $N = 59$ we had 99% power to detect the effects reported in these previous studies, and even with our reduced sample of $N = 45$ we had 99% power to detect the effect reported by Van den Bussche et al. (2009a) and 95% power to detect the effect reported by Dell'Acqua and Grainger (1999). Experiment 2 had an even larger sample size and thus even higher statistical power but still did not yield an effect from unconscious primes. Also, effect sizes for priming effects in our BM experiments fell outside the 95% confidence intervals of the effect sizes reported in these previous studies, which renders our BM experiment a genuine failure to replicate (Patil, Peng, & Leek, 2016). Clearly, our null results neither invalidate these previous findings nor do they mean that semantic picture priming does not exist. However, they suggest that these effects, if existent, are weaker than previously thought.

One advantage of using pictures to study unconscious processing is that they come from a virtually infinite set, especially when the categories, as in the present study, are very large (animals and non-animals). For this reason it seems unlikely that priming effects could reflect activation of prepared action triggers for expected stimuli. However, it may be that pictures are not optimally suited to map out the extent of unconscious processing. Visual analysis of pictures may be too complex to be carried out by unconscious processes. Alphanumeric characters may be visually less complex, and hence easier to process unconsciously. Indeed, there is evidence for unconscious semantic processing of words (reviewed by Van den Bussche et al., 2009b) and of relationships among alphanumeric characters (Van Opstal et al., 2010). Comparing unconscious semantic priming from pictures and alphanumeric characters within the same paradigm may thus represent an interesting avenue for future research.

The failure to obtain priming effects in our CFS experiment is consistent with several recent studies that did not find evidence for category-priming (Hesselmann et al., 2018) and even shape-priming (Hesselmann et al., 2016) under CFS. Together, these studies support the notion that unconscious processing under CFS is limited to basic sensory analysis (Moors et al., 2019, 2017; Stein, 2019). However, Almeida et al. (2008, Experiment 5) found significant priming effects from invisible pictures on word targets, but this effect was restricted to images of tools and did not extend to images of animals. Also, this study used a limited set of prime and target stimuli, and primes were visible in some (high-contrast) conditions, such that priming may have reflected action trigger rather than semantic activation. Nevertheless, as the stimulus set used in the present study did not allow for a separate analysis for tools (or elongated objects, see Sakuraba et al., 2012), future studies should replicate this experiment using larger stimulus sets and fully invisible primes.

Our findings leave open the possibility that unconscious semantic priming can be obtained with other stimuli and tasks. For example, Pohl et al. (2010) found unconscious priming with pictures of (small and large) animals and objects that were used both as

primes and targets. To rule out the influence of visual similarity between prime and target categories, these authors used an orthogonal task, where participants had to indicate the size of the target picture. Similarly, the use of words as prime and target minimizes visual similarity (e.g. Kiefer & Martens, 2010). One factor that may strongly influence unconscious priming is the degree of semantic relatedness between prime and target. In the present study, we adopted the same stimulus set as Van den Bussche et al. (2009a) and did not collect an independent measure of semantic relatedness. As there is evidence that unconscious priming is larger for strongly related prime-target pairs (Ortells et al., 2016; Ortells, Marí-Beffa, & Plaza-Ayllón, 2013; Van den Bussche, Smets, Sasanguie, & Reynvoet, 2012), future studies should explicitly manipulate the degree of semantic relatedness.

In conclusion, we failed to obtain evidence for unconscious semantic priming from pictures, both under backward masking and continuous flash suppression. Our results contribute to growing skepticism regarding the notion that virtually all perceptual processes can transpire outside of awareness (Hassin, 2013; Sklar et al., 2018; Soto & Silvanto, 2014; van Gaal & Lamme, 2012), and support the view that unconscious processing is rather limited in scope (Hesselmann & Moors, 2015; Moors et al., 2019, 2017; Newell & Shanks, 2014; Peters & Lau, 2015; Stein, 2019)

5. Author note

We thank Tosca Beijaert, Regis Mancini, and Simon Reichwein for help with data collection. Correspondence concerning this article should be addressed to Timo Stein, Department of Psychology, University of Amsterdam, Netherlands.

CRedit authorship contribution statement

Timo Stein: Conceptualization, Methodology, Software, Formal analysis, Visualization, Supervision. **Vanessa Utz:** Investigation. **Filip Opstal:** Conceptualization, Supervision.

Appendix A. Prime-target pairs

Animal targets

The first row for a given target word represents the congruent condition, and the second row the respective incongruent condition.

| Prime picture | Target word (Dutch) | Target word (English translation) |
|---------------|---------------------|-----------------------------------|
| bird | KAT | CAT |
| bed | KAT | CAT |
| fish | KOE | COW |
| ball | KOE | COW |
| spider | HOND | DOG |
| clock | HOND | DOG |
| bear | SPIN | SPIDER |
| book | SPIN | SPIDER |
| fly | PAARD | HORSE |
| chair | PAARD | HORSE |
| lion | VLIEG | FLY |
| candle | VLIEG | FLY |
| donkey | SLAK | SNAIL |
| glasses | SLAK | SNAIL |
| rooster | MUIS | MOUSE |
| glass | MUIS | MOUSE |
| dog | BEER | BEAR |
| lamp | BEER | BEAR |
| ant | HAAN | ROOSTER |
| door | HAAN | ROOSTER |
| snail | MIER | ANT |
| flag | MIER | ANT |
| mouse | EZEL | DONKEY |
| lock | EZEL | DONKEY |
| owl | KIP | CHICKEN |
| pen | KIP | CHICKEN |
| zebra | LEEUEW | LION |
| scissors | LEEUEW | LION |
| horse | SLANG | SNAKE |
| violin | SLANG | SNAKE |
| snake | GIRAF | GIRAFFE |
| table | GIRAF | GIRAFFE |
| chicken | MUS | SPARROW |
| axe | MUS | SPARROW |

| | | |
|---------|--------|---------|
| cat | VIS | FISH |
| comb | VIS | FISH |
| tiger | GEIT | GOAT |
| fork | GEIT | GOAT |
| pig | KREEFT | LOBSTER |
| bow | KREEFT | LOBSTER |
| cow | UIL | OWL |
| cup | UIL | OWL |
| lobster | TIJGER | TIGER |
| piano | TIJGER | TIGER |
| giraffe | KONIJN | RABBIT |
| apple | KONIJN | RABBIT |
| goat | ZEBRA | ZEBRA |
| hat | ZEBRA | ZEBRA |
| rabbit | VARKEN | PIG |
| guitar | VARKEN | PIG |

Object targets

The first row for a given target word represents the congruent condition, and the second row the respective incongruent condition.

| Prime picture | Target word (Dutch) | Target word (English translation) |
|---------------|---------------------|-----------------------------------|
| bird | BAL | BALL |
| bed | BAL | BALL |
| fish | BED | BED |
| ball | BED | BED |
| spider | BOEK | BOOK |
| clock | BOEK | BOOK |
| bear | KLOK | CLOCK |
| book | KLOK | CLOCK |
| fly | TAFEL | TABLE |
| chair | TAFEL | TABLE |
| lion | VIOOL | VIOLIN |
| candle | VIOOL | VIOLIN |
| donkey | GLAS | GLASS |
| glasses | GLAS | GLASS |
| rooster | BRIL | GLASSES |
| glass | BRIL | GLASSES |
| dog | PEN | PEN |
| lamp | PEN | PEN |
| ant | BIJL | AXE |
| door | BIJL | AXE |
| snail | LAMP | LAMP |
| flag | LAMP | LAMP |
| mouse | DEUR | DOOR |
| lock | DEUR | DOOR |
| owl | TAS | BAG |
| pen | TAS | BAG |
| zebra | STOEL | CHAIR |
| scissors | STOEL | CHAIR |
| horse | KAARS | CANDLE |
| violin | KAARS | CANDLE |
| snake | STRIK | RIBBON |
| table | STRIK | RIBBON |
| chicken | KAM | COMB |
| axe | KAM | COMB |
| cat | SLOT | LOCK |
| comb | SLOT | LOCK |
| tiger | VLAG | FLAG |
| fork | VLAG | FLAG |
| pig | SCHAAR | SCISSORS |
| bow | SCHAAR | SCISSORS |
| cow | HOED | HAT |
| cup | HOED | HAT |
| lobster | GITAAR | GUITAR |
| piano | GITAAR | GUITAR |
| giraffe | PIANO | PIANO |
| apple | PIANO | PIANO |
| goat | VORK | FORK |

| | | |
|--------|-------|-------|
| hat | VORK | FORK |
| rabbit | APPEL | APPLE |
| guitar | APPEL | APPLE |

Appendix B. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.concog.2019.102864>.

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