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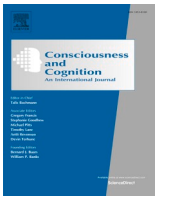

Priming of natural scene categorization during continuous flash suppression

Leonie Baumann [a], Christian Valuch [a,b,*]

[a] Department of Experimental Psychology, University of Goettingen, Germany
[b] Department of Cognition, Emotion, and Methods in Psychology, University of Vienna, Austria

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ABSTRACT

Continuous Flash Suppression (CFS) reduces conscious awareness of stimuli. Whether stimuli suppressed by CFS are processed at categorical or semantic levels is still debated. Here, we approached this question using a large set of indoor and outdoor scene photographs in a priming paradigm. Perceptually suppressed primes were followed by visible targets. Participants rapidly reported whether the targets showed an indoor or an outdoor scene. Responses were faster (and fast responses more accurate) when primes and targets came from a congruent superordinate category (e.g., both were outdoor scenes). During CFS, priming effects were relatively small (up to 10 ms) and modulated by prime visibility and stimulus onset asynchrony (SOA) of prime and target. Without CFS, the stimuli elicited consistent and more robust priming effects (about 24 ms). Our results imply that scene category is processed during CFS, although some residual prime visibility is likely necessary for significant priming effects to occur.

1. Introduction

The scope and limitations of unconscious visual processing and its effects on behavior have been widely investigated and debated throughout the last decades (Holender, 1986; Kouider & Dehaene, 2007; Marcel, 1983; Schmidt & Vorberg, 2006). Yet, as several methodological challenges exist until today, we still lack a clear picture when it comes to determining to what extent unconscious stimuli can be processed (Gayet et al., 2014; Lin & He, 2009). High-level unconscious processes can be studied using subliminal priming paradigms that examine how semantically related prime and target stimuli are processed outside of awareness (Yang et al., 2014). Semantic priming describes the acceleration of a response to a target stimulus due to the preceding presentation of a conceptually related prime stimulus (Wagner & Koutstaal, 2002). Typically, a congruency effect occurs, as congruent primes reduce the reaction time (RT) to a target stimulus while incongruent primes increase the RT (Klotz & Wolff, 1995).

Continuous flash suppression (CFS) is a rather new tool aiding the exploration of unconscious visual processing: A visual stimulus presented to one eye is suppressed and thus reduced in visibility by flashing a sequence of rapidly changing masks to the other eye. CFS allows to present visual stimuli outside of conscious awareness and can therefore be employed to probe unconscious cognitive processes in the form of unconscious priming (Hesselmann et al., 2015; Koivisto & Grassini, 2018). CFS builds upon the techniques of binocular rivalry and flash suppression that enable robust interocular suppression despite sustained visual stimulation (Tsuchiya & Koch, 2005). In CFS, multiple mask flashes lead to the summation of suppression, which does not only increase the suppression

* Corresponding author at: Department of Cognition, Emotion, and Methods in Psychology, University of Vienna, Austria.
E-mail address: christian.valuch@univie.ac.at (C. Valuch).

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duration by tenfold compared to binocular rivalry, but also raises the stimulus detection threshold by twentyfold compared to monocular viewing conditions (Tsuchiya & Koch, 2005; Tsuchiya et al., 2006).

Initial studies suggested that CFS could be particularly suitable for studying high-level unconscious processes, such as semantic processing (e.g., Mudrik et al., 2011; Sklar et al., 2012). For instance, Sklar et al. (2012) stated that *"CFS is a game changer in the study of the unconscious, because unlike all previous methods, it gives unconscious processes ample time to engage with and operate on subliminal stimuli."* (p. 19614). The underlying idea is that semantic processing may benefit from longer visual input or processing durations and may thus be limited in traditional visual masking techniques, where the processing time between a prime stimulus and a related target stimulus is more strongly constrained (Koivisto & Grassini, 2018; Valuch & Mattler, 2019). However, it is still debated if unconscious visual stimuli are processed as integrated semantic entities in CFS and if they reach and affect visual processing stages ascribed to high-level processes irrespective of conscious awareness (Moors et al., 2019; Moors et al., 2017; Sklar et al., 2018, Yang et al., 2014). Earlier CFS studies reported promising high-level priming effects using prime-target pairs that were semantically, categorically, or numerically related (Almeida et al., 2008, 2010; Bahrami et al., 2010; Zabelina et al., 2013). However, some of these results could either not be replicated (Hesselmann & Knops, 2014) or may also be explained by low-level feature effects (Sakuraba et al., 2012). Different methodological challenges and limitations of stimuli representation in CFS were discussed (Hesselmann et al., 2016; Hesselmann et al., 2015) and it was even suggested that unconscious semantic processing may not at all be possible in CFS (Kang et al., 2011; but see Heyman & Moors, 2012). Accordingly, even classical findings on unconscious semantic priming (Dell'Acqua & Grainger, 1999) could not be replicated in a recent study, neither with backward masking, nor with CFS (Stein et al., 2020). To summarize, despite extensive research it remains inconclusive whether high-level, semantic processes can withstand CFS, since several contradictive findings have been reported. Thus, more research is necessary to better understand the conditions under which certain semantic relationships between perceptually suppressed prime stimuli and visible target stimuli could be processed during CFS.

To date, only few CFS studies have investigated unconscious visual processing using natural, real-world scenes, although such stimuli have been suggested to be particularly suitable for examining semantic processing: In contrast to other kinds of meaningful visual stimuli like objects, faces, or text, accumulating evidence suggests that real-world scenes and their subcategories, such as indoor and outdoor scenes, vary in an important manner in visual and semantic characteristics (Henderson, 2005; Henderson et al., 2007). Prior CFS studies using natural prime and target stimuli mainly investigated the unconscious processing of animal and non-animal images. For instance, a study by Zhu et al. (2016) measured event-related brain potentials in response to animal, non-animal, and vehicle stimuli in CFS and found that brain responses differed between them even in unconscious conditions. Furthermore, a study by Koivisto and Rientamo (2016) examined how accurately natural scenes can be analyzed in CFS using colored natural images of animals, vehicles, and buildings. The study found semantic priming effects at the superordinate level (e.g., animal – animal) but not at the basic level (e.g., dog – dog; Koivisto & Rientamo, 2016). However, the study was criticized, as low-level features cannot be ruled out as an explanation for the effects (Koivisto & Grassini, 2018).

Natural, real-world scenes – such as indoor and outdoor scenes – possess promising semantic characteristics: Biederman et al. (1982) found that violations of semantic relations in real-world scenes were identified more accurately than other kinds of violations. Additionally, the authors suggested that semantic relations were already accessible after a single fixation and contained information about specific interactions between objects that could not be inferred from the general setting (Biederman et al., 1982). Hence, semantic and physical relations are probably analyzed simultaneously in real-world scenes, which implies that a brief presentation of a scene should suffice to understand its semantic gist. In the current study, the semantic distinction between indoor and outdoor scenes is of particular interest, as it is not only behaviorally relevant in everyday life but also entails distinct neural correlates. For instance, in a fMRI study, Henderson et al. (2007) found differential brain activation to indoor and outdoor scenes, with activation in the posterior parahippocampal cortex being significantly higher for indoor scenes. These findings suggest natural indoor and outdoor scenes are promising categories of stimuli for studying semantic processing under CFS, since their semantic distinction is not only relevant on a behavioral level but also on a neural level.

Depending on the method used to suppress perceptual awareness of stimuli, specific experimental variables can affect the strength of suppression but also the extent of priming. In a CFS study, Valuch and Mattler (2019) found that priming effects and prime visibility were modulated by prime contrast, mask contrast and the stimulus onset asynchrony (SOA) between prime and target stimuli in a parallel manner: In conditions where prime visibility was higher, action priming effects were also stronger. This finding differentiates CFS from backward masking, where priming effects are usually independent of prime visibility and increasing SOAs lead to monotonically increasing priming effects, whereas prime visibility can at times even decrease with SOA (Valuch & Mattler, 2019; Van den Bussche et al., 2009b; Vorberg et al., 2003, 2004). Another CFS study by Koivisto and Grassini (2018) reported that conscious priming effects increased with SOA, whereas unconscious priming effects were not modulated by SOA, suggesting a dissociation of conscious and unconscious processes. In a similar vein, Kiefer and Spitzer (2000) measured event-related brain potentials (ERP) as neural correlates of conscious and unconscious semantic processing under visual masking and noted dissociable time courses: For visible primes, ERP effects indicative of semantic processing increased with SOA, while for masked primes, the ERP effects decayed quickly. Hence, manipulating the prime–target SOA and the level of prime awareness experimentally can reveal possible dissociations between conscious and unconscious processing.

The present study investigated if semantic processing of natural scene relationships occurs independently of conscious perception in a priming paradigm. We manipulated conscious perception of the primes using CFS because we wanted to probe the possibility of higher-level unconscious processing in this method that has remained hotly debated until recently (Moors et al., 2017; Sklar et al. 2018). As typical for response priming paradigms, we instructed our participants to respond to the target as quickly and precisely as possible. We then compared the RT differences and response accuracies between congruent and incongruent conditions to measure priming effects (Schmidt et al., 2011). We also assessed the extent to which the primes were visible in a separate prime discrimination

task block. This dissociation procedure has been discussed as a strong and valid approach for investigating high-level unconscious processing during CFS (Hesselmann et al., 2018; Moors et al., 2019).

2. Experiment 1: Scene category priming during CFS

Experiment 1 tested if scene category priming occurs during CFS. To minimize the influence of low-level feature relationships between prime and target stimuli as a possible confound, the scenes in congruent prime-target pairs were never from the same real-world context (e.g., a kitchen prime scene was never followed by a kitchen target scene), such that there was solely a certain semantic relation between them in the sense that both could be indoor scenes or both could be outdoor scenes (e.g., kitchen – library would be a congruent prime–target pair). We hypothesized that congruent prime-target pairs (indoor – indoor, or outdoor – outdoor) facilitate the categorization performance and therefore decrease RTs and increase accuracy in the speeded choice RT task as suggested by Valuch and Mattler (2019). We also investigated if the strength of priming effects varied under different experimental conditions. Two conditions of prime visibility were created within participants by manipulating the CFS mask contrast to be either low (20%) or high (100%), whereby a low mask contrast corresponds to higher prime visibility and a high mask contrast corresponds to lower prime visibility. Moreover, two SOA conditions were created within participants by manipulating the SOA to be either short (200 ms) or long (400 ms). We expected that priming effects might vary with SOA, possibly indicating dissociations between conscious and unconscious processing whereas prime discrimination performance should not to be influenced by the SOA (Valuch & Mattler, 2019).

2.1. Method

2.1.1. Participants

Twenty participants (16 female) took part in the study. All were undergraduate psychology students (aged 18 – 26 years, $M = 21.2$, $SD = 1.87$) from the University of Goettingen. Participation was compensated with partial course credit. All participants had normal or corrected-to-normal vision. Before participation, a negative COVID-19 test result had to be provided and written informed consent was given by all participants. Due to restricted laboratory access during the COVID-19 pandemic, our maximum sample size was limited to

Fig. 1. (A) Example target stimuli of each context of the outdoor category (left: bridge, campsite, gas station, playground, tennis court, construction site, house, mountain, seaport, train, garden, parking, shopfront, street, woods) and the indoor category (right: staircase, restaurant, office, lobby, living room, library, dining room, bar, church, concert hall, kitchen, corridor, bathroom, bedroom, classroom). (B) All prime and target stimuli of one exemplary outdoor context (left: playground) and one exemplary indoor context (right: kitchen). Prime stimuli are depicted above the target stimuli.

20 participants. Based on published data, we calculated that a sample of 16 participants would provide a power of at least .95 for detecting significant priming effects under CFS conditions (see Valuch & Mattler, 2019, for priming with arrow stimuli; and Koivisto & Rientamo, 2016, for priming with scene images). Thus, we decided that conducting the study with 20 participants was feasible. The study procedures were in accordance with the ethical standards of the German Psychological Society and approved by ethics committee of the Georg-Elias-Mueller-Institute for Psychology of the University of Goettingen.

2.1.2. Apparatus

The experimental setup originally consisted of a 22-in. ViewSonic PF817 CRT monitor to present the visual stimuli at a viewing distance of 57 cm which was fixed using a head- and chinrest. Due to technical issues, the monitor had to be replaced by a 19-in. ViewSonic G90fB CRT monitor after the first participant and the viewing distance was reduced to 50 cm to keep the retinal size of the stimuli constant between both monitors. Both monitors were calibrated to the same target luminance function. Screen resolution was set to 1,024 × 768 pixels with a vertical refresh rate of 100 Hz. Monitors were connected to a Dell OptiPlex 990 PC with an Intel Core i7-2600 CPU and 16 GB of RAM. Dichoptic stimuli were presented simultaneously and alongside each other on the screen, and viewed by the participants through a mirror stereoscope that was installed on top of the chinrest (same as in Valuch & Mattler, 2019). The participants responded with their left and right index fingers using the "F" and "J" keys, which were haptically marked using rubber stickers, on a standard USB keyboard with a QWERTZ layout. The experiment was programmed and executed in MATLAB (MathWorks, Natick, MA) utilizing the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997).

2.1.3. Stimuli

Prime and target stimuli in the main experiment were 420 images depicting a variety of natural, real-world indoor and outdoor scenes in different contexts. The stimuli were grouped in 15 indoor and 15 outdoor contexts (for an overview, see Fig. 1A). Each context consisted of 14 different scenes of which 12 were used as target stimuli and two were used as prime stimuli in both tasks of the main experiment (Fig. 1B). Additionally, 16 indoor and 16 outdoor scenes were used as demo stimuli in the practice blocks of the main experiment. Demo stimuli were not repeated in the experimental blocks. All images were chosen from the Massive Memory Database (http://olivalab.mit.edu/MM/sceneCategories.html; Konkle et al., 2010) and converted to grayscale. To make the low-level visual features more similar between different stimuli, all images were processed through the SHINE toolbox (Willenbockel et al., 2010) to standardize their average luminance. An important criterion for image selection was that the scene category (indoor vs outdoor) was not readily apparent from a single dominant feature, such as a salient horizon in outdoor scenes. Therefore, images with outstanding characteristics or conspicuous objects were avoided as far as possible to minimize the likelihood of an overly easy categorization or instantaneous breach of interocular suppression. The image resolution was reduced to match the stimuli presentation size of 4° × 4°.

Suppressor stimuli were drawn randomly (on each trial) from a pool of 500 pre-generated CFS masks. The CFS masks consisted of overlapping black, gray, and white rectangles, whose edge lengths ranged from 0.1° to 1.5°. Averaged over all pixels, the selected set of CFS masks was characterized by an average luminance very close to 50% gray and a root mean square contrast of 60%. The CFS masks were presented in a randomized sequence at a rate of 10 Hz each trial. The presentation size of the full CFS masks was 4° × 4°. Square frames with an edge length of 5° × 5° bordered the dichoptic stimuli and were set to a 50% gray background, corresponding to a luminance of 27.7 cd/m^2. A checkerboard pattern on the outer edge of the frames enhanced the vergence stability when viewing the stimuli through the mirror stereoscope. Screen regions beyond the frames were set to black (0.1 cd/m^2). The fixation cross consisted of a central black dot (0.1° diameter) within a green cross (0.4° diameter) that was displayed on a black circle (0.4° diameter). The fixation cross appeared at trial onset and remained on screen until the participant responded. It was not presented during the intertrial interval. An incorrect response caused the green cross to switch to red. On-screen text (e.g., response feedback) was presented to both eyes above and below the fixation cross in black letters.

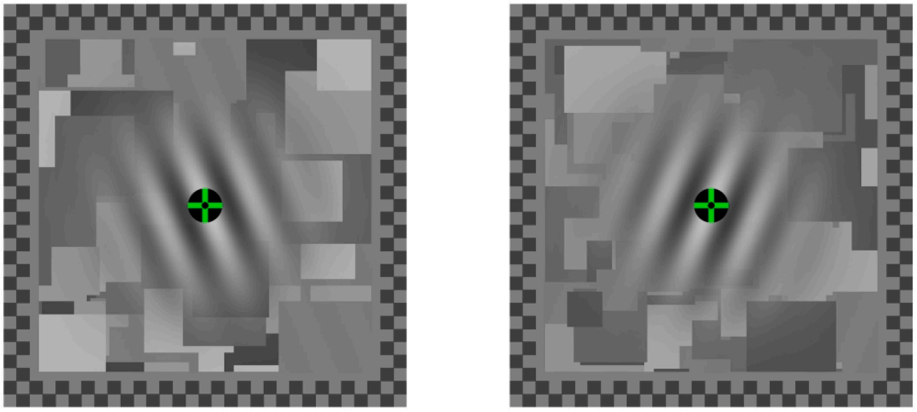

Fig. 2. Examples of binocularly fused stimuli in the eye dominance test (left: CFS mask presented to one eye, counter-clockwise tilted target grating presented to the other eye; right: CFS mask presented to one eye, clockwise tilted target grating presented to the other eye). Participants reported the tilt direction using keyboard button presses as soon as they could discern it.

2.1.4. Procedure

The experiment was conducted individually in a quiet and darkened laboratory room. Participants were prescreened for intact visual acuity of the left and right eye. They sat in front of the mirror stereoscope while the dichoptic stimuli were individually positioned on the screen to make each stimulus fully visible to the corresponding eye, thereby enabling binocular fusion. The experiment had three parts: An eye dominance test and two separate tasks in the main experiment. Before the start of each part, detailed written instructions were provided and the participants completed a practice block during which they could familiarize themselves with the task. After the experimental session, the participants were briefly interviewed about their experiences and task strategies in the main experiment. The interview was followed by a concise debriefing about the goal of the study. The full session lasted approximately 90 min.

2.1.5. Eye dominance test

At the outset of the experimental session, the participants' eye dominance was assessed in a short screening test according to the method of Yang et al. (2010). The participants' task was to indicate the tilt direction of a masked grating (Fig. 2) by button press as soon as they could discriminate it. The participants got acquainted with the task in 12 practice trials, followed by one experimental block of 100 trials. Trials started with the presentation of CFS masks to one eye at a rate of 10 Hz. A target grating, which was either tilted counter-clockwise or clockwise, was presented to the other eye after the presentation of the sixth mask (600 ms after trial onset). The target grating's contrast linearly increased with each mask presentation, starting with a contrast of four percent, and ending with the full contrast 3,000 ms after trial onset. Subsequently, the CFS mask contrast linearly decreased 4,100 ms after trial onset, resulting in the full visibility of the target grating 9,800 ms after trial onset once the CFS mask contrast reached zero percent.

In half of the trials, CFS masks were presented to the right eye and target gratings to the left eye. In the other half, the stimulus-to-eye mapping was reversed, with random order of the two mappings. A trial ended as soon as the participant responded. In the case of an incorrect response, the fixation cross switched from green to red, which served as error feedback. The duration of the eye dominance test was approximately seven minutes. The participants' dominant eye was defined as the eye with the longer median suppression duration on trials where CFS masks were presented to it. The results of the eye dominance test indicated that nine participants were right-eye dominant, while 11 participants were left-eye dominant. The results of the eye dominance test were directly applied in the main experiment, as CFS masks were presented to the dominant eye, whereas prime stimuli were presented to the nondominant eye.

2.1.6. Main experiment

2.1.6.1. Trial procedure. A schematic of the trial procedure in the main experiment is depicted in Fig. 3. Trials started after a jittered

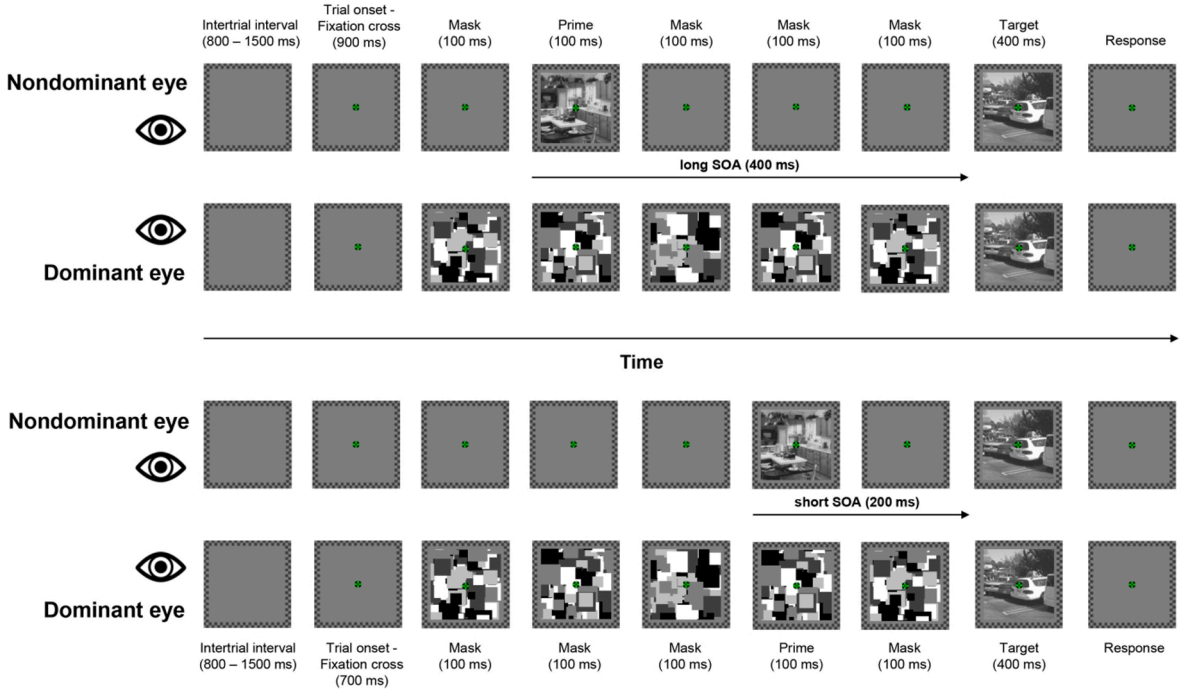

Fig. 3. Schematic of the trial procedure in the main experiment (here: incongruent prime-target condition). In the speeded choice RT task, participants categorized the target as either an indoor or an outdoor scene. In the prime discrimination task, participants categorized the prime as either an indoor or an outdoor scene. The SOA was either short (200 ms, bottom schematic) or long (400 ms, upper schematic). Note that only the full contrast mask condition (100%) is depicted in the figure.

intertrial interval ranging from 800 to 1,500 ms during which empty frames were presented to both eyes. Trial onset was indicated by the presentation of a green fixation cross to both eyes, which was temporally locked to appear 1,000 ms before prime onset. Therefore, on trials with a short SOA (200 ms), the fixation cross was presented for 700 ms, and on trials with a long SOA (400 ms), the fixation cross was presented for 900 ms. Then, CFS masks were presented to the dominant eye at a rate of 10 Hz. Prime onset was either matched with the presentation of the second mask (long SOA condition) or the fourth mask (short SOA condition). The primes were presented to the nondominant eye for 100 ms. After the presentation of the fifth CFS mask, the target was presented to both eyes for 400 ms. The trial continued with the presentation of the green fixation cross to both eyes until the participant responded. The trial procedure was identical for both tasks of the main experiment.

2.1.6.2. Tasks. Participants performed two different tasks in separate, consecutive parts of the main experiment. They were instructed to keep both eyes on the fixation cross and their index fingers resting on the response buttons throughout the blocks of both tasks. First, they performed a speeded choice RT task, categorizing visible target scenes as either indoor or outdoor scenes. The participants were instructed to respond as rapidly and precisely as possible when reporting the target scene category by pressing the allocated response button with their left or right index finger. If the participants responded too slowly (RT $>$ 2,000 ms), they received feedback to respond faster. If they responded before target onset, they received feedback to respond more slowly. The feedback text was presented to both eyes for 1,000 ms after the response.

In the second part of the main experiment, the participants performed a prime discrimination task: A nonspeeded choice task categorizing the suppressed prime scenes as either indoor or outdoor using the same response buttons as in the previous task. In the prime discrimination task, the participants were instructed to direct their attention to the suppressed prime scene that was presented before the target scene. Additionally, they were instructed to respond more slowly and aim to be as precise as possible, and to make a guess if they did not see the prime. If participants responded too fast (RT $<$ 400 ms), they received feedback to respond more slowly. The feedback text was presented to both eyes for 1,000 ms after the response. In the prime discrimination task, the participants did not receive feedback for responding too slowly, as there was no time stress. In both tasks, participants received immediate error feedback if they responded incorrectly: The color of the fixation cross switched to red, and the trial ended. The participants did not receive feedback if they responded correctly. In both cases, the next trial started after a jittered intertrial interval.

2.1.6.3. Design. A full factorial within-participant design was applied. Three factors varied at two levels: congruency of the prime and target scene category (indoor/outdoor: congruent vs incongruent), prime visibility, modulated by mask contrast (high visibility: 20% mask contrast vs low visibility: 100% mask contrast) and SOA (200 ms vs 400 ms). The dependent variables in the speeded choice RT task were the RTs of correct responses, and, additionally, the accuracy of the response (correct vs incorrect). The dependent variable in the prime discrimination task was also the accuracy of the response (correct vs incorrect). Each participant completed 720 trials in the speeded choice RT task. The participants first completed a practice block of 48 trials (which were not analyzed), before completing 12 experimental blocks of 60 trials each. Subsequently, the participants completed 240 trials in the prime discrimination task, which measured how well the participants could discern the suppressed primes' categories. Again, they completed a practice block of 48 trials (not analyzed), before completing four experimental blocks of 60 trials. In the prime discrimination practice block, the CFS mask contrast was reduced to 10% to clarify to the participants that their task was now to report the prime scenes, and also allow them some practice with easier discriminable exemplars. However, the CFS mask contrast in the experimental blocks was kept at either 20% (low) or 100% (high), same as in the choice RT task. A pause screen followed each block of 60 trials, notifying the participants of the number of completed blocks in both tasks. The participants were able to use the break to their own discretion and resume the experiment by pressing the space key.

Each of the eight conditions was presented with equal frequencies but in a random order in the practice and experimental blocks of both tasks. Moreover, every scene image was presented with equal frequencies. For each participant, half of the target images within a category were randomly assigned to the congruent and the other half to the incongruent condition (the same prime images were used for congruent and incongruent trials). The congruency assignment of the target images was kept constant throughout the experiment. To rule out purely low-level, early visual priming effects, congruent prime-target pairs were never from the same context (e.g., a 'kitchen' would never be followed by a different 'kitchen' target but only by a different indoor context such as 'bathroom'). Prime–target pairs were randomly assigned to a mask contrast condition (low vs high). Each prime-target pair was presented in both SOA conditions (short and long), which was the only repetition of the pair throughout the experiment. Furthermore, the response key assignment was counterbalanced between participants: For half of the participants, the indoor category was assigned to the left key and the outdoor category was assigned to the right key. For the other half, the assignment was reversed. Key assignment was kept constant within participants for both tasks.

2.1.7. Data analyses

All analyses were performed in R version 4.1.2 (R Core Team, 2021) using the *tidyverse* (Wickham et al., 2019), *lme4* (Bates et al., 2015), *afex* (Singmann et al., 2021), and *multcomp* (Hothorn et al., 2008) packages.

2.1.7.1. Data filtering. All participants were included in the statistical analyses. Practice trial data were not included in the analyses of either of the tasks. For the choice RT task, a total of 14,400 trials were recorded, from which trials with incorrect response were excluded from the RT analysis (966 trials or 6.7% of the data). From the correct trials, we further excluded trials on which the participants responded before target onset (17 trials or 0.1% of the data) and trials with outlier RTs that exceeded $\pm$ 2 *SD* around the

individual participant mean RT for the respective condition (overall 599 trials or 4.2% of the data). Hence, the analysis of RTs was based on 12,818 trials with a median RT of 597 ms (min = 229 ms, max = 2160 ms). For the analysis of response accuracy in the choice RT task, we excluded 35 trials (0.2% of the data) on which participants responded before target onset. For the prime discrimination task, we recorded a total of 4,800 trials from which we, in accordance with the task instructions and feedback during the experiment, excluded trials on which the participants' RT was below 400 ms (234 trials or 4.9% of the data).

Excluding these fast responses in the prime discrimination task helped ruling out the effects of primes unconsciously activating motor responses, which could lead to an overestimation of the conscious perception of the prime scene (Vorberg et al., 2003). For the analysis of accuracy in both tasks, we used the dichotomous outcome variable (correct vs incorrect).

2.1.7.2. Statistical models. Due to the wide variety of stimuli, we used (generalized) linear mixed models (GLMMs) to account for differences between real-world scene contexts in the statistical model: In addition to the random effects of the participants, the random effects of the target or prime scene context (depending on the task) were also considered (Baayen et al., 2008). As raw RTs were positively skewed and we fitted the statistical model at the single trial level, we applied a common logarithm transformation to fulfill the assumption of normality (Baayen & Milin, 2010). However, for easier interpretability of the results, we plot and discuss the inverse transformation of the log RTs that the statistical analyses are based on.

For the analysis of RT prime effects, we specified the statistical model as $logRT \sim congruency*soa*mask_contrast + (1|participant) + (1|target_context)$. An analogous model was computed for the binary outcome variable accuracy (1 = correct, 0 = incorrect) in the choice RT task. Response accuracy can also vary as a function of response time, and analyzing accuracy depending on the RT in the respective trials can reveal valuable information (Panis et al., 2020). To investigate this possibility, we also categorized the RTs of each participant into four equally sized RT bins (from fastest to slowest) and included the factor RT bin in an additional exploratory analysis of response accuracy.

For the analysis of the prime discrimination task, we specified the model as $accuracy \sim soa*mask_contrast + (1|participant) + (1|prime_context)$. Here, we omitted congruency, since in experiments on the visibility of masked stimuli followed by congruent or incongruent unmasked stimuli, this factor mostly reflects the response bias towards the unmasked stimuli (Vorberg et al., 2004). To determine the statistical significance of the fixed effects, we used Type-III *F*-tests using the Satterthwaite method for RT data and likelihood-ratio tests using on the χ^2 statistic for accuracy data. Generally, *p* values below the α significance level of .05 were deemed to be statistically significant.

2.1.7.3. Data availability. Data and R code to reproduce the analyses are freely available through the Open Science Framework (https://osf.io/4sjxz/).

2.2. Results

Fig. 4 gives an overview of our results. We first analyzed priming effects in the choice RT task (Fig. 4A) and then looked at the accuracy in the prime discrimination task (Fig. 4B) followed by an exploratory analysis of the correlation between individual prime discrimination performance and congruency effects (Fig. 4C).

2.2.1. Prime–target congruency effects

The statistical analysis of the RT data and response accuracy in the choice RT task are summarized in Table 1. Fig. 4A depicts the participants' performance (mean RT on correct trials) in the speeded choice RT task in each experimental condition. The analysis of RT data yielded significant main effects for the three experimental variables of Congruency, SOA, and Mask Contrast. On average, shorter mean RTs were found on congruent trials compared to incongruent trials (613 ms vs 617 ms, respectively). Also, shorter mean RTs were found on trials with the longer SOA compared to trials with the shorter SOA (612 ms vs 618 ms, respectively). Lastly, shorter mean RTs were found on trials with a low mask contrast compared to trials with a high mask contrast (610 ms vs 620 ms, respectively).

Furthermore, the three-way interaction of Congruency × SOA × Mask Contrast was also significant, whereas none of the two-way interactions reached significance. The three-way interaction is plotted in Fig. 4A and suggests that the congruency effects in the RT data depended on the prime–target SOA as well as the mask contrast (and in consequence, the visibility of the prime). To further explore this interaction, we examined the net congruency effects (i.e., the RT difference between congruent minus incongruent trials) for each combination of SOA and mask contrast (Fig. 4A, bottom panel). Negative congruency effects suggest that RTs in this condition were on average shorter for congruent trials than for incongruent trials. We tested the congruency effects for significance in each of these conditions with directional contrasts (see Table 2). For the 100% mask contrast, the congruency effects were significant only at the SOA of 400 ms. Conversely, at the weak mask contrast of 20%, the congruency effects were significant only at the SOA of 200 ms.

The average response accuracy in the choice RT task was 93.4% (min = 87.5%, max = 97.1%). In contrast to the RT data, the analysis of response accuracy in the Choice RT task revealed no overall significant main effects or interactions (Table 1). However, as congruency effects in accuracy can depend on RT (cf. Panis et al., 2020), we repeated the analysis after including RT bin as additional predictor. Indeed, we found a significant four-way interaction of RT Bin × Congruency × SOA × Mask Contrast, $\chi^2 = 9.21$, $p = .027$, suggesting that the size or direction of congruency effects in the accuracy data depended on the speed of the responses. In Table 3 we report contrasts for congruency effects in each RT bin, depending on the experimental condition.

In the fastest RT bins, we observed significant congruency effects, with more accurate responses on congruent compared to incongruent trials – indicative of response priming – in all conditions except for the 100% mask contrast, 400 ms SOA. Conversely, for

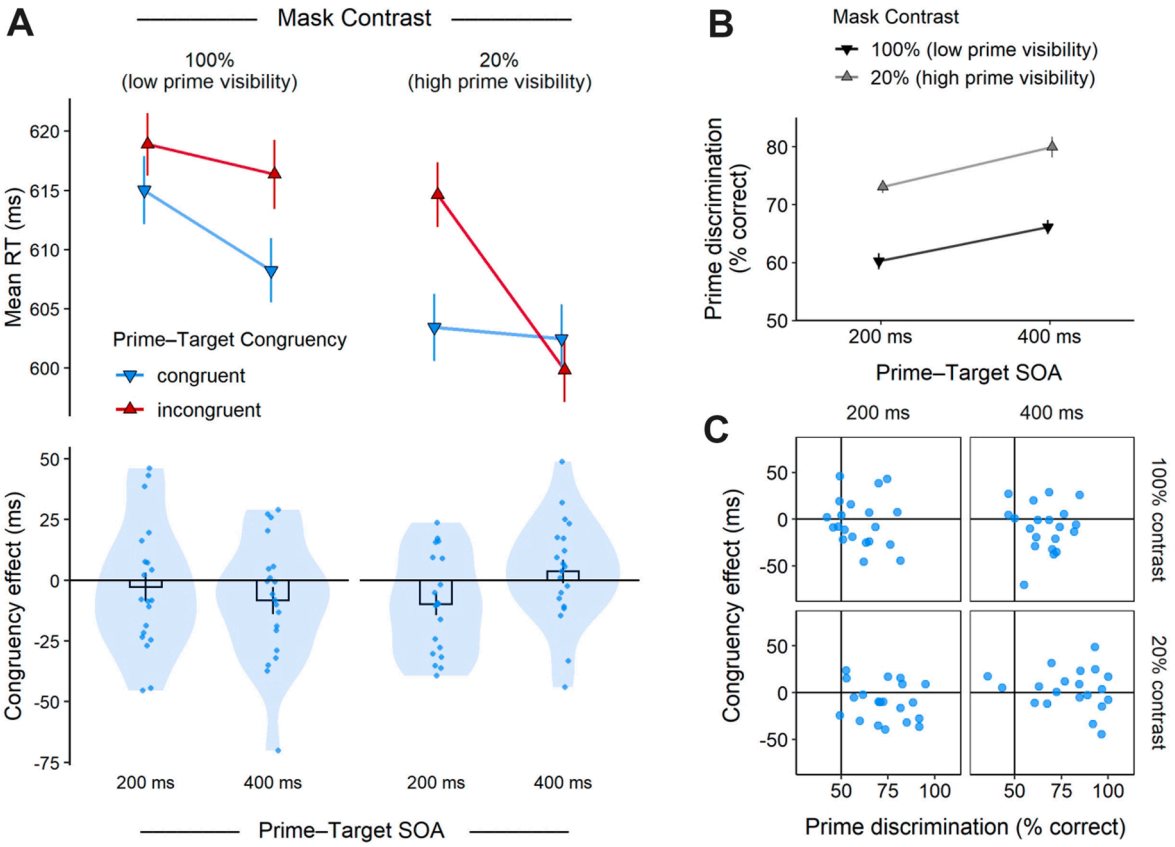

Fig. 4. (A) Results of the speeded choice RT task in Experiment 1. Upper panels: Mean correct RTs as a function of congruency, mask contrast and SOA are illustrated in the plot. Lower panel: Distribution and means of congruency effects (that is, the difference in mean RT of congruent minus incongruent trials). (B) Results of the prime discrimination task. Mean prime discrimination accuracy (shown as % correct responses) as a function of mask contrast and SOA. (C) Relationship between individual prime discrimination performance and individual congruency effects for the four combinations of SOA and mask contrast conditions. Error bars represent ± 1 *SE* after correcting for between-participants variance (Loftus & Masson, 1994).

Table 1
Analysis of experimental effects in the speeded choice RT task (GLMM results).

	Choice RTs		Accuracy	
Fixed Effect	*F*	*p*	χ^2	*p*
Congruency	6.84	.009*	2.48	.115
SOA	10.33	.001*	2.04	.153
Mask Contrast	24.31	<.001*	0.01	.939
SOA × Mask Contrast	0.55	.457	0.01	.940
SOA × Congruency	1.55	.213	2.46	.117
Congruency × Mask Contrast	0.25	.617	1.44	.230
Congruency × SOA × Mask Contrast	5.44	.020*	0.05	.830

Note. * statistically significant at $p < .05$.

the 20% mask contrast and 400 ms SOA, we observed a reversed congruency effect with more errors on congruent compared to incongruent trials, which could point to the engagement of conscious response inhibition processes, as participants could voluntarily suppress the response tendencies elicited by the better visible prime scenes.

2.2.2. Prime discrimination

Fig. 4B depicts the participants' performance (accuracy) in the prime discrimination task. Our statistical analysis revealed a main effect of mask contrast, $\chi^2 = 109.19$, $p < .001$, with a significantly lower average response accuracy at 100% mask contrast (63% correct discriminations) than at the low mask contrast of 20% (76% correct discriminations). This suggests that manipulating prime visibility by varying the contrast of the CFS masks worked as intended. In addition, however, the analysis also revealed an effect of

Table 2
Mean Congruency Effects in RTs as a function of Mask Contrast and SOA in Experiment 1.

		Congruency effect (Δms)		Statistical test	
Mask contrast	SOA	*M*	*SE*	*z*	*p*
100% (low prime visibility)	200 ms	−2.8	5.88	−1.01	.156
	400 ms	−8.4	5.59	−2.11	.018*
20% (high prime visbility)	200 ms	−9.9	4.49	−2.84	.002*
	400 ms	3.6	4.82	0.73	.768

Note. * statistically significant at $p < .05$. One-tailed tests were computed using the *multcomp* package based on our prediction that congruency effects should be reflected in shorter RTs in congruent compared to incongruent conditions. However, the same conclusions would be reached with two-tailed tests.

Table 3
Exploratory Analysis of Congruency Effects in Response Accuracy in Experiment 1 as a function of Mask Contrast, SOA and Response Time (RT Bin).

			Congruency effect (Δ%correct)		Statistical test	
Mask contrast	SOA	RT Bin	*M*	*SE*	*z*	*p*
100% (low prime visibility)	200 ms	1	6.1	1.74	2.81	.005*
		2	−2.5	1.76	−1.91	.057
		3	−0.7	1.38	−0.42	.677
		4	1.7	1.71	0.72	.470
	400 ms	1	−3.4	2.00	−1.65	.099
		2	1.1	1.58	0.66	.507
		3	1.4	1.96	0.49	.622
		4	−0.6	1.52	−0.05	.959
20% (high prime visbility)	200 ms	1	8.3	2.69	3.56	<.001*
		2	−0.6	1.91	−0.50	.618
		3	0.3	1.21	0.24	.814
		4	2.1	1.16	1.23	.220
	400 ms	1	6.0	2.42	2.82	.005*
		2	−0.9	1.44	−0.58	.564
		3	−4.0	1.63	−2.36	.019*
		4	0.2	1.90	0.22	.824

Note. * statistically significant at $p < .05$. Two-tailed tests were computed using the *multcomp* package based on the assumption that positive congruency effects in accuracy could reflect response priming and negative congruency effects response inhibition. Response times for each participant were divided into four bins from fastest (1) to slowest (4).

prime-target SOA, $\chi^2 = 26.20, p < .001$, which we had not expected in advance. On average, participants more often correctly classified the prime in the long SOA of 400 ms (73%) than in the short SOA of 200 ms (67%). The interaction of Mask Contrast × SOA was not significant, $\chi^2 = 0.98, p = .323$.

As prior research with simpler stimuli (Valuch & Mattler, 2019) suggested that individual congruency effects in CFS priming procedures could be correlated with the degree to which the participants are able to discriminate the primes we also explored the correlations between prime discrimination and congruency effects in the current study. Fig. 4C depicts the relationship between individual congruency effects and prime discrimination for the four combinations of mask contrast and prime-target SOA. Pearson correlations within each of these cells were all numerically negative (ranging from $r(18) = -.01$ for 100%/400 ms up to $r(18) = -.18$ for 20%/200 ms), suggesting that higher prime discrimination performance might be slightly associated with more pronounced congruency effects in a big sample of participants. However, in our sample of 20 participants, none of the correlations was statistically significant (all $ps > .449$) which, as of now, speaks against a strong relationship between prime discrimination and congruency effects in the present study.

2.3. Discussion

Experiment 1 revealed priming effects during CFS: On trials where the category of the prime scene was congruent with the target scene, categorization was faster. These effects were modulated by prime-target SOA and mask contrast. A closer look at the accuracy data revealed that when participants responded fast, they were also more accurate on congruent compared to incongruent trials, which is an additional indicator of response priming.

However, the observed congruency effects were relatively small-sized and rather variable between participants. Due to the high number of different scene images, the prime-target combinations were partly randomized in Experiment 1. Thus, it is possible that some real-world contexts might elicit less consistent, or maybe even reversed congruency effects compared to others which might explain the differences between participants. Moreover, obtaining robust priming effects might critically depend on the use of highly-associated prime-target exemplars (e.g., Ortells et al., 2013; Ortells, Kiefer et al., 2016). Accordingly, it is possible that while our choice

to exclude congruent prime-target pairs from the same context helped minimizing the confound of low-level visual feature similarities, it might have strongly reduced the overall priming effects. To shed some light on these possibilities, we decided to conduct a second experiment.

3. Experiment 2: A benchmark for scene category priming in the absence of CFS

Since congruency effects remained rather small even with low CFS contrast, we decided to establish a benchmark for scene category priming at a prime-target SOA of 200 ms without CFS. We expected to replicate the congruency effects from Experiment 1 and predicted them to be larger in the absence of interocular suppression. We also aimed to assess the consistency of congruency effects across specific prime contexts. Therefore, across the new sample of participants, we now presented all possible combinations of primes and targets with an equal frequency.

3.1. Method

3.1.1. Participants

We collected data from 45 participants (38 female, aged 18–31 years, $M = 22.1$ years, $SD = 3.08$) in an online experiment. None of them participated in Experiment 1. Participants could only start the experiment after informed consent was obtained in an online form. They participated voluntarily and could receive partial course credit in return. We planned 45 participants to test all possible combinations of prime and target images (balanced across participants) but also maintain a sufficient number of trials to estimate congruency effects for specific prime-contexts. Based on estimates from Experiment 1, we calculated power contours (Baker et al., 2021) to verify that our planned design would maintain 80% power for estimating congruency effects of, on average, 10 ms for specific prime contexts.

3.1.2. Apparatus

Participants used their own laptops or desktop computers to complete the online experiment. They were instructed to sit comfortably at a table and maintain the same working position and screen viewing distance over the duration of the experiment. As before, the experiment used the "F" and "J" keys as response buttons. The assignment of the buttons to scene categories was counterbalanced across participants. The online experiment was programmed and conducted using Labvanced (Finger et al., 2017).

3.1.3. Stimuli and design

The stimulus set was identical to Experiment 1. Combining each prime image with each target image would yield 21,600 prime-target pairs, which would exceed any feasible within-participant data collection. We therefore carefully balanced the assignment of primes and targets across participants to yield all of these possible combinations of stimuli with an equal frequency. For each participant, three indoor and three outdoor contexts were selected as primes (overall 12 prime images). These prime images were combined with four target images from each of the 30 targets contexts (overall 120 target images), giving 1,440 unique stimulus combinations per participant. As in Experiment 1, the screen background was set to black with a central checkerboard image frame, and the same-colored fixation crosses. Due to the varying display hardware and viewing distance, the apparent size of the stimuli differed between participants. Based on approximate viewing distance reported by the participants and matching of an on-screen rectangle to the size of a credit card (as implemented in Labvanced) we estimated that the median presentation size of the scene images in the online experiment was $4.01^\circ \times 4.01^\circ$ (range: 2.45–7.56°).

3.1.4. Procedure and tasks

Participants received a unique link by email and agreed to complete the experiment in a quiet environment without disturbances. The main part of the study consisted of a speeded choice RT task. The instructions informed participants that two scene images would be presented in rapid succession on each trial but that they should ignore the first, very briefly presented picture, and always report the category (indoor vs outdoor) of the second, somewhat longer presented picture. Each trial started with the appearance of the fixation cross. After 500 ms, the prime scene appeared for a duration of 50 ms.[1] With a fixed prime-target SOA of 200 ms, the target scene appeared for a maximum duration of 400 ms. Trials ended as soon as participants pressed a response button. After correct responses, the fixation cross remained green and the next trial started shortly after. Following wrong responses, the fixation cross turned red for 800 ms before the next trial started. Participants received on-screen feedback if they answered too early (before target onset) or too late (with an RT $>$ 2,000 ms). Participants completed 1,440 trials in the choice RT task, resulting from all combinations of prime and target images, which were presented in a random order. After blocks of 240 trials, a 'pause' screen informed them about their progress. They could choose if they wanted to take a short break before proceeding to the next block of the experiment.

After completing the speeded choice RT task, participants received instructions for an additional prime discrimination task. The stimulus sequence within each trial was identical to the choice RT task but participants were instructed to now report the category of the prime scene and ignore the target scene. They were told to take their time and respond as accurately as possible. For RTs shorter than 400 ms, they received on-screen feedback to answer more slowly. For incorrect responses, the fixation cross turned red for 800 ms

[1] We chose a shorter prime duration in Experiment 2 to counteract the much better prime visibility (due to the absence of CFS) and make it easier for the participants to distinguish the prime from the target.

before proceeding to the next trial. The prime discrimination task included 144 trials in one block, half of which were congruent and half incongruent trials. Each prime image was included with an equal frequency in a random order, paired with 50% congruent and 50% incongruent target images that were randomly chosen from the full set. Before starting either of the tasks, participants were shown 16 practice trials. After completing both tasks, participants were thanked for their participation. They could provide feedback on the study and were given a standardized debriefing text about the goal of the study.

3.1.5. Data analysis

3.1.5.1. Data filtering. In the choice RT task, we recorded a total of 64,800 trials from 45 participants. For the analysis of choice RTs, we excluded a total of 88 trials (0.1%) with early responses and 5,160 trials (8%) in which participants made an error. In addition, we excluded 326 trials (0.5%) on which the measured stimulus onset times suggested that the actual SOA was shorter than 190 ms or longer than 250 ms, presumably resulting from timing issues on the participants' devices. We further excluded 1,551 trials (2.4%) with outlier RTs (±2 *SD* around participants' mean RTs). The RT analysis was thus based on a total of 57,675 trials with a median RT of 572 ms (min = 45 ms, max = 2465 ms). For analyzing accuracy in the choice RT task, we excluded trials with early responses and with prime-target SOAs outside the acceptable range (440 trials or 0.1%), leaving 64,360 trials in the analysis. For the prime discrimination task, we recorded a total of 6,480 trials from which we excluded 77 trials (1.2%) with RTs below 400 ms.

3.1.5.2. Statistical models. We used the same analysis approach as in Experiment 1 with the model structure *logRT ~ congruency + (1|participant) + (1|target_context)* for analyzing RT priming effects and an analogous model with a dichotomous outcome variable for analyzing accuracy in the choice RT task. Apart from evaluating overall congruency effects (with a two-level factor congruent vs incongruent based on all trials) we also fitted an additional model in which we differentiated between 'same congruent', denoting the subset of congruent trials in which prime and target came from the same real-world context and 'different congruent', which included all other congruent trials, thus minimizing the overlap in visual features between prime and target (as in Experiment 1). For the analysis of accuracy, we additionally fitted a more detailed model with the factor RT bin, after splitting trials into four equally sized bins based on each participant's RT distribution.

3.2. Results

3.2.1. Overall prime-target congruency effects

Across prime contexts, we observed significant overall congruency effects on choice RTs ($F = 754.76$, $p < .001$). On average, participants responded faster on congruent trials (575 ms) compared to incongruent (600 ms) trials. We also observed significant overall congruency effects on response accuracy ($\chi^2 = 262.21$, $p < .001$), as participants responded more accurately on congruent (93.7%) compared to incongruent (90.3%) trials. As summarized in Table 2, overall congruency effects were considerably larger compared to Experiment 1, presumably due to the absence of interocular suppression.

After splitting congruent trials into 'same congruent' (where prime and target came from the same real-world context) and 'different congruent' (where prime and target came from different real-world contexts), the main effect of congruency remained significant for choice RTs ($F = 398.49$, $p < .001$) and accuracy ($\chi^2 = 263.39$, $p < .001$). Directional contrasts (Table 5) showed that congruency effects in RTs but not in accuracy were larger for 'same congruent' rather than 'different congruent' trials, suggesting an additional acceleration of responses on trials where the relatedness between primes and targets was strongest. The congruency effect for different congruent trials remained very close to the overall congruency effect, suggesting that the inclusion of 'same congruent' trials was not a driving factor for the overall larger congruency effects in Experiment 2 (Table 4).

For accuracy, we also observed a significant interaction of RT Bin × Congruency, $\chi^2 = 1{,}238.82$, $p < .001$, indicating that the presence or direction of the congruency effects in accuracy data depended on RT. Contrasts revealed significant positive congruency effects in the first RT Bin, confirming the presence of response priming, whereas the two bins with the slowest RTs yielded inverted congruency effects, suggesting that response inhibition processes were also at work (see Table 5).

Table 4
Congruency Effects in Choice RTs and Accuracy in Experiment 2.

	Choice RTs				Accuracy			
	Δms		Test		Δ%correct		Test	
	M	*SE*	*z*	*p*	*M*	*SE*	*z*	*p*
Overall congruency effect								
Congruent − Incongruent	−24.3	3.2	−27.47	<.001*	3.4	0.7	16.1	<.001*
Split for congruency types								
Same congruent − Incongruent	−37.4	5.1	−15.79	<.001*	2.8	0.8	4.4	<.001*
Different congruent − Incongruent	−23.3	3.2	−25.84	<.001*	3.4	0.7	15.9	<.001*
Same congruent − Different congruent	−14.1	3.2	−6.46	<.001*	−0.6	0.5	−1.1	.865

Note. * statistically significant at $p < .05$ (one-tailed tests).

Table 5
Analysis of Congruency Effects in Response Accuracy as a function of Response Time *(RT Bin)*.

	Congruency effect (Δ%correct)		Statistical test	
RT Bin	*M*	*SE*	*z*	*p*
1	23.0	3.08	36.64	<.001*
2	0.5	1.13	0.855	.393
3	–2.6	0.58	–7.50	<.001*
4	–1.2	0.47	–4.24	<.001*

Note. * statistically significant at $p < .05$. Two-tailed tests were computed using the *multcomp* package based on the assumption that positive congruency effects in accuracy could reflect response priming and negative congruency effects response inhibition.

3.2.2. Consistency in congruency effects

To investigate whether congruency effects depended on only a subset of certain real-world scene contexts (and if others might even result in reversed congruency effects), we also computed congruency effects separately for every prime context (see Fig. 5).

For choice RTs, congruency effects in the expected direction occurred very consistently for all 30 different prime contexts. A similar picture emerged in the accuracy data, although with a few inconsistencies for some of the outdoor contexts. It is possible that this is due to the parallel effects of response priming and response inhibition in accuracy data that were revealed in the previous analysis. Fig. 5 also illustrates that between-participant variability remained rather large, even when looking at participants that saw the same prime-target combinations.

3.2.3. Prime discrimination

In the prime discrimination block, participants reported the prime's category correctly in, on average, 93.8% ($SE = 1.01$) of the trials, suggesting that they were consciously aware of the prime's category on most trials.

3.3. Discussion

As the direction of congruency effects was consistent across prime-target combinations, it is unlikely that the randomized

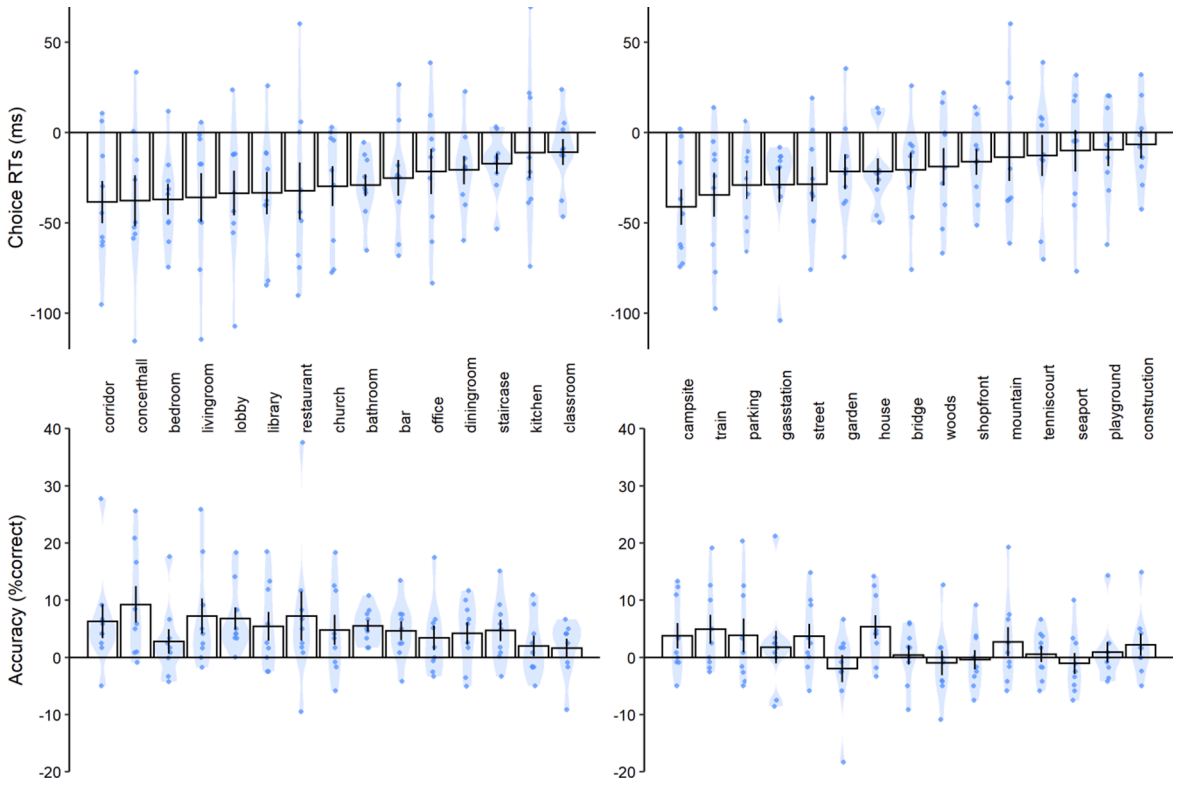

Fig. 5. Congruency effects in choice RTs (upper panels) and accuracy (lower panels), split for different indoor (left panels) and outdoor (right panels) prime contexts in Experiment 2. Data points represent individual participants, bar graphs and error bars the means ± 1 *SE*. Prime contexts are sorted according to the size of congruency effects in choice RTs.

assignment of stimuli in Experiment 1 could explain the small size and high variability of congruency effects. Even if the same prime-target combinations are presented to different participants, the between-participant variability remained relatively large (cf. Fig. 5). Congruency effects were also much larger and more robust compared to priming during CFS, even after excluding trials in which primes and targets came from the same real-world context. Therefore, this type of strong semantic (and visual) association between primes and targets does not seem to be necessary for obtaining stable congruency effects with the present stimulus set.

4. General discussion

We investigated to which extent cognitive processing of natural scene semantics could be independent of conscious perception. We employed a scene categorization task with pictures of real-world indoor and outdoor scenes as primes and targets and measured priming effects and prime discrimination performance in separate tasks. Our results suggest that the superordinate (indoor vs outdoor) category of perceptually suppressed prime scenes was processed to a level that allowed for an influence on speeded responses towards visually distinct target scenes: The categorization of visible target scenes was facilitated by semantically related congruent prime scenes, as evident by shorter RTs and (for fast responses) higher accuracy with congruent compared to incongruent prime-target pairs. The significant three-way interaction between congruency, mask contrast and SOA illustrated that prime visibility differentially affected priming effects depending on the processing time that was granted to the prime before the target appeared. With better visible primes, significant RT priming effects occurred only at the shorter SOA. For strongly suppressed primes, RT priming effects were only significant at the long SOA, while for the short SOA priming effects were observed only in the accuracy of the fastest responses.

4.1. Scene category priming depends on prime visibility and SOA

Based on prior research with arrow stimuli (Valuch & Mattler, 2019) we expected stronger priming effects with a longer SOA and high prime visibility level but we did not observe such a pattern in the current study with natural scenes. Noteworthy, Valuch and Mattler (2019) used a task-switching procedure in their Experiments 1 and 2 which yielded the strongest priming effects in their longest SOA condition of 300 ms. In that procedure, participants needed to attend prime and target simultaneously on each trial, and were only informed with the onset of the target, which of the two stimuli they should report. In Experiment 3, the authors used separate task blocks to measure priming effects and prime discrimination and found that priming effects decreased with the longest SOA of 300 ms after reaching a peak at 200 ms. In the current study the strongest priming effects also occurred at an SOA of 200 ms, which is actually consistent with the findings of Experiment 3 in Valuch and Mattler (2019).

Regarding visible primes, classic studies on the time course of faciliatory and inhibitory processing indeed suggest that automatic priming effects should be relatively transient (e.g., Posner & Snyder, 1975). In contrast, studies that manipulated prime-target SOA in a (strategic) Stroop priming task found that increasing the SOA between a visible word prime and a color target increases the influence of the primes on target responses. Yet, a critical methodological difference in studies on strategic priming effects is the ratio of congruent and incongruent trials. For instance, Fernández et al. (2021) used 75% incongruent trials and 25% congruent trials. With an SOA of 300 ms, they a observed a classic congruency effect with better performance on congruent trials but with an SOA of 700 ms the effect reversed for some of the participants, consistent with the idea that lengthening the SOA leads to more strategic and controlled use of the visible primes (cf. Noguera et al., 2019, for similar results). Unequal ratios of congruent and incongruent trials render the primes explicitly relevant for solving the task of responding to the target. In contrast, the design we used in the present study is more similar to a standard response priming paradigm (Vorberg et al., 2003) with unpredictive primes that are congruent only in 50% of the trials. Assuming that controlled processes increase with lengthening the SOA, participants should thus be more likely to actively ignore and inhibit response tendencies elicited by the visible prime at longer SOAs whereas such conscious control processes should be less evident on trials where the primes are perceptually suppressed. Our detailed analysis of accuracy in Experiment 1 supports this interpretation, revealing positive congruency effects for the first RT bins, and negative congruency effects for a later RT bin–but only in the long SOA and with higher prime visibility which could reflect active suppression of response tendencies elicited by the prime. Experiment 2 confirmed this response accuracy pattern, with strong response priming for the fastest RTs and response inhibition (i.e., inverted congruency effects) for the slower RTs. Hence, considering the different ratios of congruent and incongruent trials, the current results do not contradict the Stroop priming literature.

For strongly suppressed primes, RT priming effects in our Experiment 1 were only significant with the longer SOA of 400 ms. Yet, the analysis of response accuracy revealed that participants were more accurate on congruent compared to incongruent trials even at the 200 ms SOA (provided the response was given fast). The differential SOA effect for strongly and weakly suppressed primes in Experiment 1 suggests qualitative differences between conditions of higher and lower prime awareness. If participants were relatively unaware of the primes, conscious control or inhibition processes might have been absent more often. This is in line with the view that unconscious and conscious prime stimuli can have qualitatively different effects in priming paradigms (e.g., Merikle & Joordens, 1997; Barbot & Kouider, 2012). Based on their studies with masked arrow stimuli, Vorberg et al. (2004) noted that differences between priming with and without awareness are to be expected when prime-target SOAs exceed 100 ms, and that these qualitative differences are probably related to conscious response control processes.

Studies of unconscious semantic priming using backward masking frequently reported evidence for unconscious faciliatory effects primarily at shorter SOAs (e.g., Daza, Ortells, & Fox, 2002; Kiefer & Spitzer, 2000; Ortells, Daza, & Fox, 2003; Ortells, Kiefer et al., 2016). While we did not obtain RT congruency effects for strongly suppressed primes at the shorter SOA of 200 ms, responses were still more accurate on congruent compared to incongruent trials for the fastest RTs, which could mean that the relatively small congruency effect manifested in RT-dependent accuracy rather than overall RTs. It could also be that in these conditions RT priming effects were

largely suppressed but increased slightly at the longer SOA due to the absence of response inhibition processes. More generally, different perceptual masking techniques can affect unconscious processing of visual stimuli in rather specific ways (Wernicke & Mattler, 2019). To speculate, CFS might fractionate a visual representation of a scene at an early cortical processing stage (Moors et al., 2017) but contextual filling-in processes might complement the missing portions of a piecemeal scene representation (cf. Smith & Muckli, 2010), and this process might unfold over several hundred milliseconds.

4.2. CFS as tool to study unconscious processing of scene semantics

The continuing debate on the scope and extent of unconscious processing in CFS (Moors et al., 2017; Sklar et al. 2018) motivated us to put this technique to a test using a broad set of real-world scenes. In some sense, our results align with the idea that CFS–due to its ability to implement rather long prime-target SOAs–offers a way to investigate higher-level and perhaps semantic processing of subliminal stimuli. However, the assumption that CFS would be ideal to study unconscious semantic operations as it allows longer processing durations of unconscious stimuli (cf. Sklar et al., 2012) needs to be critically questioned. For instance, in Experiment 2, we obtained robust priming effects despite halving the prime duration to 50 ms. Hence, long presentation durations are not necessary for congruency priming effects to occur and more established experimental techniques such as backward masking could be equally used to study these phenomena (see e.g., Anderson et al., 2022, who recently reported that semantic characteristics of scenes could be extracted from backward-masked presentations as short as 13.3 ms). While CFS is a versatile tool to reduce conscious awareness of stimuli, it also comes with its own caveats and there is no strong indication that, compared to other methods, it is much better suitable for investigating semantic effects.

4.3. Scene category priming is partly independent of prime awareness

A critical aspect in interpreting the effects of masked stimuli is the question of how confidently it can be assumed that priming has occurred independently of conscious awareness (Schmidt & Vorberg, 2006; Schmidt, 2015). In practice, it is not easy to show beyond doubt that prime discriminability is at chance level, and yet there are robust priming effects (Shanks et al., 2021). CFS studies sometimes sorted their trials into an 'unconscious' condition based on their participants' subjective rating of their perceptual experience or by excluding participants for which the visibility measure exceeded some threshold. Such post hoc selection of trials (or participants) can create patterns that seemingly show priming in the absence of awareness, but it is problematic for various methodological reasons (for in-depth discussions, see e.g., Schmidt, 2015; Shanks, 2017; Shanks et al., 2021). An alternative approach that has been established in the backward and metacontrast masking literature to studying the independence of priming and prime awareness is to induce different levels of prime awareness using an appropriate experimental manipulation (Becker & Mattler, 2019; Mattler, 2003; Vorberg et al., 2003; Wernicke & Mattler, 2019). In the present CFS study, we opted for this approach and manipulated prime awareness using different mask contrast levels (Valuch & Mattler, 2019). The observed performance in the prime discrimination task suggested that our manipulation achieved the desired effect. Taking this approach, the focus lies not so much on the question of whether there are priming effects when prime discriminability is at chance level, but rather whether the experimental manipulations exert dissociable influences on priming effects and prime discriminability. For example, in the CFS study of Valuch and Mattler (2019), the experimental manipulations of prime or mask contrast had highly similar effects on priming effects as well as prime visibility; and individual priming effects were correlated with individual prime discrimination performance. This suggested that priming effects (with arrow stimuli) were linked to conscious perception of the primes and priming would not be possible without a certain minimum level of prime awareness. In contrast, in the current study, SOA had dissociable influences on the priming effects depending on the level of prime awareness. Of course, this does not mean that priming effects would occur if prime awareness would be completely eliminated, for example, by reducing the contrast of the prime scenes further, until the participants would not be able to discriminate them any better than chance. Previous research has shown more than once that a certain level of partial prime awareness is probably necessary to allow priming effects with certain experimental techniques, and this likely also concerns CFS experiments (Gelbard-Sagiv et al., 2016; Peremen & Lamy, 2014; Valuch & Mattler, 2019). Accordingly, we did not aim to induce conditions of complete prime invisibility and despite rather strong suppression prime visibility remained above chance level. In the brief interview following Experiment 1, participants were asked if they noticed the poorly visible prime scenes that were presented prior to the visible target scenes in the speeded choice RT task. Six participants reported that they did not notice the prime scenes at all until they were told about them during the instructions for the prime discrimination task. Most participants reported that they noticed the prime scenes on some trials and two participants claimed that they noticed the prime scenes on most trials.

Of note, we also did not expect a priori that the longer prime-target SOA used in the current study would result in weaker masking than the shorter SOA. In addition to the effect of interocular suppression, the greater number of CFS masks presented monocularly to the dominant eye before the prime might have enhanced the strength of interocular suppression (Tsuchiya et al., 2006). Perhaps there also was a contribution of backward masking in the short SOA condition, where prime scenes were followed by binocularly presented targets (Breitmeyer & Öğmen, 2006). In consequence, the slightly better visibility for the longer SOA condition could be an alternative explanation for the stronger priming effects in the longer SOA. However, this still cannot explain the present pattern of results, because, in the 20% mask contrast condition, the priming effects took the opposite course. Also, unlike previous research with simple arrow stimuli, there were no pronounced correlations between individual performance in the visibility task and individual priming effects in the current study. In summary, thus, the current study suggests at least a partial independence of scene category priming and prime awareness. However, it is important to stress that it does not provide evidence of priming in the complete absence of prime awareness.

4.4. Scene category priming effects are rather small and variable

In Experiment 1, the largest mean RT difference during CFS between congruent and incongruent conditions was 10 ms. In comparison, Valuch and Mattler (2019) found priming effects of about 50 ms at similar experimental conditions but using arrow stimuli as primes and targets. Using pictures of animals embedded in a natural scene background, the CFS study by Koivisto and Rientamo (2016) found RT priming effects of about 27 ms even at low prime awareness. We only found such large priming effects in Experiment 2, when we presented the primes without CFS. This could have several reasons. Our analyses of RT-dependent accuracy suggested that response priming and response inhibition were both at work–at least for better visible primes. It is possible that different participants engaged in conscious control processes to different degrees, which might explain part of the variability in congruency effects. Moreover, Van den Bussche et al. (2009b) discussed prime novelty as a factor that may reduce priming effects: Studies that did not repeat primes as targets were less likely to obtain priming effects than studies that repeated primes as targets. In our study, primes were not repeated as targets and in Experiment 1, we also excluded prime-target pairs from the same context in congruent conditions in order to limit the contribution of low-level visual feature relationships to priming effects. Indeed, our data from Experiment 2 suggest that congruent prime-target pairs that come from the same real-world context result in greater RT effects, although this smaller subset of trials did not contribute strongly to the rather robust overall priming effects in the absence of CFS. Experiment 2 also verified that the stimulus set was well suited for studying this kind of high-level categorization, as the congruency effects were rather consistent across the many different real-world scene contexts. And yet, even when different participants were presented with the same prime-target combinations, the resulting congruency effects varied considerably between participants. Perhaps the fact that all scenes were presented in black and white, which eliminated color as an otherwise highly diagnostic feature for scene categorization, made the categorization of the scenes more difficult. Future research could thus systematically investigate factors such as stimulus set size and diagnostic visual features for scene category priming with and without CFS.

4.5. Which mechanisms underlie scene category priming?

As we intentionally used different scene contexts for each prime and target combination, we are inclined to believe that scene semantics played a larger role than direct low-level visual-feature relationships between primes and targets (as would be the case, for example with oriented gratings or arrow stimuli) – but of course, scene semantics are extracted from a scenes' combination of visual features. In our experiment, indoor and outdoor categories were both very broad and each included 15 visually distinct scene contexts with different images within each context. Nevertheless, despite this variety, the superordinate categories might still be characterized by certain higher-order visual characteristics, which are more similar within than across categories. Different visual properties of indoor and outdoor scenes could also elicit dissociable effects in the brain. Neuroimaging studies suggest that indoor and outdoor scenes differentially activate category-selective cortical areas such as the posterior parahippocampal place cortex (e.g., Henderson et al., 2007). Moreover, the visual richness of scenes could also support their automatic and involuntary categorization: Natural scene categorization happens involuntarily within <100 ms (Oliva & Torralba, 2006) and requires very little attentional effort (e.g., Fei-Fei et al., 2005). Taken together, these properties create favorable conditions for a cognitive function that could be fulfilled in the relative absence of awareness. The subliminal presentation of scenes could thus pre-activate brain structures that are more sensitive to one or the other category, which could lead to faster categorization of subsequent target scenes.

While the use of pictorial stimuli for both primes and targets has the advantage of high ecological validity, one would need to prevent any potential visual similarity between primes and targets to reach to an unquestionable interpretation of the effect as being based purely on semantic processing. One way in which this can be accomplished is to present primes or targets as a symbolic word label. Stein et al. (2020) recently took this approach, pursuing a conceptual replication of the study by Van den Bussche et al. (2009a). Specifically, Stein et al. (2020) used CFS and backward masking to render the images of animals or objects invisible and then presented words of the congruent or incongruent category as targets. Using this approach, the authors did not obtain priming effects, although prime discriminability was slightly above chance level in their CFS experiment. Thus, it could be that the categorical or semantic congruency effects that occurred in the current study were due to the use of image primes and image targets in combination with a diverse set of many different real-world scene contexts.

4.6. Conclusion

The current study demonstrates that interocularly suppressed pictures of natural indoor and outdoor scenes can prime the categorization of semantically related visible target scenes. This adds a promising observation of higher-level processing to the ongoing debate on the scope of perceptual and cognitive processing during CFS. However, some degree of residual prime awareness is likely necessary for these effects to occur, and this boundary condition should be kept in mind when interpreting the present or similar results. Since humans experience natural, real-world scenes with a high frequency on an everyday basis, the use of such stimuli comes somewhat closer to what the human brain performs in day-to-day life, and thus offers a promising research avenue in the quest to understand the scope of unconscious visual processing.

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CRediT authorship contribution statement

Leonie Baumann: Conceptualization, Methodology, Investigation, Project administration, Formal analysis, Writing – original draft. **Christian Valuch:** Conceptualization, Methodology, Software, Validation, Resources, Formal analysis, Data curation, Visualization, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Almeida, J., Mahon, B. Z., & Caramazza, A. (2010). The role of the dorsal visual processing stream in tool identification. *Psychological Science, 21*(6), 772–778. https://doi.org/10.1177/0956797610371343

Almeida, J., Mahon, B. Z., Nakayama, K., & Caramazza, A. (2008). Unconscious processing dissociates along categorical line. *Proceedings of the National Academy of Sciences of the United States of America, 105*(39), 15214–15218. https://doi.org/10.1073/pnas.0805867105

Anderson, M. D., Elder, J. H., Graf, E. W., & Adams, W. J. (2022). The time-course of real-world scene perception: spatial and semantic processing. Available at SSRN: https://ssrn.com/abstract=4119815. doi: 10.2139/ssrn.4119815.

Baayen, R. H., Davidson, D. J., & Bates, D. M. (2008). Mixed-effects modeling with crossed random effects for subjects and items. *Journal of Memory and Language, 59*(4), 390–412. https://doi.org/10.1016/j.jml.2007.12.005

Baayen, R. H., & Milin, P. (2010). Analyzing reaction times. *International Journal of Psychological Research, 3*(2), 12–28. https://doi.org/10.21500/20112084.807

Bahrami, B., Vetter, P., Spolaore, E., Pagano, S., Butterworth, B., & Rees, G. (2010). Unconscious numerical priming despite interocular suppression. *Psychological Science, 21*(2), 224–233. https://doi.org/10.1177/0956797609360664

Baker, D. H., Vilidaite, G., Lygo, F. A., Smith, A. K., Flack, T. R., Gouws, A. D., et al. (2021). Power contours: Optimising sample size and precision in experimental psychology and human neuroscience. *Psychological Methods, 26*(3), 295–314. https://doi.org/10.1037/met0000337

Barbot, A., & Kouider, S. (2012). Longer is not better: nonconscious overstimulation reverses priming influences under interocular suppression. *Attention, Perception, & Psychophysics, 74*(1), 174–184. https://doi.org/10.3758/s13414-011-0226-3

Bates, D., Maechler, M., Bolker, B., & Walker, S. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software, 67*(1), 1–48. https://doi.org/10.18637/jss.v067.i01

Becker, N., & Mattler, U. (2019). Action priming suppression by forward masks. *Journal of Vision, 19*(5), 10. https://doi.org/10.1167/19.5.10

Biederman, I., Mezzanotte, R. J., & Rabinowitz, J. C. (1982). Scene perception: Detecting and judging objects undergoing relational violations. *Cognitive Psychology, 14*(2), 143–177. https://doi.org/10.1016/0010-0285(82)90007-X

Brainard, D. H. (1997). The Psychophysics Toolbox. *Spatial Vision, 10*(4), 433–436. https://doi.org/10.1163/156856897X00357

Breitmeyer, B. G., & Öğmen, H. (2006). *Visual masking: Time slices through conscious and unconscious vision*. New York, NY: Oxford University Press.

Daza, M. T., Ortells, J. J., & Fox, E. (2002). Perception without awareness: Further evidence from a Stroop priming task. *Perception & Psychophysics, 64*(8), 1316–1324. https://doi.org/10.3758/BF03194774

Dell'Acqua, R., & Grainger, J. (1999). Unconscious semantic priming from pictures. *Cognition, 73*(1), B1–B15. https://doi.org/10.1016/s0010-0277(99)00049-9

Fei-Fei, L., VanRullen, R., Koch, C., & Perona, P. (2005). Why does natural scene categorization require little attention? Exploring attentional requirements for natural and synthetic stimuli. *Visual Cognition, 12*, 893–924. https://doi.org/10.1080/13506280444000571

Fernández, S., Ortells, J. J., Kiefer, M., Noguera, C., & De Fockert, J. W. (2021). Working memory capacity modulates expectancy-based strategic processing: Behavioral and electrophysiological evidence. *Biological Psychology, 159*, Article 108023. https://doi.org/10.1016/j.biopsycho.2021.108023

Finger, H., Goeke, C., Diekamp, D., Standvoß, K., & König, P. (2017). LabVanced: A unified JavaScript framework for online studies. *International Conference on Computational Social Science (Cologne)*.

Gayet, S., Van der Stigchel, S., & Paffen, C. L. E. (2014). Breaking continuous flash suppression: competing for consciousness on the pre-semantic battlefield. *Frontiers in Psychology, 5*, 460. https://doi.org/10.3389/fpsyg.2014.00460

Gelbard-Sagiv, H., Faivre, N., Mudrik, L., & Koch, C. (2016). Low-level awareness accompanies "unconscious" high-level processing during continuous flash suppression. *Journal of Vision, 16*(1), 3. https://doi.org/10.1167/16.1.3

Henderson, J. M. (2005). Introduction to real-world scene perception. *Visual Cognition, 12*(6), 849–851. https://doi.org/10.1080/13506280444000544

Henderson, J. M., Larson, C. L., & Zhu, D. C. (2007). Cortical activation to indoor versus outdoor scenes: an fMRI Study. *Experimental Brain Research, 179*(1), 75–84. https://doi.org/10.1007/s00221-006-0766-2

Hesselmann, G., Darcy, N., Ludwig, K., & Sterzer, P. (2016). Priming in a shape task but not in a category task under continuous flash suppression. *Journal of Vision, 16 (3):17*, 1–17. https://doi.org/10.1167/16.3.17

Hesselmann, G., Darcy, N., Rothkirch, M., & Sterzer, P. (2018). Investigating masked priming along the "vision-for-perception" and "vision-for-action" dimensions of unconscious processing. *Journal of Experimental Psychology: General, 147*(11), 1641–1659. https://doi.org/10.1037/xge0000420

Hesselmann, G., Darcy, N., Sterzer, P., & Knops, A. (2015). Exploring the boundary conditions of unconscious numerical priming effects with continuous flash suppression. *Consciousness and Cognition, 31*, 60–72. https://doi.org/10.1016/j.concog.2014.10.009

Hesselmann, G., & Knops, A. (2014). No conclusive evidence for numerical priming under interocular suppression. *Psychological Science, 25*(11), 2116–2119. https://doi.org/10.1177/0956797614548876

Heyman, T., & Moors, P. (2012). Using interocular suppression and EEG to study semantic processing. *Journal of Neuroscience, 32*(5), 1515–1516. https://doi.org/10.1523/JNEUROSCI.5726-11.2012

Holender, D. (1986). Semantic activation without conscious identification in dichotic listening, parafoveal vision, and visual masking: A survey and appraisal. *Behavioral and Brain Sciences, 9*(1), 1–23. https://doi.org/10.1017/S0140525X00021269

Hothorn, T., Bretz, F., & Westfall, P. (2008). Simultaneous inference in general parametric models. *Biometrical Journal, 50*(3), 346–363. https://doi.org/10.1002/bimj.200810425

Kang, M.-S., Blake, R., & Woodman, G. F. (2011). Semantic analysis does not occur in the absence of awareness induced by interocular suppression. *Journal of Neuroscience, 31*(38), 13535–13545. https://doi.org/10.1523/JNEUROSCI.1691-11.2011

Kiefer, M., & Spitzer, M. (2000). Time course of conscious and unconscious semantic brain activation. *NeuroReport, 11*(11), 2401–2407. https://doi.org/10.1097/00001756-200008030-00013

Klotz, W., & Wolff, P. (1995). The effect of a masked stimulus on the response to the masking stimulus. *Psychological Research, 58*, 92–101. https://doi.org/10.1007/BF00571098

Koivisto, M., & Grassini, S. (2018). Unconscious response priming during continuous flash suppression. *PLoS One, 13*(2), e0192201. https://doi.org/10.1371/journal.pone.0192201
Koivisto, M., & Rientamo, E. (2016). Unconscious vision spots the animal but not the dog: Masked priming of natural scenes. *Consciousness and Cognition, 41*, 10–23. https://doi.org/10.1016/j.concog.2016.01.008
Konkle, T., Brady, T. F., Alvarez, G. A., & Oliva, A. (2010). Scene memory is more detailed than you think: The role of categories in visual long-term memory. *Psychological Science, 21*(11), 1551–1556. https://doi.org/10.1177/0956797610385359
Kouider, S., & Dehaene, S. (2007). Levels of processing during non-conscious perception: A critical review of visual masking. *Philosophical Transactions of the Royal Society B: Biological Sciences, 362*(1481), 857–875. https://doi.org/10.1098/rstb.2007.2093
Lin, Z., & He, S. (2009). Seeing the invisible: The scope and limits of unconscious processing in binocular rivalry. *Progress in Neurobiology, 87*(4), 195–211. https://doi.org/10.1016/j.pneurobio.2008.09.002
Loftus, G. R., & Masson, M. E. (1994). Using confidence intervals in within-subjects designs. *Psychonomic Bulletin & Review, 1*(4), 476–490. https://doi.org/10.3758/BF03210951
Marcel, A. J. (1983). Conscious and unconscious perception: An approach to the relations between phenomenal experience and perceptual processes. *Cognitive Psychology, 15*(2), 238–300. https://doi.org/10.1016/0010-0285(83)90010-5
Mattler, U. (2003). Priming of mental operations by masked stimuli. *Perception and Psychophysics, 65*(2), 167–187. https://doi.org/10.3758/BF03194793
Merikle, P. M., & Joordens, S. (1997). Parallels between perception without attention and perception without awareness. *Consciousness and Cognition, 6*(2–3), 219–236. https://doi.org/10.1006/ccog.1997.0310
Moors, P., Gayet, S., Hedger, N., Stein, T., Sterzer, P., van Ee, R., et al. (2019). Three criteria for evaluating high-level processing in continuous flash suppression. *Trends in Cognitive Sciences, 23*(4), 267–269. https://doi.org/10.1016/j.tics.2019.01.008
Moors, P., Hesselmann, G., Wagemans, J., & van Ee, R. (2017). Continuous Flash Suppression: Stimulus Fractionation rather than Integration. *Trends in Cognitive Sciences, 21*(10), 719–721. https://doi.org/10.1016/j.tics.2017.06.005
Mudrik, L., Breska, A., Lamy, D., & Deouell, L. Y. (2011). Integration without awareness: Expanding the limits of unconscious processing. *Psychological Science, 22*(6), 764–770. https://doi.org/10.1177/0956797611408736
Noguera, C., Fernández, S., Álvarez, D., Carmona, E., Marí-Beffa, P., & Ortells, J. J. (2019). The implementation of expectancy-based strategic processes is delayed in normal aging. *Plos one, 14*(3), e0214322. https://doi.org/10.1371/journal.pone.0214322
Oliva, A., & Torralba, A. (2006). Building the gist of a scene: The role of global image features in recognition. *Progress in Brain Research, 155*(Part B), 23–36. https://doi.org/10.1016/S0079-6123(06)55002-2
Ortells, J. J., Daza, M. T., & Fox, E. (2003). Semantic activation in the absence of perceptual awareness. *Perception & Psychophysics, 65*(8), 1307–1317. https://doi.org/10.3758/BF03194854
Ortells, J. J., Kiefer, M., Castillo, A., Megías, M., & Morillas, A. (2016). The semantic origin of unconscious priming: Behavioral and event-related potential evidence during category congruency priming from strongly and weakly related masked words. *Cognition, 146*, 143–157. https://doi.org/10.1016/j.cognition.2015.09.012
Ortells, J. J., Marí-Beffa, P., & Plaza-Ayllón, V. (2013). Unconscious congruency priming from unpracticed words is modulated by prime–target semantic relatedness. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 39*(2), 394–413. https://doi.org/10.1037/a0028876
Panis, S., Moran, R., Wolkersdorfer, M. P., & Schmidt, T. (2020). Studying the dynamics of visual search behavior using RT hazard and micro-level speed–accuracy tradeoff functions: A role for recurrent object recognition and cognitive control processes. *Attention, Perception, & Psychophysics, 82*(2), 689–714. https://doi.org/10.3758/s13414-019-01897-z
Pelli, D. G. (1997). The VideoToolbox software for visual psychophysics: transforming numbers into movies. *Spatial Vision, 10*(4), 437–442. https://doi.org/10.1163/156856897X00366
Peremen, Z., & Lamy, D. (2014). Comparing unconscious processing during continuous flash suppression and meta-contrast masking just under the limen of consciousness. *Frontiers in Psychology, 5*, 969. https://doi.org/10.3389/fpsyg.2014.00969
Posner, M. I., & Snyder, C. R. R. (1975). Facilitation and inhibition in the processing of signals. In P. M. A. Rabbit (Ed.), *Attention and Performance V* (pp. 669–682). London: Academic Press.
R Core Team. (2021). *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing. https://www.R-project.org/.
Sakuraba, S., Sakai, S., Yamanaka, M., Yokosawa, K., & Hirayama, K. (2012). Does the human dorsal stream really process a category for tools? *Journal of Neuroscience, 32*(11), 3949–3953. https://doi.org/10.1523/JNEUROSCI.3973-11.2012
Schmidt, T. (2015). Invisible stimuli, implicit thresholds: Why invisibility judgments cannot be interpreted in isolation. *Advances in Cognitive Psychology, 11*(2), 31–41. https://doi.org/10.5709/acp-0169-3
Schmidt, F., Haberkamp, A., & Schmidt, T. (2011). Dos and don'ts in response priming research. *Advances in Cognitive Psychology, 7*, 120–131. https://doi.org/10.2478/v10053-008-0092-2
Schmidt, T., & Vorberg, D. (2006). Criteria for unconscious cognition: Three types of dissociation. *Perception & Psychophysics, 68*(3), 489–504. https://doi.org/10.3758/BF03193692
Shanks, D. R. (2017). Regressive research: The pitfalls of post hoc data selection in the study of unconscious mental processes. *Psychonomic Bulletin & Review, 24*(3), 752–775. https://doi.org/10.3758/s13423-016-1170-y
Shanks, D. R., Malejka, S., & Vadillo, M. A. (2021). The challenge of inferring unconscious mental processes. *Experimental Psychology, 68*(3), 113. https://doi.org/10.1027/1618-3169/a000517
Singmann, H., Bolker, B., Westfall, J., Aust, F., & Ben-Shachar, M. S. (2021). afex: Analysis of factorial experiments. R package version 1.0-1. https://CRAN.R-project.org/package=afex.
Sklar, A. Y., Deouell, L. Y., & Hassin, R. R. (2018). Integration despite Fractionation: Continuous Flash Suppression. *Trends in Cognitive Sciences, 22*(11), 956–957. https://doi.org/10.1016/j.tics.2018.07.003
Sklar, A. Y., Levy, N., Goldstein, A., Mandel, R., Maril, A., & Hassin, R. R. (2012). Reading and doing arithmetic nonconsciously. *PNAS, 109*(48), 19614–19619. https://doi.org/10.1073/pnas.1211645109
Smith, F. W., & Muckli, L. (2010). Nonstimulated early visual areas carry information about surrounding context. *PNAS, 107*(46), 20099–20103. https://doi.org/10.1073/pnas.1000233107
Stein, T., Utz, V., & van Opstal, F. (2020). Unconscious semantic priming from pictures under backward masking and continuous flash suppression. *Consciousness and Cognition, 78*, 102864. https://doi.org/10.1016/j.concog.2019.102864
Tsuchiya, N., & Koch, C. (2005). Continuous flash suppression reduces negative afterimages. *Nature Neuroscience, 8*(8), 1096–1101. https://doi.org/10.1038/nn1500
Tsuchiya, N., Koch, C., Gilroy, L. A., & Blake, R. (2006). Depth of interocular suppression associated with continuous flash suppression, flash suppression, and binocular rivalry. *Journal of Vision, 6*(10), 1068–1078. https://doi.org/10.1167/6.10.6
Valuch, C., & Mattler, U. (2019). Action priming is linked to visual perception in continuous flash suppression. *Journal of Vision, 19(7)*(13), 1–25. https://doi.org/10.1167/19.7.13
Van den Bussche, E., Notebaert, K., & Reynvoet, B. (2009). Masked primes can be genuinely semantically processed: A picture prime study. *Experimental Psychology, 56*, 295–300. https://doi.org/10.1027/1618-3169.56.5.295
Van den Bussche, E., Van den Noortgate, W., & Reynvoet, B. (2009). Mechanisms of masked priming: a meta-analysis. *Psychological Bulletin, 135*(3), 452–477. https://doi.org/10.1037/a0015329
Vorberg, D., Mattler, U., Heinecke, A., Schmidt, T., & Schwarzbach, J. (2003). Different time courses for visual perception and action priming. *Proceedings of the National Academy of Sciences of the United States of America, 100*(10), 6275–6280. https://doi.org/10.1073/pnas.0931489100
Vorberg, D., Mattler, U., Heinecke, A., Schmidt, T., & Schwarzbach, J. (2004). Invariant time course of priming with and without awareness. In *Psychophysics Beyond Sensation: Laws and Invariants of Human Cognition* (pp. 271–288). Mahwah, NJ: Lawrence Erlbaum Associates Publishers.
Wagner, A. D., & Koutstaal, W. (2002). Priming. In V. S. Ramachandran (Ed.), *Encyclopedia of the Human Brain* (pp. 27–46). Cambridge, MA: Academic Press.

Wernicke, M., & Mattler, U. (2019). Masking procedures can influence priming effects besides their effects on conscious perception. *Consciousness and Cognition, 71*, 92–108. https://doi.org/10.1016/j.concog.2019.03.009

Wickham, et al. (2019). Welcome to the tidyverse. *Journal of Open Source Software, 4*(43), 1686. https://doi.org/10.21105/joss.01686

Willenbockel, V., Sadr, J., Fiset, D., Horne, G. O., Gosselin, F., & Tanaka, J. W. (2010). Controlling low-level image properties: The SHINE toolbox. *Behavior Research Methods, 42*, 671–684. https://doi.org/10.3758/BRM.42.3.671

Yang, E., Blake, R., & McDonald, J. E., II. (2010). A new interocular suppression technique for measuring sensory eye dominance. *Investigative Ophthalmology & Visual Science, 51*(1), 588–593. https://doi.org/10.1167/iovs.08-3076

Yang, E., Brascamp, J., Kang, M.-S., & Blake, R. (2014). On the use of continuous flash suppression for the study of visual processing outside of awareness. *Frontiers in Psychology, 5*, 724. https://doi.org/10.3389/fpsyg.2014.00724

Zabelina, D. L., Guzman-Martinez, E., Ortega, L., Grabowecky, M., Suzuki, S., & Beeman, M. (2013). Suppressed semantic information accelerates analytic problem solving. *Psychonomic Bulletin & Review, 20*(3), 581–585. https://doi.org/10.3758/s13423-012-0364-1

Zhu, W., Drewes, J., Peatfield, N. A., & Melcher, D. (2016). Differential visual processing of animal images, with and without conscious awareness. *Frontiers in Human Neuroscience, 10*, 513. https://doi.org/10.3389/fnhum.2016.00513