Does Location Uncertainty Modulate Unconscious Processing Under Continuous Flash Suppression?

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ABSTRACT

Previous research suggests that selective spatial attention is a determining factor for unconscious processing under continuous flash suppression (CFS), and specifically, that inattention toward stimulus location facilitates its unconscious processing by reducing the depth of CFS (Eo et al. , 2016). The aim of our study was to further examine this modulation-by-attention model of CFS using a number priming paradigm. Participants ($N = 26$) performed a number comparison task on a visible target number ("*compare target to five*"). Prime-target pairs were either congruent (both smaller or larger than five) or incongruent. Spatial attention toward the primes was varied by manipulating the uncertainty of the primes' location. Based on the modulation-by-attention model, we hypothesized the following: In trials with uncertain prime location, RTs for congruent prime-target pairs should be faster than for incongruent ones. In trials with certain prime location, RTs for congruent versus incongruent prime-target pairs should not differ. We analyzed our data with sequential Bayes factors (BFs). Our data showed no effect of location uncertainty on unconscious priming under CFS ($BF_{0+} = 5.16$). However, even visible primes only weakly influenced RTs. Possible reasons for the absence of robust number priming effects in our study are discussed. Based on exploratory analyses, we conclude that the numerical order of prime and target resulted in a response conflict and interfered with the predicted priming effect.

KEYWORDS
continuous flash suppression
interocular suppression
unconscious processing
priming

INTRODUCTION

A substantial part of empirical consciousness research consists of studies about the unconscious processing of subliminally or periliminally presented visual stimuli (Rothkirch et al., 2018). Various techniques are available to transiently suppress visual stimuli from awareness (e.g., binocular rivalry; Blake, 1989; for a review, see Kim & Blake, 2005). One remarkably potent "blinding" technique is continuous flash suppression (CFS; Tsuchiya & Koch, 2005). It is a variant of binocular rivalry and uses interocular suppression to render stimuli invisible. It consists of dynamically changing high-contrast patterns (Mondrian patterns) presented to one eye. These CFS masks can disrupt the conscious perception of a stimulus shown to the other eye. Since its introduction in 2005, the number of studies using CFS has steadily risen due to its reported advantages, notably, the reliable suppression of stimuli for a duration of up to several seconds (Tsuchiya et al., 2006).

Depth of Unconscious Stimulus Processing

Several publications have provoked debates about the limits of unconscious processing and the depth of processing that is possible outside of awareness (Moors et al., 2016; Mudrik et al., 2011). The question is whether our brain can extract and process complex, semantically relevant information from invisible stimuli or whether only low-level

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basic stimulus features are processed during interocular suppression. Recently, Breitmeyer (2015) proposed a hierarchical model delineating the relative degree of unconscious processing possible under the diverse suppression methods. Interocular suppression, the mechanism underlying CFS, is tentatively located on the lower end of the hierarchy, but overall, the CFS literature is very heterogeneous. On the one hand, there are studies showing high-level effects suggesting that semantic stimulus information is processed and that complex tasks can be performed unconsciously. For example, it has been suggested that solving simple arithmetic equations and processing of multiple word expressions are possible outside of awareness (Sklar et al., 2012; but see Moors & Hesselmann, 2018). Similarly, previous studies reported large and robust semantic priming effects for invisible symbolic numbers (Bahrami et al., 2010). On the other hand, replication studies failed to find comparable high-level effects. For example, one study only found repetition priming instead of high-level numerosity priming under CFS (Hesselmann et al., 2015). Another important study on this issue was conducted by Kang et al. (2011). They presented semantically related and unrelated words, respectively, and analyzed the N400 of the event-related potential (ERP) as a measure of semantic processing. The results showed a lack of an N400 effect when stimuli were invisible, and thus, no find evidence for the semantic analysis of primes under interocular suppression. However, taken together, there is yet no consensus yet about the depth of processing possible under CFS.

Attentional Modulation of Unconscious Processing

Behavioral and neurophysiological evidence suggests that reduced spatial attention, that is, spatial attention withdrawn from a suppressed stimulus, weakens interocular suppression and thus might boost unconscious processing (Brascamp & Blake, 2012; Zhang et al., 2011). In a recent ERP study by Eo et al. (2016), spatial attention was manipulated using a cueing paradigm in which target words appeared either at a cued or noncued location. This study found no unconscious semantic processing (as indexed by an absent N400 effect) in the attended condition, but semantic processing when stimuli were not attended. Based on this, the authors hypothesized that attention directed away from a stimulus location facilitates its semantic processing by attenuating the interocular suppression mechanism. In order to integrate the seemingly incongruous effects in interocular suppression literature, the authors proposed that spatial ambiguity or location uncertainty of stimuli, respectively, might significantly modulate attention, and therefore, influence the depth of unconscious processing. This mechanism could thus explain several high-level processing effects under CFS and the lack of an N400 effect in the study of Kang et al. (2011) in which attention was directly pointed toward the stimulus.

Not surprisingly, not all reported results are in agreement with this modulation-by-attention model. For example, some studies measuring the speed of stimulus detection during breaking CFS (b-CFS) found high-level effects for stimuli presented in a central location (Alsius & Munhall, 2013; Gobbini et al., 2013; Lupyan & Ward, 2013), while other studies employing spatial ambiguity did not find any high-level influence on breaking times (Heyman & Moors, 2014; Moors et al., 2016). It might also be the case that behavioral effects on a semantic level do not require the measurable presence of the N400 effect, which is why some previous studies did not observe semantic processing despite attenuated suppression. The N400 effect may indicate semantic processing not associated with effects on a behavioral level. Taken together, the effect of spatial ambiguity (or, location uncertainty) and depth of processing under CFS needs to be investigated more closely. Finding that attentional modulation is a determining factor that influences the depth of processing under CFS would also result in the necessity to reevaluate Breitmeyer's (2015) model and the position of CFS in the functional hierarchy.

The Present Study

In the present study, our aim was to further examine the influence of attentional modulation due to location uncertainty of stimuli on semantic processing under CFS. We employed a priming paradigm with numerical stimuli in which we presented prime and target numbers in sequence, and participants were asked to perform a number comparison task on the target number. Primes were presented either at one location (focused attention, location certain), or at one of two possible locations (diverted attention, location uncertain). The processing of the semantic numerical information outside of awareness was investigated by measuring and comparing RTs in the congruent and incongruent conditions. Following the modulation-by-attention model, we expected to find larger behavioral effects indicating unconscious processing in the location uncertain condition. Specifically, we hypothesized that if the location of the prime stimulus is uncertain, RTs for trials with congruent prime-target pairs (both smaller or larger than five) should be shorter than for trials with incongruent prime-target pairs (i.e., prime smaller and target larger than five, or prime larger and target smaller than five). If the location of the prime is certain, we did not predict a significant difference between RTs for congruent versus incongruent trials. Furthermore, we expected prime numbers in the visible conditions to be semantically processed. Therefore, we hypothesized that RTs for congruent prime-target pairs should be faster than for incongruent pairs (e.g., Dehaene et al., 1998).

METHOD

Participants

All participants (N = 31) were naive to the purpose of the study, had normal or corrected-to-normal vision, and provided written informed consent. The study was conducted with ethics approval by the local ethics committee (approval number PHB10032019). Participants were recruited mainly from a student pool at the Psychologische Hochschule Berlin (PHB). They were compensated with course credit or with 8 €/hour. Employing the preregistered exclusion criteria resulted in omitting three participants (see the Exclusion Criteria section). Furthermore, two participants were excluded because they did not follow the instructions. In total, data of 26 participants (20 females, M_{age} =

25 years, SD_{age} = 3.97, range: 19-36, 3 left-handed, 7 left eye dominant) were used for statistical analyses (for details on our sampling plan, see the Data Analysis section.).

Apparatus and Setup

The experiment took place in a dimly lit room. Participants viewed the dichoptic images on a 19 in. CRT monitor (SAMTRON 98PDF; effective screen diagonal: 43.6 cm; refresh rate 60 Hz) via a mirror stereoscope (ScreenScope, Stereoaids, Australia). To stabilize the head position, participants placed their heads on chin and forehead rests. The viewing distance from the eyes to the screen (not including distances within the mirror system) was 41 cm. Responses were provided via the computer keyboard.

Stimuli and Continuous Flash Suppression

All stimuli were created with the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997) running under MATLAB 2019a (MathWorks Inc., USA) on a computer with Windows 10 and an AMD Radeon 6450 graphics card. We generated 25 different CFS masks that were presented in a randomized order and changed at a 10 Hz rate. All masks consisted of 1018 multicolored (including also black, white and grey) circles and rectangles with randomized orientation (size range: 0.14 °–0.84 °). The participants' dominant eye was assessed using the hole-in-card-test (Miles, 1930), and CFS masks were presented to the dominant eye. Prime and target stimuli (size: 0.84 ° × 0.70 °) were Arabic numbers from one to nine (i.e., primes: 1, 3, 7, 9; targets: 2, 4, 6, 8; font: Courier New) and were presented in a 6.56 ° × 6.56 ° rectangle. The size of the centered fixation cross was 0.28 ° × 0.28 °. The eccentricity for peripherally presented primes in the "location uncertain" conditions was 1.8 ° from the center.

Prime Contrast and Visibility

To ensure that prime stimuli were not consciously visible under CFS, and to control for between-subject variability of interocular suppression (Yamashiro et al., 2014), prime contrasts were adjusted for each participant individually in an extra experiment prior to the main experiment. We presented numerical stimuli identical to the prime stimuli in the main experiment (i.e., 1, 3, 7, 9), and participants had to indicate their ability to detect the stimulus in a simple two-alternative forced-choice task via up and down arrow keys (up arrow: yes; down arrow: no). The stimulus contrast for the next trial was then decreased or increased depending on the prior response following a logarithmic scale (1-up-1-down staircase) which resulted in an individual contrast value for each participant. The staircase included 25 trials and every participant completed it twice. For the main experiment, we then used the highest contrast that was always judged invisible (Rothkirch & Hesselmann, 2018). This adjustment procedure allowed us to minimize regression-to-the-mean effects (Shanks, 2017), as only one participant had to be excluded from further analyses due to residual prime visibility under CFS. The individual adjustment resulted in a mean Michelson stimulus contrast of 0.30 (range: 0.04–0.81).

Procedure

Figure 1 illustrates the experimental paradigm. There were four conditions presented in four separate blocks of trials: two invisible conditions where primes were suppressed by CFS, and two visible conditions without CFS masks. Location uncertainty of the prime stimulus was manipulated via instruction screens before each block of trials. For the location certain conditions, one centered asterisk was shown. For the location uncertain conditions, two asterisks were presented peripherally, on the top and at the bottom of the stimulus rectangle. In either case, participants were instructed to direct their attention toward the asterisks throughout the following block of trials. To ensure that participants followed the instruction, they were told that the prime stimulus could appear centered or peripherally, and that they might have to identify it afterwards. Prime numbers were shown centered (location certain condition), or with equal probability above or below the fixation in randomized order (location uncertain condition), in the invisible as well as the visible condition. Following the presentation of the instruction screen, participants could start the next block by pressing the space bar. Prior to each trial, a green fixation cross was displayed in the center of the rectangle for a random duration between 500 and 750 ms (following a uniform distribution). In the invisible conditions, CFS masks were shown for 200 ms, including a prime number shown to the nondominant eye that was either larger or smaller than five. The visible conditions consisted of the prime exclusively displayed for 200 ms. Immediately after the prime, the target number was presented binocularly and always clearly visible for up to 1 s. Within this second, participants had to indicate as fast and accurately as possible if the target was smaller or larger than five by pressing the left (*smaller*) or right (*larger*) arrow key with their right hand. If the response time exceeded 1000 ms, we displayed a red fixation cross indicating that the participant had to be faster in the next trial. Participants started the next trial via pressing the space bar with the left hand. After the last trial in each block, we presented the instruction screen showing the condition of the following block. Altogether, the main experiment consisted of 576 trials equally divided into the four conditions (144 trials each). Condition blocks were presented in random order.

Following the main experiment, we conducted a control experiment ("awareness check") with the same four condition blocks, but without presenting the visible target. With the CFS-masked trials, we assessed the objective unawareness of the CFS primes. The visible trials tested whether the prime stimulus contrasts were set adequately, that is, whether participants were able to identify the different prime numbers without CFS masks. In all control trials, participants performed two tasks. First, similar to the main experiment, they performed the number comparison task indicating if the prime was smaller or larger than five via the arrow keys. In case of prime invisibility, participants were instructed to guess. In contrast to the main experiment, the task did not include a time limit. In the next task, prime visibility was rated on the subjective Perceptual Awareness Scale (PAS, Ramsøy & Overgaard, 2004). The four visibility levels (1 = *invisible*, 2 = *weak glimpse*, 3 = *almost clear*, 4 = *absolutely clear*) were displayed vertically on the screen. Participants chose their rating via up and down arrow keys and

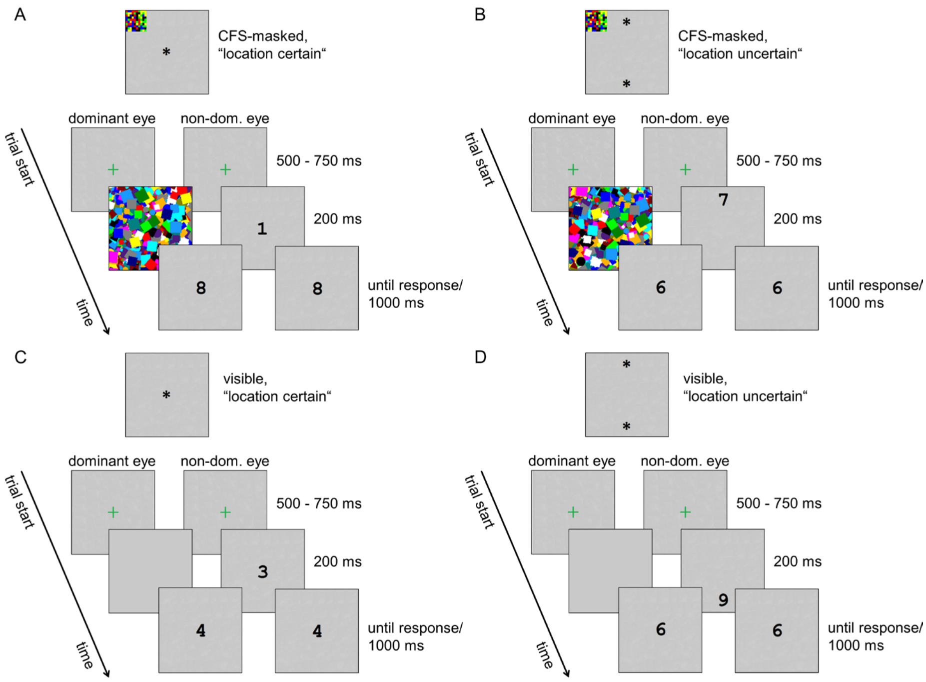

FIGURE 1.

Experimental procedure in the continuous flash suppression (CFS)-masked location certain (Panel A), location uncertain (Panel B) condition, the visible location certain (Panel C), and location uncertain (Panel D) condition. After presenting instruction screens for each condition, experimental trials started. The CFS-masks were shown for 200 ms including a prime, and the prime was shown exclusively for 200 ms in visible conditions, respectively. Subsequently, the target was presented until response or for a maximum of 1000 ms.

confirmed it by pressing the space bar, which also started the next trial. Instruction screens were displayed, as in the main experiment. The control experiment included 256 trials (64 trials in each condition). The entire experiment lasted between 60 and 90 minutes.

Exclusion Criteria

The contrasts of the prime stimuli were adjusted individually to ensure prime invisibility under CFS. We expected participants to provide only a few ratings of high visibility on the PAS in the masked trials (Ramsøy & Overgaard, 2004). In trials without CFS, we expected the opposite, namely, participants rating high visibility more likely than low visibility. This resulted in excluding the participants with positive slopes of the regression of rating frequency against PAS level (1–4) in the invisible trials as well as the participants with negative slopes of the regression of rating frequency against PAS level in the visible conditions (Rothkirch & Hesselmann, 2018). Figure 2 plots the individual ratings for each participant in the CFS-masked conditions and the visible nonmasked conditions.

Employing the aforementioned criteria, we had to exclude three participants from further analyses. Participants 19 and 29 (red and dark blue dashed lines; see Figure 2, Panel A) were excluded due to negative regression slopes in the visible condition ($b_{19} = -.98$; $b_{29} = -.09$). Their individual contrasts were set on a very low level (Michelson contrasts: 0.01 and 0.03, respectively) so that prime numbers were barely visible even without CFS masks. Furthermore, Participant 18 (black dashed line; see Figure 2, Panel B) was excluded because of a positive regression slope in the invisible condition ($b_{18} = .05$). Presumably, the individual stimulus contrast level was set too high (Michelson contrast: 0.59) so that even with CFS masks, the prime stimuli were at least partly visible. For all three excluded participants, it also may have been that the CFS masks were presented to the nondominant eye as we used the hole-in-card test to determine eye dominance (Miles, 1930), which is only one of diverse methods that provide potentially inconsistent results (Pointer, 2012). Additionally, this test does not give information about the strength of eye dominance (Li et al., 2010) so that eye dominance for these participants was perhaps not determined correctly, which is why CFS was not successful.

Data Analysis

Data preprocessing and descriptive analyses were computed using Matlab2019a (MathWorks Inc., USA), as well as *R* 3.5.1 (R Core Team, 2018) and RStudio 1.1.463 (RStudio Team, 2016). Data visualization was created with the *R* package *ggplot2* (Wickham, 2016). We preregistered all methods for data preprocessing and analyses as described in the following section (http://aspredicted.org/blind.php?x=ze647k). Our raw data and *R* code are available at an online repository (www.osf.io/frz5d/).

For the RT analyses of the data in the main experiment, the first 16 trials of each condition were removed as training trials so that each condition consisted of 128 trials. Only trials with correct responses were included in the RT analyses. Moreover, anticipatory responses, namely, RTs faster than 100 ms, were excluded. As preregistered, we

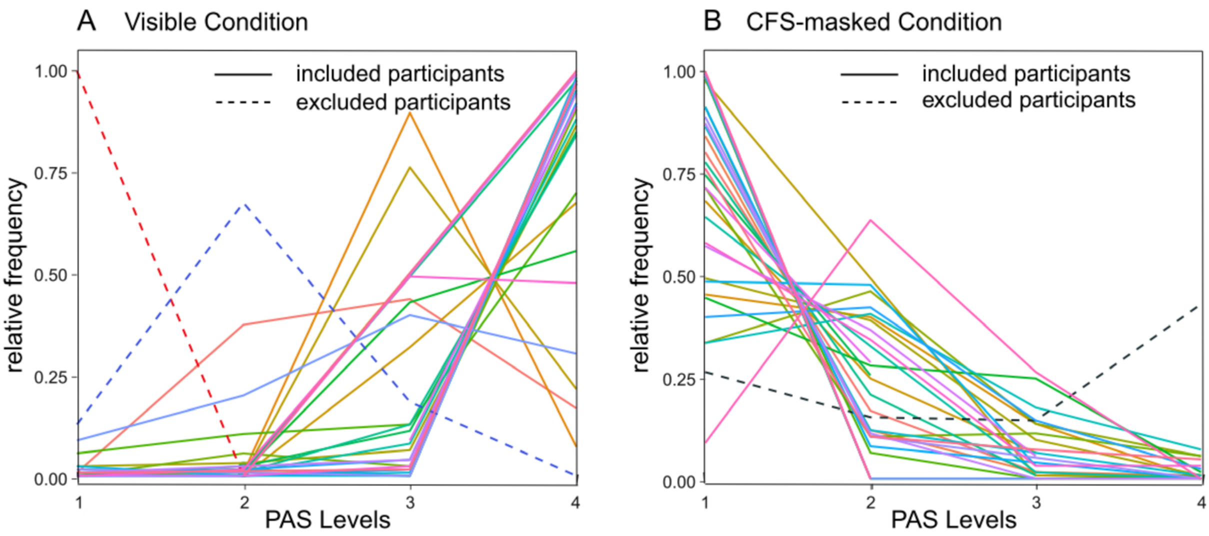

FIGURE 2.

Distribution of visibility ratings on the Perceptual Awareness Scale (PAS), individually for each participant across all trials in the nonmasked condition with visible primes (Panel A) and the continuous flash suppressionmasked condition with suppressed primes (Panel B) of the control experiment. The colored lines represent the relative frequency of PAS level ratings individually for each participant. Dashed lines show excluded participants.

used the interquartile range (IQR) method (Tukey, 1977) to define and exclude all trials with RTs located 1.5 IQR outside the lower and upper quartiles as outliers (per participant, across all conditions). Next, for the descriptive analysis, we computed RT means, *SD*s and 95% CIs across all participants for each condition individually.

For the awareness check, we computed the median of PAS ratings per participant for each condition separately and then calculated the mean per condition across all participants. Expecting prime invisibility under CFS, the discrimination performance was evaluated against chance level (0.5), assuming that in invisible trials in which the prime stimuli were not consciously available, discrimination accuracy should not exceed the chance level. Again, we calculated 95% CIs for the discrimination accuracy.

Bayesian Statistics

As an alternative to the null hypothesis significance testing (NHST), we analyzed our data using the sequential Bayes factor (SBF). The Bayes factor approach allowed us to quantify the power of evidence in the present empirical data for competing hypotheses, namely, the null hypothesis (H0) and one alternative hypothesis (H1). The Bayes factor (BF) refers to the ratio of marginal likelihoods of different statistical models under consideration (e.g., a model H1 with a main effect of prime-target congruency versus an empty model H0 with only random effects), quantifying the change from prior to posterior model odds. The indices show which hypothesis is tested against the other. For example, a BF10 of 4 indicates that the data are four times more likely under H1 than under H0 (BF10 for an undirected H1, BF+0 for a directed H1). Likewise, a BF01 of 4 indicates that the data are four times more likely under H0 than under H1. The advantage of the SBF is that BFs are computed sequentially until a predetermined level of evidence is reached (Schönbrodt et al., 2017). As BFs quantify evidence for one hypothesis relative to another, they provide a nonbinary measure. However, the BF continuum may be divided using certain thresholds to classify the evidence and facilitate the interpretation. For instance, a BF between 1 and 3 represents only anecdotal evidence, a BF of at least 3 indicates moderate evidence, and a BF higher than 10 indicates strong evidence (Jeffreys, 1961; Lee & Wagenmakers, 2013).

To analyze the data of our main experiment, two pairwise comparisons were of particular interest regarding our hypothesis: (a) congruent versus incongruent trials in the invisible location certain condition, and (b) congruent versus incongruent trials in the invisible location uncertain condition. For this, we computed RT means separately for each participant and then calculated the participant-specific differences of RT means in each relevant condition. Thus, we calculated the differences of incongruent and congruent trials in the location uncertain condition, and the differences of incongruent and congruent trials in the location certain condition, both under CFS as well as for nonmasked trials. We then calculated Bayesian one sample *t*-tests (location uncertain versus location certain, directional tests against zero). In addition to our main hypothesis, we tested the congruency priming model, expecting that if visible prime stimulus and target are congruent, the prime should facilitate the response to the target (i.e., Bayesian one sample *t*-test for the main effect of prime-target congruency, directional test against zero).

The BFs were calculated and visualized using the open source software JASP 0.9.2 (JASP Team, 2019). Based on our limited resources and time, we preregistered the aim to obtain valid data of at least 25 participants (latest data collection date was set to July 15th, 2019). As a further stopping rule, we set a critical BF of 10 or 1/10, respectively. For all analyses, we used the JASP default Cauchy prior with the default scale parameter r = .707. Our final sample size was 26, but BFs larger than 10 or smaller than 1/10 were not obtained.

RESULTS

Awareness Check

The awareness check served to evaluate the objective awareness of the primes on the one hand, and the adequacy of individual prime contrasts via discrimination performance, on the other hand. At the individual level, the analysis of the discrimination performances revealed two notable cases. Participant 30 performed on chance-level (exactly 50% correct responses) in all four conditions, because they always provided a "larger" response. We observed the same for Participant 31 in more than half of the control trials (response always "smaller"). Assuming that these participants did not respond adequately in the number comparison task, we decided to exclude their data from all further analyses. Our final results are therefore based on data from 26 participants (see Figure 3).

In CFS-masked trials, the discrimination performance was 58% (CI [55; 61]), with similar performances in the location certain (59%, CI [54; 64]) and location uncertain conditions (57%, CI [53; 61]). In both conditions, the lower bound of the CIs indicated that participants performed above chance-level (50%). Isolating the trials which were rated as completely invisible (PAS level 1) shows that participants performed on chance level (51%, CI [49; 54]) when they did not consciously detect the prime. This indicates that CFS masks in most trials successfully suppressed the prime stimuli from visibility under the set contrasts. In the visible control trials in which stimuli were not suppressed, the overall discrimination performance was at ceiling level (98%, CI [97; 98]), and virtually identical for the visible location certain (98%, CI [97; 99]) and the visible location uncertain condition (98%, CI [97; 99]). We conclude that the individually adjusted contrasts were as low as necessary to allow CFS masks to render the prime stimuli invisible, and as high as possible so that participants were able to perform the number comparison task when no masks were presented.

In trials in which primes were suppressed by CFS, the mean of median PAS ratings was 1.18 (SD = 0.39), suggesting very low visibility. In 72% of all CFS trials, participants reported that the prime was fully invisible (PAS level 1) indicating that they had no conscious perception of the prime stimulus. The mean of median PAS ratings in the location certain (M = 1.17, SD = 0.37) and the location uncertain conditions (M = 1.21, SD = 0.40) under CFS were virtually identical. In the visible trials without CFS masks, the mean of median PAS ratings was 3.77 (SD = 0.47) which indicates almost full visibility. Participants reported that the prime stimulus was clearly visible (PAS level 4) in 77% of all visible trials. The mean of median PAS ratings in the visible location uncertain condition (M = 3.69, SD = 0.55) was comparable to the mean in the visible location certain condition (M = 3.85, SD = 0.37). We conclude that both centered and peripherally presented stimuli were nearly fully visible without CFS. Taken together, the data from the awareness check show that CFS significantly suppressed the primes' visibility, as expected, suggesting that interocular suppression was effective.

Confirmatory Data Analysis

The discrimination accuracy for the number comparison task ("*compare target to five*") in the main experiment was near ceiling level in all conditions (overall accuracy: 96%, CI [95; 97]; range across conditions: 95-97%), as the target number was always displayed at the fixation and was fully visible.

Employing the IQR method (Tukey, 1977) across all trials, as preregistered, resulted in 5.2% of the data being removed as outliers (range across participants: 0–19%). After removing all outliers, we calculated the mean RTs for the correct trials in all conditions for further analyses (see Table 1). In error trials, RTs turned out to be longer in the congruent than in the incongruent condition, both in CFS (440 vs. 408 ms) and no CFS (470 vs. 417ms) trials. This difference was significant only for the no CFS trials, BF_{10} = 20.14, t(19) = 3.58, p = .002; CFS: BF_{10} = 0.81, t(19) = 1.72, p = .102 (N = 20 because six participants had no error trials in at least one of the four conditions).

Our main aim was to examine whether location uncertainty had an effect on the semantic processing of stimuli rendered invisible by

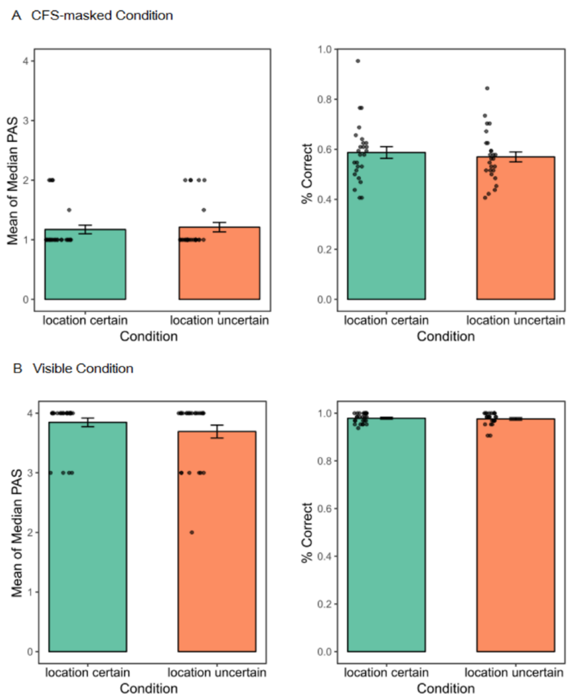

FIGURE 3.

Results from the awareness check in the continuous flash suppression-masked conditions (Panel A) and the visible conditions (Panel B). Left panels illustrate the mean of median PAS ratings for location certain and location uncertain conditions. Right panels plot the discrimination performance in % for location certain and location uncertain conditions. Colored bars show the means across participants, error bars represent the SEM, and dots indicate median data for PAS ratings and mean data for discrimination accuracy individually per participant.

TABLE 1.
Mean Correct RTs in All Experimental Conditions

Congruency	CFS-masked condition		Visible condition	
	Location certain	Location uncertain	Location certain	Location uncertain
Congruent	473 [455; 491]	477 [460; 494]	491 [472; 510]	478 [457; 499]
Incongruent	477 [460; 494]	481 [462; 499]	497 [477; 516]	485 [467; 504]

Note. CFS = continuous flash suppression. RTs are presented in ms, 95% CIs are in parentheses.

CFS. We expected larger behavioral effects, that is, a larger difference in RTs between congruent versus incongruent trials, when the prime's location was uncertain than when it was certain. Figure 4 illustrates mean RTs for the relevant comparisons. We investigated the difference between the two pairwise comparisons of congruent versus incongruent trials for the location certain and the location uncertain condition. The final BF0+ for the interaction effect of prime-target congruency × location uncertainty under CFS was 5.16. Thus, our data were 5 times more likely under H0 than under H1 (moderate evidence for H0; $t[25] = -0.09$, $p = .536$). We then computed the same BF for the visible condition without CFS. This analysis yielded a similar result of BF0+ = 3.95 (moderate evidence for H0; $t[25] = 0.25$, $p = .402$). The evolution of the sequentially calculated BFs for the invisible and visible condition is shown in Figure 5, Panels A and B. Altogether, we did not find evidence that location uncertainty modulated the processing of numerical primes under CFS.

Next, we calculated BFs for the main effect of prime-target congruency in the visible condition, namely, the differences of RT means between incongruent and congruent trials. We obtained a final BF+0 of 1.97, indicating that our data were 2 times more likely under H1 than H0 (anecdotal evidence for H1; $t[25] = 1.93$, $p = .033$). Figure 5, Panel C illustrates the evolution of the sequentially computed BFs. Visual inspection of the sequential BFs seems to suggest that in the visible condition, our data show some evidence of congruency priming. While this conclusion would be in line with our exploratory data analysis (see below), the trajectories of sequential BFs should not be overinterpreted for small sample sizes and BFs (e.g., see the CFS work by Moors and Heyman: http://www.the100.ci/2019/11/06/sequential-testing-replication-and-the-unconscious/).

Exploratory Data Analysis

During the debriefing, several participants reported that they had experienced an unexpected response conflict in the main experiment, especially when the primes were visible (i.e., not masked by CFS). In addition to the instructed number comparison task, participants reported having compared the target to the prime stimulus as well. This resulted in a subjective response conflict for certain prime-target pairs: Whenever the target was larger than the prime, but smaller than five, or when the target was smaller than the prime, but larger than five, it took the participants more effort to respond because the target-prime relation and the number comparison task ("compare target to five") were in conflict. In other words, whenever the prime-target sequence was ascending ("getting larger"), or when the prime-target sequence was descending ("getting smaller") the opposite response in the number comparison task (i.e., "smaller than five" or "larger than five") was experienced as more effortful.

We had not anticipated this potential conflict, but in retrospect, it seems plausible. Previous research points to the possibility of the existence of multiple cognitive processes underlying numerical judgments, such that order-dependent and distance-related processes might turn out to be superposed (Turconi et al., 2006). Therefore, we performed exploratory analyses to elucidate the response conflict described by participants.

In the first approach, we recomputed BFs for the congruency priming model in the visible condition excluding the two prime-target pairs with the largest numerical distance (i.e., the largest potential response conflict; target pairs 1–4 and 9–6). Although the mean RT difference between incongruent and congruent trials was small (12 ms), it was

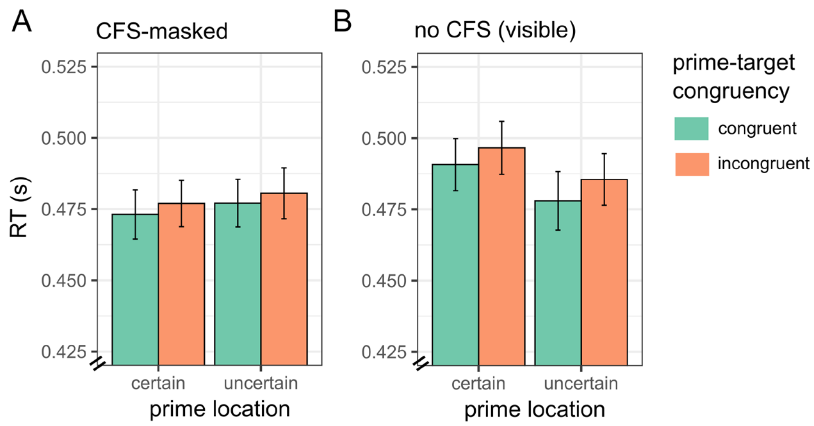

FIGURE 4.
Reaction time (RT) means for congruent versus incongruent trials in the location certain and location uncertain conditions, under continuous flash suppression (CFS, Panel A) and in the visible no CFS condition (Panel B). Bars indicate mean RTs in seconds, error bars represent the SEM.

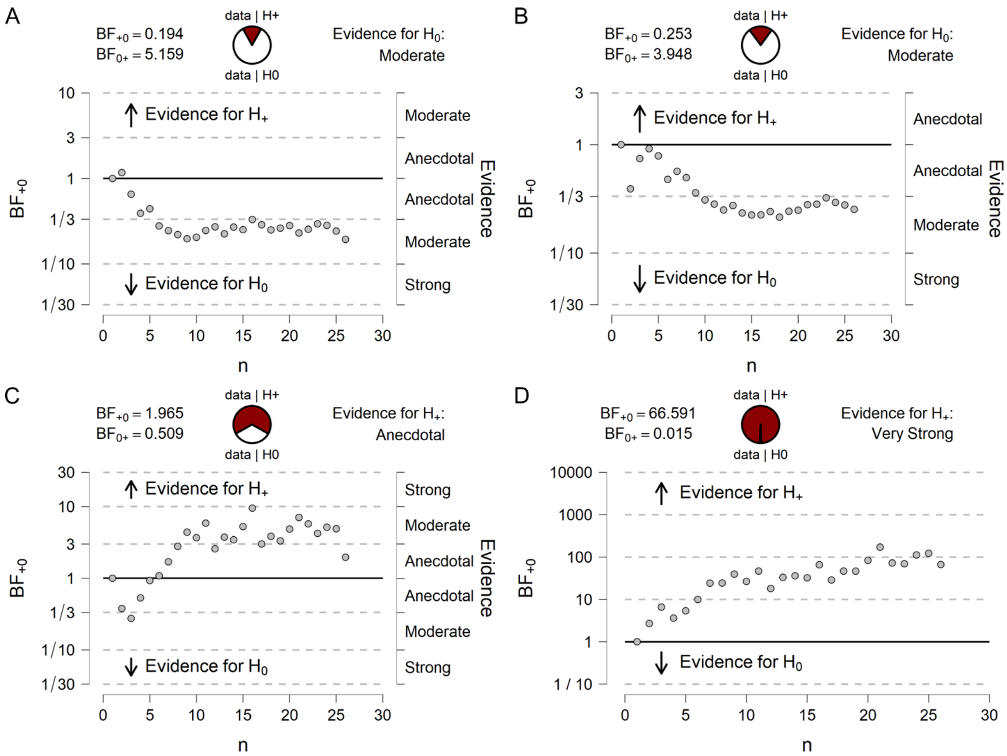

FIGURE 5.

Evolution of sequentially conducted Bayes factors (SBFs) based on the complete sample ($N = 26$). Top panels illustrate the evidential flow against the presence of an effect of location uncertainty × prime-target congruency in the invisible (Panel A) and the visible condition (Panel B). Bottom panels show the evidence for an effect of prime-target congruency in the visible condition (Panel C) and the evolution of BFs against the presence of an effect for congruency priming in the visible condition, after the exclusion of prime-target pairs 1-4 and 9-6 (Panel D). Figure generated with the JASP software.

consistent across participants, and we obtained a final BF+0 of 66.59, indicating that the data were 67 times more likely under H1 than H0 (very strong evidence for H1; $t[25] = 3.71$, $p < .001$). Figure 5, Panel D shows the sequential BFs for this analysis. In the second approach, all 16 prime-target pairs in our experimental design were assigned to a conflict condition (six prime-target pairs: 1–2, 1–4, 3–4, 7–6, 9–6, and 9–8), and a no conflict condition (10 prime-target pairs: 1–6, 1–8, 3–2, 3–6, 3–8, 7–2, 7–4, 7–8, 9–2, and 9–4). Within the conflict condition, we further differentiated between prime-target pairs with either small or large numerical distances (small: 1–2, 3–4, 7–6, and 9–8; large: 1–4 and 9–6). In a new variable, we coded the no-conflict condition as 0, and the small and large conflict conditions as 1 and 2, respectively.

Based on previous work, we calculated Bayesian linear mixed-effects models (LMMs), including participants and the target stimuli as random intercepts (Moors & Hesselmann, 2018). Prime-target congruency and response conflict were included as fixed factors. We used the *generalTestBF* function from the *BayesFactor* package (version 0.9.12-4.2; richarddmorey.github.io/BayesFactor/) with default prior settings. We extracted the model with the highest BF compared to an empty model (i.e., an intercept-only model) and considered this to be the model that best predicted the data (referred to as "best fitting model"). We then recalculated all BFs such that they were compared to this best fitting model. Table 2 shows an overview of the best model (BF = 1) for no CFS and CFS-masked trials, and how strongly the data support the predictions made by this model compared to all other models. Models were assumed to be equally plausible a priori, so that BFs are equal to the posterior odds. Therefore, BFs greater than 1 indicate how much more the data are consistent with this best fitting model compared to the model under consideration.

In no CFS (visible) trials, the best fitting model included participants and the target (probe) stimulus as random intercepts, and prime-target congruency as main effect. This model was only weakly (BF = 1.3) favored over a model that additionally included response conflict as main effect, thus suggesting a joint contribution of both factors. The best fitting model was preferred 3.9 times over a model also including the interaction between the main effects. Furthermore, a model including only random intercepts was 9.1 times less likely than the best fitting model. For all other models (e.g., a model with a main effect of response conflict only), the best fitting model was more than 100 more likely (i.e., BFs > 100). In CFS-masked trials, the best fitting model included only participants and the target stimulus as random intercepts. The best fitting model was preferred 5 times over a model also including prime-target congruency as main effect, thus suggesting an absence of priming effects in trials with perceptually suppressed prime stimuli.

TABLE 2.

Bayes Factor (BF) Analysis Using Participants and Target Stimuli as Random Intercepts, and Prime-Target Congruency and Response-Conflict as Fixed Factors

No-CFS trials (visible)	BF	Error
congruency + subj + probe	1	0
congruency + conflict + subj + probe	1.309389	0.0267657
congruency + conflict + congruency*conflict + subj + probe	3.933456	0.0443864
subj + probe	9.138548	0.0229350
All other models	>100	NA
CFS-masked trials		
subj + probe	1	0
congruency + subj + probe	4.974977	0.0202789
All other models	>100	NA

Note. subjs = participants; probe = target stimuli; congruency = prime-target congruency; conflict = response conflict. All reported BFs are calculated with the best fitting model in the numerator (the model for which BF = 1, top row), separately for no-CFS and CFS-masked trials. An asterisk indicates that both the main effects and the interaction between the variables were incorporated in the model.

DISCUSSION

Our aim was to investigate the influence of location uncertainty of prime stimuli on unconscious semantic processing under CFS. Our hypothesis was that in the location uncertain condition, RTs for congruent trials (prime and target smaller or larger than five) should be faster than for incongruent trials, suggesting that diverted attention due to location uncertainty attenuates interocular suppression, and hence, semantic information can be processed unconsciously. We expected this difference between incongruent versus congruent trials to be smaller (or absent) in the location certain condition.

Our data did not provide evidence for the predicted effect of location uncertainty on unconscious semantic processing. The final Bayes factor showed moderate evidence for the null hypothesis. Thus, our results do not support the modulation-by-attention model by Eo et al. (2016). There may be several different reasons why our experiment did not reveal the predicted effect.

Modulation of Attentional Focus

The modulation of the attentional focus may have failed. Specifically, the presented asterisks (intended to modulate the attentional focus) were irrelevant for the required number comparison task, as the participants were instructed to only respond to the centrally presented target number ("compare target to five"). Thus, it is possible that instead of diverting the attention toward the two different possible prime locations in the location uncertain condition, participants held their attention fixed to the center, or their attention switched back to the center unintentionally. Another influencing factor may have been the eccentricity of the primes from the center. As it was only 1.8 ° it may have been too small to divert the attentional focus from the center. Furthermore, irrespective of the condition, each trial started with a centered fixation cross. In the location uncertain condition, this might have contradicted the instruction to point the attention toward the two asterisks. As a result, inattention toward the prime may not have been achieved and, following Eo et al.'s (2016) model, the processing of semantic information of the prime number was not possible due to enhanced interocular suppression. Follow-up studies could test whether the predicted effect emerges in a spatial cueing paradigm, as in Eo et al. (2016). Finally, in our experimental design, location certainty (and thus the locus of attention) was confounded with location of the prime (central vs. peripheral). The central prime was always the certain prime, and the peripheral primes were the uncertain ones. Therefore, it cannot be excluded that these two factors (location certainty and absolute prime position) will cancel each other out. This confound needs to be addressed and avoided in follow-up studies.

Priming Effects with Visible Primes

One could argue that a precondition for an effect of location uncertainty on unconscious processing would have been to find convincing and robust evidence for priming effects in the visible conditions. However, analyzing the data according to the congruency priming modelresulted only in anecdotal evidence in favor of this model. Nevertheless, RT differences were in the expected direction. We conclude that priming effects in our study were so small that they could not be detected based on our sample size.

Too Low Prime Contrasts

One could argue that the suppression of the prime stimuli by the CFS masks was too strong, or that the prime contrasts were set too low, and this is why participants could not process the semantic information of the prime stimuli. In our study, we adjusted prime contrasts individually for each participant, and thus ensured that the stimulus contrast was as high as possible to still be judged invisible, and as low as needed for CFS to operate. Furthermore, the results of the awareness check prove that prime contrasts were not too low. The accuracy in the number comparison task for the visible primes indicates that participants were able to correctly distinguish the centered as well as the peripherally presented primes at the set contrasts. The distribution of PAS visibility ratings suggests that the suppression by CFS operated in the intended way. The discrimination performance for the prime stimuli was even above chance level in all CFS conditions. On the contrary, this observation suggests that complete unawareness of the primes was not reached. If anything, prime stimuli may have been processed at least partly consciously, which may have given rise to other effects interfering with priming effects.

The Importance of Stimulus Onset Asynchrony

In our experimental design, prime stimuli were presented for 200 ms during the CFS-masks prior to the target stimuli that were displayed immediately after the prime and CFS masks disappeared. Therefore, the stimulus onset asynchrony (SOA), namely, the time between the onset of the prime and the onset of the target, was 200 ms. The study by Dehaene et al. (1998) found priming effects for numerical primes similar to the ones used here, but using a SOA of about 114 ms. A SOA of 200 ms as in our study therefore might simply be too long to allow priming effects to occur. This could be explained by an unconscious "overstimulation cost" as reported by Barbot and Kouider (2012). They found that when primes were displayed for a much longer duration (1000 ms) during CFS, the priming effect was reversed and the primes did not facilitate responses to the subsequent target. In contrast, for short prime durations (60 ms), the typical response facilitation occurred. However, in addition to the SOA, one must also take into account the grade of the primes' visibility, and the level of suppression achieved, respectively. There is evidence that priming effects of completely invisible prime stimuli are not influenced by SOA durations that were similar to the one in our study (94, 188, and 282 ms; Koivisto & Grassini, 2018). However, when primes were not completely suppressed and hence, partly consciously available, priming effects were reduced. As we stated before, the results of the awareness check indicate that complete unawareness of the prime stimuli was not reached. Therefore, it might be that primes were at least partly consciously processed which, interfered with or inhibited the response to the target at the SOA duration of 200 ms. This could be one reason why we did not find the typical priming effect consisting of facilitated responses to congruent compared to incongruent trials. Nevertheless, RT means in our study were within the range of RTs in comparable studies (~ 480 ms; e.g., Dehaene et al., 1998).

The Absence of Online Prime Visibility Ratings

Another reason for the lack of priming effects in our study may lie in the chosen procedure of visibility ratings. There are two common ways to measure the visibility of stimuli. Online ratings include trial-by-trial visibility ratings regarding the prime in the main experiment. In contrast, offline ratings measure the visibility in an additional experiment, as we did in the awareness check. For our experimental design, we decided not to include online visibility ratings, as these trial-by-trial ratings are associated with dual-tasking costs which might interfere with priming effects (Schmidt et al., 2011). Previous research has found priming effects for visible and invisible primes when primes are not linked to a visibility rating task (Dehaene et al., 1998; Hesselmann et al., 2018). In contrast, one masked priming study using meta-contrast masking found larger response priming effects when online prime visibility ratings were provided than when they were not provided (Peremen & Lamy, 2014). The authors argue that the prime stimulus is attended in case of trial-by-trial visibility ratings but not sufficiently attended when the only task is to respond to the target. Therefore, one can speculate that the absence of online prime visibility ratings in our experimental design resulted in less prime-directed attention and, consequently, in the reduction of priming effects to the degree that priming effects could no longer be detected. A possible follow-up study involving trial-by-trial visibility ratings in addition to offline awareness checks could investigate this further. However, it remains debatable if online visibility ratings providing more prime directed attention may interfere with the former goal of this study to achieve inattention toward the prime due to location uncertainty, and thus, allow its processing under CFS by attenuating the interocular suppression mechanism.

The Conflict Hypothesis

In addition to our confirmatory analyses, we explored an alternative conflict hypothesis in an additional exploratory analysis because several participants reported a response conflict concerning the target-prime relation and the required number comparison task ("compare target to five") that we had not anticipated. Their subjective impression was that whenever the target was larger than the prime but smaller than five, or when the target was smaller than the prime but larger than five, the required response to the number comparison task took them more effort. In other words, whenever the prime-target sequence was ascending ("getting larger") or when the prime-target sequence was descending ("getting smaller"), the opposite response in the number comparison task (i.e., "smaller than five" or "larger than five") was experienced as more effortful. The results of the exploratory analysis show that our data did reflect the subjective extra effort indexed by slower RTs. We speculate that other cognitive processes underlying numerical judgments were activated by the presented prime-target pairs, and interfered with priming effects in our experiment (Turconi et al., 2006).

According to the triple code model (Dehaene, 1992) numbers are located on a mental numerical magnitude dimension that represents an ascending order of numbers from left to right. The processing of numbers is automatically related to this dimension as shown by the distance effect (e.g., Moyer & Landauer, 1967). The distance effect refers to the observation that in comparison tasks in which, for example, two numbers are compared, RTs decrease as the distance between the two compared numbers increases. In other words, RTs for far numbers with a larger distance on the mental number representation are faster than for close or adjacent numbers on this representation. This effect suggests that number pairs with large distances may produce numerical vectors with a stronger cognitive impact than number pairs with small distances. In our case, the ascending prime-target pair 1–4 may have produced a vector activating the ascending order and larger numbers on the right side of the mental number representation, and the descending prime-target pair 9–6 may have produced a vector activating the descending order and smaller numbers. As the distance for both pairs is 3, the numerical vector would be stronger than for the other conflicting prime-target pairs (distance of 1). Instead of the typical distance effect with faster RTs for far numbers, we speculate that in our study, these two large distance prime-target pairs produced a strong response conflict between the target-prime relation and the number comparison task. This could be interpreted as a reverse distance effect, as shown in the study by Turconi et al. (2006) for order-related tasks. In sum, we tentatively conclude that other cognitive processes such as order-dependent and distance-related processes interfered with the number comparison task in our experiment, and thus, strong priming effects did not occur.

Sequential Bayes Factors

The sequentially computed Bayes factors allowed us to monitor the evidential flow regarding our hypotheses as the data came in, and to stop data collection whenever this was deemed desirable or necessary (Wagenmakers et al., 2016). In our study, it was necessary to stop data collection due to time limitations, even though we did not reach our predetermined level of evidence. The visual inspection of our plots revealed that for some tests, the SBFs were rather uneven, and thus did not provide conclusive evidence, even when approaching the final number of participants (see Figure 5, Panel C). In essence, this means that adding or leaving out the last participant can decide whether the final BF is close to 1 or close to 3. Optimally, this unsatisfactory situation can be overcome by adding more participants, or alternatively, by increasing measurement precision, for example, by adding more trials to the experimental design (Smith & Little, 2018).

Limitations and Further Research

First, the awareness check indicates that CFS sufficiently suppressed the prime in the way that participants reported almost full invisibility. However, full objective unawareness of the primes was not achieved. Follow-up studies should ensure that prime stimuli are fully suppressed from consciousness, for example, by adjusting the prime contrast more carefully or readjusting it during the main experiment. Second, our experimental design seemingly did not allow robust priming effects to occur. We suggest that follow-up research should better control for potentially interfering cognitive processes that may inhibit or reduce number priming effects and address confounds in the experimental design (see above). Moreover, trial-by-trial online visibility ratings could be included and compared to conditions without online ratings. The chosen SOA should vary in different conditions to investigate if priming occurs under different SOAs. With respect to the applied statistical methods, we conclude that the SBF design was useful as we could interpret our "null" findings as moderate evidence for the null hypothesis.

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