Methods for Investigating Unconscious Visual Motion Processing Based on Camouflage Principles

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Abstract

This study proposes a novel Continuous Flash Suppression (CFS) paradigm that employs the principle of alpha blending to maintain real-time color consistency between the target stimulus and the masking stimulus at corresponding locations. Eight subjects were randomly recruited and presented with a Mondrian image sequence to their dominant eye and multiple squares moving at a fixed velocity to their non-dominant eye. The results indicate that this paradigm remains effective for masking dynamic stimuli composed of multiple moving points, with optimal masking achieved when the colors of the target and masking stimuli are perfectly matched at corresponding locations. This demonstrates that the novel paradigm offers superior masking effects for dynamic stimuli compared to traditional CFS paradigms. Unlike previous approaches that modified CFS masking stimuli, this paradigm provides a new methodology for studying unconscious visual motion processing with greater generalizability.

Full Text

Abstract

This study introduces a novel continuous flash suppression (CFS) paradigm based on the principle of camouflage. By leveraging alpha blending, we ensured that the color of target stimuli remained perfectly matched with the corresponding regions of the mask stimuli at all times. Eight participants were randomly recruited and presented with Mondrian image sequences to their dominant eye while multiple squares moving at a constant rate were presented to their non-dominant eye. The results demonstrated that this paradigm maintains effective masking even when the target consists of multiple dynamic moving points. Masking was most effective when the target stimulus color perfectly matched the corresponding mask stimulus color, proving that this new paradigm provides superior masking for dynamic stimuli compared to traditional CFS. Unlike previous approaches that modified the CFS mask itself, this paradigm offers a new method for studying unconscious visual motion processing with broader applicability.

Keywords: continuous flash suppression, unconscious processing, motion, camouflage, alpha blending
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Introduction

Vision is one of the most important human senses, enabling perception of object size, brightness, color, and motion—information critical for survival. In most vision research, stimuli are presented consciously. However, the visual system' s capacity is limited, and not all stimuli enter awareness. To investigate visual stimuli that fail to reach consciousness, researchers have developed several methods for studying unconscious visual perception (Kim & Blake, 2005). One widely used technique is continuous flash suppression (CFS) (Tsuchiya & Koch, 2005).

In classic CFS paradigms, one eye receives rapidly presented, high-contrast images composed of random colored patches (such as Mondrian patterns, see [Figure 1: see original paper]), which serve as mask stimuli. Simultaneously, the other eye receives a static target stimulus. Because the target is suppressed by the mask, observers typically remain unaware of it for several seconds, allowing only unconscious-level visual processing (Tsuchiya & Koch, 2005; Faivre et al., 2014). As the masking effect gradually weakens, the target stimulus eventually breaks through suppression and becomes visible—a phenomenon known as breakthrough.

Previous studies have employed CFS to investigate numerous aspects of unconscious visual processing. For example, several researchers have used face images with different features or valences as target stimuli to explore unconscious face processing. Jiang et al. (2007) used upright and inverted faces and found that upright faces broke through suppression faster than inverted faces. Yang et al. (2007) employed upright and inverted faces with fearful, neutral, and happy expressions, replicating this result while additionally demonstrating that fearful faces consistently broke through faster than neutral or happy faces, even when only eye regions were presented rather than full faces. Capitao et al. (2014) used threatening, positive, and neutral faces and found that anxious patients showed easier breakthrough of threatening faces during CFS. Other researchers have used words as target stimuli to investigate whether semantic processing can occur unconsciously. Jiang et al. (2007) presented Chinese and Hebrew words, finding faster breakthrough for native language words. Heyman and Moors (2014) used English words and pseudowords, finding no significant difference in breakthrough times. Lang et al. (2018) presented paired Chinese words and asked participants to judge their relatedness during CFS, concluding that semantic processing cannot occur unconsciously. Additionally, Moors et al. (2016) used CFS to explore whether Gestalt principles of completeness and closure persist under unconscious conditions.

While CFS has been widely applied, researchers have continuously modified the paradigm to suit their specific research questions. Korisky et al. (2018) transformed the traditional two-dimensional target stimuli into three-dimensional, real-world objects, demonstrating that such objects can also be masked in CFS paradigms for unconscious visual processing. Cha et al. (2019) replaced meaningless Mondrian sequences with normal, dotted, and scrambled object and scene images as masks, finding that object-based CFS masks produced stronger suppression than scene-based masks, and that dotted patterns were more effective than scrambled ones. Han et al. (2021) modified the dynamic Mondrian masks used in CFS by employing upright faces, inverted faces, and scrambled faces as dynamic masks, testing their suppression of face or grating targets presented to the other eye, and found that these novel mask types also produced strong suppression.

However, most CFS studies have used static target stimuli (or gratings that translate horizontally or rotate in place, e.g., Hong & Blake, 2009; Veto et al., 2018). Only Moors et al. (2014) investigated CFS masking when target stimuli undergo spatial displacement. They used a red circle translating in left-right, up-down, or 45-degree diagonal directions as the target, along with numerous squares of the same size as mask stimuli. Their mask presentation had two conditions: a "moving Mondrian mask" (MMM) where mask squares translated frame-by-frame in six random directions (ensuring one direction always matched the target' s motion), and a classic CFS condition where squares did not translate frame-by-frame but instead randomly changed position every 100 ms, as in traditional CFS. Their results showed that when MMM speed approximated target speed, MMM produced better masking for moving targets than classic CFS. This supports the general principle that masking effectiveness increases as mask and target attributes become more similar. However, Moors et al. (2014) did not address scenarios with multiple moving points or complex motion patterns, and their design fundamentally depended on incorporating target-like motion into the mask. How to overcome these limitations and better mask motion stimuli at the unconscious level requires further investigation.

The present study proposes a novel paradigm that combines classic CFS masks with a special target presentation method to examine whether this improved CFS paradigm provides better masking for multi-point moving targets than classic CFS alone. Numerous studies have demonstrated that CFS masking improves as mask and target attributes become more similar (Han et al., 2021; Mei et al., 2015; Moors et al., 2014; Stein et al., 2011; Valuch, 2021). Therefore, we exploited the camouflage principle by manipulating color consistency between target and mask stimuli to test whether higher color consistency enhances CFS masking. Like chameleons that camouflage themselves by matching their coloration to the complex environment, making them less detectable to predators or prey, we named this the “chameleon” paradigm. We predicted that when target and mask colors are perfectly matched, participants would find it more difficult to break through CFS suppression. Because this camouflage approach does not modify the CFS mask to incorporate target motion information but instead relies on color attributes independent of motion, it ensures that the consciously perceived CFS mask contains no motion information that could reveal the target’ s movement. This represents a key advantage of our method.

Experiment 1: The Chameleon Paradigm

2.1 Participants

We used G*Power to calculate the required sample size, which indicated that at least 7 participants were needed to detect a medium effect size (f = 0.40, α = 0.05, power = 0.95) in a repeated-measures ANOVA (Faul et al., 2007). We randomly recruited 8 participants from several universities in Beijing, China (4 male, 4 female). Participants ranged in age from 21 to 26 years (M = 23, SD = 1.66). All had normal or corrected-to-normal vision, no color blindness or weakness, and no prior experience with similar experiments. Informed consent was obtained from all participants before the experiment.

2.2 Apparatus

The experiment was conducted using a 27.2-inch ASUS VG278HE monitor (1920$×1080*pixels*; *refreshrate* : 120*Hz*; *gamma*−*corrected*; *meanluminance* : 40*cd*/*m*^{2}$) calibrated with a Photo Research PR-655 spectroradiometer. The screen background was gray (RGB: 128, 128, 128) with a red central fixation point. We used the NVIDIA 3D Vision 2 system, comprising an NVIDIA GPU supporting 3D stereo technology, a certified display, active shutter glasses (NVIDIA 3D Vision 2 P1431), an infrared emitter, Windows operating system, NVIDIA 3D stereo drivers, and applications supporting quad-buffered OpenGL stereo. Participants viewed the screen through active shutter glasses to ensure distinct visual input to each eye.

2.3 Stimuli

Stimuli were generated using PsychToolbox-3 (Brainard, 1997) in MATLAB (The MathWorks, Natick, MA). Visual stimuli consisted of two components: CFS masks and target stimuli. The CFS masks comprised 60 Mondrian-patterned images created by drawing rectangles of random colors and sizes (8°$×8°, *flickeringat*10*Hz*).*Colorandcolorspacedatafortherectanglesareprovidedin*.*Targetstimuliweretens*
presented in each frame, categorized into four conditions based on color consistency with the mask.

The positions of the ten squares were randomly selected to ensure they fell within the area corresponding to the CFS stimulus (8°$×$8°) and did not overlap with each other. All ten squares moved upward or downward at a constant velocity of 12 pixels/second. After moving for one second, the positions of the ten squares were refreshed, with new squares appearing at different locations and continuing to move in the same direction at the same speed. During the experiment, target stimuli were presented for a maximum of ten seconds (with ten position updates). Among the four target conditions, Condition 1 was our primary experimental condition, while the other three served as control conditions. Specific descriptions follow:

Condition 1: In each frame, the color of the ten moving squares perfectly matched the pixel colors of the CFS stimulus presented to the dominant eye in the corresponding regions. **Condition 2:** In each frame, the color of the ten moving squares did not match the pixel colors of the CFS stimulus in the corresponding regions. **Condition 3:** In each frame, the color of the ten moving squares matched the pixel colors of the *first* frame of the CFS stimulus presented to the dominant eye. **Condition 4:** In each frame, five of the ten squares were pure black (RGB: 0, 0, 0) and five were pure white (RGB: 255, 255, 255).

Conditions 1-3 were created using alpha blending. In Condition 1, each frame' s image was an RGBA matrix where the RGB layers contained the CFS image, while the alpha layer defined the positions of the ten squares. Alpha values were 255 within square regions and 0 elsewhere. This rendered target stimuli as ten squares, each filled with the pixel colors from the corresponding CFS locations, with a gray background outside the squares. Condition 2 differed in that the RGB layers contained *different* pre-generated CFS images, making target square colors mismatched with the corresponding CFS regions. Condition 3 used the RGB layers from the *first* CFS frame of that trial. Thus, only Condition 1 maintained perfect color consistency between target and CFS stimuli at all times. Compared to Condition 1, Condition 2 preserved flicker but lacked color consistency. Condition 3 eliminated flicker while maintaining colors from the first CFS frame. Condition 4 eliminated both flicker and color variation. In all conditions, the contrast between mask and target stimuli remained constant at 100%.

2.4 Procedure

The experiment was conducted in a dark room. Participants sat directly in front of the screen with their head positioned in a chin rest to maintain a viewing distance of approximately 90 cm. First, participants completed a pre-test to assess eye dominance. The pre-test environment and equipment matched the formal experiment, with stimulus procedures adapted from Dong et al. (2022). We randomly selected one eye to present CFS stimuli (identical to the formal experiment) while presenting a weak target stimulus to the other eye—a black square (1.2°$×1.2°)withaninternalblackbar(0.4°×4pixels)atthescreencenter.Participantswereinstructedtoreportthe
" ↑ "key; down : " ↓ "key; left : "←"key; right : "→$" key) upon detecting the black square.

The pre-test comprised 3 blocks of 80 trials each. Target presentation eye (left vs. right) and black bar position (up, down, left, right) were balanced and randomly ordered across trials. Each trial began with an 800 ms red fixation point presented alone, followed by CFS stimulation for a variable duration (100, 200, 300, or 400 ms) to one eye while the other eye viewed only the fixation point. The target stimulus was then presented to the other eye, during which participants could respond. Upon keypress, the target disappeared and CFS stimulation continued for 600 ms before the trial ended. If no response occurred, the target disappeared after 2 s and CFS continued for 600 ms (see [Figure 1: see original paper]). We recorded correct responses to calculate breakthrough rates for each eye, designating the eye with the higher rate as dominant. The pre-test lasted approximately 15 minutes.

Based on pre-test results, we presented CFS stimuli to the dominant eye and target stimuli to the non-dominant eye. If eye dominance could not be determined, the target presentation eye was selected randomly. Before the formal experiment, the experimenter explained the procedure in detail and participants practiced several trials to ensure complete understanding. The formal experiment comprised 14 blocks of 16 trials each (4 trials per condition), with upward and downward motion balanced (2 trials each). Each trial began with 500 ms or 1500 ms of CFS pre-exposure to the dominant eye, followed by the response task. During this phase, CFS was presented to the dominant eye while one of the four target conditions moved upward or downward in the non-dominant eye. Participants reported the motion direction (up: "↑" key; down: "↓" key) upon detecting the targets, and we recorded response accuracy and reaction time. If participants responded (correct response = breakthrough; incorrect = no breakthrough), the target disappeared and CFS continued for 500 ms before both stimuli vanished. If no response occurred (no breakthrough), both stimuli disappeared after 10 s. A 1 s gray background was presented between trials regardless of response. After each trial, the message "Take a break! You have N blocks remaining. Press 'space' to continue." appeared, allowing participants to rest before proceeding. The formal experiment lasted approximately 35 minutes.

2.5 Data Analysis

This study employed a within-subjects design. The independent variables were the four target conditions and four time periods (blocks grouped into quarters). The dependent variable was breakthrough rate, defined as the percentage of trials where participants overcame interocular suppression and transitioned the target from unconscious to conscious processing. The first two blocks were excluded from analysis to avoid instability at the experiment's onset; only the final 12 blocks were analyzed. Our analysis proceeded as follows: First, we calculated each participant' s breakthrough rate per condition and divided the 12 analyzed blocks into four groups to examine trends across the experiment. Second, we conducted a 4 (Condition: 1 vs. 2 vs. 3 vs. 4) × 4 (Block Group: 1 vs. 2 vs. 3 vs. 4) repeated-measures ANOVA on breakthrough rates to assess significant differences across conditions and time. Finally, we report mean reaction times for breakthrough trials in each condition.

Results

3.1 Breakthrough Rate Trends

Only the final 12 blocks were analyzed, divided into four groups of three blocks each. We calculated mean breakthrough rates for each group and condition, plotting these trends. Individual participant trends are shown in [Figure 3: see original paper], revealing that most participants exhibited substantially lower breakthrough rates in Condition 1 than in the other three conditions, which showed minimal differences. The grand average breakthrough rate trend is displayed in [Figure 4: see original paper], confirming that Condition 1’ s breakthrough rate remained markedly lower throughout the experiment, while the other three conditions showed no substantial differences.

3.2 Repeated Measures ANOVA Results

A two-factor repeated-measures ANOVA on breakthrough rates revealed a significant main effect of Condition (F(1, 1.201) = 32.38, $p < 0.001$, $^{2} = 0.82$, Greenhouse-Geisser corrected), a non-significant main effect of Block Group (F(1, 3) = 1.62, p = 0.215, $^{2} = 0.19$), and a non-significant interaction (F(1, 3.038) = 0.72, p = 0.552, $^{2} = 0.09$, Greenhouse-Geisser corrected). These results align with our hypothesis that target condition differences produce significant breakthrough rate variations.

Given the significant main effect of Condition, we conducted post-hoc comparisons. Condition 1’ s breakthrough rate (0.26 ± 0.11) was significantly lower than all other conditions (Condition 1 vs. 2: p = 0.008, 95% CI [-1.011, -0.176]; Condition 1 vs. 3: p = 0.002, 95% CI [-1.063, -0.307]; Condition 1 vs. 4: p = 0.003, 95% CI [-1.053, -0.254]). No significant differences emerged among the three control conditions (Condition 2 (0.85 ± 0.08) vs. 3 (0.94 ± 0.04): p = 0.417, 95% CI [-0.246, 0.064]; Condition 2 vs. 4 (0.91 ± 0.06): p = 0.057, 95% CI [-1.121, 0.002]; Condition 3 vs. 4: p = 1.000, 95% CI [-0.135, 0.073]).

3.3 Breakthrough Trial Reaction Time Results

[Figure 5: see original paper] displays mean reaction times for breakthrough trials per participant across conditions. It is important to note that reaction time is not an ideal measure in this study because each trial had a 10 s time limit and terminated automatically regardless of breakthrough. Had we extended the limit to 1 minute or until response, Condition 1’ s mean reaction time would likely far exceed its current value, possibly surpassing 10 s. We therefore do not treat reaction time as a reliable indicator. We avoided an “until-response” design because pilot testing revealed Condition 1’s exceptionally strong masking effect, raising concerns that some participants might experience intolerably long total experiment durations. Nevertheless, [Figure 5: see original paper] shows that even among breakthrough trials, most participants exhibited the longest reaction times in Condition 1, further corroborating our findings that higher target-mask color consistency makes breakthrough more difficult.

Supplementary Experiment: Unconscious Motion Processing

4.1 Purpose

The results demonstrate that the "chameleon"paradigm effectively masks moving targets. To validate its application in unconscious motion processing research, we conducted a supplementary experiment to test whether motion information from masked targets can be processed by the brain. We compared masking effectiveness for targets with and without motion information in the "chameleon" paradigm. If moving targets break through suppression more readily than static targets, this would indicate that unconsciously processed motion information facilitates breakthrough, confirming that the brain can process motion information under masking.

4.2 Participants

To ensure sufficient breakthrough trials for comparison, we selected two participants from the original experiment (one male, one female) who showed relatively high breakthrough rates in Condition 1 (Participants 2 and 4 in [Figure 3: see original paper]; Participant 1 also had high breakthrough but could not participate due to COVID-19). Informed consent was obtained and participants received compensation after completing the experiment.

4.3 Materials and Procedure

Materials and procedures mirrored the formal experiment with one modification: Condition 1 was split into two sub-conditions. The original Condition 1 trials were divided equally into a **Condition 1-motion** group (identical to the original: ten squares moving in the same direction each frame, with colors perfectly matching the CFS stimulus) and a **Condition 1-stationary** group (identical except the ten squares remained stationary each frame, eliminating motion information). All other conditions (2, 3, and 4) remained unchanged. In all conditions, mask-target contrast remained constant at 100%.

4.4 Data Analysis and Results

Data analysis followed the same procedure as the main experiment: analyzing the final 12 blocks divided into four groups to examine breakthrough rate trends. Results are shown in [Figure 6: see original paper]. Both participants exhibited the lowest breakthrough rates in Condition 1-stationary, significantly lower than in Condition 1-motion. Since motion information was the only difference between these conditions, the breakthrough rate difference must be attributed to motion processing. This indicates that unconscious processing of motion information "helped" participants break through the mask, confirming that motion information in the "chameleon" paradigm can be processed by the brain.

General Discussion

This study introduces a novel method—the "chameleon" paradigm—for maintaining multi-point moving targets at the unconscious level. We found that CFS masking remains effective for dynamic targets with multiple moving points, and that presenting dynamic targets with colors perfectly matched to the mask enhances suppression, enabling sustained unconscious processing of motion stimuli.

First, our results demonstrate that CFS effectively masks multi-point dynamic targets. Extending beyond Moors et al. (2014), who used single moving points, we generalized the approach to multiple moving points. Many motion perception studies involve multiple moving targets (e.g., optic flow, biological motion stimuli), so our findings further establish the applicability of CFS for investigating unconscious processing of motion stimuli.

Second, based on the camouflage principle, we found that CFS masking was significantly stronger when mask and target colors were perfectly matched versus mismatched. Both breakthrough rates and reaction times for breakthrough trials support this conclusion. Moors et al. (2014) similarly showed that greater similarity between mask and target features enhances masking. Valuch (2021) also demonstrated that color-matched mask-target pairs produce longer suppression than color-mismatched pairs. Numerous studies have established that the degree of feature matching between binocular stimuli critically affects masking duration—the more similar the CFS mask and target, the longer the suppression (e.g., Stein et al., 2011). However, these studies achieved better masking by modifying CFS mask features, an approach with inherent limitations. For instance, Moors et al. (2014) found that traditional CFS poorly masked moving stimuli, requiring incorporation of target-like motion information into the mask for effective suppression. This modified CFS may only suit simple, constant-velocity translation of a few targets; for multi-point or variable-velocity complex motion (e.g., biological motion), matching MMM mask direction and speed to the target becomes difficult or impossible. Similarly, Valuch (2021) improved masking by changing mask color to a uniform color matching the target, but complex targets would require correspondingly complex mask modifications to maintain effectiveness.

In contrast, our method uses classic CFS with unaltered mask features, instead modifying target appearance based on camouflage principles to maximize non-motion feature consistency (e.g., color) with the CFS mask. This approach easily masks complex moving targets and ensures the visual pathway receiving the CFS mask does not input the motion information researchers intend to suppress. If masks contain the motion information of interest, interpreting results becomes problematic: it would be unclear whether behavioral or neural signals reflect unconscious processing of the target' s motion or processing of motion information in the CFS mask itself. Our alpha blending method maintains shape and color consistency between target and mask while keeping their motion information completely independent, theoretically enabling effective masking of various motion target types. The supplementary experiment strongly supports the notion that the brain can process masked motion information. Therefore, compared to mask-modification approaches, our method offers greater potential for broad, flexible application in unconscious motion processing research.

Regarding target breakthrough, one might question whether it results from unconscious motion processing or simply from occasional binocular misalignment. We address this concern from two perspectives. First, unlike many CFS studies using stereoscopes, we employed NVIDIA 3D Vision 2 active shutter glasses (NVIDIA 3D Vision 2 P1431) for dichoptic presentation. A major advantage over stereoscopes is that these glasses effectively prevent binocular misalignment. They resemble ordinary eyewear, allowing participants to view the laboratory environment (natural lighting, not screen light) normally except for the stimulus region. This means that beyond the fused stimulus area, all visual input is viewed binocularly through the glasses. Based on everyday experience, wearing plano glasses does not cause binocular convergence problems. This explains a crucial difference: the visible environment scene objectively facilitates natural binocular convergence. Second, even if breakthrough were due to binocular misalignment, this cannot explain our supplementary experiment results. Conditions 1-motion and 1-stationary differed only in target motion. At any moment, the "chameleon" property ensures identical fusion difficulty for both conditions, so any binocular alignment issues should affect them similarly, predicting comparable breakthrough rates. However, Condition 1-motion showed higher breakthrough rates than Condition 1-stationary, consistent with unconscious motion processing facilitating breakthrough but difficult to explain by binocular misalignment alone. These considerations suggest that breakthrough likely results from unconscious motion processing rather than mere binocular misalignment.

Additionally, CFS paradigms are commonly used to study interocular suppression, with typical control methods superimposing target and mask stimuli for monocular presentation to ensure suppression differences arise from interocular mechanisms (Wang et al., 2012). We must note that this traditional control cannot validate our "chameleon" paradigm' s effectiveness via interocular suppression because target and mask colors are perfectly matched; monocular superposition would make them indistinguishable. However, our goal was to develop a paradigm for masking motion information to study unconscious motion processing, not to investigate the underlying mechanism. Interocular suppression is merely one necessary but insufficient condition for achieving unconscious processing; many methods such as crowding and backward masking also produce unconscious processing without involving interocular suppression. Given that CFS conveniently studies stimuli presented near central vision for extended durations, we chose to modify this common paradigm. We believe that as long as target motion information remains undetectable for a period, ensuring the "chameleon" paradigm enables unconscious motion processing, our goal is achieved. Whether interocular suppression plays a role requires future investigation.

In summary, this study validates CFS' s capacity to mask dynamic targets and, for the first time, examines how color consistency between mask and dynamic target affects CFS masking based on camouflage principles. Results demonstrate that higher color consistency produces stronger masking, with such dynamic targets rarely breaking through CFS within 10 s. Moreover, this modified CFS paradigm largely ensures that perceived motion information originates exclusively from the target. Thus, this study provides a preliminary reference for applying CFS to unconscious visual motion processing research.

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Note: Figure translations are in progress. See original paper for figures.