doi:10.20944/preprints202101.0347.v1

Article

Color modulates the timing of conscious perception via bottom-up and top-down attention

Christian Valuch

Department of Experimental Psychology, University of Goettingen, Germany
Correspondence: christian.valuch@psych.uni-goettingen.de

Abstract: Color can direct visual attention to specific locations through bottom-up and top-down mechanisms. Using Continuous Flash Suppression (CFS) as way to investigate the factors that gate access to consciousness, the current study investigated whether color also directly affected the timing of conscious perception. Low or high spatial frequency (SF) gratings with different orientations were shown as targets to the non-dominant eye of human participants. CFS patterns were presented at a rate of 10Hz to the dominant eye to delay conscious perception of the targets, and participants had the task to report the target's orientation as soon as they could see it. With low-SF targets, two types of color-based effects became evident. First, when the targets and the CFS patterns had different colors, the targets entered consciousness faster than in trials where the targets and CFS patterns had the same color. Second, when participants searched for a specific target color, targets that matched these search settings entered consciousness faster compared to conditions where the target color was irrelevant and could vary from trial to trial. Thus, the current study demonstrates that color is a central feature of human perception and leads to faster conscious perception of visual stimuli through bottom-up and top-down attentional mechanisms.

Keywords: interocular suppression; consciousness; color vision; visual search; attentional templates; early visual system; awareness; continuous flash suppression; binocular rivalry.

1. Introduction

1.1. Background

Color vision allows to distinguish different wavelengths within the visible light spectrum and is central to the human visual system. Color vision has probably evolved because the ability to discriminate colors provided critical survival benefits in foraging [1] and social [2] situations. Color also is a central feature for guiding selective visual attention [7,8]. Local color contrasts increase the bottom-up saliency of an object [3,5], which in turn directs spatial attention, resulting in prioritized neurocognitive processing of the attended information [4]. In everyday environments, local color contrasts are usually associated with interesting and often relevant objects which can grab attention in a bottom-up manner, such as red light or a stop sign at an intersection [4,5]. However, color can also be used for directing attention in a top-down way, such as when looking for friends in a crowd of people and expecting them to wear clothes of a particular color [7,8]. While it is well established that color is a powerful feature for guiding selective visual attention, it is not entirely clear through which mechanisms color affects how quickly an object is consciously perceived [9]. A traditional view of the relationship between attention and consciousness posits that attention acts as a 'gatekeeper for consciousness,' i.e., that the selection of a stimulus by attention precedes conscious perception. However, attention and consciousness are distinct processes that are not always aligned [11], which is why top-down attention does not necessarily entail conscious processing [9,10].

To investigate the factors involved in conscious perception and to understand which types of processing occur unconsciously, a range of perceptual suppression techniques has been developed to render stimuli temporarily invisible [12–14]. Continuous Flash

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 18 January 2021 doi:10.20944/preprints202101.0347.v1

Suppression (CFS) is a relatively new technique which provided numerous insights into the factors that influence consciousness [15–17]. CFS builds upon the binocular rivalry (BR) phenomenon that occurs when the same participant's left and right eye is presented with different, incompatible images [18–20]. Under such dichoptic conditions, conscious perception usually settles on one of these rival images while the other image remains invisible or unconscious due to interocular suppression. In classical BR, perception cycles through distinct phases of perceptual dominance of one or the other stimulus, with a perceptual switch usually occurring every few seconds [19,21]. CFS is a particular version of BR in which one is presented with a high-contrast pattern stimulus that is updated over time, often at a frequency of 10 Hz [17,20]. The other eye is presented with a relatively static and usually smaller target stimulus. The steep difference in stimulus strength between these two eyes' inputs ensures that the CFS pattern is always perceived at the beginning of each experimental trial [19], and it usually takes several seconds until the initially invisible target stimulus breaks through the suppression and enters consciousness [9,16].

1.2. The present study

The current study used CFS to investigate whether colors and color contrasts can accelerate conscious perception of a relevant target stimulus. The present study used a "breaking CFS" procedure, in which the *breakthrough time* measures the time it takes for an initially invisible stimulus to break CFS and become consciously accessible. Specifically, the present study investigated how breakthrough time is influenced by the color contrast between the relevant target stimuli and the CFS pattern on the one hand, and the participants' attentional tuning for a specific color on the other hand. To that end, the current study used oriented gratings as targets and asked participants to report the orientation as soon as they could consciously perceive it. The relevant targets were rendered in of two possible colors (cyan or yellow). Typical CFS pattern stimuli were used to suppress conscious perception of the targets. The (bottom-up) color contrast between the targets and the CFS patterns was manipulated by either using the same color for the target and the CFS pattern (resulting in a low color contrast), or the different color for the target and the CFS pattern (resulting in a high color contrast). To investigate whether color can also have top-down effects on conscious perception [9], the present study also manipulated the participants' task. In one block of experimental trials, participants performed a singleton search task, where color was irrelevant. Here, only one grating was presented in each trial, and the color of this target grating could change randomly from trial to trial. The time it took for the targets to break suppression was compared to another block of experimental trials, in which participants performed a color search task. In the color search task, participants were always presented with two gratings of different colors, and needed to report the grating with a specific task-relevant color.

The hypotheses for the different conditions in the present study were the following. First, suppose color leads to faster conscious perception via bottom-up feature salience. In that case, the breakthrough time should be shorter in trials in which the color of the target and the CFS pattern color were different (i.e., where the color contrast was high). Conversely, the breakthrough time should be longer in trials in which the targets and CFS patterns had the same color (i.e., where the color contrast was low). Second, suppose a specific color is relevant for solving the task, and participants can focus their attentional resources on this relevant color to bring matching stimuli into consciousness faster (as invited in the color search condition of the present experiment). In that case, stimuli matching this attentional set should enter consciousness faster in the color search condition than in the singleton search condition where color where participants did not search for a specific color. The design of the present study also allowed to test if color saliency still plays a role for conscious perception despite the specific attentional tuning instantiated by the color search task. In that case, the breakthrough time in trials in which the targets and the CFS patterns had the same color should still be longer than in trials in which the targets and CFS patterns had different colors. Moreover, it allowed investigating whether stimuli that match specific attentional search settings are prioritized for conscious perception, which should be reflected in a shortened breakthrough time under color search conditions compared to singleton search conditions.

To verify whether any color-related effects are indeed related to faster conscious perception of a stimulus rather than merely attentional processing *after* the target entered consciousness, the present study also manipulated the effectiveness of the CFS method. Previous research demonstrated that CFS could strongly and robustly suppress gratings with a relatively low spatial frequency (SF) [22,23]. In contrast, gratings with a higher spatial frequency usually remain relatively unperturbed by CFS. With the low-spatial frequency (LSF) gratings, CFS can thus be used to test whether factors related to color can reliably accelerate or delay conscious perception of a stimulus. Conversely, the perception of high spatial frequency (HSF) gratings is barely affected by CFS. Therefore, the present study used LSF gratings as the main experimental conditions to test for the modulation of conscious perception by color and HSF gratings as control conditions to check if any color-related effects occured independently of whether the gratings are robustly suppressed from perception. If color-related benefits would be similar in the LSF and HSF conditions, the attentional benefits through color would probably be operating at a level after the stimuli became consciously accessible. If, on the other hand, the color-related benefits were more pronounced in the LSF condition, this would mean that the bottom-up and top-down attentional effects precede the stage of conscious perception and directly influence the timing of conscious perception of the relevant target stimulus.

2. Materials and Methods

2.1. Participants

A total of 40 students from Goettingen participated in return for partial course credit or financial compensation. All participants were pre-screened for intact or fully-corrected visual acuity and color perception, as well as their ability to fuse the frames of the dichoptic stimuli into one stable percept, when viewed through the mirror stereoscope. Any recruited participant who failed in one of these initial screening tests was excluded from participant in the experiment.

2.2. Apparatus

Visual stimuli were presented on a 22-in. color CRT monitor (ViewSonic PF817). The screen resolution was set to 1024 × 768 pixels with a vertical refresh rate of 140 Hz. The viewing distance was fixed at 57 cm by means of a chin and forehead support, on which a mirror stereoscope was mounted. Dichoptic stimulation was realized by presenting different stimuli side-by-side at peripheral screen locations and viewing the screen through the stereoscope such that each of the rivalrous stimuli was delivered to one eye only. Participants reported the target stimuli manually using the left and right "control" keys on a standard USB keyboard. The experiment was implemented using the software Presentation (Neurobehavioral Systems, Berkeley, CA) and run under Windows 7 on a PC with an Intel Core i7 2600 CPU and 16 GB of RAM. The luminance of the colored stimuli was measured using a PR-524 LiteMate photometer (Photo Research Inc., Chatsworth, CA) to ensure that the two alternative colors (cyan vs. yellow) were isoluminant.

2.3. Stimuli

Dichoptic stimuli were displayed on a neutral gray background (27.7 cd/m²) within circular apertures with a diameter of 9° to facilitate stable vergence. The apertures had a 1/f noise pattern at their outer border, which extended about 2° into the center, where it smoothly faded into the gray background. Screen areas outside the circular apertures

doi:10.20944/preprints202101.0347.v1

were set to black (0.1 cd/m²). A red fixation oval with a diameter of 0.5° and a small black dot (0.1°) in the center were presented throughout the experiment as a fixation point. The participants were instructed to fixate on this dot with their eyes throughout the experiment.

The target stimuli were colored sinusoidal gratings covering a square region of 2°, that were masked with a circular Gaussian window (*SD* = 0.25°). The targets were always presented to the non-dominant eye at a center-to-center distance of 1.5° above or below the central fixation point. Targets varied in color (cyan vs. yellow), orientation (45° left- or right-tilted) and spatial frequency (2 vs. 4 cycles per degree; cpd). The high SF gratings of 4 cpd served as a control condition, in which the effect of CFS should be minimal, whereas strong suppression effects were expected for the low SF of 2 cpd [22]. The maximum contrast of the targets was set to 30% to ensure robust suppression effects.

Conscious perception of the targets was delayed by presenting a high-contrast CFS pattern to the participants' dominant eye, which was updated at a rate of 10 Hz. A set of CFS patterns was pre-generated using MATLAB (MathWorks, Natick, MA) to standardize the visual properties of the different CFS patterns. The CFS patterns consisted of randomly arranged and partly overlapping filled circles, with diameters ranging from 0.5° to 1.7° and different gray and color values. A goal characteristic of the CFS patterns was that about half of all pixels in each mask should have one of three gray values (dark gray: 6.1 cd/m²; medium gray: 27.7 cd/m², light gray: 67.3 cd/m²), whereas the other half of all pixels should have one of the color values (yellow with RGB values of 250/227/60 and a luminance of 100.0 cd/² and cyan with RGB values of 72/255/255 and a luminance of 100.1 cd/m²). From a large number of randomly generated CFS patterns, 100 patterns were selected that fulfilled these criteria most closely. Two versions of each pre-selected CFS pattern were generated (one for each target color). This minimized the possibility that CFS patterns could be more effective in one of the conditions due to a particular spatial configuration of the elements of the patterns.

2.4. *Procedure and design*

At the beginning of each experimental session, the stereoscope was calibrated for each participant to achieve stable binocular fusion and it was verified that each eye's stimulus frame was fully visible through the respective mirror's field of view. Before starting the experiment, participants underwent a brief screening procedure to determine their sensory eye dominance [17,24].

2.4.1. Trial procedure

During the experiment, CFS masks were always presented to the dominant eye, whereas targets were presented to the non-dominant eye (see Figure 1). Each trial of the main experiment started with the presentations of CFS masks to the dominant eye at a rate of 10 Hz. The onset of the targets occurred at 0.5 s into the trial. Target contrast increased from 0 to 30% over a period of 1 s and remained constant at 30% until the trial ended. This contrast ramp was implemented to avoid abrupt onsets of the target, which might capture attention and break suppression instantly. Participants were instructed to report the orientation of the targets as soon as possible. If participants did not respond before 5 s into the trial, the contrast of the CFS masks decreased to zero over the next 3 s. This allowed all participants to eventually recognize the target, which otherwise might not be the case, as individual differences in interocular suppression are rather large and suppression could last longer than the maximum trial duration for some participants [17,21]. After reaching the lowest contrast level, the CFS patterns were factually invisible so that only the medium gray stimulus background was presented to the participant's dominant eye for the remainder of the trial. Trials ended immediately after participants gave a response or after a maximum duration of 10 s.

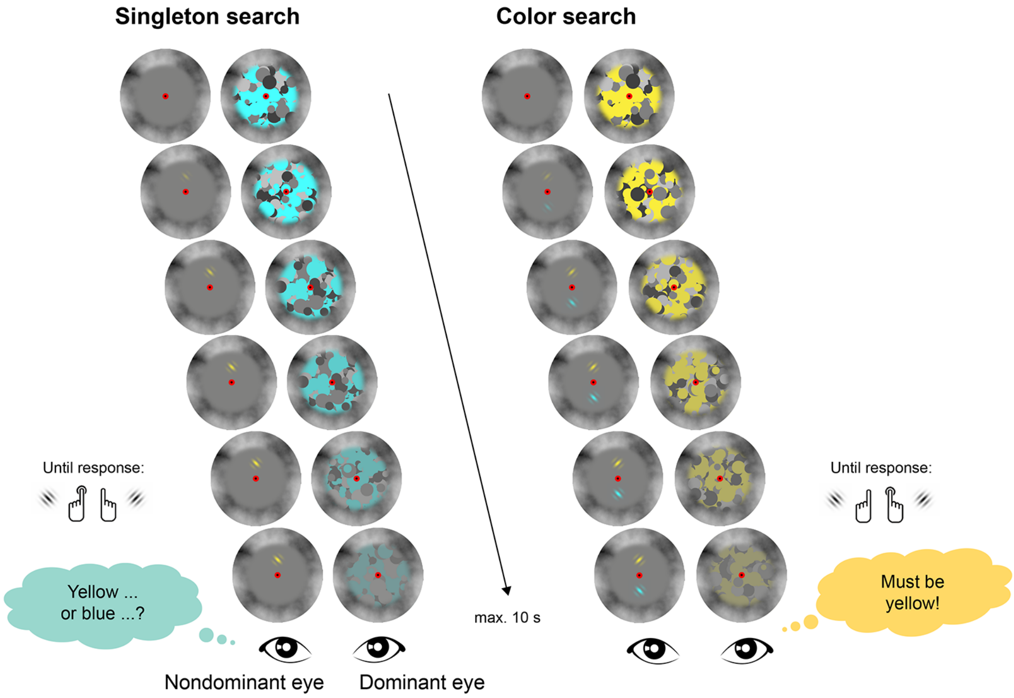

Figure 1. Trial procedure of the present study. The relevant target stimuli were left- or right-oriented Gabor gratings presented above or below the fixation point. The targets were delivered to the non-dominant eye using a mirror stereoscope. Conscious perception of the targets was interocularly suppressed by presenting a random sequence of CFS patterns with a 10Hz update frequency to the dominant eye. The targets had either the same or different color as the CFS patterns. The color of the CFS patterns varied randomly between cyan and yellow from trial to trial. In each trial, the participants' task was to report the target's orientation using key presses as soon as they could perceive it. As soon as the participants responded, the trial ended. The target grating's contrast was ramped up in the first phase of the trial, while the contrast of the CFS patterns decreased over time in the second phase of the trial. The trials had a maximum duration of 10 seconds but ended as soon as the participants gave a response. Left: in singleton search condition, color was irrelevant, and only one grating was shown in each trial, which varied randomly between cyan and yellow from one trial to the next. Right: In color search, participants were explicitly instructed to report the orientation of gratings with a specific color. This target color remained constant throughout the whole experimental block. Two gratings were presented in each trial of the color search block, but only one of these gratings had the relevant color.

2.4.2. Task

The participants' task required to press the left "control" key using the left index finger, if the target grating was tilted 45° to the left (from the vertical), and to press the right "control" key with the right index finger, if the target grating was tilted 45° to the right. If participants gave an incorrect response (e.g. if they pressed the right "control" key when the target was in fact tilted to the left), they were played a brief error tone (430 Hz, for a duration of 150 ms). If they did not respond before the maximum trial duration of 10 s, they also received this error feedback. The start of the next trial was briefly delayed whenever the participants received the error feedback. Otherwiese, if participants gave the correct response, the next trial started after a fixed inter-trial interval of 1 s.

2.4.3. Experimental design

Every participant was measured in all experimental conditions in a full factorial 2 (Target SF: 2 cpd vs. 4 cpd) × 2 (Target/CFS color: same vs. different) × 2 (Task: singleton search vs. color search) design. Each participant completed 768 experimental trials, divided into two blocks of 384 trials. The task varied between blocks and the order of the tasks was counterbalanced across participants. Within each block, all combinations of grating and CFS pattern colors, target positions (above or below fixation), orientations (left- vs. right-tilted) and SF (low vs. high) occurred with equal frequency and varied randomly from trial to trial.

In the *singleton search* block, only one grating was presented to the non-dominant eye. Participants reported this gratings' orientation irrespective of its color. In half of the trials, the target had the same color as the CFS pattern, in the other half of trials, the target had the different color. In the *color search* block, the procedure was identical, only that two gratings were presented in each trial, and these two gratings always had different colors. Importantly, participants were instructed to report the orientation of a grating with a particular color (e.g., 'yellow') throughout the block and ignore gratings of the other color, which served as a distractor. In half of the trials, the orientation of the distractor grating was the same as the orientation of the target grating, in the other half of the trials, the orientation of the distractor grating was different than the target grating. The instructed target color was counterbalanced across participants. In a given trial, target and distractor grating always had the same spatial frequency.

After completing runs of 64 trials in one go, participants were always shown a message reading (e.g., "Pause – block 1 of 6 completed". Participants were instructed to use these pauses to rest briefly and press the "enter" key to continue with the experiment as soon as they were ready. At the outset of each task block, participants received written instructions and underwent a training block consisting of 32 trials, which allowed them to get acquainted with the task and the experimental stimuli.

3. Results

The full dataset encompassed 30,720 trials (768 trials for each of the 40 participants). In 15 trials (0.05% of the data), participants failed to respond within the maximum trial duration of 10 s. These trials were excluded from further analyses. In 1,059 trials (3.4% of the data), participants gave the wrong response. These trials were thus also excluded from the analyses. The statistical analyses was therefore based on a total of 29,646 valid trials (or 96.5% of the presented trials). The median breakthrough time in milliseconds within for each participant and condition was entered into a repeated measures ANOVA with the within-participant factors *target SF* (2 cpd vs. 4 cpd), *target/CFS color* (same color vs. different color), and *task* (singleton search vs. color search). The significant effects of this analysis are plotted in Figure 2. The statistical analysis was conducted using R [25].

3.1. Main effects

As expected, the breakthrough times yielded a significant main effect of target SF, $F(1, 39) = 57.9$, $p < .001$, $\eta_p^2 = 0.60$, with robust and long suppression durations with low spatial frequency targets of 2 cpd ($M = 3209$ ms, SE = 252.5), and rather ineffective suppression, resulting in much shorter breakthrough times when targets had a high spatial frequency of 4 cpd ($M = 1762$ ms, $SE = 165.6$).

Furthermore, the analysis revealed a main effect of Target/CFS color, $F(1, 39) = 15.1$, $p < 0.001$, $\eta_p^2 = 0.28$, with, on average, shorter breakthrough times when the target and the CFS suppressor had different colors ($M = 2366$ ms, $SE = 190.5$) compared to when they had the same color ($M = 2604$ ms, $SE = 196.6$).

Finally, the analysis also yielded a main effect of search task, $F(1, 39) = 5.5$, $p = 0.024$, $\eta_p^2 = 0.12$, with shortened breakthrough times when participants searched for a specific color ($M = 2327$ ms, $SE = 167.1$) compared to when they searched for a singleton target of any color ($M = 2643$ ms, $SE = 232.7$).

doi:10.20944/preprints202101.0347.v1

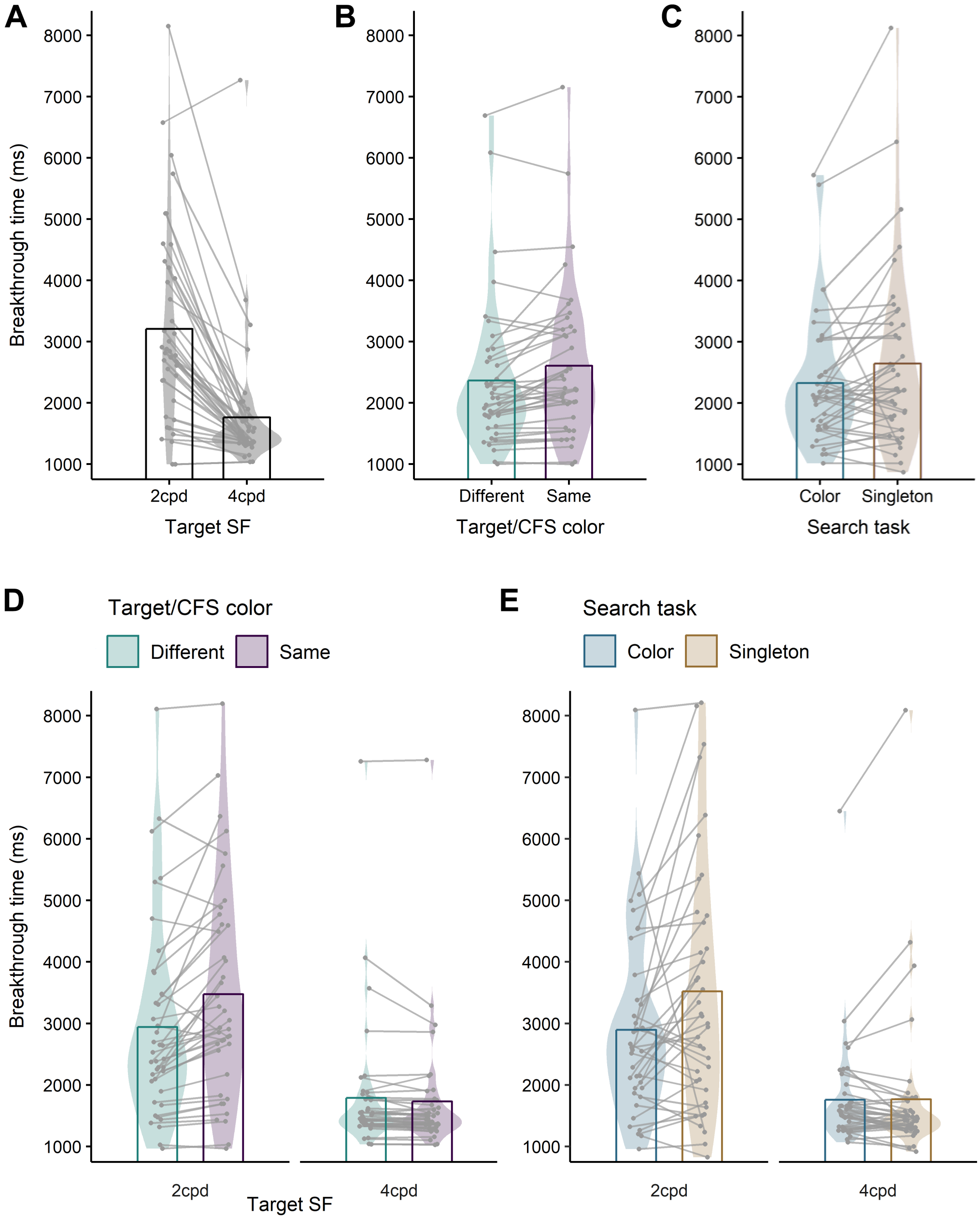

Figure 2. Significant results of the repeated measures ANOVA of breakthrough times in trials with correct responses. The data points in each plot's background represent the medians of the breakthrough time of individual participants, which were entered into the statistical model. Lines connect data points belonging to the same participants. The violin plots represent the distribution of data within each condition, and the bars represent the condition means. **(A)** Main effect of target SF. **(B)** Main effect of target/CFS color. **(C)** Main effect of search task. **(D)** Interaction of Target SF × Target/CFS color. **(E)** Interaction of Target SF × Search task.

3.2. Interaction effects

The analysis revealed a significant interaction of Target SF × Target/CFS color, $F(1, 39) = 27.1$, $p < .001$, $\eta_p^2 = 0.41$. For low SF targets, post-hoc tests showed that in trials where targets and CFS suppressors were differently colored, the suppression durations were shorter (different colors: $M = 2942$ ms, SE =247.2; same color: $M = 3475$ ms, $SE = 270.1$; $t[39] = -4.6$, $p < .001$). In contrast, for high SF targets, there was a slight, albeit statistically signficantly, opposite tendency, resulting in *longer* suppression durations when targets and CFS suppressors were differently colored (different colors: M = 1789 ms, SE = 170.0; vs. same colors: M = 1734 ms, SE = 162.1; $t[39] = 2.1$, $p = 0.047$).

The analysis also revealed an interaction of Task × Target SF, $F(1, 39) = 9.0$, $p = 0.005$, $\eta_p^2 = 0.19$. Follow-up t-tests for depended samples showed that the effect of task was significant for low-spatial frequency targets (color search: M = 2896 ms, SE = 228.2; vs. singleton search: M = 3521 ms, SE = 318.2, $t[39] = -2.7$, $p = .009$) but not for high SF targets targets (color search: M = 1758 ms, SE = 139.9; vs. singleton search: M = 1766 ms, SE = 195.0, $t[39] = -0.1$, $p = .918$).

There was no interaction of Task × Color congruence, $F(1, 39) = 0.6$, $p = 0.435$, suggesting that the influence color contrast was independent of of whether participants searched for a specific target color, or not. There was also no sign of a three-way interaction of Task × Target/CFS color × Target SF, $F(1, 39) = 1.2$, $p = 0.279$.

4. Discussion

The current study investigated whether and how color accelerates conscious perception of a relevant target stimulus. Using CFS, the perception of target stimuli presented to the non-dominant eye was suppressed and delayed by presenting dynamic visual patterns to the dominant eye [15–17]. The present study also manipulated the efficacy of CFS by using either low-SF targets (which are usually robustly suppressed by CFS) and high-SF (which typically remain relatively unperturbed by CFS [22]) in order to test if any color-related effects actually modulated the timing of conscious perception or instead reflected attentional or response selection benefits *after* the target stimulus reached consciousness. Consistent with previous research, low-SF targets were robustly suppressed from conscious perception, which was not the case for high-SF targets [22,23].

Color accelerated conscious perception of the low-SF targets through two mechanisms. First, color led to faster conscious perception through a bottom-up (or sensory) benefit [3,4]. When the color the targets and the CFS patterns had different colors (that is, when the color contrast was high), the initially invisible targets broke into consciousness faster than when the targets and CFS patterns had the same color (that is, when the color contrast was low). The size of this effect was independent of whether or not participants searched for a specific color. Second, it generally mattered whether participants searched for *one* particular target color, or not. During color search, for example, when participants always reported the yellow targets' orientation but ignored cyan targets, the yellow targets entered consciousness significantly faster compared to a singleton search condition where the target color was irrelevant and could change from trial to trial. This confirms that color has a substantial top-down effect on conscious perception [9]: When a specific color is instantiated as an attentional template, a grating that matches this template breaks into consciousness more quickly.

4.1. The bottom-up effect of color on conscious perception

The bottom-up effect of target/CFS color similarity was robust and independent of whether subjects searched for one specific color. Previous research on the CFS method showed, to some extent, that the similarity between the features of the suppressed stimulus and the CFS pattern affects the strength of suppression. For example, previous research reported that the degree to which CFS suppresses oriented gratings could depend on orientation similarity: Gratings with cardinal orientations were robustly suppressed by traditional Mondrian patterns, which primarily consist of cardinal orientations (vertical and horizontal edges), whereas gratings with oblique orientations escaped suppression by the same Mondrian patterns more easily [22]. Another study found that moving stimuli are better suppressed by moving Mondrian patterns than traditional Mondrian patterns with a discrete update frequency [26]. Regarding color, however, the results so far have been less clear. While one study found that achromatic CFS patterns more strongly suppress achromatic gratings compared to colorful CFS patterns [22], a subsequent study reported the opposite, namely that even achromatic

doi:10.20944/preprints202101.0347.v1

stimuli are more robustly suppressed when the CFS patterns contain a range of different colors, in comparison to CFS patterns that consist of different gray values only [27].

The current study clarifies the open question of whether feature-selective suppression also occurs for colors during CFS by explicitly manipulating the similarity or contrast between the targets' and CFS patterns' color. The present data leaves barely any doubt that in CFS, feature-selective suppression also occurs for the color dimension of the rivaling stimuli. This bottom-up effect is robust and occurs independent of the participants' specific attentional set, suggesting that it is situated at an early, presumably sensory level of the visual processing hierarchy, where it directly affects the competition between the different eyes' stimulus signals. Previous studies on binocular rivalry and CFS often focused on luminance contrast as a central stimulus-dependent determinant of interocular suppression. Typically, increasing the luminance contrast of one stimulus will increase its perceptual predominance and likelihood to break interocular suppression [17–19]. The results of the current study suggest that such contrast effects are not limited to the luminance dimension. Noteworthy, the luminance of the rivalrous stimuli in the present study was kept constant, but the color contrast was manipulated by using targets of either the same or different colors as the CFS suppressors. The neural processing of a relevant stimulus at early levels of the visual processing hierarchy and the timing of when this stimulus enters consciousness might thus generally benefit from a stronger feature salience, regardless of the exact feature dimension [4]. Strong contrasts in the neural representations between the irrelevant CFS pattern and the relevant target might represent a good signal-to-noise ratio in terms of neural processing of the sensory signals. In contrast, with low contrast, the resulting signal-to-noise ratio would be poor.

The current study draws a parallel between the mechanisms responsible for (bottom-up) attentional selection, where color contrasts also play a central role [3,4], and the factors that influence the emergence of stimuli into conscious awareness. Noteworthy, the present results cannot merely result from selective attention being more efficiently directed to the location of a differently colored target stimulus *after* it has entered consciousness. In this case, the same pattern of results should have occurred with HSF gratings, where interocular suppression was minimal. However, in this control condition, the participants' responses did not differ as a function of color contrast. Therefore, the present results suggest that color contrast affects conscious perception in conditions where CFS is effective. The effect could reflect the operation of a general attentional tuning for (bottom-up) stimulus salience, operating at an early visual processing stage, at a level before the stimulus reaches awareness.

In addition to these theoretical considerations, the finding that the color contrast determines the strength of interocular suppression also has methodological implications for studies that use CFS to render stimuli invisible and study the extent of unconscious processing. Some studies emphasized the importance of low-level stimulus features in CFS [22,23,27]. However, there is little consistency concerning the choice of stimuli between different studies [33]. Specifically, the variability in the choice of spatial, temporal, and chromatic features of the CFS suppressors is high across studies [23,27,33]. The critical importance of feature similarity between suppressed stimulus and CFS suppressor entails the risk of theoretically problematic confounds, especially when the stimuli differ visually between different experimental conditions [30]. For example, if a study finds that emotional pictures break suppression faster than neutral pictures, one might be inclined to conclude that emotional stimuli have preferred access to consciousness. However, upon closer examination, one might find that the color distribution in the emotional pictures is simply more distinct from the color distribution of the CFS suppressor. In contrast, the emotionally neutral pictures might share more features with the CFS pattern, hence leading to a more robust suppression. Thus, such an effect could be entirely explained by low-level feature differences and might have little to do with the semantic or emotional significance of the pictures. Excluding such confounds is not necessarily an easy endeavor. Still, it is of central importance for experimental consciousness research to take sensory explanations into account in order to make theoretical progress in understanding the extent and limits of unconscious cognition gain a better understanding of the factors that accelerate access of a stimulus to conscious awareness [13,14,16].

4.2. The top-down effect of color on conscious perception

The second major finding of the current study is that color can also accelerate conscious perception via top-down attentional settings [9], as observed in the present color search condition. Specifically, if one color was task-relevant, target stimuli that matched this attentional setting entered consciousness more quickly compared to the singleton search condition where color was irrelevant for the task, and the targets could change color from trial to trial. This observation is closely related to prior research using the CFS paradigm, which showed that stimuli that match visual working memory (VWM) contents enter consciousness faster [9,28]. In these studies, participants were typically instructed to keep an initially presented and visible stimulus in working memory and compare it to a stimulus presented after a delay. Within the delay between presenting the to-be-memorized stimulus and the comparison stimulus, participants were presented with a CFS sequence that rendered a probe stimulus invisible. Importantly, this initially invisible probe stimulus could either match the stimulus features held in VWM, or not. A consistent finding was that visually similar stimuli (e.g., had the same color) as the contents of VWM escape interocular suppression faster [9]. The current study illustrates that an explicit instruction to search for a specific color also leads to faster conscious awareness of stimuli that match this color, meaning that such effects are not limited to delayed matching tasks. The parallels between the present findings and the results from VWM experiments also further support the view that VWM and top-down guided visual attention are closely related processes [29].

A wealth of research into the factors that guide selective visual attention confirmed that color is one of the most powerful features for directing visual attention in a goal-directed manner [8]. In terms of cortical processing, incoming stimulus information that matches a top-down attended feature could be amplified for further processing at the expense of other stimuli that do not possess this feature. This could explain why in the color search condition of the current study, stimuli that matched the attentional setting broke into consciousness faster compared to the singleton search condition, where color was irrelevant. However, compared to classical studies on visual attention mechanisms, in which conscious perception is usually not impeded by CFS, the current study revealed the novel result that searching for a specific color also accelerates conscious perception of this relevant target stimulus.

Of note, faster conscious perception of targets occurred selectively with LSF gratings, where CFS reliably impaired conscious perception. This could mean that attention operates on initially unconscious neural stimulus representations, that is, at a level before the stimulus neural processing is consciously accessible. In this sense, attention could indeed act as a 'gatekeeper to consciousness'. Further research should be conducted to clarify whether, apart from color, other features that typically guide attentional selection, such as orientation or shape [8], could also influence and accelerate the access of faint stimuli to conscious processing. Based on the findings about the relationship of VWM contents and conscious access [9,28,29], an explicit attentional tuning for such features should also lead to faster cosncious pecpetion of the initially invisible stimuli.

An open question concerns the flexibility and complexity of top-down guided attention on conscious perception. At first glance, the current study suggests that the attentional setting allows only limited flexibility. Perception was significantly faster when subjects paid attention to targets with one specific color only, compared to trials where the color was not task-relevant, and the target could have one of two possible colors. This pattern of results is all the more impressive because only one object was presented in the singleton search condition, and no decision was necessary whether it was the correct target object or the incorrect distractor object. Moreover, the singleton search condition's target objects could always have only either one or the other color. Suppose participants would be able to search for two different colors in parallel. In that case, they should have easily taken advantage of the two possible target colors in the singleton search condition. Surprisingly, however, the opposite was the case. Although one could argue that the task itself is objectively easier, since there is no need to decide whether an object has the 'correct' color or not, the target gratings, in fact, remained perceptually suppressed for a longer time under singleton search compared to the color search condition where participants were looking for only one specific color.

This result draws yet another parallel to research on top-down guidance of selective visual attention. In visual search experiments, where conscious perception is usually not delayed by CFS, the participants' performance is usually hampered whenever there is a need to search for more than one target color in parallel [34–36]. Something similar seems to manifest in the present result, where the attentional tuning to one specific target color increased performance. Still, participants did not benefit from knowing that the target could have either one or the other color under singleton search conditions. However, whether or not this observation corroborates the view that participants cannot search for more than one color in parallel needs to be further clarified in future research. After all, participants could also have strategically disregarded color in singleton search conditions. They might have realized quickly, that the targets and CFS pattern can both change color randomly from trial to trial, which is why they might have thought of it as a feature that is not helful for identifying the target. Thus, future research could instruct participants more explicitly to search for one or the other target color among differently colored distractors under CFS conditions to test whether particpiants could set up a an attentional template for two different colors, and any stimulus matching to either of those two colors might gain preferential access to consciousness.

A potentially fruitful future research avenue opens up by asking whether the limitation of top-down guidance to simple templates of one specific feature depends on the level in the visual processing hierarchy at which selective attention operates. Interestingly, previous research using the CFS paradigm also showed that expectations about the appearance of more "high-level" stimulus categories could also shorten the time that stimuli require to break into consciousness [31,32]. In these experiments, before the start of each run, an explicit word cue was presented that either matched the perceptually suppressed object or not. Valid expectations regarding the stimulus category consistently accelerated conscious awareness: A picture of a face breaks into consciousness faster if preceded by the congruent word cue "face," whereas it takes longer if it is preceded by the incongruent word cue "house."

An open question is whether such expectancy effects are ultimately due to specific attentional settings and might result from relatively coarse attentional tuning. Following this hypothesis, the word "house," for example, might tune attention to vertically and horizontally oriented lines. In contrast, the presentation of the word "face" might tune attention to more curved shapes, or a typical facial configuration of two eyes and a mouth. It could also be that attention can be tuned to different feature dimensions in parallel. For example, when searching for faces, not only shape features but also typical colors commonly seen in faces could be part of the top-down attentional tuning for faces. Future research should clarify if color-guided attention can work in parallel with feature templates from other dimensions, such as orientation or shape, in together allows more effective attentional guidance and facilitated access to consciousness.

5. Conclusions

Color is a powerful feature for guiding selective visual attention, both via sensory benefits (when strong color contrasts capture attention in a bottom-up manner) as well as top-down modulations (when participants selectively search for specific colors). The present CFS study investigated whether these attentional mechanisms can also accelerate conscious perception of a relevant target stimulus. The results confirm that a strong color contrast between targets and CFS patterns accelerates the conscious perception of the targets. Moreover, top-down attentional settings tuned to a specific target color also accelerate the conscious perception of objects matching this color.

Funding: This research received no external funding.

Institutional Review Board Statement: The study was conducted according to the guidelines of the Declaration of Helsinki. The study procedures were approved by the ethics committee of the Georg-Elias-Mueller-Institute of Psychology, University of Goettingen (reference no. 245/2019).

Informed Consent Statement: Informed consent was obtained from all participants involved in the study.

Data Availability Statement: The data presented in this study are openly available through the Open Science Framework at https://osf.io/mb6da/.

Acknowledgments: The author thanks Carl Husemann and Philip Sulewski for their valuable support with recruiting participants and collecting the data.

Conflicts of Interest: The author declares no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

BR	Binocular Rivalry
CFS	Continuous Flash Suppression
cpd	Cycles per degree of visual angle
CRT	Cathode Ray Tube
HSF	High Spatial Frequency
LSF	Low Spatial Frequency
SF	Spatial Frequency
VWM	Visual Working Memory

References

1. Sumner, P.; Mollon, J. D. Catarrhine photopigments are optimized for detecting targets against a foliage background. *J Exp Biol* **2000**, *203*, 1963–1986.
2. Pflüger, L. S.; Valuch, C.; Gutleb, D. R.; Ansorge, U.; Wallner, B. Colour and contrast of female faces: attraction of attention and its dependence on male hormone status in Macaca fuscata. *Anim Behav* **2014**, *94*, 61–71.
3. Theeuwes, J. Perceptual selectivity for color and form. *Percept Psychophys* **1992**, *51(6)*, 599–606.
4. Itti, L.; Koch, C. A saliency-based search mechanism for overt and covert shifts of visual attention. *Vision Res* **2000**, *40(10–12)*, 1489–1506.
5. Einhäuser, W.; Spain, M.; Perona, P. Objects predict fixations better than early saliency. *J Vision* **2008**, *8(14)*, 18.
6. D'Zmura M. Color in visual search. *Vis Res* **1991**, *31(6)*, 951–966.
7. Duncan J.; Humphreys G.W. Visual search and stimulus similarity. *Psychol Rev* **1989**, *96(3)*, 433.
8. Wolfe J.M.; Horowitz T.S. What attributes guide the deployment of visual attention and how do they doit? *Nat Rev Neurosci* **2004**, *5(6)*, 495–501.
9. Gayet, S.; Douw, I.; Van der Burg, V.; Van der Stigchel, S.; Paffen, C. L. Hide and seek: Directing top-down attention is not sufficient for accelerating conscious access *Cortex* **2020**, *122*, 235–252.
10. Lamy, D.; Alon, L.; Carmel, T.; Shalev, N. The role of conscious perception in attentional capture and object-file updating *Psychol Sci* **2015**, *26(1)*, 48–57.
11. Koch, C.; Tsuchiya, T. Attention and consciousness: Related yet different *Trends Cogn Sci* **2015**, *16(2)*, 103–105.
12. Kim, C. Y.; Blake, R. Psychophysical magic: Rendering the visible "invisible." *Trends Cogn Sci* **2005**, *9(8)*, 381–388.
13. Dehaene, S.; Changeux, J.-P. Experimental and theoretical approaches to conscious processing. *Neuron* **2011**, *70(2)*, 200–227.
14. Breitmeyer, B. G. Psychophysical "blinding" methods reveal a functional hierarchy of unconscious visual processing. *Conscious Cogn* **2015**, *35*, 234–250.
15. Tsuchiya, N.; Koch, C. Continuous flash suppression reduces negative afterimages *Nat Neurosci* **2005**, *8(8)*, 1096–1101.
16. Stein, T.; Hebart, M. N.; Sterzer, P. Breaking Continuous Flash Suppression: A New Measure of Unconscious Processing during Interocular Suppression? *Front Hum Neurosci* **2011**, *5*, 167.
17. Valuch, C.; Mattler, U. Action priming is linked to visual perception in continuous flash suppression *J Vision* **2019**, *19(7)*, 13.
18. Levelt, W. J. M. *On binocular rivalry.*; Van Gorcum: Assen, Netherlands, 1965.

19. Brascamp, J. W.; Baker, D. H. Psychophysics of binocular rivalry. In *The consitution of visual consciousness*; Miller S. M., Ed.; John Benjamins: Amsterdam, Netherlands, 2013; pp. 109–139.
20. Tsuchiya, N.; Koch, C.; Gilroy, L. A.; Blake, R. Depth of interocular suppression associated with continuous flash suppression, flash suppression, and binocular rivalry *J Vision* **2006**, *6(10)*, 6.
21. Valuch, C.; Kulke, L. Predictive context biases binocular rivalry in children and adults with no positive relation to two measures of social cognition *Sci Rep* **2020**, *10*, 2059.
22. Yang, E.; Blake, R. Deconstructing continuous flash suppression *J Vision* **2012**, *12(3)*, 8.
23. Han, S.; Lunghi, C.; Alais, D. The temporal frequency tuning of continuous flash suppression reveals peak suppression at very low frequencies *Sci Rep* **2016**, *6*, 35723.
24. Yang., E.; Blake, R.; McDonald, J.E. A new interocular suppression technique for measuring sensory eye dominance. *Invest Opht Vis Sci* **2010**, *51*, 588–593.
25. R Core Team. *R: A language and environment for statistical computing*; The R Foundation for Statistical Computing: Vienna, Austria, 2020; https://www.R-project-org/.
26. Moors, P.; Wagemans, J.; de-Wit, L. Moving stimuli are less effectively masked using traditional continuous flash suppression (CFS) compared to a moving mondrian mask (MMM): A test case for feature-selective suppression and retinotopic adaptation *PLoS One* **2014**, *9(5)*, e98298.
27. Drewes, J.; Zhu, W.; Melcher, D. The edge of awareness: Mask spatial density, but not color, determines optimal temporal frequency for continuous flash suppression *J Vision* **2018**, *18(1)*, 12.
28. Gayet, S.; Paffen, C. L.; Van der Stigchel, S. Information matching the content of visual working memory is prioritized for conscious access *Psychol Sci* **2013**, *24(12)*, 2472–2480.
29. Olivers C.N.L.; Meijer F.; Theeuwes J. Feature-based memory-driven attentional capture: visual working memory content affects visual attention *J Exp Psychol Hum Percept Perform* **2006**, *32(5)*, 1243.
30. Gayet, S.; Stein, T.; Peelen, M. V. The danger of interpreting detection differences between image categories: A brief comment on "Mind the snake: Fear detection relies on low spatial frequencies" (Gomes, Soares, Silva, & Silva, 2018) *Emotion* **2019**, *19(5)*, 928–932.
31. Stein, T.; Peelen, M. V. Content-specific expectations enhance stimulus detectability by increasing perceptual sensitivity *J Exp Psychol Gen* **2015**, *144(6)*, 1089.
32. Pinto, Y.; van Gaal, S.; de Lange, F. P.; Lamme, V. A.; Seth, A. K. Expectations accelerate entry of visual stimuli into awareness *J Vision* **2015**, *15(8)*, 13.
33. Ludwig, K.; Hesselmann, G. Weighing the evidence for a dorsal processing bias under continuous flash suppression. *Conscious Cogn* **2015**, *35*, 251–259.
34. Huang, L.; Pashler, H. A Boolean map theory of visual attention. *Psychol Rev* **2007**, *114*, 599–631.
35. Olivers, C. N.; Peters, J.; Houtkamp, R.; Roelfsema, P. R. Different states in visual working memory: When it guides attention and when it does not. *Trends in Cognitive Sciences* **2011**, *15*, 327–334.
36. Büsel, C.; Pomper, U.; Ansorge, U. Capture of attention by target-similar cues during dual-color search reflects reactive control among top-down selected attentional control settings. *Psych Bull Rev* **2019**, *26*, 531–537.