Breakthrough thresholds in continuous flash suppression are tuned to mask temporal frequency but suppression depth is constant

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Abstract
Continuous flash suppression (CFS) is a popular method for suppressing visual stimuli from awareness for extended periods. It involves a dynamic, high-contrast masking stimulus presented one eye which suppresses a target stimulus presented to the other. The strength of suppression is usually inferred from how long it takes for the target to breakthrough from suppression into awareness (the bCFS threshold). A new variant known as 'tracking CFS' (tCFS) directly measures the strength of suppression by measuring both breakthrough and suppression thresholds. Here, we employ the tCFS paradigm while varying the temporal frequency of the masking stimulus. Our data reveal two clear results: (i) CFS exhibits a clear temporal frequency tuning, with bCFS thresholds peaking for masks modulating at ~1 Hz; (ii) suppression depth (the difference between breakthrough and suppression thresholds) remains constant despite changes in bCFS. The first result confirms an earlier finding that peak bCFS occurs for very low temporal frequencies. The second result provides a valuable insight in showing that bCFS changes occur completely independently of suppression strength, which remains constant. In this study, suppression averaged 13 dB, around 2–3 times stronger than suppression reported in binocular rivalry studies.

Introduction

Continuous flash suppression (CFS) is a very popular paradigm for studying visual suppression and has been employed in hundreds of published studies since the method was first reported by Tsuchiya and Koch (2005). Typically, CFS is produced by presenting one eye with a large, high-contrast, dynamic pattern (often a termed a 'Mondrian' because it commonly takes the form of a patchwork of coloured squares, though here we use a dynamic noise stimulus and refer to it more generically as a 'mask' or masker) while the other views a stimulus that is usually smaller, static, low-contrast and achromatic (the 'target'). Because the monocular inputs are so mismatched, the usual process of binocular fusion that occurs when correlated left- and right-eye inputs arrive in primary visual cortex is not possible (Blake & Boothroyd, 1985). Instead, a process of interocular suppression is triggered in which the stronger image (the mask) is invariably perceived and the target stimulus in the other eye does not reach awareness, even though it enters the visual system. Several key questions arise: (i) how far beneath the threshold for visual awareness is the suppressed target (i.e., suppression depth), (ii) does the target's suppression depth vary among different kinds of maskers, and (iii) where along the visual pathway does this suppression occur? This paper addresses the first two questions experimentally.

Until the CFS paradigm appeared, binocular rivalry had been the preferred way to render a stimulus invisible (Alais, 2012; Kim & Blake, 2005) and had been studied experimentally for well over 100 years (Alais & Blake, 2005; Blake, 2001). CFS, however, was rapidly embraced as it offered several advantages over binocular rivalry. First, in rivalry, the suppression periods are typically only 1–3 seconds in duration while in CFS the suppression periods are about an order of magnitude longer. Second, because the competing stimuli in the CFS paradigm are highly mismatched in salience, CFS always begins with the target being suppressed by the mask. This offers a procedural advantage over binocular rivalry in which the initially dominant image is typically unpredictable and the dominant eye switches relatively quickly and irregularly. Another important reason for the rapid growth of CFS over binocular rivalry was that it better suited growing interest in new research questions concerning consciousness. Beginning in the 1990s, experimental psychology began to explore visual consciousness and binocular rivalry was proposed as a key paradigm (Crick, 1996; Logothetis, 1998). A tantalising question that emerged from this work was whether a stimulus suppressed from awareness could still guide conscious awareness and the long stable periods of target suppression in CFS suited experimental investigation of these questions.

Although the CFS paradigm seemed suitable to answer questions relating to the extent of target suppression, this topic has not received a much attention. This differs starkly from the binocular rivalry literature, which contains many studies of 'suppression depth' (Alais & Melcher, 2007; Blake & Camisa, 1979; Hollins & Bailey, 1981; Lunghi & Alais, 2015; Makous & Sanders, 1978; Nguyen, Freeman, & Alais, 2003; Nguyen, Freeman, & Wenderoth, 2001; Ooi & Loop, 1994; Tsuchiya, Koch, Gilroy, & Blake, 2006; Watanabe, Paik, & Blake, 2004). These studies determine the strength of rivalry suppression using a probe stimulus and measuring contrast thresholds for detecting the probe in a given eye when that eye is in a dominant phase and again when it is suppressed. The ratio of the dominance and suppression thresholds quantifies the degree of suppression. Typically, this approach reveals contrast sensitivity for an image suppressed from awareness in binocular rivalry is attenuated by about 50% (or in decibels, as it is usually measured, about 4-6 dB of suppression). In contrast, the matter of suppression depth in CFS has scarcely been investigated.

Of the several hundred published studies using CFS since it first emerged in 2005, only three have measured CFS suppression depth. These studies did so using the methods used in the many rivalry studies of suppression depth (Ludwig, Kathmann, Sterzer, & Hesselmann, 2015; Tsuchiya et al., 2006; Yang & Blake, 2012) which involves comparing monocular contrast increment thresholds when the eye was in a state of dominance and when it was suppressed. This process requires compiling a psychometric function or running a staircase procedure or similar for each perceptual state and so requires a large number of trials. In a comprehensive study by Yang & Blake (2012), their third experiment alone required 5 hours per participant! The results of all three studies, however, converge on the conclusion that interocular suppression from CFS is much stronger than for binocular rivalry (to be discussed in more detail in the General Discussion).

Attempts to measure suppression strength in CFS have usually taken a much easier approach by focusing on how long it takes a suppressed target to reach awareness (CFS RTs). In particular, a variant known as 'breaking CFS' (bCFS) is used for this and it has become the dominant CFS method (Gayet, Van der Stigchel, & Paffen, 2014; Jiang, Costello, & He, 2007; Stein, 2019). bCFS trials begin with a target at zero (or very low) contrast which gradually ramps up in contrast until eventually it breaks into awareness. Breakthrough time is the dependent variable and stimuli that take longer to reach awareness are often interpreted as having been more deeply suppressed, although, without comparing breakthrough to suppression thresholds (as done in rivalry studies of suppression depth), this is not a valid conclusion. It is even less valid in more recent versions of the bCFS paradigm where it has become common to ramp up the target's contrast very quicky to maximum in as little as 1 s, and then wait for it to breakthrough into awareness. The problem here is that the target often reaches maximum contrast before breaking through and remains there until breakthrough is reported. This means that at no point during the ramp-up period was a contrast threshold reached and the eventual moment of breakthrough will involve an effect of contrast adaptation weakening the masker and thus releasing the target from suppression. This confounds bCFS RTs as a dependent measure as they reflect both target contrast and mask adaptation. In addition, the problem remains that bCFS RTs are not compared to a suppression threshold and so there is no way to quantify the degree of threshold elevation.

A very recent CFS study employed a simple variant of the bCFS approach in a paradigm called 'tracking CFS' (tCFS: Alais et al., 2024). tCFS provides a quick and easy way to measure both breakthrough and suppression thresholds within a single trial (see Fig. 1) and thus obtain suppression depth values. All three of the dependent variables are defined in terms of contrast (rather than reaction times), as was done in the classical studies of rivalry suppression depth and which maps well onto cortical activity and suppression (unlike RTs). The method is a convenient way to test whether suppression depth varies with the kind of image being suppressed, to evaluate whether certain images are prioritised and spared a degree of suppression so that they remain close to consciousness awareness. To date, the evaluation of different kinds of images has usually been done using breakthrough times. Although numerous studies have shown that bCFS times can vary between different kinds of images, without a comparison of breakthrough and suppression thresholds, it is unclear how variations in bCFS times should be interpreted given the limitations noted in the previous paragraph.

This study has two aims. The first is to examine the temporal frequency tuning of CFS by varying the masker's temporal frequency. In a previous study using bCFS (Han, Lunghi, & Alais, 2016), target breakthrough times depended strongly on the masker's temporal frequency, with low temporal frequencies (peaking at ~1 Hz) producing longer breakthrough times. What this implies for contrast thresholds and CFS suppression depth is not clear. For example, the longer breakthrough times seen for slowly modulating masker patterns might indicate stronger suppression at low temporal frequencies. This interpretation is intuitively appealing, yet, changes in breakthrough can be misleading: in the original tracking CFS study (Alais, Coorey, Blake, & Davidson, 2024), we observed significant bCFS differences between images yet found suppression depth remained constant because suppression thresholds co-varied with breakthrough thresholds. This was true for a range of targets, from low-level images (gratings and noise patches) to high-level images (faces and objects). Thus, the second aim is to measure the temporal tuning of suppression depth to see whether it remains constant if, as expected based on Han et al. (2015), breakthrough thresholds vary with masker temporal frequency. If breakthrough and suppression thresholds are again found to covary (as in Alais et al., (2024)), suppression depth will remain constant.

Experiment 1

A previous study conducted using bCFS found that target breakthrough times were strongest at low temporal frequency (1 Hz) compared to all higher frequencies up to 25 Hz (Han et al., 2016). It is not clear, however, whether the longer breakthrough time at low temporal frequency indicates a greater strength of suppression at low frequency. By using tCFS, which measures both breakthrough and suppression thresholds, the current study will reveal whether there is any change in suppression strength with masker temporal frequency. Here we use a broad temporal frequency range composed of 8 frequencies from 0.12 Hz to 15 Hz spaced in one-octave steps (i.e., each frequency is the double of the preceding one). Given the findings of Han et al. (2016), we predict bCFS thresholds should exhibit a peak in the centre of the range around 1 Hz.

Methods

Participants

Thirteen undergraduate psychology students from the University of Sydney participated in these experiments. Participation was voluntarily in exchange for course credit and all participants had normal or corrected-to-normal vision and provided informed consent. The experiment was approved by the University of Sydney Human Research Ethics Committee (protocol 2021/048). All participants were tested to ensure they had normal stereovision, assessed using the Fly Stereo Acuity Test (Stereo Optical Company Inc., Chicago, IL).

Apparatus

A mirror stereoscope was used to partition the participant's vision into separate left- and right-eye views and was placed approximately 51 cm from the screen and had a total optical path length of approximately 57 cm. The experiment was programmed using custom MATLAB code and the Psychtoolbox (ver 3.0.13: Brainard, 1997). Visual stimuli were displayed in greyscale on an Apple LED Cinema monitor with a 60 Hz refresh rate (24 inch, 1920 x 1200 pixel resolution) running off a Mac Pro computer (2013; 3.7 GHz Quad-Core Intel Xeon E5). The participants' responses indicating when the target emerged from suppression (breakthrough) or disappeared from awareness (suppression) as the target cycled up and down in contrast were collected via a mouse click.

Stimuli

Two stimuli were presented dichoptically to participants via the stereoscope, with a temporally modulating mask stimulus (320 x 320 pixels, approximately 5.6 x 5.6 degrees of visual angle [dva]) presented to one eye and a small target stimulus (80 x 80 pixels, 1.4 x 1.4 dva) presented to the other (see Figure 1). The mask and target stimuli were both located inside fusion frames which allowed participants to maintain stable fusion of the images. A fixation cross (18 x 18 pixels; 0.3° x 0.3°) was located in the centre of the fusion contours.

The target in all experiments was a sinewave grating in a soft-edged circular window with a spatial frequency of 2.25 cycles per degree. Over trials its orientation varied randomly between ±45 degrees from vertical and its location varied among 4 locations equally spaced around a set of circular locations (upper left or right, lower left or right) with the target's centre being 1.5 dva from fixation. During the experiment the target grating's contrast was continuously rising (to find a breakthrough threshold) or falling (to find a suppression threshold) between minimum and maximum limits of 0.01 and 0.30, respectively, although all trials began

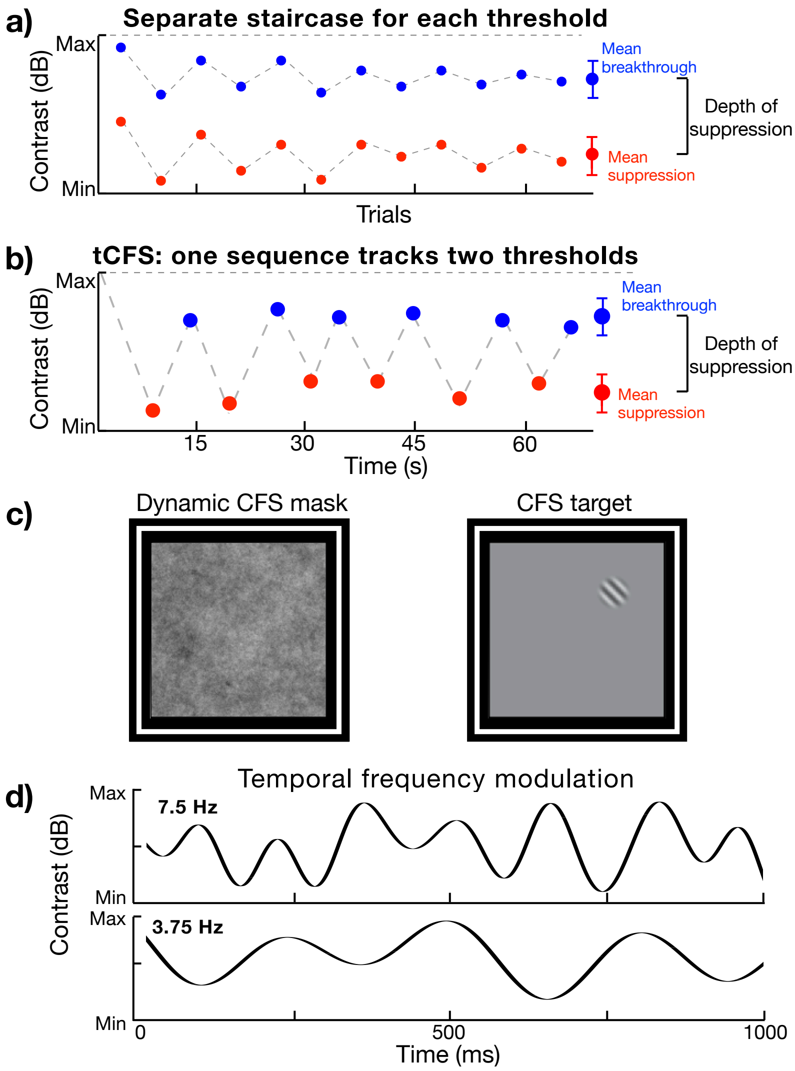

Figure 1. a) Calculating suppression depth requires measuring contrast thresholds for both suppression and breakthrough. One approach would be to use staircase procedures to obtain an estimate of each threshold separately. b) In the tCFS paradigm, the target continually rises and falls in contrast and participants indicate when their perceptual state changes with a mouse click. Each response reverses the direction of contrast change. The target starts visible at high contrast and declines until suppression is indicated (red circles), then it rises in contrast until breakthrough into awareness (blue circles), and so on. This provides a quick and efficient measure of breakthrough (bCFS) and suppression (reCFS) thresholds because each turning point is a threshold estimate. Suppression depth is calculated as the difference between the thresholds. c) The CFS mask was an achromatic pink-noise pattern that smoothly modulated over time in a narrow temporal frequency band. The target was always a grating. Mask contrast is set based on pilot data at a level that allows targets to breakthrough before reaching maximum contrast. d) The temporally filtered noise patterns used in these experiments modulate smoothly at a given frequency. This differs from most CFS studies which abruptly update the mask image at fixed intervals, resulting in step changes that produce a broad spectrum of temporal frequency energy that cannot be used to isolate specific temporal frequencies (see figure 1d of Han et al., 2016).

with the grating visible and descending from maximum contrast so that there was no uncertainty about what the target was and where it would appear. The contrast changes were linear on a decibel (i.e., logarithmic) scale where: Con_{dB} = 20 x

$log10(Con_{Lin})$. The minimum contrast was -40 dB and maximum was -10.46 dB (0.01 and 0.30, respectively.

The justification for using a decibel contrast scale is twofold. First, neurons in early visual cortex exhibit a logarithmic-like response to contrast that grows rapidly at low contrasts and then saturates at higher contrasts. Data from single V1 neurons show that these contrast response functions (CRFs) to linear contrast can be very adequately described by fitting a logarithmic curve, but not by linear or power functions (Albrecht & Hamilton, 1982). Consistent with a logarithmic response, perceptual thresholds for contrast increments tend to be a constant proportion of the base contrast (i.e., Weber's law holds). For these reasons, logarithmically scaled contrast changes should therefore produce approximately linear changes in perceived contrast and should be used when ramping contrast in CFS procedures. Second, once contrast is log-transformed to decibels, the difference between bCFS and reCFS thresholds used to obtain suppression depth is effectively a ratio and our finding of constant suppression depth indicates that whatever value the bCFS threshold has, the reCFS threshold will be lower by a fixed proportion. Without the log-linearisation of contrast, small differences between conditions can be spuriously inflated or large differences diminished depending on the contrast range.

Target contrast changed in small steps of 0.07 dB per video frame (at 60 Hz) and it took approximately 7 seconds to increase from minimum to maximum contrast. The slow rate of target change ensured that the target would not reach maximum contrast and remain there (as is often the case in bCFS studies). This is particularly important in the tCFS paradigm so that breakthrough and suppression can be quantified as a contrast threshold (and thus the strength of suppression calculated in contrast terms). If the rising contrast arrives at ceiling without yet breaking through, it will eventually breakthrough once adaptation weakens the dominant mask percept but then the target contrast threshold is contaminated by adaptation effects. For that reason, we use masks of quite low contrast (here, 0.10 RMS contrast) to allow target breakthrough before reaching maximum contrast.

The mask stimuli were made from a stack of 4000 random noise images (grayscale) that were then filtered into one of several narrow temporal frequency bands and played as an animation. At the framerate of 60 Hz, the animation lasted 66.67 s which was more than enough to complete each tracking trial. The stack of noise images was first converted to the frequency domain using a three-dimensional Fast Fourier Transform (FFT), before applying spatial and temporal filters. In the temporal dimension, a log-Gaussian filter with a half-octave full bandwidth was used to isolate narrow passbands of temporal frequency at the following peak frequencies: 0.12, 0.23, 0.47, 0.94, 1.88, 3,75, 7.5 and 15 Hz. The noise images were also filtered spatially to have a broadband 1/f ('pink') spatial spectrum.

Once temporally filtered, the stack of noise images was then inverse transformed and played as an animation, resulting in a CFS mask that modulated continuously and smoothly within a narrowly specified temporal frequency band (as opposed to the broad temporal spectrum produced by the usual 'step-change' method in which the mask pattern is updated every100 ms or so with a new image). The amplitude of the mask stimuli was scaled to produce a RMS contrast of 0.10.

Procedure

The experiment used the tCFS paradigm (Alais et al., 2024) with a temporally filtered noise mask and a sine-wave grating as a target. The participant's task was to track their perceptual state as the grating steadily rises or falls in contrast, indicating the moment when an invisible rising target breaks into awareness (i.e., bCFS threshold) or when a visible falling target returns to suppression (reCFS threshold). bCFS and reCFS thresholds are defined in terms of log contrast and the difference between bCFS and reCFS quantifies suppression depth. A trial continued until 10 reversals were recorded (as illustrated in Figure 1) and the eight frequencies were presented twice in unique random orders making a total of 16 trials.

Participants were given practice trials until they were familiar with the procedure of monitoring their changing perceptual states and were instructed to maintain fixation on the central fixation cross. Trials always began with the target visible at max contrast and slowly declining from high contrast. The participant's task was to report (with a mouse click) when it became suppressed. The moment suppression was reported the contrast change reversed sign and the invisible target increased in contrast until it broke through suppression (signalled with another mouse click), which reversed the contrast again so that the target once more declined in contrast towards resuppression, and so on in a cycle, as shown in Figure 1 (note that in developing the tCFS method, we compared starting with the target visible and starting with the target invisible and there was no difference in thresholds). The breakthrough contrasts were averaged into an estimate of the bCFS contrast threshold and the suppression contrasts were averaged into an estimate of the reCFS contrast threshold. To help the participant remember whether the target was rising in contrast towards breakthrough or declining towards suppression, an arrowhead was added to the upper or lower end of the vertical line forming the fixation cross.

Results

The results from Experiment 1 are shown in Figure 2. The thresholds obtained from the tCFS procedure as a function of mask temporal frequency are plotted in Figure 2a and suppression depth for each temporal frequency is plotted in Figure 2b. The threshold data were analysed in a 2 x 8 repeated-measures ANOVA (threshold type x temporal frequency) and this revealed a significant main effect of threshold, such that bCFS thresholds were significantly higher than reCFS thresholds ($F(1,15) = 86.126$, $p < .0001$, $\eta_p^2 = .852$). The main effect of temporal frequency was also significant ($F(7,105) = 6.679$, $p < .0001$, $\eta_p^2 = .308$), and the two factors did not interact ($F(7,105) = 0.620$, $p = .738$, $\eta_p^2 = .040$).

Figure 2a shows a clear peak in thresholds near the centre of the range around 1–2 Hz with a clear inverted-U shape. This was confirmed in a polynomial

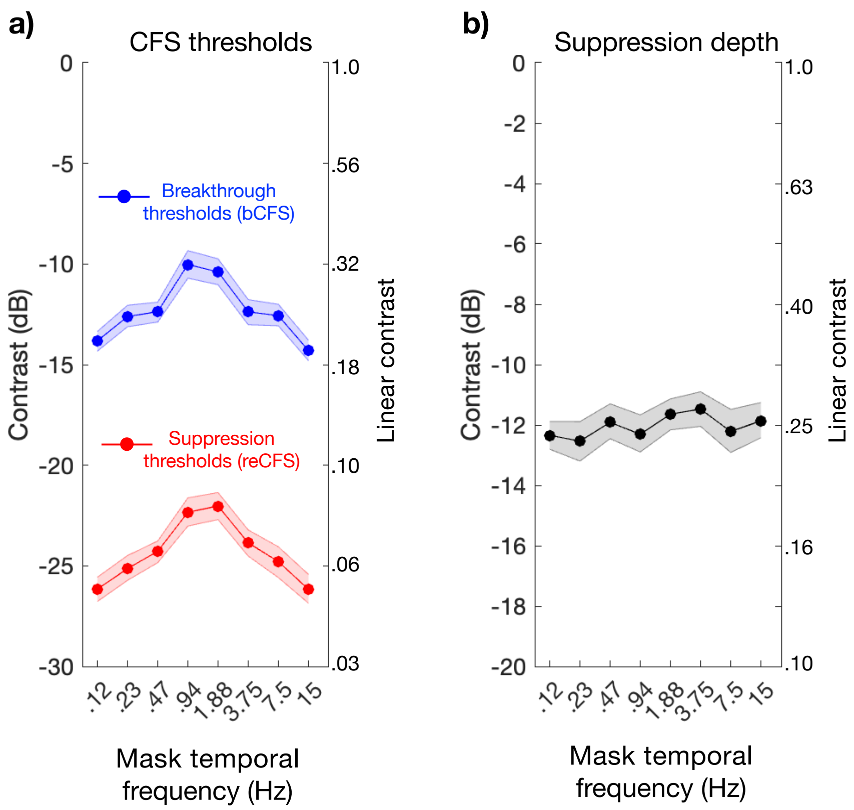

Figure 2: Group mean results from Experiment 1 for 16 observers. (a) Breakthrough and suppression thresholds from the tCFS procedure plotted as a function of temporal frequency with error shading showing ±1 standard error of the mean. Contrast is plotted logarithmically in decibels on the first y-axis and in linear contrast on the second y-axis. Breakthrough thresholds varied with the temporal frequency of the mask and peaked at 1.27 Hz. Suppression thresholds showed a very similar pattern and peaked at 1.455 Hz. (b) Suppression depth (the difference between breakthrough and suppression thresholds) as a function of masker temporal frequency. Despite the very large 7-octave (128x) range of temporal frequency, there was no significant variation in the strength of suppression.

trend analysis which showed the temporal frequency main effect exhibited a strong quadratic trend ($t(7) = 6.324$, $p < .0001$). All other polynomial trends (from linear to seventh order) were not significant.

To specify the peak of the temporal frequency data, we fit Gaussian functions to the bCFS and reCFS thresholds to obtain three parameters: (i) the frequency where the temporal frequency effect peaks (i.e., the Gaussian mean), (ii) the amplitude at the peak frequency, and (iii) the standard deviation of the Gaussian. For the bCFS data: thresholds peaked at 1.275 Hz with an amplitude of 4.005 dB and a standard deviation (i.e., sigma) of 1.602 octaves, corresponding to full bandwidth (2 x sigma) ranging from .420 Hz to 3.872 Hz. The Gaussian provided a good fit to the bCFS data, with $r^2 = 0.884$. For the reCFS data ($r^2 = 0.972$): thresholds peaked at 1.455 Hz with an amplitude of 4.156 dB and a standard deviation (i.e., sigma) of 1.419 octaves, corresponding to full bandwidth (2 * sigma) ranging from .544 Hz to 3.891 Hz.

Figure 2b plots suppression depth (the difference between bCFS and reCFS thresholds) as a function of temporal frequency. It is clear the value of suppression depth varies very little over a very large range of masker temporal frequencies. A one-way ANOVA confirmed there was no significant effect of masker temporal frequency ($F(7,84) = 0.752$, $p = .629$, $\eta_p^2 = .059$) and thus there was no evidence of the quadratic trend seen in the CFS threshold analysis ($t(105) = .771$, $p = .479$) or even a linear trend ($t(105) = 1.123$, $p = .264$). The grand mean for suppression depth was -12.038 dB.

Discussion

Our manipulation of masker temporal frequency by smoothly modulating the masker revealed breakthrough thresholds that varied systematically with the temporal frequency of the mask, peaking at 1.27 Hz (Fig. 2a). This confirms a similar finding reported by Han et al. (2016) who also varied masker temporal frequency by smoothly modulating the masker and found a similarly low peak at ~1 Hz. In their study, the bCFS method was used and so their data were reported in terms of breakthrough times. Here, we have replicated the same pattern of results using breakthrough thresholds defined by contrast. Another point of difference is that in their study there was only one temporal frequency lower than the peak value whereas we included several very low values. Our data confirmed there is a continued decline in breakthrough thresholds down to a very low and near-static modulation rate of 0.12 Hz (i.e., an 8-second period) and that a Gaussian function therefore provides a good description of the temporal frequency function.

As suppression thresholds are not normally measured in CFS experiments, apart from very recent studies using the new tCFS paradigm (Alais et al., 2024; Alais, Ye, Coorey, & Davidson, 2025), it was not clear what pattern the suppression thresholds would show as a function of temporal frequency. The results, however, were very clear: suppression thresholds (Fig. 2a) exhibited a strikingly similar pattern to the breakthrough thresholds. This was confirmed by the very similar best-fitting parameters for the Gaussian fits. Thresholds for suppression peaked at 1.45 Hz (compared to 1.27 Hz for breakthrough) and both threshold functions showed very similar bandwidths (1.41 vs1.60 octaves) and amplitudes (4.15 vs 4.00 dB). Not surprisingly, the two-way ANOVA showed no interaction between breakthrough and suppression functions,

Figure 2b shows CFS suppression depth, the difference between breakthrough and suppression thresholds. The recent studies using the tCFS paradigm have reported a conspicuous absence of variation in suppression depth despite testing a variety of target types from low-level stimuli (gratings and noise patches) to high-level stimuli (faces and natural scenes). These studies used typical flickering masks and varied the target, whereas here we have systematically altered the temporal content of the mask. Here, too, we found no interaction between the breakthrough and suppression functions and thus suppression depth is remarkably consistent as a function of temporal frequency. Thus, interocular suppression in CFS shows no selectivity for masker temporal frequency, just as it has shown no variation in suppression a variety of different target types.

The results revealed by using the new tCFS paradigm underline the need for caution in interpreting CFS data that rely on bCFS values alone. This is clear from the data in Figure 2a which show a pronounced peak in the bCFS function at around 1 Hz yet no such peak is seen in the suppression depth data in Figure 2b which shows suppression depth was uniform over all temporal frequencies. This challenges the interpretation of bCFS breakthrough times as an index of access to awareness because if all stimuli are equally suppressed then they must all overcome equal resistance to reach awareness, thus none has priority access. It is only by measuring both breakthrough and suppression thresholds that this point becomes clear. The co-variation of breakthrough and suppression thresholds seen in this experiment agree with the results of the original tCFS study by Alais et al., (2024) in which breakthrough and suppression thresholds tightly co-varied and thus maintained constant suppression depth.

Experiment 2

The aim of Experiment 2 was to test whether certain spatiotemporal combinations would make the CFS mask a stronger suppressor than other combinations. It has been suggested that interocular suppression is driven by spatial conflict (He, Carlson, & Chen, 2005) and that interocular motion conflict does not produce binocular rivalry (Ramachandran, 1991). This line of argument fits with the conditions of interocular conflict as they usually occur in real-world contexts (Arnold, 2011; O'Shea, 2011) which primarily involve spatial conflict. This suggests that interocular suppression would be tuned to spatiotemporal combinations which favour the parvo pathway and ventral/form processing (low temporal and high spatial frequency) compared to combinations favouring the magno pathway and dorsal/motion processing (high temporal and low spatial frequency). Experiment 2 tests this by measuring bCFS and reCFS thresholds and suppression depth for 6 different masks composed of all combinations of two spatial frequencies (1 or 10 cpd) and three temporal frequencies (0.12, 0.96, 15 Hz).

Methods

Thirteen participants did 12 trials of tCFS. The target grating was paired with a masker modulating at one of three temporal frequencies: 0.12, 0.94, or 15 Hz. Spatially, the masker was filtered into narrow spatial passbands centred at 1 or 10 cycles per degree with a half-octave full bandwidth. Thus, there were 2 x 3 conditions and participants did two repetitions. Each trial consisted of 12 reversals and conditions were completed in a random order.

Results

Experiment 2 results are shown in Figure 3. The threshold data were analysed in a 2 x 3 x 2 repeated-measures ANOVA (threshold type x temporal frequency x spatial frequency) and are plotted in Figure 3a. The main effect of CFS threshold showed bCFS thresholds were significantly higher ($F(1,12) = 163.034$, $p < .0001$, $\eta_p^2 = .931$)

and a low spatial frequency mask produced higher thresholds than a high spatial frequency mask ($F(1,12) = 24.770$, $p = .0003$, $\eta_p^2 = .674$). The effect of mask temporal frequency was also significant ($F(2,24) = 3.912$, $p = .034$, $\eta_p^2 = .246$). The only significant interaction was between spatial and temporal frequency ($F(2,24) = 5.276$, $p = .013$, $\eta_p^2 = .305$), with the low spatial frequency mask showing a peak at 0.94 Hz. Although the peak was not present for the high spatial frequency mask, overall, the main effect of temporal frequency still displayed a significant quadratic trend ($t(24) = 2.667$, $p = .013$), as in Experiment 1.

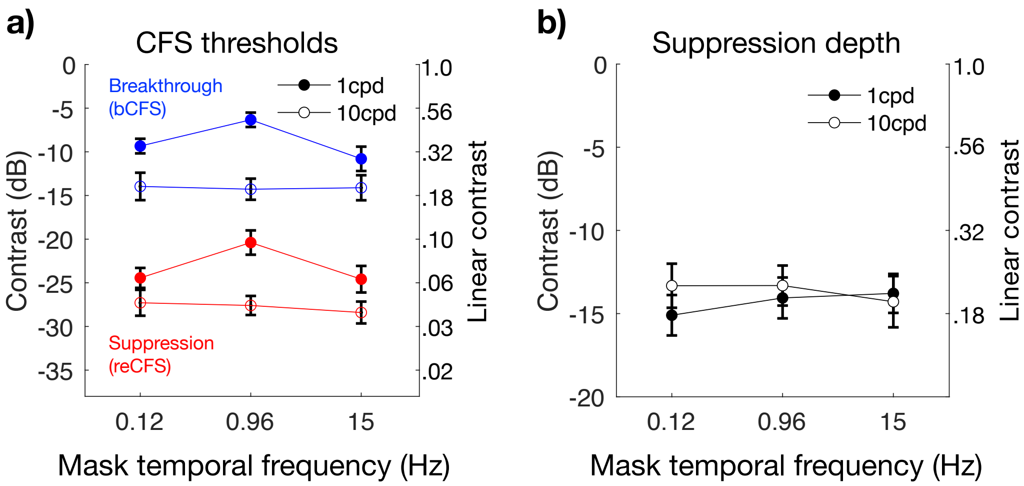

Figure 3: Group mean results from Experiment 2 for 13 observers. (a) Breakthrough and suppression thresholds from the tCFS procedure plotted as a function of mask temporal frequency with spatial frequency as a parameter. Thresholds were higher for the low spatial frequency mask compared to high, indicating greater suppression occurs at low spatial frequency. Thresholds for the low spatial frequency mask exhibit a peak near ~1 Hz, echoing the quadratic effect seen in Experiment 1. Spatial and temporal frequency did not interact significantly. (b) Suppression depth data (suppression minus breakthrough thresholds) showed no significant variation. Main effects of masker temporal or spatial frequency were not significant and neither was their interaction. All error bars show ±1 standard error of the mean.

Suppression depth results are plotted in Figure 3b and were analysed in a 2 x 3 repeated-measures ANOVA (spatial frequency x temporal frequency). There was no main effect of mask temporal frequency ($F(2,24) = 0.652$, $p = .530$, $\eta_p^2 = .052$) or spatial frequency ($F(1,12) = 0.384$, $p = .547$, $\eta_p^2 = .031$) and no interaction between them ($F(2,24) = 2.423$, $p = .110$, $\eta_p^2 = .168$). The grand mean suppression depth was -13.978 dB.

Discussion

The aim of Experiment 2 was to test whether certain spatiotemporal combinations – those favouring spatial processing – would make the CFS mask a more effective suppressor than masks designed to favour temporal processing. This was motivated by theoretical arguments and empirical studies suggesting that interocular suppression is a process tuned to spatial conflict (Arnold, 2011; He et al., 2005;

O'Shea, 2011; Ramachandran, 1991). This would suggest that suppression depth of the static target should be strongest for the mask that most favours spatial processing, that is, the mask combining the lowest temporal frequency (0.12 Hz) and the higher spatial frequency (10 cpd), consistent with the spatiotemporal preference of the parvo pathway (Livingstone & Hubel, 1988; Nassi & Callaway, 2009; Schiller & Logothetis, 1990). The suppression depth data, however, do not show a greater suppression depth for the low temporal/high spatial conditions (Figure 3b). Indeed, more broadly, the notable result is that suppression depth shows no significant change across the three levels of temporal frequency and two levels of spatial frequency. The finding of constant suppression depth in Experiment 2 matches the finding of constant suppression depth in Experiment 1 and elsewhere (Alais et al., 2024; Alais et al., 2025).

As was observed in Experiment 1, the finding of constant suppression depth was obtained even though the manipulations of the masker were effective at changing bCFS thresholds. This is clear in Figure 3a where breakthrough thresholds (blue data points) are clearly higher for the 1 cpd masks. However, because thresholds were also clearly higher for suppression (red data points), and by the same extent, there was no change overall in suppression depth. In two experiments, then, we have successfully manipulated bCFS thresholds and yet found no change in suppression depth because bCFS and reCFS thresholds in both experiments exhibited a tight covariation. That is, any rise or fall in bCFS thresholds was accompanied by a corresponding change in reCFS thresholds so that their difference (i.e., suppression depth) remained the same. Therefore, although changing the spatial or temporal frequency of the masker does produce changes in bCFS, those changes do not alter the magnitude of target suppression. The implications of this, and what drives the changes in bCFS threshold, are taken up in the General Discussion.

Experiment 3

Perceptual alternations in interocular suppression are thought to be due to a combination of mutual inhibition between competing left- and right-eye cortical neurons plus a key role for adaptation (Laing & Chow, 2002; Lehky, 1995; Wilson, 2003, 2007). At a given moment, one eye's neurons will be dominant (with a threshold equal to non-rivalrous monocular viewing) and will inhibit the other eye's neurons (thereby elevating their threshold). Due to adaptation, however, the threshold for the strongly responding dominant neurons will progressively weaken and, in a reciprocal inhibition model, this will progressively release the other eye's neurons from suppression. Over time, the threshold difference between the competing neural populations reduces and converges towards equivalence where a perceptual switch will occur (Alais, Cass, O'Shea, & Blake, 2010; Brascamp, van Ee, Noest, Jacobs, & van den Berg, 2006; Kang & Blake, 2010; Suzuki & Grabowecky, 2002; van Ee, 2009). On this model, bCFS and reCFS thresholds should converge over time and this can be quantified by varying the rate of contrast change of the target grating. With a fast-changing target, thresholds should be reached quickly and yield a larger suppression depth because the bCFS and reCFS thresholds will be less affected by adaptation-related convergence. Conversely, a slow-changing target should yield a smaller bCFS/reCFS difference, hence less suppression depth. Experiment 3 tests these predictions by varying the rate of contrast change of the target over 3 levels.

Methods

Twelve participants did 4 trials of tCFS with 18 reversals in each. The target grating was paired with a masker modulating at a temporal frequency of either 0.94 or 7.5 Hz with a 1/f spatial frequency spectrum (as in Experiment 1). There were two repetitions of each temporal frequency and condition order was randomised. The key variable was the rate of contrast change of the target grating. Three step sizes were compared, 0.035, 0.07 (as in Experiments 1 and 2) or 0.105 dB/s and they were interleaved randomly within a single trial. This was done by randomly selecting one of the step sizes after each turning point, with the constraint that each step size was selected six times over the 18-reversal trial and three of those were upward and three were downward. This meant that within each trial, the grating's contrast rose and fell at unpredictable rates. After the experiment, the turning point data were divided into to three bins corresponding to the different rates of change so the effect of contrast rate could be compared.

Results

Experiment 3 results are shown in Figure 4. The threshold data were analysed in a 2 x 3 x 2 repeated-measures ANOVA (threshold type x contrast change rate x temporal frequency) and are plotted in Figure 4a. The main effect of CFS threshold was significant, with bCFS thresholds being significantly higher ($F(1,11) = 139.013$, $p < .0001$, $\eta_p^2 = .927$), as was the main effect of temporal frequency, with a low temporal frequency mask producing higher thresholds than high frequency ($F(1,11) = 13.718$, $p = .003$, $\eta_p^2 = .555$). The rate of contrast change of the target grating was not significant as a main effect ($F(2,22) = 0.021$, $p = .979$, $\eta_p^2 = .002$), but with the data diverging equivalently in opposite directions there is no overall effect expected). However, there was a strong interaction between rate of contrast change and CFS thresholds, with bCFS trending higher and reCFS trending lower as rate of contrast change increased ($F(2,22) = 69.900$, $p < .0001$, $\eta_p^2 = .864$). None of the other interactions was significant.

The dashed lines in Figure 4a indicate how the breakthrough and suppression thresholds would vary based solely on an observer's reaction time to indicate the changes in their perceptual state. Because the target contrast continues to rise (or fall) over time, then a degree of rise/fall in the breakthrough/suppression plots is expected simply because the contrast change rate increases along the y-axis. We modelled that by assuming a rather long response time of 800 ms. It is clear that even with such a sluggish response time, the changes in the breakthrough and suppression thresholds are far in excess of a simple reaction time account (compare dash vs continuous lines).

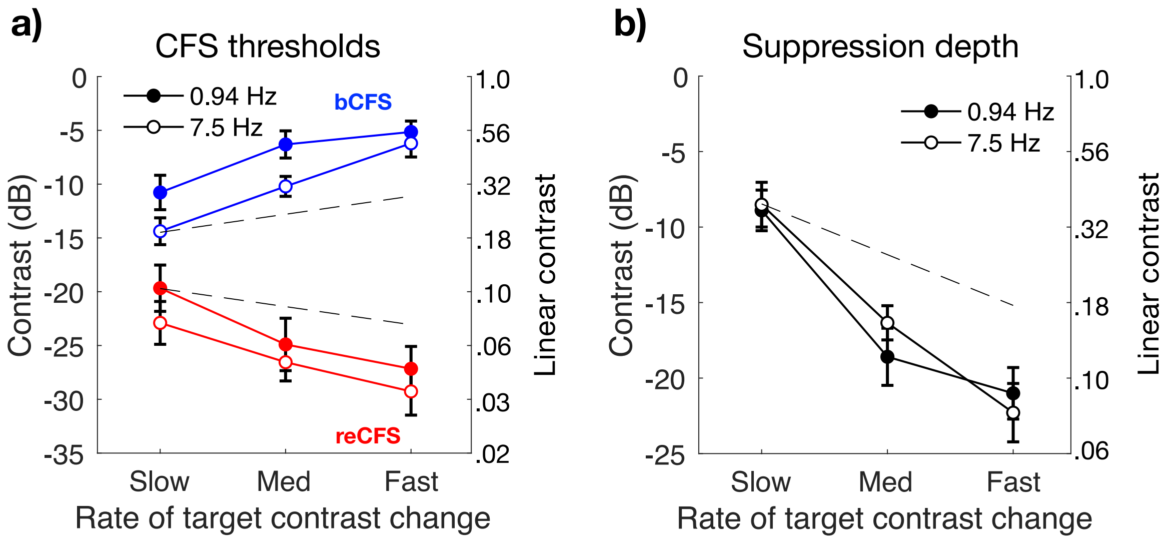

Figure 4: Group mean results from Experiment 3 for 11 observers. (a) Breakthrough and suppression thresholds from the tCFS procedure plotted as a function of target contrast change with mask temporal frequency as a parameter. Thresholds were higher for the low temporal frequency mask, consistent with the previous experiments. Dashed line: Because the target continues to increase (or decrease) until a response is recorded, a degree of threshold 'overshoot' is expected due to reaction time alone. The dashed line is the expected change in threshold based a fixed reaction time of 800 ms. The data clearly exceed the reaction time prediction. (b) Suppression depth (suppression minus breakthrough thresholds) was greater for faster changing targets, as expected of the adaptation hypothesis. The dashed line is again the reaction time prediction, here with a slope twice as steep as the slopes in panel a to capture their combined effect. All error bars show ±1 standard error of the mean.

Suppression depth results are plotted in Figure 4b and were analysed in a 3 x 2 repeated-measures ANOVA (rate of contrast change x temporal frequency). There was no main effect of mask temporal frequency ($F(1,11) = 1.009$, $p = .337$, $\eta_p^2 = .084$) but a strong effect of contrast change rate ($F(2,22) = 69.000$, $p < .0001$, $\eta_p^2 = .864$). The two factors did not interact ($F(2,22) = 1.422$, $p = .263$, $\eta_p^2 = .114$). The grand mean suppression depth was -16.237 dB. Again, (see dashed line) the changes in suppression depth over the different levels of contrast change far exceed what would be expected based simply on an observer with a response lag of 800 ms. Moreover, fitting a line to the suppression depth points in Figure 4b over the steps of contrast change rate (which are linearly spaced) reveals a deepening of suppression by 6.5 dB per interval. That can be compared to the dashed line which declines by 3.3 dB per interval. Therefore, if response times alone were to explain the empirical data the assumed response time would need to be an implausibly long 1575 ms.

Discussion

The results of Experiment 3 showed that CFS thresholds are higher for masks modulating at 0.94 Hz than 7.5 Hz but suppression depth remains constant despite the threshold changes. This replicates key findings from Experiment 1. The more important manipulation, however, was the comparison of three levels of rate of target contrast change designed to test the prediction that suppression depth should be greater for a fast-changing target as it will reach bCFS and reCFS thresholds quickly, before adaptation causes them to converge over time. These predicted results are clear in Figure 4a, showing diverging thresholds as the rate of contrast change increased and a consequent deepening of suppression in Figure 4b. This confirms a similar finding reported in the first tCFS paper (Alais et al., 2024) which used a standard Mondrian masker and also found greater suppression depth as the target's rate of contrast change increased.

We also tested whether the effects of target contrast change rate were attributable solely to a reaction time effect. For a given reaction time, a target rising quickly in contrast will always have a higher bCFS threshold than a target rising slowly. We assumed a slow reaction time of 800 ms and the dashed lines in Figure 4 show the changes in thresholds and suppression depth expected given that response time. It is clear the data show changes that far exceed the reaction time prediction. Indeed, an extremely slow reaction time of 1575 ms would be needed to produce the same slope as exhibited by the data points and thus argues against a response-time account and in favour of the hypothesised adaptation account.

A final point to note is that reaction times are longer for low than for high contrasts. Thus, a target declining in contrast towards reCFS threshold will have a lagged response relative to a rising target approaching breakthrough. However, these RT differences are small relative to the size of the effects reported in this experiment. In primate primary visual cortex, average response latencies increase by 8 ms for each halving of contrast (Oram, 2010). As our targets had a contrast range varying between 0.02 and 0.30 contrast (a range of almost 4 octaves), early cortical latencies would be expected to vary by about 32 ms. A study of simple reaction times in human observers to gratings found that at a similar spatial frequency to the grating target we used, RTs are on the order of 45 ms longer for 0.02 contrast compared to 0.30 contrast (Felipe, Buades, & Artigas, 1993). These effects are small in the context of our results where an RT of 1575 ms is needed to account for the effect in Figure 4b. Again, this favours an interpretation in terms of adaptation.

General discussion

The aims of this study was to test how manipulating mask temporal frequency would affect CFS thresholds and suppression depth and to reexamine an earlier study that found bCFS breakthrough times depended on mask temporal frequency and peaked for a modulation rate of ~1 Hz (Han et al., 2016).

In the first tCFS paper (Alais et al., 2024), a standard Mondrian mask was used and various categories of target image were compared (grating, noise, natural object, face). The present study used the converse arrangement, with the mask varying while the target was always a sinewave grating. The two key findings of the original paper were that: (i) bCFS threshold varied depending on the type of target (replicating many previous studies), and (ii) despite those changes in bCFS threshold, there was no change in suppression depth because any change in bCFS threshold was accompanied by a parallel change in reCFS threshold. In the current study, we confirm the same two results occur for the inverse arrangement in which the mask is manipulated and the target is constant. Indeed, the results of Experiment 1 provide a particularly striking illustration of these points. First, Figure 2a shows a systematic change in breakthrough thresholds as a function of temporal frequency that is almost perfectly repeated in the suppression thresholds, and second, Figure 2b shows a constant suppression depth for the same stimuli with no sign of the temporal frequency tuning seen Figure 2a. Experiment 2 confirms this result and extends it by introducing spatial frequency. Figure 3a shows that low spatial frequency masks produce higher thresholds than high frequency masks, yet suppression depth is constant over both levels of spatial frequency. These experiments, in finding constant suppression depth despite significant changes in breakthrough thresholds, match the findings of other reports that have used the tCFS paradigm (Alais et al., 2024; Alais et al., 2025).

Experiment 1, which tested the effect of masker temporal frequency, was motivated by an earlier paper which also examined the role of masker temporal frequency and showed that breakthrough times in the bCFS paradigm peaked at a very low frequency of ~1 Hz (Han et al., 2016). With the advent of the tCFS paradigm, we were curious to know whether the peak in breakthrough times at 1 Hz was due to greater suppression depth of the target at that frequency. We also wanted to extend the frequency range lower than Han et al. used because the Gaussian function they fitted to their data had only one data point below the Gaussian mean (versus five points above it) and so it was not entirely clearly if there was a Gaussian tuning or perhaps a general trend to longer breakthrough times as temporal frequency declined. The results of Experiment 1 answer both points very clearly. First, there is a clear tuning of bCFS threshold to masker temporal frequency that is well described by a Gaussian function and which peaks at ~1.3 Hz. Second, as noted above, there was no sign of temporal tuning evident in suppression depth (Figure 2b). Note that the peak in bCFS for very slow modulating targets is not due to the visual system's peak sensitivity for temporal frequency which occurs around 8 Hz (Derrington & Lennie, 1984; Livingstone & Hubel, 1988). Han et al. confirmed that temporal contrast sensitivity for their mask stimuli did indeed peak at 8 Hz, and so the peak in bCS at 1 Hz must be related to the characteristics of the interocular suppression mechanism and not to the visual system's sensitivity to temporal frequency more generally.

The finding of no change in suppression depth despite significant variations in bCFS, found here and in our other studies (Alais et al., 2024; Alais et al., 2025), means that researchers need to be very careful about the implications they draw from differences in bCFS thresholds. It is clear that bCFS values do systematically vary depending on specific combinations of stimulus and mask, but the degree of suppression exerted on a target remains constant. This does not support the interpretation that some stimuli are prioritised for processing despite no awareness of the stimulus or are given preferential access to awareness. Conclusions along these lines have proliferated in the CFS literature, despite attempts by several authors to critique this line of reasoning and bring some rigour to the field (Gayet et al., 2014; Moors, Hesselmann, Wagemans, & van Ee, 2017; Stein, Awad, Gayet, & Peelen, 2018; Stein & Peelen, 2021). In addition to their cautionary arguments, we advocate the use of tCFS as an ideal paradigm to test claims around consciousness because as well as measuring breakthrough it simultaneously measures suppression. Thus, any breakthrough threshold can be expressed relative to its suppression baseline, providing an inbuilt control condition that has been absent from previous CFS paradigms. In our use of tCFS, we have always found a uniform degree of suppression depth. It remains unanswered for the moment whether a careful replication using tCFS of some of the key CFS studies claiming special access to awareness for certain stimuli (Costello, Jiang, Baartman, McGlennen, & He, 2009; Gayet, Paffen, Belopolsky, Theeuwes, & Van der Stigchel, 2016; Gobbini et al., 2013; Jiang et al., 2007; Lee, Chien, Lin, & Yeh, 2022; Mudrik, Breska, Lamy, & Deouell, 2011; Yang, Zald, & Blake, 2007) would yield different suppression levels for those stimuli.

Another point of interest is that adaptation appears to modulate suppression depth. This is the conclusion based on the results of Experiment 3 which showed that increasing the rate of contrast change of the target leads to greater suppression depth. This result replicates the same finding in the original tCFS paper (Alais et al., 2024) and we believe it is most parsimoniously explained by a process of adaptation operating within a mutual inhibition model of interocular suppression. In the early phase of interocular suppression, one eye's neurons will be dominant and inhibit the other eye's neurons. Over time, however, adaptation causes the dominant response to weaken which concurrently eases suppression of the competing neurons and response levels in the two populations converge. This predicts that sensitivity to the suppressed stimulus should slowly increase over time and sensitivity to the dominant stimulus should decrease. This is exactly the pattern reported in binocular rivalry where the two sensitivities converge near the end of a rivalry phase (Alais et al., 2010), at which point noise fluctuations exert a role and will inevitably tip the inhibitory balance the other way (Brascamp et al., 2006; Kang & Blake, 2010; van Ee, 2009). By using a target that rises and falls in contrast to probe the breakthrough and suppression thresholds, a target undergoing fast contrast change will reach these thresholds sooner and reveal more divergent thresholds because less time will have elapsed and hence less adaption would have occurred. The data shown in Figure 4a show this pattern.

Given that suppression depth does not vary with masker temporal frequency (or image category: Alais et al., (2024)), why do bCFS thresholds change? It is likely due to variations in stimulus salience based on local image properties. It is well known that visual features such as orientation and spatial and temporal frequency play a role in determining suppression in interocular conflict in both binocular rivalry and CFS paradigms (Alais & Melcher, 2007; Alais & Parker, 2012; Drewes, Zhu, & Melcher, 2020; Fahle, 1982; Hong, 2015; Stuit, Cass, Paffen, & Alais, 2009; Stuit, Paffen, & Van der Stigchel, 2023; Webb & Hibbard, 2020; Yang & Blake, 2012; Zhu, Drewes, & Melcher, 2016). More fundamentally, these basic features also determine visual sensitivity (Derrington & Lennie, 1984; Tolhurst & Movshon, 1975). For different combinations of stimulus features, visual neurons in general, and those involved in interocular suppression in particular, will be more or less activated. We propose the particular salience associated with a given CFS target stimulus determines the level of CFS breakthrough, with high salience stimuli breaking through at lower contrasts. Correspondingly, due to their high salience, the same stimuli must descend to a low contrast to become suppressed again. For this reason, bCFS and reCFS thresholds are yoked and suppression depth tends not to vary.

Although it is popular to interpret a faster CFS breakthrough as indicating preferential access to awareness, we believe differences between images in bCFS breakthrough times are likely to reflect more basic factors (such as the fundamental salience of a target image to the visual system). If CFS breakthrough times differ because of stimuli varying in their low-level image properties, the claim about it being due to conscious prioritising is not needed. Often the argument goes that early breakthrough happens because certain images are special or ecologically important (e.g., fearful faces), but in that case, they would be expected to undergo less suppression and remain closer to the threshold for awareness. Yet this is not the case: suppression depth is constant in all the conditions we have measured so far – here for temporal frequency and elsewhere for other stimuli (Alais et al., 2024; Alais et al., 2025). Another reason to attribute CFS breakthrough to basic visual factors is that interocular suppression arises in primary visual cortex where left- and right-eye inputs are still separate (Polonsky, Blake, Braun, & Heeger, 2000) and where CFS suppression is particularly strong (Chen, Wang, Jiang, Tang, & Yu, 2025; Yuval-Greenberg & Heeger, 2013). In V1, neurons have small receptive fields sensitive to specific features and interocular suppression is triggered there by featural conflict. How could such a process spare a fearful face from suppression when faces are not represented until well after primary visual cortex? Perhaps some residual signal survives CFS suppression and advances to object processing areas, although this would likely be a weak signal as very recent 2-calcium neuroimaging data from awake primates experiencing CFS shows that suppression exerts an 80% reduction (~15 dB) in V1 activity (Chen et al., 2025), very similar to the suppression levels we report of ~15 dB (Alais et al., 2024).

Another interesting question is why the peak temporal frequency for bCFS occurs around 1 Hz. Han et al.'s (2016) study of temporal frequency included a stationary control condition and the bCFS peak at 1.3 Hz was well above bCFS for the stationary condition. Interocular suppression in CFS, then, does prefer a modulating stimulus but at a very low rate. The reason for this may relate to adaption. Because adaption weakens interocular suppression, as implied by the results of Experiment 3 and other findings (Alais et al., 2010; Kang & Blake, 2010; Suzuki & Grabowecky, 2002), a slowly modulating mask may provide just enough change and phase shift to activate new neurons over time so that they are free from adaptation. A similar account explains a finding in binocular rivalry that perceptual alternations are slowed when the rivalry stimuli slowly orbit around fixation so as to engage fresh neurons (Blake, Sobel, & Gilroy, 2003). A slow rate of change around 1 Hz or so is probably ideal because interocular suppression takes time to initiate (Wolfe, 1986) and has a sluggish time constant (van Boxtel, Alais, Erkelens, & van Ee, 2008) and so faster rates would disrupt the maintenance of stable suppression. An interesting follow up would be to examine CFS between maskers and targets that are both modulating, as rivalry has been shown to occur between conflicting temporal frequencies (Alais & Parker, 2012) and there is evidence that form and motion rivalry occur independently (Alais & Parker, 2006; Denison & Silver, 2012) and may therefore exhibit different characteristics.

Conclusion

We have used the new tCFS paradigm to examine suppression depth of targets rendered invisible by a CFS mask. Suppression depth averaged 13 dB across Experiments 1 and 2, which is 2-3 times the level of suppression produced by binocular rivalry (Alais & Melcher, 2007; Blake & Camisa, 1979; Nguyen et al., 2001). A key finding was that suppression depth is uniform despite mask manipulations which significantly altered bCFS thresholds. In light of this, we propose it is unwise to draw inferences from bCFS values alone concerning unconscious processing as all stimuli here and in another tCFS paper (Alais et al., 2024) showed uniform suppression. This is most consistent with a single suppression mechanism operating on all stimuli and one that likely occurs in primary visual cortex (Polonsky et al., 2000; Tong & Engel, 2001; Tong, Meng, & Blake, 2006), even though it may receive feedback from higher levels (Alais & Blake, 1998; van Boxtel, Alais, & van Ee, 2008). If interocular suppression does arise at such an early stage, suppression would be applied without regard to semantics or global properties and thus we caution, as others have (Moors & Hesselmann, 2018; Moors et al., 2017; Stein, 2019; Stein & Sterzer, 2014), against over-interpreting bCFS differences. Without a corresponding suppression threshold, breakthrough differences can be very misleading.

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