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# Binocular switch suppression: A new method for persistently rendering the visible 'invisible'

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## Abstract

Rendering the usually visible 'invisible' has long been a popular experimental manipulation. With one notable exception, 'continuous flash suppression' [Tsuchiya, N., & Koch, C. (2005). Continuous flash suppression reduces negative afterimages. *Nature Neuroscience, 8*, 1096–1101], existing methods of achieving this goal suffer from being either unable to suppress stimuli from awareness for prolonged periods, from being unable to reliably suppress stimuli at specific epochs, or from a combination of both of these limitations. Here we report a new method, binocular switch suppression (BSS), which overcomes these restrictions. We establish that BSS is novel as it taps a different causal mechanism to the only similar pre-existing method. We also establish that BSS is superior to pre-existing methods both in terms of the depth and duration of perceptual suppression achieved. BSS should therefore prove to be a useful tool for the large number of researchers interested in exploring the neural correlates and functional consequences of conscious visual awareness.
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## 1. Introduction

Suppressing usually salient images from awareness is a very popular empirical manipulation. Of course this can be achieved by simply closing the eyes, but more interesting manipulations achieve this goal without degrading the retinal image. This offers researchers an opportunity to examine both the neural and behavioural consequences of conscious visual awareness and the ramifications of subconscious processing. But the success these efforts is often limited by the methods used to achieve perceptual suppression.

Perhaps the most popular means of suppressing usually salient images from awareness is visual masking (see Breitmeyer, 1984), in which awareness of a transient target image is suppressed by presenting a masking image either shortly before or after. While this method is highly success-

ful its dependence on transient target presentations (just 10s of milliseconds) limits its potential as an empirical tool. For instance, using this method the consequences of visual suppression can usually only be measured after (but not during) the target presentation.

Another popular method, binocular rivalry (see Alais & Blake, 2005), makes use of the fact that when different images are presented to either eye the human brain will sometimes suppress one of the two from awareness and allow the other to dominate perception. One substantial benefit of binocular rivalry is that suppressions of usually salient images can persist for several seconds at a time, allowing researchers to investigate the consequences of suppression *during* the period of suppression (Haynes, Deichmann, & Rees, 2005; Logothetis & Schall, 1989; Tong, Nakayama, Vaughen, & Kanwisher, 1998). However, binocular rivalry is also characterised by unpredictable changes in perceptual dominance, which can make it difficult to probe a period of suppression with confidence. Also, binocular rivalry is usually characterised by periods during which parts of both images can be seen. Notably

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one of these tends to occur at the start of stimulus presentations (Wolfe, 1983). Thus, at least when using classical measures of binocular rivalry, it is probable that observers will be aware of the suppressed image content.

Although the causal mechanism(s) need to be clarified, a more recent method appears to combine and enhance the benefits of both visual masking and binocular rivalry. In this method, continuous flash suppression (CFS), a sequence of high contrast contour-rich patterns is shown to one eye to suppress awareness of persistent target images shown to the other (Tsuchiya & Koch, 2005). The optimal rate of presentation for the contour-rich patterns is reported to be approximately 10 Hz (Tsuchiya & Koch, 2005). Using this method awareness of target images can be reliably suppressed for minutes at a time (Jiang, Costello, Fang, Huang, & He, 2006; Tsuchiya, Koch, Gilroy, & Blake, 2006). Importantly, CFS can render observers completely unaware of the content of the suppressed image (Jiang et al., 2006). Thus CFS appears to be the best method so far reported for persistently suppressing usually salient images from awareness without degrading the retinal image.

Research from our own lab suggests an alternative method (Arnold, Grove, & Wallis, 2007). We have found that blurred images can be suppressed by better focussed images for prolonged periods (often for more than 40 s) if the different images are repeatedly switched between the eyes (at a rate of approximately 1 Hz). We link this persistent suppression with two well established concepts, signal strength and neural adaptation.

Historically it has not been clear precisely what is meant by "signal strength". However, it is well established that multiple factors, including the contrast and the spatial frequency content of the image, contribute to this construct (Fahle, 1982a,b; Levelt, 1968; Mueller & Blake, 1989). One suggestion is that signal strength relates to proximity in depth to the point of fixation (Arnold et al., 2007; Fahle, 1982a,b). In virtually all viewing conditions the eyes accommodate at the point of fixation, blurring the images of objects and surfaces displaced in depth from fixation. Blurring an image reduces both high spatial frequency content and image contrast. Thus many of the factors known to influence signal strength correlate with distance in depth from fixation.

According to this view signal strength would be functionally relevant in our daily lives. For instance, it could be beneficial to suppress weak images in our cluttered environment as we are often confronted with overlapping but conflicting images in the two eyes (Arnold et al., 2007; Fahle, 1982a,b; also see Changizi, in press). An obvious example is provided by peeking around a corner. When we do so one eye can be exposed to an image of the corner whereas the other can be exposed to an image of a distant person. Provided that we are peeking at the person (i.e. that we are fixated on them), the signal strength associated with the corner image will be weak as this image will be blurred. Suppressing awareness of this weak image could therefore enhance visibility of the person that we are peeking at, thereby increasing the probability of seeing without being seen.

The other relevant concept is neural adaptation. One aspect of neural adaptation is that the firing rates of neurons responding to visual input tend to diminish over time. A perceptual consequence of this is that visual stimuli can appear to fade if they are presented in a fixed retinal position for prolonged periods (Eagleman, Jacobson, & Sejnowski, 2004; Troxler, 1804). Many researchers have linked these effects to changes of perceptual dominance during binocular rivalry (Blake, Westendorf, & Fox, 1990; Lehky, 1988; Wilson, Blake, & Lee, 2001). The implication of these observations is that relative signal strength can change because of neural adaptation.

Combining these concepts suggests the following. If we ensure that one of two conflicting images has greater signal strength, and then take steps to mitigate the effects of neural adaptation, we should be able to ensure that the stronger image reliably dominates perception for prolonged periods. Note that this does not mean that the to-be-suppressed image need have a very weak signal strength, just weaker than the conflicting image with which it is paired.

These suggestions are consistent with a number of empirical observations. For instance, changes of perceptual dominance during binocular rivalry can be reversed by increasing image contrast (which is a contributing factor to signal strength) each time an image begins to be suppressed (Blake & Fox, 1974). This procedure would compensate for neural adaptation. Other measures can be taken to stop, or at least to diminish, neural adaptation from developing in the first place. For instance, movement can be introduced to the stimulus. Doing so considerably strengthens the probability that a stimulus will dominate perception during binocular rivalry (Breese, 1899). The presence of motion does not stop neural adaptation from occurring, but it can diminish adaptation related to visual contours being stabilised on the retina, and the perceptual fading of these that can occur as a consequence (Eagleman et al., 2004; Troxler, 1804).

Introducing movement is most likely to mitigate neural adaptation to contours at early stages of the visual system, such as the retinal ganglion cells. However, any mitigation of the rate of adaptation at early stages of the visual system is also likely to influence processing at subsequent stages. Note that the introduction of movement need not be planned. It seems that motion induced by small involuntary eye movements might be particularly effective in this context (Georgeson, 1984; Martinez-Conde, Macknik, Troncoso, & Dyar, 2006; van Dam & van Ee, 2005).

We believe that there is a still simpler and more effective way of mitigating neural adaption. Conflicting images can simply be repeatedly switched between the eyes, a method that we refer to as binocular switch suppression (BSS). This procedure will predominantly perturb adaptation within monocular neurons at early stages of visual processing. However, as discussed previously, mitigating adaptation rates at early stages of the visual hierarchy is also likely to influence subsequent processing. We believe that these effects are why we have previously observed that stronger

images can dominate perception for prolonged periods when the conflicting images are switched between the eyes (Arnold et al., 2007).

Readers should note that there are similarities between BSS and another popular binocular rivalry manipulation—flicker switch suppression (Lee & Blake, 1999; Logothetis, Leopold, & Sheinberg, 1996). In the latter, relatively persistent suppression (for seconds at a time) can be observed if equally focused images are both flickered (at ~18 Hz) while also being swapped between the eyes. Debate persists concerning the degree to which flicker switch suppression is analogous to classical measures of binocular rivalry (see Lee & Blake, 1999). However, BSS differs in that images do not have to be flickered while being swapped between the eyes. Instead persistent perceptual suppression can be achieved by simply swapping the images between the eyes, so long as one of the two is more blurred and therefore has a lower signal strength.

Here we will validate BSS as a means of inducing reliable and persistent perceptual suppression. We will assess both the optimal switch rate for inducing BSS and the strength of suppression that can be achieved with this procedure. We shall also explore the duration for which usually salient images can be suppressed from awareness during BSS. All of these measures will be contrasted with matching measures of CFS. We find that on all measures BSS is superior to CFS.

## 2. General methods

Visual stimuli were generated using Matlab software to drive a stimulus generator (Cambridge Research Systems) and were displayed on a gamma corrected 21″ Samsung SyncMaster 1100p+ monitor (1024 × 768 resolution; 120 Hz refresh rate). All stimuli were viewed, from a distance of ~57 cm, through an individually adjusted mirror stereoscope. A chin rest was used to stabilise the head.

Binocular fusion was facilitated in all experiments by the provision of red (CIE 1931; $x = 0.63$, $y = 0.33$, $Y = 24$ cd/m$^2$) dots (diameter subtending ~0.2° of visual angle) positioned ~2.2° above, below, and to either side of the centre of white noise/image(s) in both eyes. The persistent presence of these dots helped to maintain binocular fusion and minimize fixation drift.

All images were derived from greyscale pictures. A total of eight were created (see Fig. 1). They subtended ~4.7° (width) and 3.5° (height) at the retina. Contrast was linearly reduced from a peak in the middle of the images such that, by a radius of 1.5°, the image was reduced to a uniform grey (CIE 1931; $x = 0.28$, $y = 0.29$, $Y = 60$). The display background was also grey. Image RMS luminance contrasts were 0.14 and their mean luminance was 60 cd/m$^2$. Note that RMS luminance contrast calculations were based on a pixel by pixel analysis of luminance output across the entire image.

Square random white noise patterns were used to suppress perception of the greyscale images. These subtended ~5.4° and contained elements subtending ~0.2°. Such patterns provide a strong image signal as they can be made to have a high image contrast and, possibly more importantly, to contain a broad distribution of higher spatial frequency content.

In all experiments there were six observers, including one of the authors and five observers who were naïve as to the purpose of the study. All observers had stereo vision and normal, or corrected to normal, visual acuity.
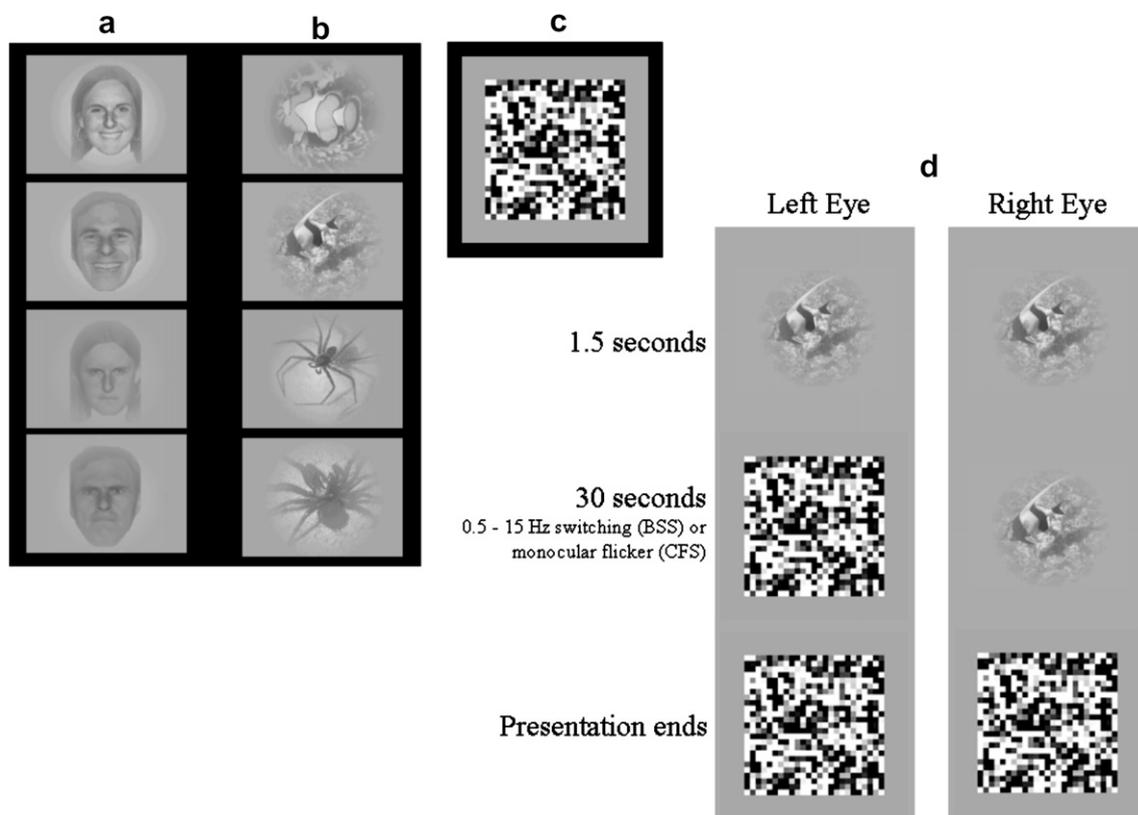


Fig. 1. Depictions of the human (a), non-human (b), and white noise pattern (c) images used in the experiments reported. (d) Depiction of a trial sequence in Experiment 1 (see text).

## 3. Experiment 1: Establishing optimal rates for BSS and CFS

BSS requires that conflicting images be repeatedly switched between the eyes. Doing so generates intermittent flicker in both eyes. In contrast, CFS requires that flicker be shown selectively to just one eye. It is possible, therefore, that the two methods are really just different ways of tapping the same neural mechanism. To assess this possibility we first determined the optimal rates of change for both BSS and CFS using the same experimental apparatus and observers.

### 3.1. Methods

During a run of individual trials, nine change rates (0.5–15 Hz) were each sampled twice in a pseudo random order. At the start of each trial a target image was presented to both eyes for 1.5 s (see Fig. 1d). This ensured that observers were familiar with the target image and could therefore report if, during the subsequent presentation, they could detect any part of it. Observers then heard a beep. In BSS runs of trials, after this a white noise pattern and a target image began to switch between the eyes at a persistent rate. In CFS runs of trials a sequence of different white noise patterns were shown selectively to one of the two eyes (selected at random on a trial by trial basis) and updated at a set rate whereas the target image was persistently shown to the other eye. In both cases observers tracked target image visibility by pressing and holding down a button whenever they could detect any part of it. Each individual

trial ended with both eyes being presented with an identical static white noise pattern. At this point another beep was sounded to cue the observer to prepare for the next trial.

Different white noise contrast levels (~0.11, ~0.23, and ~0.34 RMS luminance contrasts) were sampled during different runs of individual trials. Two runs of trials were completed by each observer for each of these three contrast values. The sequence in which these runs of trials were completed was randomised for each observer.

### 3.2. Results

For each observer we recorded average proportions during which observers reported being able to detect any part of the target image. These are expressed, for each white noise contrast level, as a function of the switching frequency between the eyes (BSS, Fig. 2a) or as a function of the white noise update frequency within a single eye (CFS, Fig. 2b).

The averaged data depicted in Fig. 2 show that observers tended to report greater levels of suppression during BSS than they did during CFS. However, our primary interests here are the optimal frequencies (of binocular switching or monocular flicker) for suppressing the target image. To determine these estimates we first normalised the data for each individual by summing proportions of disappearances across all frequencies (independently for each contrast level) and then dividing proportions of disappearance at each frequency by these summed values. This procedure controls for any individual bias in willingness to report suppression and provides an accurate sense of
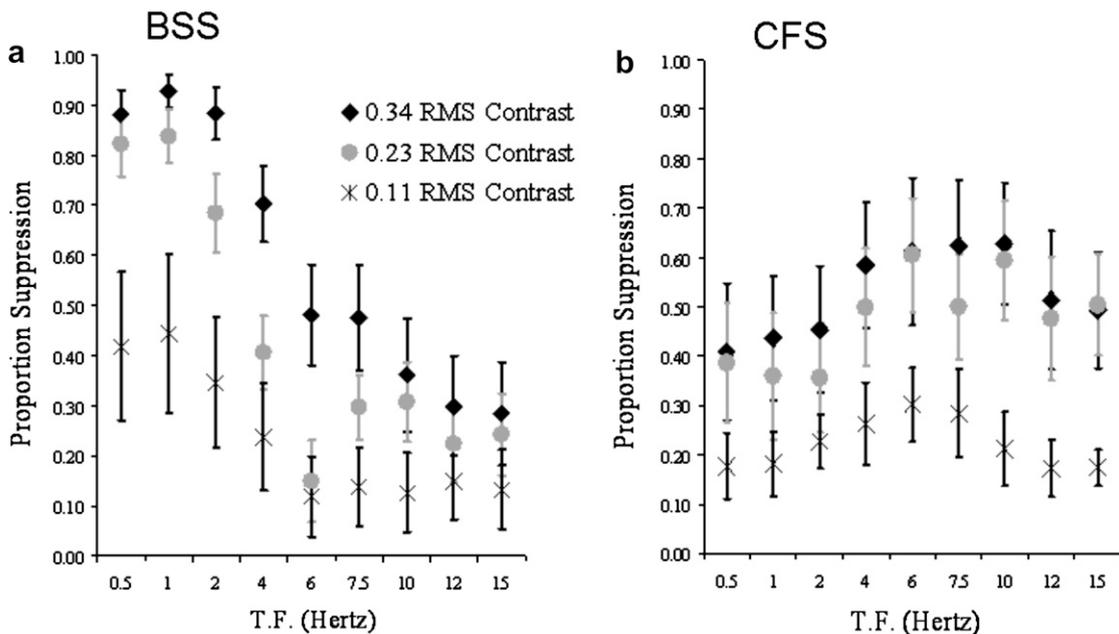


Fig. 2. Plots depicting proportions of stimulus presentation times during which observers reported being unable to detect any part of usually salient target images as a function of stimulus change rates (Hz). Change rates either refer to the frequencies at which images were switched between the eyes (a: BSS trials) or at which white noise patterns were updated in a single eye (b: CFS trials). The three levels of RMS contrast refer to the different levels of white noise luminance contrasts sampled (see text).

the variance of suppression as a function of change frequency. Normalised suppression functions are depicted in Fig. 3.

Estimates of the optimal frequencies for suppressing target images were determined by taking the fitted peaks of gamma functions. We also calculated upper and lower 95% confidence intervals associated with each fitted peak. For BSS we found that, on average, suppression peaked at 1 Hz binocular switch rates. This value falls well within the confidence intervals associated with each of the individual fitted peaks, indicating that the average value of 1 Hz provides a good estimate of the optimal switch rate for BSS. For CFS we found that, on average, suppression peaked at 7 Hz. Again, this estimate fell within the confidence intervals associated with each of the individual fitted peaks. This 7 Hz estimate is quite similar to previously reported optimal rates for CFS (Tsuchiya & Koch, 2005).

The most important feature of these data is that there was no overlap between the confidence intervals associated with the fitted peaks for BSS and for CFS. This shows that the two methods tap different neural mechanisms tuned to different rates of change. Thus BSS is a new and novel method for suppressing images, not a rediscovery of CFS.

## 4. Experiment 2: Assessing the strengths of suppression induced by BSS and CFS

Experiment 1 established that BSS is a new method for suppressing usually salient images from awareness. In Experiment 2 we will assess the strengths of suppression induced by BSS and CFS.

### 4.1. Methods

To assess the relative suppression strengths induced by BSS and CFS, we determined measures of $d'$ (Green & Swets, 1966), an objective measure of sensitivity. BSS and CFS were assessed during different runs of individual trials.
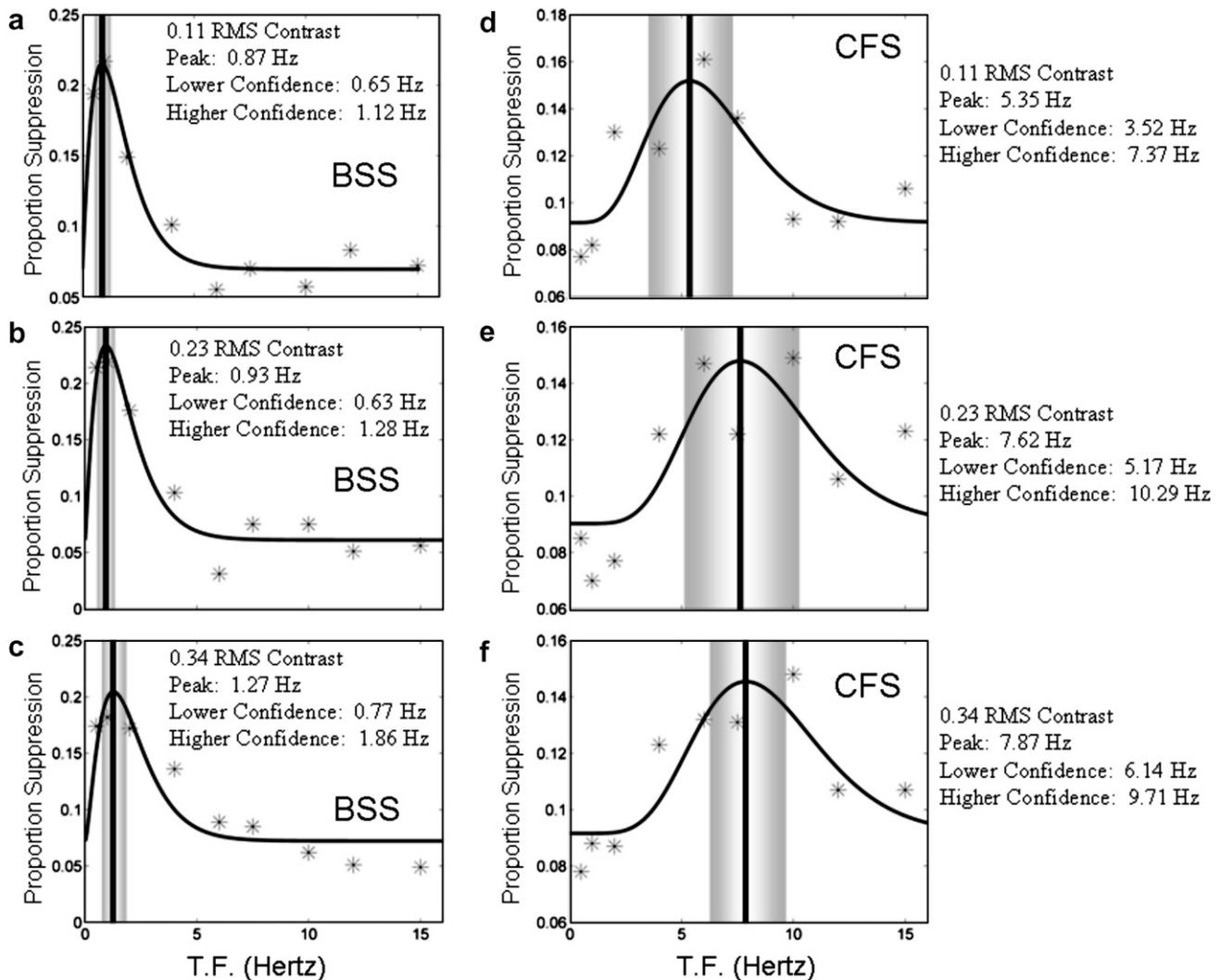


Fig. 3. Plots depicting normalized (see text) proportions of stimulus presentation times during which observers reported being unable to detect any part of usually salient target images as a function of stimulus change rates (Hz). Plots are shown for both BSS trials (a–c) and for CFS trials (d–f). Gamma functions have been fitted to these data. Fitted peaks are depicted by bold vertical lines and the 95% confidence intervals associated with fitted peaks by shaded grey bars.

At the start of all trials, observers were presented with matching static white noise patterns (RMS luminance contrasts ~0.56) in both eyes. In BSS trials (see Fig. 4a) one of the white noise patterns then disappeared and the remaining noise pattern began switching between the eyes at a rate of 1 Hz (the optimal switch rate determined in Experiment 1). One of the eight target images was then introduced, switching with the noise pattern between the eyes at a rate of 1 Hz for the next 3 s. In CFS trials (see Fig. 4b) presentations of the target image and dynamic white noise patterns started simultaneously and persisted for 3 s. The dynamic noise was created by updating white noise patterns fixed in one of the two eyes, determined at random on a trial by trial basis, at a rate of 7 Hz (again, the optimal rate determined in Experiment 1).

The end of all presentations was signalled by a beep, at which time matching static white noise patterns were presented to each eye. At this point the observer was required to indicate if they thought that the image presented on that trial had been of a human or a non-human. In most cases this necessitated that the observer guess.

All observers completed two runs of trials for both BSS and CFS consisting of 48 individual trials, with each of the eight images presented six times in a random order. The order in which the different runs of trials were completed was determined at random for each observer.

## 4.2. Results

Data were analysed to determine hit rates and false alarm rates. These were used to calculate $d'$ values which are depicted in Fig. 4c. A $d'$ value of 0 indicates a complete lack of sensitivity. A single sample $t$-test against a $d'$ of zero revealed that during BSS our observers were insensitive to the content of the suppressed images ($t_5 = -0.895$, $p = .412$). However, during CFS our observers were somewhat sensitive to the content of suppressed images ($t_5 = 4.364$, $p = .007$). This shows that, of the two methods, BSS was more effective at suppressing awareness of visual content.

## 5. Experiment 3: Assessing the durations for which images are suppressed during BSS, CFS and a combination of the two

Experiments 1 and 2 have established that BSS is both a new and an improved method for suppressing usually sali-
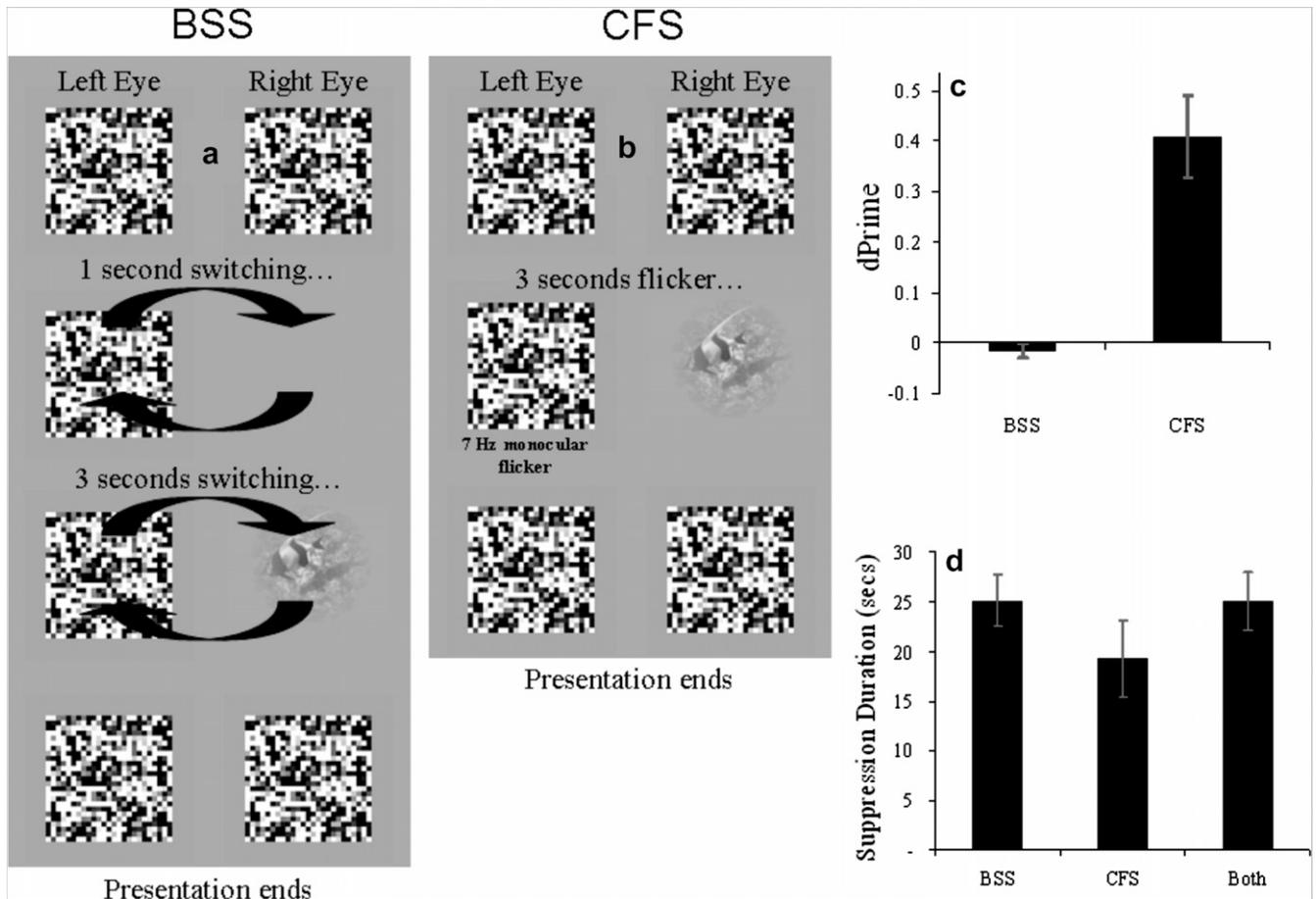


Fig. 4. (a) Depiction of a BSS trial sequence in Experiment 2. (b) Depiction of a CFS trial sequence in Experiment 2. (c) Bar plot depicting $d'$ values calculated from BSS and CFS trials in Experiment 2. (d) Bar plot depicting average suppression durations during BSS and CFS trials in Experiment 3. Data is also shown for trials that combined these two methods.

ent images from awareness. However, in Experiment 2 target images were only shown for 3 s. In Experiment 3 we will assess how long target images can be suppressed via BSS and CFS. We shall also assess whether the two methods can beneficially be combined.

### 5.1. Methods

The procedures for Experiment 3 were similar to those in Experiment 1 with the following exceptions. First, the target image for the trial was not shown before the stimulus presentation period. Second, only one frequency of binocular switching (1 Hz) and monocular flicker (7 Hz) was used. Third, only one level of white noise RMS contrast was used (~0.56). Fourth, each trial terminated when observers either classified the target image as human or non-human (by pressing one of two buttons) or after 30 s had elapsed. Observers were asked not to guess, so points in time at which classification responses were made should indicate when observers could clearly discern the image content. Data from incorrect classifications were excluded from subsequent analyses.

Three different types of trial were equally interspersed during runs of 48 individual trials. These included BSS and CFS trials, both similar to those described in Experiment 1. In the third type of trial we combined both BSS and CFS by updating the white noise patterns at a rate of 7 Hz while also swapping them between the eyes at a rate of 1 Hz.

### 5.2. Results

To determine an estimate of the durations for which images could be suppressed, we averaged the times at which observers could correctly classify image content with the trials that terminated before observers could do so. The latter were considered to provide a value of 30 s. These average estimates are therefore conservative as the maximal possible suppression duration is 30 s.

Average suppression duration estimates for each type of trial are depicted in Fig. 4d. On average BSS kept images suppressed for 25 ($\pm$2.6) seconds, CFS for 19.3 (3.9) s, and combinations of both BSS and CFS for 25 ($\pm$2.9) s. BSS therefore kept images suppressed for longer than did CFS ($t_7 = 2.45$, $p = .044$). Surprisingly, combining BSS with CFS did not induce longer lasting suppression ($t_7 = -1.16$, $p = .285$). Note that this is unlikely to be a consequence of a ceiling effect as neither condition prompted complete suppression.

We have treated trials that concluded before observers could classify the target image as having suppressed the target for 30 s. This happened on 71% ($\pm$12) of BSS trials, on 40% ($\pm$15) of CFS trials, and on 77% ($\pm$13) of trials that combined both methods. Thus the target image was suppressed throughout the stimulus presentation more often during BSS than it was during CFS ($t_7 = 2.65$, $p = .033$). However, combining BSS with CFS did not increase the

percentage of trials during which the target was suppressed throughout ($t_7 = -0.01$, $p = .996$).

### 6. Discussion

Here we have reported a simple new method for persistently suppressing usually salient images from conscious visual awareness. We have compared this new method, binocular switch suppression (BSS), to the best of the existing methods for this purpose, continuous flash suppression (CFS). We have shown that BSS and CFS tap different neural mechanisms each tuned to different rates of change (Experiment 1). Thus our report of BSS is novel. We have also shown that suppression induced by BSS is both more extensive (Experiment 2) and longer lasting (Experiment 3) than the suppression induced by CFS.

While we believe that our data show that BSS can be a stronger and more reliable method for suppressing images than is CFS, we hasten to point out that CFS is very effective and that, in some circumstances, it is likely to remain the preferred option. We anticipate this as BSS depends on the ability to seamlessly switch different images between the eyes. This is easy to do using mirrors, or perhaps stereo goggles, but it may be difficult to achieve with other methods. For instance, filtering images through red/green goggles is a popular and inexpensive means of presenting different images to either eye. Using this mode of presentation it would be necessary to change the physical colours of the different images in order to switch them between the eyes. Such changes are likely to disrupt BSS and are unnecessary during CFS.

We believe that BSS works because of two factors, a relative difference in image signal strength and because neural adaptation is mitigated. We link relative signal strength to distance in depth from the point of fixation, and thus to image blur, image contrast and spatial frequency content (Arnold et al., 2007; Fahle, 1982a,b). We link neural adaptation mitigation to the fact that switching conflicting images between the eyes precludes the build up of any adaptation related to an image being stabilised in a specific eye.

This last suggestion is conceptually interesting. It has previously been argued, from a functional perspective, that image signal strength is independent of both eye of origin and stimulus type (Arnold et al., 2007). Accordingly, perceptual dominance during binocular rivalry would track the stronger signal and not the content of a specific eye (Blake, Westendorf, & Overton, 1980; Polonsky, Blake, Braun, & Heeger, 2000; Tong & Engel, 2001) or a particular stimulus (Dorrenhaus, 1975; Logothetis et al., 1996; see Blake & Logothetis, 2002, for a review of this issue). However, even if these arguments are accepted, this leaves open the question of where in the visual system the competition to determine the stronger signal is likely to be carried out.

Readers should note that while we and others (Blake et al., 1990; Lehky, 1988; Wilson et al., 2001) have linked changes in perceptual dominance during binocular rivalry to neural adaptation, there is surprisingly little evidence

to establish this link. Some evidence is provided by the observation that perceptual dominance changes during binocular rivalry can be reversed by increasing image contrast (Blake & Fox, 1974). This manipulation would compensate for adaptation related reductions in image contrast (Eagleman et al., 2004; Troxler, 1804). Changes of perceptual dominance during binocular rivalry have also been linked to involuntary eye movements (van Dam & van Ee, 2005), which could alleviate the effects of contour adaptation (Georgeson, 1984; Martinez-Conde et al., 2006). We believe that, to some extent, the success of BSS provides still further evidence. However, it is at least possible that BSS is successful not because it mitigates neural adaptation, but because of some other consequence of the manipulation. Further investigations are therefore essential to elucidate the neurophysiological substrates tapped by BSS.

Rendering usually visible images invisible has long been a popular experimental manipulation. CFS (Tsuchiya & Koch, 2005) has proven very useful in this context (Bahrami, Lavie, & Rees, 2007; Jiang, Costello, & He, 2007; Jiang et al., 2006; Kanai, Tsuchiya, & Verstraten, 2006; Tsuchiya & Koch, 2005; Tsuchiya et al., 2006). We suspect that CFS works in a similar fashion to BSS, the difference being that CFS mitigates adaptation by presenting a succession of new images (Tsuchiya et al., 2006). However, we believe that BSS will also prove useful in allowing investigators to explore the neural, behavioural and cognitive influences of images while they are reliably and persistently suppressed from awareness.

## Acknowledgments

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