Visual Cognition

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/pvis20

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To cite this article: Mar S. Nikiforova, Rosemary A. Cowell & David E. Huber (2023) Gestalt formation promotes awareness of suppressed visual stimuli during binocular rivalry, Visual Cognition, 31:1, 18-42, DOI: 10.1080/13506285.2023.2192991

To link to this article: https://doi.org/10.1080/13506285.2023.2192991

Published online: 04 Apr 2023.

VISUAL COGNITION
2023, VOL. 31, NO. 1, 18–42
https://doi.org/10.1080/13506285.2023.2192991

Gestalt formation promotes awareness of suppressed visual stimuli during binocular rivalry

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ABSTRACT

Continuous flash suppression leverages binocular rivalry to render observers unaware of a static image for several seconds. To achieve this effect, rapidly flashing noise masks are presented to the dominant eye while a static stimulus is presented to the non-dominant eye. Eventually "breakthrough" occurs, wherein awareness shifts to the static image shown to the non-dominant eye. We tested the hypothesis that Gestalt formation can promote breakthrough. In two experiments, we presented pacman-shaped objects that might or might not align to form illusory Kanizsa objects. To measure the inception of breakthrough, observers were instructed to press a key at the moment of partial breakthrough. After pressing the key, which stopped the trial, observers reported how many pacmen were seen and where they were located. Supporting the Gestalt hypothesis, breakthrough was faster when the pacmen were aligned and observers more often reported pairs of pacmen if they were aligned. To address whether these effects reflected illusory shape perception, a computational model was applied to the pacman report distributions and breakthrough times for an experiment with four pacmen. A full account of the data required an increased joint probability of reporting all four pacmen, suggesting an influence of a perceived illusory cross.

ARTICLE HISTORY
Received 18 February 2022
Accepted 15 March 2023

KEYWORDS
Binocular rivalry; Gestalt perception; illusory contour; continuous flash suppression

Hold one hand a few inches in front of one eye, while keeping both eyes open. If you look at something in the distance while doing this, it will seem as if you are seeing through your hand. This is an example of "binocular rivalry" (Meenes, 1930) – while one eye can only see the hand, the other eye can see the world beyond it, and these two views are in conflict. Because the view for the unobstructed eye contains more meaningful/salient information, the visual system prioritizes it, creating the impression of a ghostly hand. If you close the unobstructed eye, the other eye will focus on the hand, revealing previously unappreciated details of the now opaque hand. Despite a considerable literature on binocular rivalry, the mechanisms by which awareness switches from one eye to the other are not fully understood; the current study tests the hypothesis that Gestalt formation contributes to these shifts of awareness.

Because the two eyes typically have a similar view of the world, awareness is most often combined or fused across them. This binocular fusion underlies 3D stereopsis and occurs as early as region V2 in the visual cortex (Howard & Rogers, 2012; Tong et al., 2006). However, if the two eyes have radically different views, awareness may be patchy across the two eyes, or entirely favour one eye, suppressing awareness for visual information from the other eye (Meenes, 1930; Sharp, 1928). Even with complete suppression, the visual information from the suppressed eye is active in primary visual cortex (V1) and is possibly active in higher-level cortical regions to a lesser extent (Blake, 2001; Tong et al., 2006).

If suppressed visual information is processed beyond the visual primitives found in primary visual cortex, high-level perceptions may play a critical role in determining a switch of awareness between eyes during binocular rivalry. Specifically, we hypothesize that Gestalt perception (Koffka, 1935) plays a role in shifts of awareness, such that a representation of a whole object is more likely to enter conscious

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awareness than a collection of separate parts. The specific Gestalt we use is an illusory rectangle arising from a Kanizsa figure induced by pacman-shaped objects (Kanizsa, 1976; Koffka, 1935). A useful property of this Gestalt is that the presence of an illusory rectangle can be disrupted without significantly changing the positions and orientations of edges in the image, by rotating the pacmen through 180°.

Binocular rivalry and gestalt perception

Prior work demonstrated that Gestalt information can affect awareness shifts between the eyes during binocular rivalry when the two eyes are shown different static images that conflict. For instance, de Weert et al. (2005) presented different geometric stimuli to each eye that contained different shapes and colours in the upper and lower halves. For all stimuli, half of the stimulus from one eye could be combined with half of the stimulus from the other eye to form a higher-level Gestalt percept, such as an arrow, cross, or diamond; in some cases, the binocular combination resulted in a uniform colour (representing Gestalt grouping by colour similarity) and in other cases it resulted in a shape with horizontal symmetry (representing Gestalt grouping by shape similarity). Supporting a role for Gestalt formation in capturing awareness during binocular rivalry, awareness was more often captured by Gestalt objects that combined halves across the eyes than by non-Gestalt, monocular objects (six participants formed binocular Gestalt percepts driven by shape similarity and two by colour similarity). A closely related study by Arnold et al. (2009) presented four pacman objects to the non-dominant eye that were either aligned, forming an illusory square, or individually rotated to disrupt the Gestalt. The other eye viewed a static noise mask at the locations corresponding to the four pacmen. Rather than measuring spontaneous alternations of awareness between eyes, this study manipulated awareness by changing the contrast of one pacman to draw awareness away from the dominant eye viewing the noise mask. The contrast change often triggered awareness of the contrast-manipulated pacman and this awareness then spread to other pacmen. Supporting the hypothesis that awareness is drawn to the suppressed eye by perception of an illusory shape, when the pacmen could form a Kanizsa square, awareness more readily cycled around the four pacmen in a clockwise or counter-clockwise direction.

A major limitation of prior binocular rivalry studies investigating Gestalt perception is the use of traditional rivalry manipulations, presenting static images to both eyes. With this technique, suppression is partial, tenuous, and fleeting. Rather than complete suppression of visual information from onset of the image, awareness often flips back and forth between the images shown to the two eyes. As a result of this alternation, even if one eye is currently suppressed, the visual information shown to that eye may have been recently active, and this lingering activation could prime the Gestalt that is supposed to be suppressed. For instance, in the Arnold et al. (2009) study, participants were explicitly allowed to perceive the Gestalt (or lack thereof) on every trial, prior to pressing a key to indicate that suppression was finally achieved, thus triggering the start of the trial. Consequently, participants may have previously been aware of the Gestalt. Thus, it is not clear from these rivalry studies whether the active formation of a new Gestalt percept triggered a shift of awareness or whether prior, conscious Gestalt perception primed a visual representation that promoted awareness of the suppressed Gestalt in a top-down manner.

Continuous flash suppression (CFS)

To determine if the inception of Gestalt perception is an endogenous trigger for shifts of awareness during binocularly rivalry, it is important that observers were not previously aware of the Gestalt. In other words, the Gestalt image needs to be fully suppressed both before and immediately after its presentation. To achieve this, we presented dynamically varying noise masks to the dominant eye to direct awareness away from the non-dominant eye before the onset of the image shown to the non-dominant eye. This technique – known as Continuous Flash Suppression (CFS) – produces a much stronger form of suppression, in which observers often remain completely unaware of a static image shown to the non-dominant eye for several seconds, or even tens of seconds (Tsuchiya & Koch, 2005).

Using CFS, our study builds on the work of Arnold et al. (2009), examining awareness for aligned versus misaligned pacmen. Arnold et al. used an exogenous trigger by changing the contrast of one pacman to draw awareness to that pacman, but here we ask whether Gestalt perception can be an endogenous trigger for shifts of awareness. To ask this question, the current study used the "breaking" continuous flash suppression (b-CFS) paradigm (e.g., Gayet et al., 2014), in which observers are aware of only the constantly changing noise masks shown to the dominant eye at the start of the trial, and this continues until they become aware of the static image presented to the non-dominant eye. The key dependent measure in prior b-CFS studies was how quickly this breakthrough occurs, with different times-to-breakthrough for different kinds of images. It is described as breakthrough because it appears as if the static image is punching through the noise mask in a piecemeal fashion (e.g., awareness starts in one location and then spreads to the whole image). We hypothesize that an illusory shape might be the first piece that breaks through.

Findings from b-CFS studies are mixed, but some suggest that the visual system can perform high-level processing of the suppressed static image, as indicated by faster time-to-breakthrough for meaningful objects such as upright faces, words, or faces displaying fear (Jiang et al., 2007; Yang et al., 2007). However, the stimuli that foster faster breakthrough often differ from control stimuli in their low-level visual attributes, providing an alternative explanation of faster breakthrough for more meaningful images. For instance, rather than the perception of a fearful expression providing the trigger for faster breakthrough, it might be that a difference in the distribution of spatial frequency information for fearful faces versus neutral faces underlies this effect (Gayet et al., 2014; Stein et al., 2011).

It is impossible to control all visual properties when comparing a Gestalt stimulus to a non-Gestalt stimulus – doing so would necessarily result in identical images. Instead, we sought to control the most relevant low-level visual properties for our particular research question. More specifically, it is well documented that simple cells tuned to orientation in primary visual cortex exist in ocular dominance columns, with receptive fields favouring one eye or the other (Hubel & Wiesel, 1959). Thus, perception of oriented lines occurs prior to fusion between the eyes. Furthermore, oriented lines are thought to be the basic building blocks for shape and object perception (Lindsay, 2021). Therefore, we used stimuli that were nearly identical in terms of the positions and orientations of edges. This was achieved by presenting pacman-shaped objects in all conditions, with the pacmen presented in the same locations in all conditions, differing only in terms of whether the pacmen were oriented to suggest an illusory shape or were rotated by 180° to prevent such an illusion.

Prior studies showing Kanizsa figures viewed under CFS provide a complicated picture. Harris et al. (2011) presented Kanizsa triangles for a brief duration under CFS, asking observers to make a guess as to whether the illusory triangle was pointed left or right. Suggesting that illusory contours are unprocessed or unavailable under suppression, performance was at chance. However, the use of brief CFS trials rather than b-CFS might explain this finding. If Gestalt perception serves as the trigger for breakthrough, this result is expected because trials were purposely kept to a duration too short to allow breakthrough (see also Banica & Schwarzkopf, 2016). In a different study, Wang et al. (2012) presented Kanizsa triangles in a b-CFS paradigm, measuring time to breakthrough. In support of our hypothesis that Gestalt perception can trigger breakthrough, they observed faster breakthrough compared to a control condition with randomly rotated pacmen. However, casting doubt on this conclusion, Moors et al. (2016) found similar results in conditions that displayed weak or even absent illusory surfaces (induced through pacmen with curved mouths or crosses, respectively). In other words, the effect did not depend on the stimuli producing Gestalt perception and may have instead reflected some sort of uncontrolled stimulus differences between the Gestalt and non-Gestalt displays. The authors suggested that faster breakthrough in the Wang et al. study might have reflected a greater preponderance of cardinal orientations, which are known to be over-represented in primary visual cortex (Furmanski & Engel, 2000; Li et al., 2003), in comparison to the control condition with randomly oriented pacmen. However, these need not be mutually exclusive explanations, and it is possible that Gestalt formation and the presence of cardinal orientations both play a role in promoting shifts of awareness to the suppressed eye. Nevertheless, this highlights the need to control low-level aspects of the images (e.g., equate the orientation of edges in the Kanizsa and non-Kanizsa conditions) when assessing the influence of Gestalt-based illusory contours.

The present research

Binocular rivalry is a dynamic process: the dominance of one eye over the other can unfold gradually, like a travelling wave along the visual field (Maruya & Blake, 2009; Wilson et al., 2001). Because this process takes time, it may be possible to interrupt the process at its earliest stage to determine which aspects of the image triggered the awareness shift to the suppressed eye. In the current study, we instructed observers to press a button as soon as they were able to see any aspect of the static image presented to the non-dominant eye. Once they pressed the button, the CFS trial was immediately interrupted to stop the gradual breakthrough process. Following interruption of the CFS trial, observers gave a detailed report of which aspects of the suppressed image were seen. Consider the image in Figure 1, which shows one of the stimuli used in Experiment 2 of the current study. The light grey ellipse was not visible to participants and is shown here to illustrate a hypothetical situation in which breakthrough occurs in a piecemeal fashion centred on the illusory rectangle. Two of the pacmen are facing each other (so-called "talkers"),

Figure 1. An example of a stimulus display containing aligned pacman-shaped objects (so-called "biters") that could give rise to perception of an illusory rectangle. If perception of the illusory rectangle is a trigger that shifts awareness away from the dominant eye (viewing a dynamic mask, not shown) to the suppressed eye (viewing the biter array, shown), then awareness may first occur for the biters that give rise to the illusory rectangle. Furthermore, breakthrough should occur more quickly for images that can give rise to illusory shapes.

while the other two are facing away (so-called "haters"). The talkers are aligned and might create the Gestalt percept of an illusory rectangle partially occluding two dark circles. If the illusory rectangle is the initial trigger for breakthrough, then awareness may first shift to the non-dominant eye at locations corresponding to the illusory rectangle and its two associated pacmen. Thus, a key dependent measure in our study assesses the breakthrough of pairs of pacmen (i.e., whether awareness is reported for both pacmen of a pair) that are or are not aligned to suggest the presence of an illusory rectangle.

We hypothesize that the onset of Gestalt perception serves as an endogenous trigger that shifts awareness from one eye to the other during binocular rivalry. To test this hypothesis, we used the CFS technique to limit awareness of the pacman inducers prior to the moment of breakthrough, thus ruling out a priming explanation based on alternation of awareness between the eyes. Because this hypothesis assumes that the onset of Gestalt perception is a trigger, we used a time-to-breakthrough paradigm to ensure that all trials progressed to the point of this trigger. To determine the attributes that triggered breakthrough, we asked participants to give a detailed report of the observed pacmen at the inception of breakthrough (i.e., the point of partial breakthrough). To preview our results, we found faster breakthrough when the suppressed image could produce a Kanizsa Gestalt and we found that observers were more likely to become aware of both pacmen needed to form a Gestalt, suggesting that Gestalt perception itself was the trigger.

This study is necessarily correlative in nature because it is not possible to manipulate whether Gestalt perception does or does not occur while holding everything else constant. To address this limitation, Experiments 1 and 2 controlled different aspects of the stimuli when comparing an experimental condition that entailed the possibility of Gestalt perception to a non-Gestalt condition. Experiment 3 was an in-depth analysis of the Experiment 2 data, using formal model comparison to ascertain whether certain aspects of the Gestalt stimuli (e.g., inward pointing pacmen and collinearity) could fully explain the results, or whether Gestalt perception was also needed to explain the data patterns.

The experimental paradigm attempts to induce illusory perception of contours and shapes by presenting pacmen that are aligned, but this does not necessarily mean that Gestalt perception occurs at the point of breakthrough. Perception of an illusory shape results from a multi-stage process, involving feedback from shape perception onto earlier visual stages (Wokke et al., 2013; Yan et al., 2021). When participants become aware of aligned pacmen, it may be that this feedback process has not yet produced Gestalt perception of an illusory shape. Instead, it might be that aligned pacmen are more readily noticed owing to other properties, such as collinearity, which has been shown to produce simultaneous report of pairs of Gabor patches with binocular rivalry (Alais et al., 2006). To address this possibility, we developed a computational modelling framework; we constructed different models of the factors contributing to breakthrough and compared how well they explained the patterns of pacman report data and breakthrough times. One model included enhanced report for pairs of collinear pacmen whereas another included enhanced report for all pacmen needed to form an illusory shape. For instance, in Experiment 2, the four pacmen might be positioned to indicate an illusory cross, and the question asked is whether the probability of being aware of all four pacmen is greater than would be expected from separate pairs of collinear pacmen. If so, this suggests that an illusory cross linking all four pacmen was perceived, and provides further support for the hypothesis that Gestalt perception can trigger shifts of awareness during binocularly rivalry.

Experiment 1

Using binocular rivalry induced by CFS, Experiment 1 investigated whether observers would more quickly become aware of a pair of objects shown to the non-dominant, suppressed eye when that pair could be connected by an illusory rectangle. This prediction follows from the proposal that illusory shape perception can trigger a shift of awareness to the suppressed eye.

On every trial, two pacman-like objects were shown to the non-dominant eye. These objects were circles with a square cut out on one side (Moore et al., 1998; Sobel & Blake, 2003) and we refer to these objects as "biters" because they resemble a mouth that is closing (whereas "pacman," with a large wedge cut out of the circle, is a mouth that is wide open). When the cut-out mouths were facing towards each other, we refer to the pair as "talkers," and this can produce an illusion of a long rectangle overlying two black circles. To equate the stimuli between conditions in terms of spatial orientation of edges, the non-gestalt control condition was created by rotating one biter by 180°. In this case, we refer to the pair as "spooners."

To avoid the use of cardinal orientations, the line connecting the two biters in a pair was always at an oblique angle (i.e., when present, the illusory rectangle was at an oblique angle). Observers were instructed to press a key as soon as they became aware of any objects presented to their non-dominant eye, thus interrupting the trial. They then indicated how many biters they saw, allowing for the possibility that a biter was only partially seen (i.e., half a biter). Thus, the possible answers were, .5, 1, 1.5, and 2. Finally, they indicated whether the biters were facing towards each other. If an illusory rectangle can draw awareness to the non-dominant eye, we expected that time to breakthrough would be faster for trials that presented talkers, and, furthermore, that observers would be more likely to report both biters in a pair when they were talkers than when they were spooners.

Method

Participants

In Experiment 1, sixty adults (47 female, ages 18–22) were tested (two were removed from analysis owing to outlying performance, defined as having an overall median breakthrough time more than two standard deviations away from the median of individual participant median RTs, leaving fifty-eight for analysis). This sample size yielded 1860 datapoints in total across participants for each condition, for a full breakdown of the 8 conditions when including the 4 screen positions as an independent variable of interest. Subsequent analyses failed to find screen position differences and so the reported results are collapsed across screen position. All experiments were conducted in accordance with protocols approved by University of Massachusetts Amherst Human Research Protection Office (HRPO). All sixty participants in the experimental task were naive to its purpose, had normal or corrected-to-normal vision, and were confirmed as having low risk of seizure. Participation took about one hour, followed by debriefing and compensation with academic credit. Prior to beginning the task, each participant determined their dominant eye through the Porta test as described in Roth et al. (2002).

Apparatus

The stimuli were displayed on a 24″ LED monitor (approximately 56° visual angle, with participants about 22.5″ from the screen) with a resolution of 1920 × 1080 pixels at a 100 Hz refresh rate. The experimental tasks were written in MATLAB 2018a using PsychToolBox and run on a Windows PC (Brainard, 1997). Participants wore NVidia 3D shutter glasses synchronized in their left/right alternation with the monitor refresh rate for the duration of the experiment to allow presentation of different stimuli to the two eyes (referred to as dominant versus non-dominant). Thus, the images shown to each individual eye refreshed at a rate of 50 Hz rather than the 100 Hz refresh rate of the monitor. Responses were recorded via keypress.

Stimuli

All stimuli were presented on a grey (76.5 RGB value) background within a centred, 450 × 450-pixel area onscreen, along with a central white fixation dot with a radius of 8 pixels. A white 8-pixel wide border was placed around the stimulus array to aid stable binocular fusion. The participant's non-dominant eye was shown a pair of black "biter" Kanizsa inducers that were angled at 45° from each other (e.g., some trials presented a pair of biters positioned along a diagonal from lower-left to upper-right, while other trials presented biters positioned along a diagonal from upper-left to lower-right). The pair of biters was located straddling an imaginary middle point, with the centre of each biter placed an equal distance from the middle point, and with the middle point located either above, below, to left, or to right of the central fixation point (the example stimuli shown in Figure 2 might appear to violate these positions as described, but this is a visual illusion; the midpoint is directly above fixation for the left stimulus and directly to the right of fixation for the right stimulus). Above/below/left/right placement varied from trial to trial, with equal numbers of each location employed across the whole experiment. The biters each had a radius of 20 pixels and were either facing in the same direction ("spooners") or towards each other such that they might give rise to the perception of an illusory rectangle ("talkers"). The onset of the biters to the non-dominant eye was gradual, to avoid drawing awareness: the two biters gradually appeared via linear stepwise increases in opacity every 100 ms, reaching full opacity after four seconds (Figure 3).

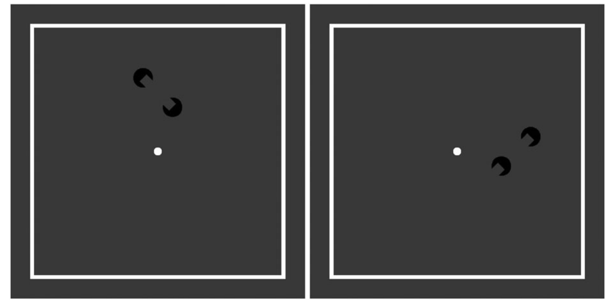

Figure 2. Examples of "Talker" biters (left panel) and "spooner" biters (right panel) presented to the non-dominant eye in Experiment 1. On a given trial, the pair of biters could be oriented in either direction, and could be located in any one of four locations: above (left panel), below, left or right (right panel) of the central fixation point.

In all conditions, the dominant eye was presented with eight circular patches of a visual noise mask (refreshed with a new pattern at a rate of 10 Hz throughout the trial) at the screen locations where the biters were permitted to appear. As viewed on the screen, these circular patches extended 5 pixels beyond the edge of the biters (i.e., the circular apertures had a radius of 25 pixels, compared to the biter radius of 20 pixels). Circular patches were used instead of full screen noise masks to allow unobstructed viewing of the regions between adjacent biter pairs where an illusory rectangle might be perceived (Harris et al., 2011). Each noise mask was created by randomly placing 1150 squares on top of each other with full opacity, with the squares randomly varying in size from 32 to 38 pixels across. Each square was randomly assigned to be bright red, yellow, or blue. The result was an abstract, colourful pattern like a painting by Piet Mondrian (hence, these noise masks are referred to as "Mondrians").

Procedure

Each participant completed a short practice block of 20 trials, followed by 7 blocks of 32 trials each, for a total of 224 experimental trials. There was an equal number of spooner and talker trials in each block,

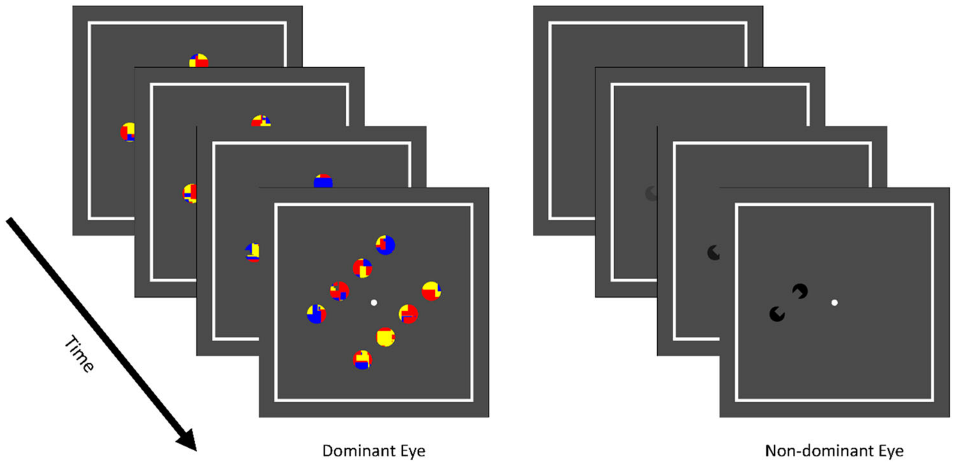

Figure 3. Stimulus sequence for Experiment 1. Because this particular trial presented the two biters along the diagonal from lower-left to upper-right, the eight Mondrian patches shown to the dominant eye lie along this same diagonal, appearing at all possible positions where biters might appear (above, below, left or right of central fixation). Other trials presented biters along the upper-left to lower-right diagonal, in which case the eight Mondrian patches were positioned along the corresponding diagonal.

presented in random order. The 16 talker trials within each block were created with two repetitions for each combination of the four stimulus locations (above/below/left/right) and two levels of diagonal tilt. The 16 spooner trials within each block were created with one instance for each combination of stimulus location (4 levels), diagonal tilt (2 levels), and direction of spooning (2 levels). The task was self-paced.

Participants were instructed to fixate on the binocularly viewed central dot and to initiate stimulus presentation by pressing the space bar when ready. Upon keypress, stimulus presentation began immediately, i.e., Mondrian noise masks and biters were shown to their respective eye. Participants were told to press any key as soon as they saw any visual stimulus other than the circular Mondrian masks; in the absence of a keypress, presentation continued for 20 s before the trial was terminated. If the trial was terminated without a keypress, the same trial was re-initiated as a new trial, with a reset of the time-to-breakthrough clock. In other words, trials were repeated until such time as breakthrough occurred. Upon registration of a keypress, the masks and stimuli were replaced by a white noise mask for 100 ms. Next, the participant was asked to indicate how many biters they had seen, using a scale extending from half a biter (0.5) to both biters (2) in increments of 0.5. Following half of all trials (randomly selected), the participant was asked whether the biters had been facing towards each other (talkers) or facing in the same direction (spooners), providing an answer by keypress; this task was included to ensure that participants remained attentive and were motivated to wait almost until breakthrough before terminating the trial with a keypress. Participants received feedback about their average performance (i.e., facing towards versus same direction judgement accuracy) at the end of each block. Between each block of 32 trials, participants took a mandatory two-minute break to reduce eyestrain.

Results

The two dependent variables of interest were time to breakthrough and the probability of reporting both biters. Time to breakthrough was the measure used in the prior literature and we first consider this measure. Breakthrough time was defined as the latency between the beginning of the trial (i.e., the start of fading in the biters) and the eventual keypress. Breakthrough time is a highly skewed distribution, with some trials requiring tens of seconds but most requiring only a second or two. Thus, to avoid issues arising from outlier trials, we examined the median rather than mean breakthrough time. The median was calculated separately for each participant and separately for trials that presented the biter pair as spooners versus talkers. As seen in Figure 4, breakthrough time was nearly 100 ms faster for talker trials as

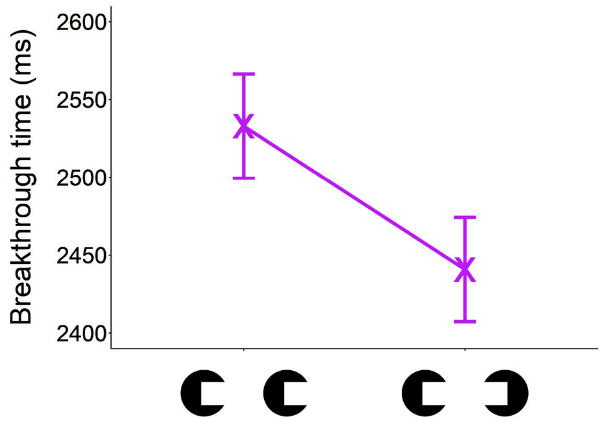

Figure 4. Experiment 1 results, showing average median breakthrough time for each biter condition ("spooners" on the left and "talkers" on the right). Error bars are 95% confidence intervals calculated using the Cousineau-Morey within-subjects error bar method as described in Baguley (2012).

compared to spooner trials, $t(57) = 3.90$, $p < .01$, supporting the hypothesis that an illusory shape draws awareness to the suppressed eye.

If the illusory shape is the cause of breakthrough, then participants might be more likely to report both biters for talker trials compared to spooner trials. In other words, if the participant becomes aware of the illusory rectangle, then they are likely to be aware of the two biters needed to create the illusory rectangle. However, participants were in general very likely to report more than one biter (they reported 1.5 or 2 biters on 79.5% of trials) and there was no reliable difference between rate of reporting two biters on talker trials (61%) compared to spooner trials (62%), $t(57) = 1.67$, $p = .1$.

One concern with the use of reaction time measures is that speed and accuracy can trade off with each other. For example, the observation of faster reaction times in one condition could reflect greater tolerance for uncertainty (and a lower criterion for responding) rather than faster processing speed; if so, we would expect to see lower accuracy in the condition with faster reaction times. However, accuracy to judge whether the biters pointed toward each other versus in the same direction was very high (94.7%) and there was no reliable difference in accuracy between the talker and spooner conditions, $t(57) = 1.49$, $p = 0.14$. Thus, it does not appear that faster breakthrough times on talker trials occurred at the expense of accuracy. Instead, this appears to reflect faster awareness when the biters were facing towards each other.

Experiment 1 discussion

When the image presented to the non-dominant eye under CFS suppression could give rise to the perception of an illusory rectangle, participants experienced faster breakthrough (i.e., they more quickly became aware of the pacman-shaped "biters" presented to the suppressed eye). In contrast to prior work, this breakthrough time difference occurred even though the suppressed image did not contain any orientations along the cardinal axes and even though the stimuli in the two conditions were nearly identical in terms of the positions and orientations of edges, differing only in terms of whether one of the two biters was rotated by 180°. This effect did not reflect a speed-accuracy trade-off considering that accuracy to report whether the biters were facing each other was nearly perfect in both conditions.

One potential concern is that within a block of 32 trials, each suppressed stimulus appeared on two separate trials for the talker condition whereas the suppressed stimuli for spooner conditions appeared only once. Thus, it is possible that some sort of short-term repetition priming resulted in faster breakthrough for talker trials. Experiment 2, below, addressed this concern by rotating both biters in the non-Gestalt condition (i.e., so-called "haters"), such that the Gestalt condition and the non-Gestalt condition included the same number of stimulus repetitions within each block of trials (i.e., with spooners there were more stimuli than for talkers because the spooners could be pointing one way or the other; in contrast, with haters, there is only one possibility, because both biters are facing away from each other).

If the illusory rectangle is the cause of the shift of awareness to the suppressed eye, we would expect participants to report awareness more readily for both biters in the talker condition than in the spooner condition. However, breakthrough was often all-at-once in Experiment 1, with participants reporting 1.5 or 2 biters on 79.5% of trials, and there was no reliable difference between report of both biters for the two conditions. It is possible that the task of reporting whether the biters were facing each other – implemented on half of trials to ensure attention and to encourage waiting for breakthrough – resulted in participants waiting until both biters were seen. Supporting this conclusion, participants were accurate 95% of the time on the biter orientation task, suggesting that they saw both biters on 90% of trials, combined with random guessing for 10% of trials (i.e., 90% + .5*10% = 95%). It is also possible that the presentation of only two biters made it difficult to catch the point of partial breakthrough.

To address these concerns, we ran another study, Experiment 2, in which: (1) we rotated both biters in the non-Gestalt condition to equate the number of stimulus repetitions; (2) stimulus arrays contained four rather than two biters, to provide a greater range of possible reports; and (3) participants were asked to indicate the orientation of only the biters that they saw, rather than the orientations of all biters, to discourage waiting until all biters were seen.

Experiment 2

Experiment 1 confirmed the prediction of faster breakthrough time when the image could give rise to Gestalt perception of an illusory shape. However, Experiment 1 produced inconclusive results as to whether the Gestalt was itself the cause of breakthrough. If the illusory rectangle triggers the shift of awareness toward the suppressed eye, then the biters on either end of the illusory rectangle should be noticed. But, even in the condition where it was not possible to perceive an illusory rectangle, participants typically reported both biters and were nearly perfect in judging whether the biters were pointing in the same direction, suggesting that participants waited until they were aware of both biters (e.g., most trials progressed to full breakthrough, rather than stopping at partial breakthrough). Thus, the failure to find any difference in the simultaneous report of aligned biter pairs might have been a kind of ceiling effect. Experiment 2 addressed this problem by using four rather than two biters, allowing more opportunity to catch the stimulus array at partial breakthrough, and by using a different post-trial task that no longer incentivized waiting until all biters were seen. In Experiment 2, the four biters always appeared in the same locations on all trials and the conditions were defined by whether the biters were oriented toward each other along the diagonal (talkers) or away from each other (so-called "haters"). Unlike the spooner condition in Experiment 1, this non-Gestalt control condition equated the conditions in terms of the number of different orientations of the biters (i.e., the number of stimuli), thus equating conditions in terms of the number of stimulus repetitions.

After stopping the CFS sequence at the point of first awareness, participants indicated which of the four biters were seen, and then indicated the arrangement/orientation of only those biters that were seen. With this task, participants could be perfectly accurate even if they saw only one biter. The aim of these changes was to produce more trials with partial report, allowing comparison between report probabilities for pairs of biters that could or could not give rise to perception of an illusory rectangle.

Method

Participants

Twenty-nine individuals (eighteen female) participated in Experiment 2. This number was approximately half the number of participants as compared to Experiment 1 because Experiment 1 included 8 conditions of interest (2 biter alignments for each of 4 different screen positions) whereas Experiment 2 only included 4 conditions of interest (4 biter alignments with no variation in screen positions). Twenty-two participants were compensated by receiving extra credit for a course, while the remaining seven were compensated $15 per hour. One participant was dropped because they admitted to misunderstanding the task instructions during a post-session debriefing, leaving twenty-eight for analysis. Screening and consenting procedures were identical to those in Experiment 1.

Apparatus

All equipment for Experiment 2 was identical to that of Experiment 1.

Stimuli

As in Experiment 1, biters were presented to the non-dominant eye, with circular patches of dynamic (10 Hz) Mondrian masks presented to the dominant eye to induce suppression. In Experiment 2, the sizes of stimulus elements were as follows: biter radius 39 pixels, aperture radius 44 pixels, squares for the Mondrian mask ranging from 30 to 40 pixels across, with 1000 squares being used to construct each mask. (The biters and apertures were increased in size relative to Experiment 1 because the biters lay further apart on the screen in Experiment 2, which might otherwise

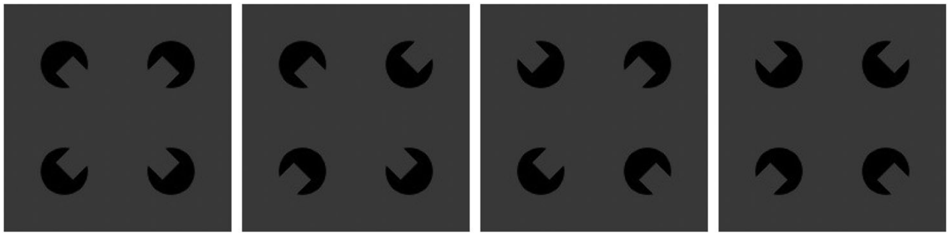

Figure 5. The four possible stimulus arrangements in Experiment 2, consisting of both diagonal pairs of biters "talking" to potentially form an illusory cross (both-talk; leftmost panel), one pair of diagonal biters "talking" and the other pair "hating" (mixed; two middle panels), or both diagonal pairs of biters "hating" such that there were no illusory rectangles (both-hate; rightmost panel).

have weakened the perception of illusory contours). Unlike in Experiment 1, each trial contained a total of four biters arranged around the fixation dot, rather than two biters presented to one side of fixation. The biters were always in the same positions (upper-left, upper-right, lower-left, and lower-right from fixation) and were orientated in one of four ways: all facing inwards (both diagonal pairs being talkers) to imply an illusory cross, the upper-left to lower-right pair facing inwards (talkers) and the upper-right to lower-left pair pointing outwards (haters), the upper-left to lower-right pair pointing outward and the upper-right to lower-left pair pointing inwards, or both of the diagonal pairs pointing outwards. This created a gradient in the number of potential illusory rectangles, depending on the condition (see Figure 5). Of the 210 experimental trials, 70 could produce an illusory cross (both-talk), 70 did not contain any illusory rectangles (both-hate), and the remaining 70 were mixed, with one pair of talking biters and one pair of hating biters.

Procedure

Participants completed a short 30-trial practice block followed by 7 blocks of 30 trials for a total of 210 experimental trials per person completed over about one hour, including two-minute breaks between each block to reduce eyestrain. Each block included equal numbers of both-talking, both-hating and mixed arrangements of biters, with mixed trials split equally into the two possible choices for which pair of biters in the array were talking. As with Experiment 1, the task was self-paced, with each trial initiated through a keypress when the participant was ready. Each trial began with the dynamic mask and biter stimuli presented to separate eyes (see Figure 6). Participants were instructed to stop stimulus presentation by pressing any key as soon as they became aware of any part of a biter, triggering a white noise mask for 100 ms, followed by the stimulus arrangement task for that trial.

In the stimulus arrangement task, participants were first presented with an array of numbered circles in the locations previously occupied by the Mondrian masks. They indicated the screen locations in which they had seen biters by typing the corresponding numbers (1–4) to indicate the combination of locations that were seen. Next, they were presented with a multiple-choice screen, on which the available options conformed to the locations they had just reported; here, the task was to select the arrangement of biters that matched what they had seen at the first moment of breakthrough (see Figure 7). For instance, the right hand panel in Figure 7 shows the display that participants would see after typing in all four locations ("1 2 3 4"), prompting a choice between the four possible stimulus arrangements with all biters shown. However, if the participant had typed in "2 3 4" (omitting position 1), they would see a similar choice display except that the upper-left biter would not appear on each of the four choice options. After receiving feedback about the accuracy of their choice, participants initiated the next trial when ready. Although participants received accuracy feedback, this feedback concerned only their knowledge of the biter configuration and not their report of the number of biters seen (meaning there was no pressure to report more biters). Throughout the experiment, an emphasis was placed on stopping the CFS trial as soon as any biters were seen.

Results

As seen in the left hand graph of Figure 8, the breakthrough time results of Experiment 2 were similar to Experiment 1 both in terms of magnitude

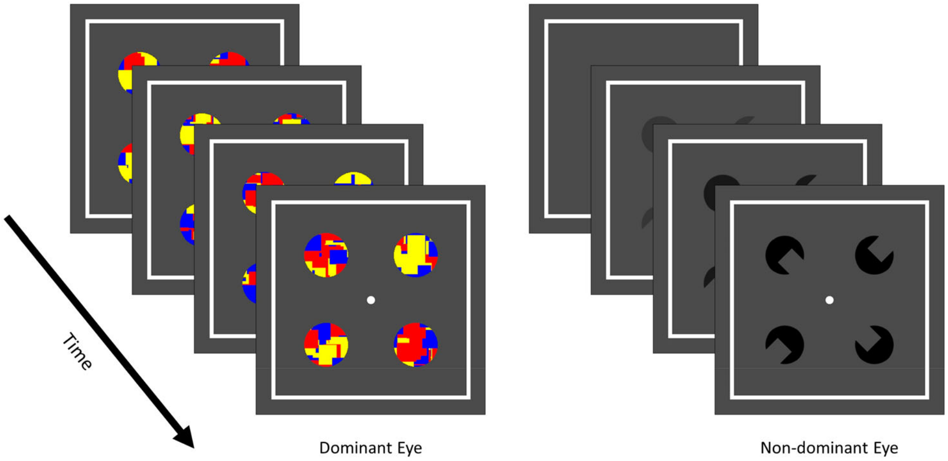

Figure 6. Stimulus sequence for Experiment 2.

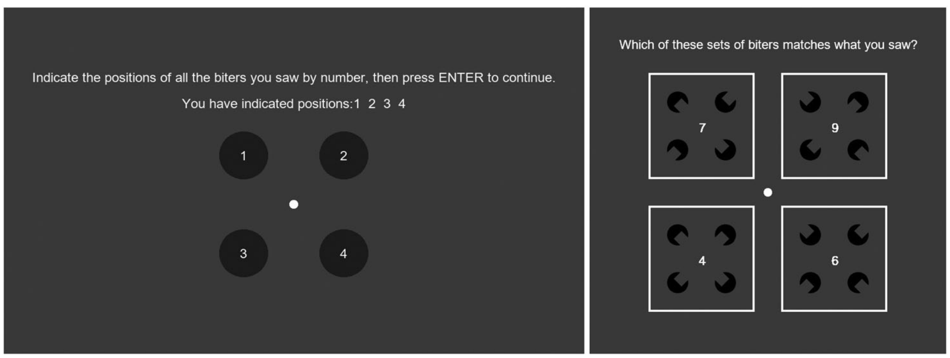

Figure 7. Stimulus arrangement task given at the end of each trial in Experiment 2. First (left panel), participants entered a combination of numbers 1 through 4 to indicate the stimulus locations where they first experienced breakthrough. Next (right panel), depending on which stimulus locations participants entered on the first test screen, a screen displayed all possible (visible) biters for those locations. Participants were asked to select the arrangement they believed they saw by entering the corresponding number.

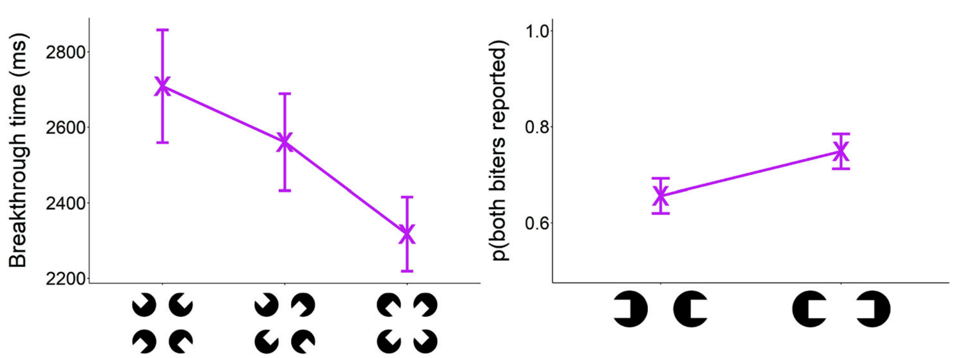

Figure 8. Experiment 2 results. Left Graph: Average median breakthrough time for each stimulus arrangement. The middle arrangement included both mixed arrangements (there was no reliable difference between them, $p = .97$). Right Graph: Average probability of reporting both biters for each pair of diagonally opposite biters given the stimulus arrangement of the biter pair (talking versus hating). Error bars are 95% confidence intervals calculated using the Cousineau-Morey method as described in Baguley (2012).

(approximately 2.5 s) and in terms of the effect of aligned biters (approximately 150 ms faster when there was one pair of talkers). The effect of stimulus arrangement across the three trial types was highly reliable, $F(2,54) = 10.17$, $p < .001$. Specific contrasts between each condition as assessed with the Tukey multiple comparisons of means test revealed significant differences between the both-talk and both-hate conditions ($p < .001$), as well as between the mixed and both-talk conditions ($p < .001$), but the difference between the both-hate and mixed conditions failed to reach the conventional level of statistical significance ($p = .056$). Across the three conditions, the trend shows a somewhat larger difference between the mixed conditions and the both-talk condition (approximately 250 ms), and the both-talk condition was nearly 400 ms faster than the both-hate condition. There were no reliable differences in stimulus arrangement accuracy across the three conditions, $F(2,54) = 1.801$, $p = 0.18$, indicating that the breakthrough time effect did not reflect a speed-accuracy trade-off; mean accuracy for the stimulus arrangement task was 84.2%.

If Gestalt perception of an illusory rectangle can trigger breakthrough, whenever it does, the biters needed to create the illusory rectangle should both be reported. This means that the probability of report for pairs of biters that create an illusory rectangle should be greater than for pairs that do not, supplying a measure that can index whether Gestalt perception influences breakthrough. To extract this measure, the stimulus arrangement report task data were broken down into the two diagonally opposite pairs of biters for each trial. In this way, each trial provided two arrangement report measures because there were two pairs of diagonally opposite biters that were, or were not aligned. The key result was the probability that both biters in a pair were reported, as a function of whether the biters in the pair pointed towards each other (talkers) or away from each other (haters). For this analysis, three participants were removed because they saw only one biter on all trials; their probability of reporting both biters was zero for all conditions and so including them in the statistical test would not add any information.[1] As seen in the right-hand graph of Figure 8, it was more likely that both biters were reported for biter pairs that were in a talking arrangement as compared to hater pairs, $t(24) = 3.70$, $p < .001$. In summary, not only did aligned biters promote faster breakthrough, replicating Experiment 1, but in addition, it was more likely that both biters in a talking pair were reported as the visual objects that first broke through. This simultaneous capture of awareness for both biters of a talking pair is expected if the illusory rectangle is the cause of breakthrough.

Experiment 2 discussion

To promote greater opportunity for observing partial breakthrough, Experiment 2 presented four biters rather than two and used a stimulus arrangement task at the end of each trial that asked only about the biters that were seen. In addition, Experiment 2 used biter pairs that were oriented away from each other (haters) in the non-Gestalt condition, thus equating the conditions in terms of the number of different stimuli and the number of stimulus repetitions, to rule out a priming explanation of the results (in Experiment 1, Gestalt stimuli were repeated more frequently than non-Gestalt stimuli across the experiment). Despite these changes, Experiment 2 replicated the breakthrough time results of Experiment 1. Biter report revealed the predicted effect that participants were more likely to report awareness for both biters when they could be connected by an illusory rectangle. This assessment of the stimulus attributes that first broke through into awareness supports the hypothesis that it was the illusory rectangle itself that grabbed awareness, rather than the separate biters on either end of the illusory rectangle. Furthermore, the effect of aligned biters appeared to be cumulative, with two such pairs (the both-talk condition) producing faster breakthrough than only one pair (the mixed conditions).

One concern with the results of Experiment 2 is that only the Gestalt condition presents biter stimuli that have inward pointing mouths (pointing toward fixation). Furthermore, only in the Gestalt condition is the mouths of the biters closer to fixation. These inward, more proximal biter mouths might have been more visually salient, causing a more rapid shift of awareness to the suppressed eye, providing an alternative explanation of the breakthrough time results. However, it is important to note that Experiment 1 controlled for this stimulus confound. In Experiment 1, none of the biters was pointing towards fixation. In addition, the biter that lay more proximal to fixation always had its mouth positioned either the same distance or further from fixation in the Gestalt condition than in the control condition, but never closer to fixation in the Gestalt condition. That is, in Experiment 1, the mouth proximity confound could only work in the opposite direction, reducing the effect we predicted. Despite this, Experiment 1 produced faster breakthrough times when the pair of biters was talking rather than spooning. Nevertheless, it possible that proximity of the biter mouths played an important role in Experiment 2. This possibility is considered in Experiment 3 through an in-depth analysis of the Experiment 2 data, using formal model comparison to ascertain whether factors other than Gestalt perception (biter salience and collinearity) can fully explain the report data and breakthrough time data of Experiment 2, or whether Gestalt perception is needed as an additional causal factor.

Experiment 3: Modelling experiment 2

As detailed in the introduction, this study is necessarily correlative in nature – just because biter pairs were aligned to suggest an illusory rectangle does not mean that participants achieved illusory perception at the moment of breakthrough (Wokke et al., 2013; Yan et al., 2021). Instead, the finding of faster breakthrough for aligned pairs might reflect an effect of collinear edges, which precedes shape perception (Alais et al., 2006). Furthermore, although the stimuli are well-controlled in terms of the positions and orientations of edges, they are not controlled in terms of the positions of light versus dark regions (i.e., the distribution of luminance). More specifically, the inward pointing biters have light patches (i.e., their mouths) that are closer to fixation as compared to outward pointing biters and perhaps it is this more central light patch that triggers a shift of awareness, rather than an interaction between the aligned biters. This greater "saliency" for inward pointing biters would boost the probability of reporting both biters simply via a higher probability of reporting each of the aligned biters (i.e., an increased chance that both patches are separately noticed).

These concerns about the cause of faster breakthrough and greater report of both biters can be addressed through an in-depth analysis of the biter report data, going beyond the analyses presented in Experiments 1 and 2. More specifically, because there are four biters in Experiment 2 that might or might not be reported, there are 2^4 or 16 possible report combinations. However, because participants must wait until at least one biter is seen, the report combination in which no biters are reported is not allowed, leaving 15 possible combinations. To address alternative explanations of the Experiment 2 data, we compared how well different models of the factors contributing to breakthrough could quantitatively and qualitatively explain the 15 possible report combinations for each of the four conditions. We also required the models to capture the breakthrough time results. Report probabilities for each of the 15 possible report combinations are shown in Figure 9, with the both-hate condition in the first row. The other experimental conditions (in which at least some biters are pointing towards each other) are shown as differences from the both-hate condition (i.e., the both-hate is taken as a baseline), to assess which report combinations are boosted by the presence of biters that could lead to Gestalt perception.

Each model entails a different theoretical explanation that makes unique predictions about how likely each of these 15 combinations will be in each of the four conditions. The models incorporate "boosts" to perception of certain biters according to factors like "increased salience for an inward pointing biter" or "increased detectability of biters forming an illusory shape." These boosts manifest in increases in predicted probability of report for different subsets of the 15 possible report combinations. Thus, the models make distinct predictions that allow them to be differentiated. For instance, consider the right-talk condition (third row of Figure 9), in which the biter pair on the lower-left to upper-right diagonal are talkers while the other pair are haters. Under a "Salience Only" model (i.e., a model in which the stimulus confound of inward pointing biters is the only factor explaining differences between the conditions), the talking biters are more salient because their mouths are closer to the centre, so there should be a higher probability of reporting either the lower-left or upper-right biters as the only reported biter. Indeed, as seen in the third row of Figure 9, this is the case. In addition, this model predicts a smaller boost to the probability of reporting both talking biters (note that this smaller boost is not shown in Figure 9; the "Shapes + Salience" model in Figure 9 combines the smaller boost to the probability of reporting both talking biters owing to salience with an additional boost owing to perception of an illusory rectangle). Under the "Salience Only" model, this boost should be smaller because it is assumed that the

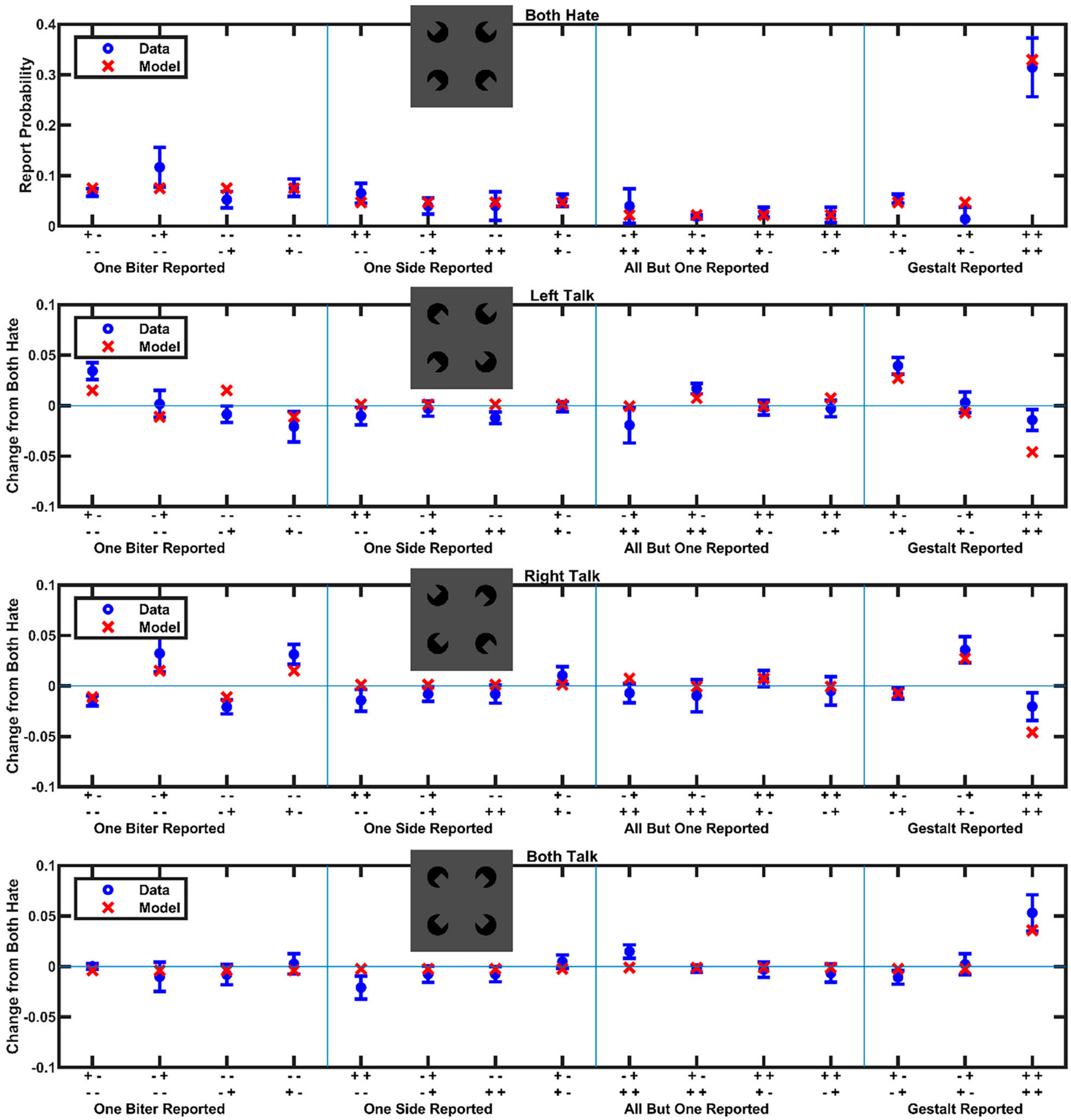

Figure 9. Experiment 2 report data (blue circles) and results of fitting the Shapes + Salience Model (red crosses), which includes increased salience for inward pointing biters plus a boost to reporting sets of biters that could create an illusory shape (rectangle or cross). The bottom three rows show differences from the both-hate condition. The labels on the x-axis show which of the four biters (+) were reported. Error bars are +/- one standard error of the mean (both-hate condition) or of the mean difference from the corresponding report probability of the both-hate condition (other three conditions).

cause of breakthrough is either one biter or the other, with report of both the lower-left and upper-right biters occurring only if breakthrough spreads from the biter that caused breakthrough to the other biter (but the probability of this spread is less than 1, hence the boost to reporting both is smaller than the boost to reporting each one). In contrast, under a model that incorporates "Collinearity Only," an interaction between the biters owing to collinearity is the trigger for breakthrough, which predicts a boost to the joint probability of reporting both the lower-left and upper-right biters (but this model would not predict the observed boost to each of the lower-left and upper-right biters separately).

Experiment 2 also included the both-talk condition in which there was the potential to perceive an illusory cross (see the last row of Figure 9). This condition is crucial for differentiating between an explanation based on illusory perception versus an explanation based on collinearity. More specifically, if the boost in the joint probability of reporting all four biters reflects an effect of two separate pairs of collinear biters, then the data should also show boosts to the joint probability of reporting one talker pair but not the other talker pair (the two datapoints shown in the far-right panel, immediately to the left of the right-most datapoint). In contrast, if perception of an illusory cross is the trigger for breakthrough, this should selectively boost the joint probability of reporting all four pacmen without changing the probability of reporting only one of the talker pairs. This is indeed the data pattern seen in the last row of Figure 9, although a statistical assessment of these theoretical alternatives requires formal model comparison.

Method

Basic equations for Both-Hate condition

It is assumed that there is just one cause of breakthrough on each trial and that the possible causes correspond to different visual objects that compete against each other. This "sampling" of a visual object is akin to throwing a dart at a dartboard, with different objects entailing different sized pieces on the dartboard. Formally, this is implemented with the softmax sampling equation, which is based on Luce's choice axiom (1959) when deciding between multiple alternatives. In this case, the sampling of each visual object is proportional to Euler's number (*e*) raised to a parameter (γ), with this exponentiated value representing the perceptual salience of the visual object. Salience increases sampling probability.

If one of the visual objects shown to the suppressed eye is sampled, then breakthrough occurs, and the biters associated with that object are reported. However, if the visual object shown to the dominant eye (the Mondrian noise mask) is sampled, then suppression continues. This sampling occurs at every time step during suppression and continues until such time as a visual object other than the Mondrian noise mask is sampled, at which time breakthrough occurs. There are 8 possible choices in the softmax. One choice possibility is the Mondrian noise mask presented to the dominant eye, which is fixed at a perceptual salience of 1.0, which occurs by setting $\gamma_M = 0$. This provides a baseline salience against which objects presented to the suppressed eye can be compared (the best-fitting γ values for visually suppressed objects are less than zero, corresponding to exponentiated perceptual salience values that are less than the value of 1.0 for the Mondrian noise mask). Equation (1) shows the softmax equation for the probability of suppression continuing at each moment by sampling the Mondrian noise mask.

$$p(\text{suppress}) = \frac{e^{\gamma_M}}{e^{\gamma_M} + e^{\gamma_{UL}} + e^{\gamma_{UR}} + e^{\gamma_{BL}} + e^{\gamma_{BR}} + e^{\gamma_{BL+UR}} + e^{\gamma_{UL+BR}} + e^{\gamma_{ALL}}}. \quad (1)$$

Besides the Mondrian noise mask, the other 7 visual objects are: (1) each of the 4 biters in isolation, using the subscripts of U for upper, B for lower, L for left, and R for right ($\gamma_{UL}, \gamma_{UR}, \gamma_{BL}, \gamma_{BR}$); (2) each of the two diagonal rectangles, or equivalently collinear biters ($\gamma_{BL+UR}, \gamma_{UL+BR}$); and finally (3) simultaneous breakthrough for all biters (γ_{ALL}). The probability of sampling each of these 7 visual objects uses the same denominator as Equation (1), but with the appropriate gamma term in the numerator. Collectively, this sampling equation defines a multinomial distribution over the 8 possible outcomes (i.e., the 8 possible items that might hold awareness, including the Mondrian and the 7 other visual objects) at each moment in time.

Before turning to the various alternative models, we define the model for the both-hate condition (both-hate) as follows. In this case, the perceptual salience for all four biters is set according to the free parameter ($\gamma_{ALL} = \gamma_{eye}$) to capture simultaneous breakthrough of all biters of the suppressed image even in the absence of any Gestalts or collinear biters. Such all-at-once breakthrough is readily apparent in the data (see the rightmost value in the first-row graph of Figure 9) and may reflect eye movements that trigger awareness for the entire suppressed image (participants are instructed to keep their eyes fixated but will occasionally fail to do so). The perceptual salience for each of the four biters separately is set according to a free parameter (γ_{out})

capturing salience of an outward pointing biter ($\gamma_{UL} = \gamma_{UR} = \gamma_{BL} = \gamma_{BR} = \gamma_{out}$). The perceptual salience of both diagonal rectangles is set to zero.

In the both-hate condition, participants sometimes report more than one but fewer than four biters. We assume that this occurs when one biter is the cause of breakthrough and then breakthrough rapidly spreads to other biters before the participant manages to press a key to stop the trial. This is captured by a probability of spread (p_{sprd}). Because the fitting of a probability parameter value that is bounded between 0 and 1 can complicate the fitting routines, this is realized as a z-score parameter value (or probit) which is then converted to a spread probability. The probability of reporting each of the other biters after breakthrough for one biter is calculated from this spread probability, assuming statistical independence. For instance, upon breakthrough for the upper-right biter, spread to the upper-left and lower-right, but not the lower-left biter would be calculated as, $p_{sprd} * p_{sprd} * (1-p_{sprd})$. Thus, the reported set of biters includes the biter that is the cause of breakthrough, but might also include other biters as dictated by this spread parameter. In this manner, the reported set of biters is imperfectly related to the cause of breakthrough under an assumption of statistical independence for spread of awareness to each of the biters other than those that caused breakthrough. This spread of awareness is applied in the same manner to all candidate models.

In summary, the both-hate condition uses three free parameters: γ_{eye}, γ_{out}, and p_{sprd}. These three free parameters produce a multinomial distribution over the 16 report possibilities when including the probability that suppression continues. Because the trial continues until breakthrough occurs, the 15 possible report possibilities, as shown along the x-axis of Figure 9, are calculated by normalizing each of the 15 values by removing the probability that suppression continues. In other words, each of the 15 values for report of some combination of biters is divided by the value 1-p(suppress). The value of 1-p (suppress) is also used to produce the predicted breakthrough time. More specifically, iterative sampling from the softmax equation defines a geometric distribution in which either something other than the Mondrian is sampled, with probability 1-p (suppress), or else the Mondrian is sampled, with probability p(suppress), in which case the geometric progression stops at that iteration. The mean of the geometric distribution with parameter p is $1/p$ and so the average stopping time is 1/{1-p(suppress)}. This average is multiplied by 1000 to yield a time in milliseconds, under the assumption that each sampling cycle is a second. Because p(suppress) depends on the sum of all visual objects (the denominator of Equation (1)), if there are more perceptually salient objects in the suppressed image, p(suppress) is smaller, and average breakthrough time is shorter.

Data fitting

The models were fit to the Experiment 2 data by minimizing G^2 as defined by the likelihood ratio test. This measure compares the likelihood of the data for the model of interest (a constrained "null" model) as compared to the likelihood of the data for a "full model" that has as many parameters as observed response categories (i.e., a model that sets the predicted probability equal to the observed average of the data for each report category). G^2 can be used for statistical goodness of fit tests with model comparison because it is distributed as a chi-squared distribution with degrees of freedom equal to the difference between the number of free parameters for the more restricted model in the numerator and the number of free parameters for the less restricted full model in the denominator (Riefer & Batchelder, 1988). For instance, Equation (2) shows the calculation of G^2 for the report data, found by summing across the 15 report categories (i) for each of the 4 conditions (j), treating each of the mixed conditions separately. L stands for likelihood of the data under each model, f stands for the observed frequency of each response category (the data are collapsed across subjects: e.g., 28 subjects by 70 trials = 1960 observations for the both-hate and both-talk conditions), and p is the probability of the response category according to either the model or the average of the observed data.

$$G^2_{report} = -2\log\left[\frac{L(data \mid model)}{L(data \mid ave\ data)}\right] = 2\sum_{j=1}^{4}\sum_{i=1}^{15} f_{ij}^{obs}[\log(p_{ij}^{obs\ ave}) - log(p_{ij}^{model})] \quad (2)$$

The second half of Equation (2) is derived from the multinomial distribution, but this distribution is not appropriate for the breakthrough time data. For the breakthrough time data, we assume that the response time on each trial is sampled from a normal distribution with a mean set equal to the predicted average breakthrough time for that condition and a standard deviation set equal to the observed standard deviation of breakthrough time for that condition (i.e., we do not attempt to model breakthrough time variance). Because the model makes the same predictions for breakthrough time for the Illusory-Left and Illusory-Right conditions, these "mixed" conditions were combined, yielding a total of three different breakthrough time conditions (see lefthand panel of Figure 8). Equation (3) calculates the G^2 for the breakthrough time data across these 3 conditions (j), where [?] is the normal distribution density function with mean μ and standard deviation σ. In this case, because the observed data are breakthrough time averages, the observed standard deviation is set equal to the standard error (SE) of the mean as calculated using the within subjects Cousineau-Morey method (see Figure 8).

$$G^2_{breakthrough\ time} = 2\sum_{j=1}^{3}\left[log(\phi(\mu_j^{obs\ ave},\ \sigma_j^{obs\ SE})) - log(\phi(\mu_j^{model},\ \sigma_j^{obs\ SE}))\right] \quad (3)$$

Because the two G^2 values – for report and breakthrough time – follow a chi-squared distribution if N is large, they can be added together to calculate a combined goodness of fit that reflects both the likelihood of the report data and the likelihood of the breakthrough times under different models. This combined G^2 (i.e., the sum of Equations (2) and (3)) was minimized when fitting the data from Experiment 2.

Different models for Gestalt conditions

The Model described above for the both-hate condition served as a Null Model for all conditions. In other words, this model assumes that there are no differences across the conditions and attempts to fit the $4 \times 15 = 60$ report categories and 3 breakthrough time categories using 3 free parameters (γ_{eye}, γ_{out}, and p_{sprd}.). The Null Model is graphically portrayed in the first row of Figure 10, showing that all biters are equally non-salient whether inward or outward pointing (all are grey) and that no sets of biters are linked by being collinear or by being part of an illusory shape. This low level of salience for all biters is taken as a baseline that will appear in all models for outward pointing biters, termed as γ_{out}.

Inward pointing biters might enhance breakthrough owing to their more central mouths and so the Salience Model (second row of Figure 10) augmented the Null Model by using a different perceptual salience parameter for inward pointing biters (γ_{in}), resulting in 4 rather than 3 free parameters. For instance, for the left-talk condition, the upper-left and lower-right biters are more salient (e.g., $\gamma_{BL} = \gamma_{UR} = \gamma_{in} > \gamma_{out}$).

The Collinearity Model (third row of Figure 10) augments the Null Model in a different manner, by including an additional free parameter (γ_{col}) that captures breakthrough based on *pairs* of aligned biters (e.g., $\gamma_{BL+UR} = \gamma_{col}$), as illustrated by the blue arrow that couples each pair of talking biters. This breakthrough from alignment does not require illusory perception (Alais et al., 2006), but nonetheless provides a selective boost to the joint probability of reporting both biters that are talking. When applied to the both-talk condition, there are two such couplings between talking biters, which are competing causes of breakthrough. Thus, this collinear boost increases the probability of reporting one pair of talking biters or the other pair, but not both.

Finally, the Illusory Shapes Model (fourth row of Figure 10) assumes that illusory perception can occur for an illusory rectangle (e.g., $\gamma_{BL+UR} = \gamma_{rec}$), if there is a single pair of aligned biters, or for an illusory cross when both pairs are aligned ($\gamma_{ALL} = \gamma_x > \gamma_{eye}$).[2] Note that, in the both-talk condition, there is no illusory perception of the separate rectangles that comprise the illusory cross. In other words, if there is illusory perception, it will be for the single most coherent interpretation of the suppressed image. Allowing for the possibility that an illusory cross in the both-talk may be easier or more difficult to perceive than an illusory rectangle in one of the mixed conditions, this model requires 2 additional free parameters as compared to the Null Model.

Matlab code for implementing these models is found at: https://github.com/dhuber1968/CFS.

Results

Multiple models were fit to the data to determine whether different stimulus confounds could fully

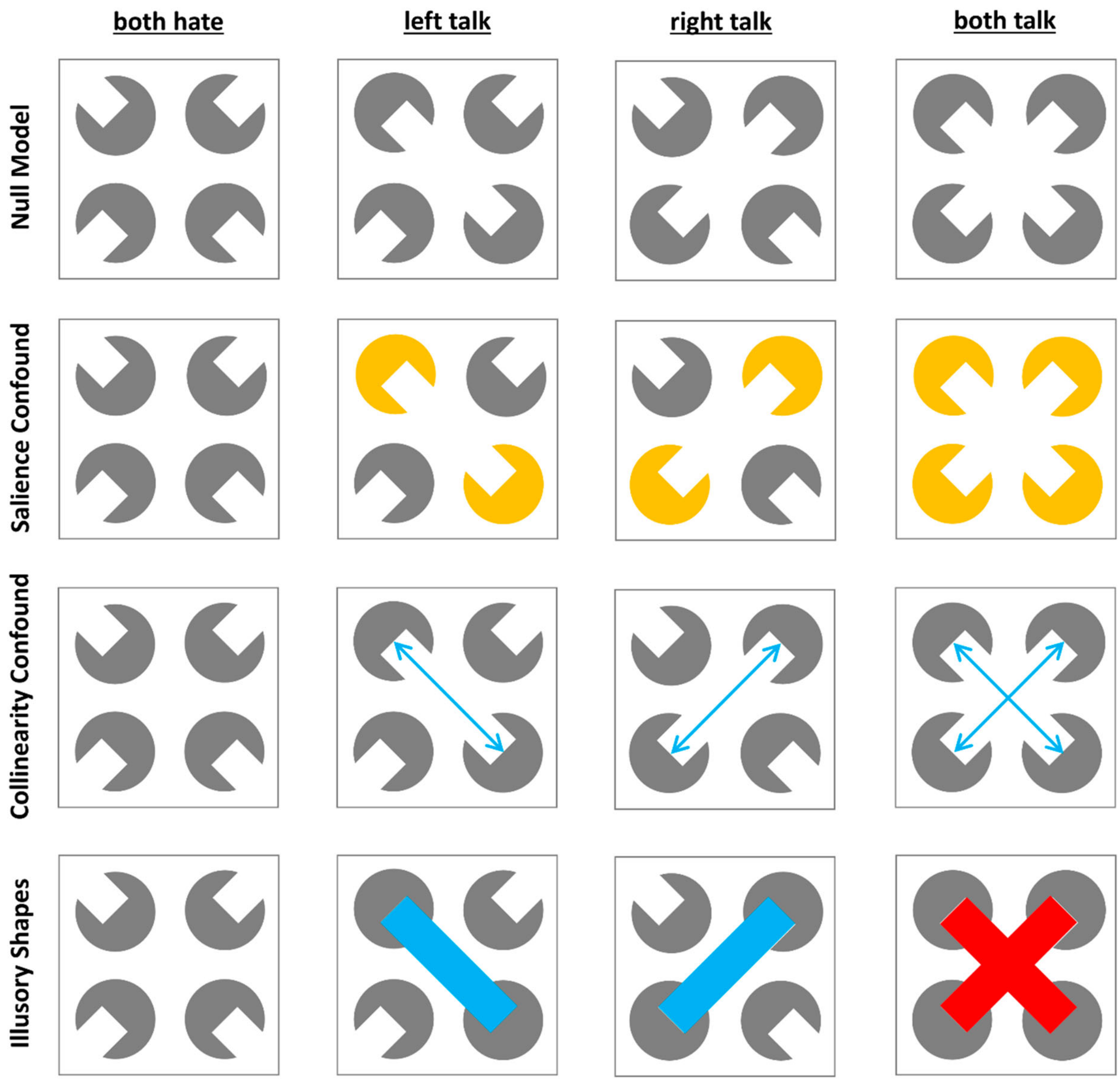

Figure 10. Illustration of how two possible stimulus confounds (Collinearity and Salience) and the Illusory Shapes account differ from the Null Model. In the figure, each coloured element corresponds to an extra cause of breakthrough that is added to the Null Model, with the number of additional free parameters corresponding to the number of colours. For the Null Model, each biter has the same probability of causing breakthrough. For the Salience Confound, biters that face the middle have an increased probability of report (e.g., they are visually salient thanks to their orientation), as illustrated by their yellow colour. The Collinearity Confound includes an increased probability of reporting *pairs* of biters that have collinear mouths, as illustrated by coupling the collinear biters with a blue arrow. For the both-talk condition, there are two such couplings (crossing blue arrows) that are separate causes of breakthrough. The Illusory Shapes Model is similar to the Collinearity Model as applied to the left-talk and right-talk conditions, although the coupling between talking biters is assumed to reflect perception of an illusory rectangle (shown in blue). For the both-talk condition, the Illusory Shapes Model couples all four biters simultaneously through perception of an illusory cross (shown in red, indicating that perception of the cross is more likely than perception of an illusory rectangle).

explain the results or whether illusory perception provided the best account. In addition, all combinations of these factors were considered. Table 1 shows the goodness of fit results from the models, rank ordered from worst to best in terms of how well they could explain both the report data and breakthrough time data. As shown in the table, when choosing a single explanation of the results, breakthrough from perception of an illusory shape provided a better account of the data than either the salience confound (inward pointing biters) or the collinear confound (breakthrough for aligned biters rather than shape perception). Furthermore, the illusory shapes model provided a better account than a

Table 1. Goodness of fit for each model.

Model	Total G^2	Number Free parameters	Report G^2 (LR)	Time G^2 (LR)
Null Model	660.8	3	655.3 (–)	5.462 (–)
Collinearity Confound	656.8	4	652.1 (4.95)	4.676 (1.48)
Salience Confound	646.0	4	644.3 (244)	1.674 (6.65)
Salience + Collinearity	645.2	5	643.6 (1.42)	1.666 (1.00)
Shapes + Collinearity	627.2	5	626.1 (6311)	1.14 (1.30)
Illusory Shapes	603.6	5	601.2 (3×10^5)	2.485 (.511)
Shapes + Sal + Coll	578.1	6	575.0 (5×10^5)	3.146 (.719)
Shapes + Salience	568.7	6	566.7 (63.4)	1.509 (2.27)

model that included both confounds (Salience + Collinearity) even though this was a comparison between two models with the same number of free parameters. However, the best model was one that combined illusory shape perception with the salience confound, suggesting that inward pointing biters contributed to the results of Experiment 2 (although we reiterate that the salience confound cannot explain the results of Experiment 1).

Statistical comparisons between models can be made because G^2 follows a chi-squared distribution. The chi-squared test asks whether the model with more parameters provided a significantly better fit of the data. For instance, G^2 differences between models that differ by one extra free parameter are significant if the difference is larger than 3.84 (the criterial chi-squared value for one degree of freedom and a type 1 error rate of .05). As seen in Table 1, better fit always emerged when adding an extra parameter, except for adding the Collinearity confound to the Salience confound. In this case, Collinearity did not significantly improve the results. Indeed, the best-fitting salience for collinear biters was .003 in this case. In other words, the collinear parameter did not improve the fit and was essentially turned off. When comparing models with the same number of free parameters, the better fitting model is preferred. For instance, of the three models that contain 5 parameters, the Illusory Shapes model provided the best account of the data.

Although the models were fit to minimize total G^2, Table 1 also reports G^2 separately for report probabilities versus breakthrough times. The values in parentheses are likelihood ratios (LR), showing how much more likely the Report or Time data are under the indicated model as compared to the model in the row above. Likelihoods for each model are calculated by taking the natural exponent of G^2 divided by -2, and then these likelihoods are put into a ratio for comparing models. As seen in the table, the G^2 values for breakthrough time are fairly low. Correspondingly, the likelihood ratios for breakthrough time do not vary much. This is because there are just three median breakthrough times to explain. Furthermore, all models except the Null Model capture the qualitative trend of faster breakthrough for the mixed conditions and even faster breakthrough for the both-talk condition. In contrast to the breakthrough time results, the G^2 values for the report data are much higher because there are $4 \times 15 = 60$ report frequencies that need to be explained. Correspondingly, the likelihood ratios for the report data are huge in some cases. For instance, under the Illusory Shape perception model, the Report data were three hundred thousand times more likely as compared to the model in the row above. Thus, the Illusory Shapes model performs better than the stimulus confound models by a wide margin.

The Shapes + Salience Model produced the lowest G^2 (best fit), providing a significantly better fit than the other models (i.e., its extra parameters are justified). The results of this model, with best-fitting parameters, are shown for the 15 report categories in Figure 9, and the 3 breakthrough time conditions in Figure 11. In general, this model captures all

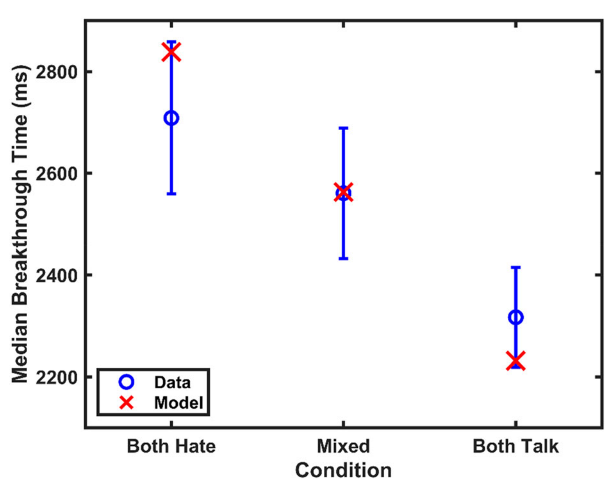

Figure 11. Modelling of breakthrough time results (same data as left graph of Figure 8) for Shapes + Salience Model. The parameters maximized the likelihood of both the biter report data and the breakthrough times (i.e., a joint fit of both dependent measures).

major trends in the data. Its best-fitting perceptual salience values (i.e., after exponentiating each parameter to provide a value that can be compared to the fixed perceptual salience of 1.0 for the Mondrian noise mask) are as follows: outward pointing biters, derived from γ_{out} (.09), inward pointing biters, derived from γ_{in}, (.13), simultaneous breakthrough of all four biters from eye movements alone, derived from γ_{eye} (.17), simultaneous breakthrough of all four biters from *either* eye movements or the illusory cross, derived from γ_x (.29)[3], and illusory rectangles, derived from γ_{rec} (.02). The best-fitting probability of breakthrough spreading to each biter, p_{sprd}, was .24.

Figure 12 illustrates why stimulus confounds, as captured by the Salience Model and Salience + Collinearity Model, were ultimately rejected as viable full explanations of the data. This plots the results from the Salience Model for the both-talk condition, but the results are nearly identical for the Salience + Collinearity Model. As seen in Figure 12, these models predict a decrease in the probability of reporting all four biters and yet the data show a substantial increase (rightmost datapoint). This decrease is predicted because each biter is more salient and thus more likely to be the cause of breakthrough, which necessarily reduces the probability that all four biters are the cause of breakthrough (i.e., the 15 change values must sum to zero). To explain the result seen in the rightmost data point requires a cause of breakthrough that leads to a selective increase for the probability of reporting four biters, such as is the case with perception of an illusory cross in the Shapes + Salience Model. For the confound models, there is a small increase in the probability of reporting just one of the four biters (i.e., the cause of breakthrough). There is also an exceedingly small increase in the probability of reporting 2 or 3 of the biters owing to the spread parameter (awareness spreads from the biter that caused breakthrough to other biters). But because spread is statistically independent for each biter, and because these probabilities must add up to zero considering that something is reported on every trial, the probability of reporting all four biters necessarily decreases for the confound models.

General discussion

Binocular rivalry occurs when the two eyes have radically different views that cannot be fused to provide a unitary three-dimensional percept. In this case, the view from one eye is prioritized over the other, leading to suppression of the information from the non-prioritized eye. However, with time, awareness may shift from the dominant eye to the suppressed eye. Our study investigated the conditions that promote this endogenous shift of awareness to the suppressed eye. We used the Continuous Flash Suppression (CFS) technique because it effectively blocks awareness of the non-dominant eye by showing constantly changing Mondrian patterns to the dominant eye. Thus, the observer is never consciously aware of the image shown to the suppressed eye until that image breaks through into awareness, usually after several seconds. With this technique, the shift of awareness to the suppressed image cannot reflect priming arising from prior awareness of the suppressed image within the trial, because there was no awareness prior to breakthrough. Our results suggest that the act of visually piecing

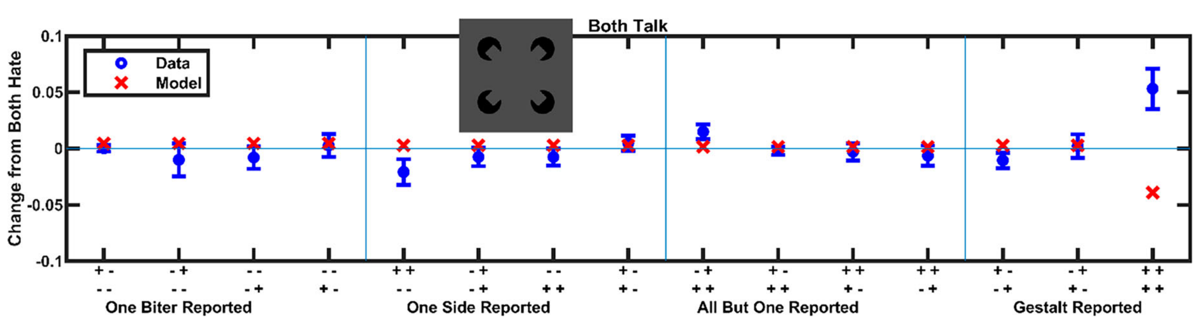

Figure 12. Results from the Salience Confound model for the both-talk condition, revealing that the model predicts a decreased tendency to report all four biters, rather than the observed increase (rightmost datapoint). The same results are found with the Salience + Collinearity Confound model because, in that model, the best-fitting parameters resulted in a negligible effect of collinearity (i.e., it was essentially the same as the Salience model).

together elements to form an illusory shape can serve as the trigger that draws awareness to the suppressed eye. In other words, the event of forming a meaningful Gestalt percept may underlie endogenous shifts of awareness with binocular rivalry.

We found evidence supporting this conclusion across two behavioural experiments and with formal model comparison. Experiment 1 presented a pair of pacman-shaped objects (biters) to the suppressed eye that were either facing toward each other (talkers) giving rise to a potential illusory rectangle, or facing the same direction (spooners), precluding any illusory shapes. Participants more quickly became aware of the talkers than spooners. However, this might have been caused by the occurrence of more stimulus repetitions for talkers (i.e., priming from previous trials) and so Experiment 2 equated stimulus repetitions across the conditions. In addition, to allow more opportunity for partial breakthrough, Experiment 2 presented two pairs of biters on each trial and encouraged participants to terminate the CFS trial before awareness had spread to all four biters. This experiment replicated the Experiment 1 finding of faster breakthrough for talkers. Furthermore, a post-trial stimulus arrangement report task revealed that participants were more likely to report both biters of a diagonally opposite pair of biters that was facing each other than a pair that was facing away from each other. This result is expected if perception of an illusory shape serves as the endogenous trigger for the shift of awareness.

Formal model comparison was applied to the results of Experiment 2 to address several alternative explanations. For instance, inward pointing biters have “mouths” that are closer to fixation, which might make them more perceptually salient. Indeed, greater salience for inward pointing biters was needed to fully explain the 15 possible report combinations for the data of Experiment 2. Nevertheless, the assumption of greater salience for inward biters could not capture the increased tendency to report all four biters in the both-talk condition where all biters were inward pointing (see Figure 12). Another potential concern over our interpretation arises from considering that it cannot be known whether illusory Gestalt perception was the cause of breakthrough (we manipulated the stimuli to enable Gestalt perception, but there is no guarantee that Gestalt perception occurred). Rather than illusory shape perception, it might be that pairs of talking biters are reported because their mouths are aligned, which has been found to produce breakthrough for pairs of Gabor patches (Alais et al., 2006). However, this collinearity account also failed to explain the data shown in Figure 12, because it predicts a greater tendency to report individual pairs of talking biters, but no such increase is seen in the data. In summary, by ruling out alternative explanations, we found support for the proposal that illusory perception causes endogenous shifts of awareness to the suppressed eye.

Our findings are analogous to results in the object attention literature with binocular displays (Duncan, 1984; Hollingworth et al., 2012). For instance, using biters that were essentially identical to the ones in our study, Moore et al. (1998) found that after cueing one of the biters, response time to report a target letter was faster when that letter was inside the mouth of a biter that was “talking” to the attention-cued biter (i.e., the biter located opposite to the attention-cued biter) as compared to an equally distant adjacent biter. In other words, when the illusory object was cued at one end, visual objects placed at the other end of that illusory object were facilitated. In a follow up experiment, the introduction of a black bar between the biters disrupted illusory rectangle perception and, correspondingly, eliminated the object attention effect. The Moore et al. study indicates that object-based attention can be applied to illusory objects, and our results with CFS suggest that the perception of an illusory object can draw awareness to the suppressed eye during binocular rivalry.

CFS has been used to study unconscious processing, with many experiments determining the high-level stimulus attributes that promote faster breakthrough to awareness (e.g., a fearful face) as compared to other stimulus attributes (e.g., a face with a neutral expression). Such results have been interpreted as indicating greater unconscious processing for some kinds of stimuli. However, this interpretation has been called into question by pointing out that the stimuli in the different conditions also differ in terms of low-level properties (Gayet et al., 2014; Stein et al., 2011), and perhaps it is these low-level differences that explain the breakthrough time difference. To address this concern, our study controlled the number, position and orientation of the edges in the stimuli, by enabling or disabling Gestalt perception only through 180° rotations of the biters. Despite adopting these controls, we found faster breakthrough for images that could give rise to Gestalt perception, and we found that subjects were more likely to become aware of the biters needed to create illusory shapes.

Our results may be a special case of a more general theory in which perception of something meaningful and coherent serves as the trigger for shifts of awareness. That is, Gestalt perception is one way to create a meaningful, coherent percept, but not the only way. This more general theory would suggest a radically different interpretation of bCFS studies, which use breakthrough time as the dependent measure (see also Gayet et al., 2014). If perception of something meaningful and attention demanding (e.g., a fearful face) is a trigger that draws awareness to the suppressed eye, this suggests high-level unconscious processing is simultaneous with breakthrough, rather than occurring prior to breakthrough. Instead of reflecting unconscious perception of high-level attributes, the results of breakthrough time CFS studies might indicate how quickly *conscious* perception occurs for different kinds of stimuli; that is, as soon as meaningful perception is achieved, breakthrough is triggered.

Under this alternative explanation of the bCFS literature, the primary effect of CFS might be to radically slow down the onset of high-level perception (e.g., perception of a fearful face or perception of an X occluding four circles). If so, bCFS should be viewed as a tool for studying differences in high-level perception rather than a tool for studying unconscious processing. For example, suppose that, under conditions of high-contrast binocular viewing, a particular image of a fearful face is perceived 10 ms faster than a face with a neutral expression precisely because fear is a meaningful emotion. Such a small difference in the speed of perception may be difficult to measure with binocular viewing conditions. Similarly, it may be that a set of inward pointing biters are perceived a little faster than outward pointing biters under binocular viewing precisely because they are interpreted as an X occluding four circles. This interpretation of the image contains more meaning in the sense that it contains several well-known objects (X and circle) as well as depth information. However, when the face image (or inward pointing biters) are suppressed by CFS, high-level perception may operate much more slowly (say, ten times slower), and an otherwise subtle difference in speed of perception becomes a measurable difference of 100 ms as revealed with breakthrough times. In support of the proposal that CFS is akin to extremely slow/weak perception, a previous fMRI study with CFS has indicated that the effect of CFS is akin to lowering visual stimulus contrast, reducing neural activity not only in higher brain regions, but also primary visual cortex (Yuval-Greenberg & Heeger, 2013). In addition, it is well established that low contrast stimuli are perceived more slowly than high-contrast stimuli (Harwerth & Levi, 1978). Thus, the period in CFS during which participants are unaware of the suppressed eye may be akin to a binocular viewing situation in which an observer initially fails to understand the contents of a very low contrast image, or an image with high noise. In this challenging binocular viewing scenario, no-one would suggest that slow, arduous perception of a high-level attribute such as facial expression provides evidence that the observer is unconsciously processing facial expression until the moment when the expression is consciously identified; instead, we would say that it took a while for the meaningful percept to be formed, and that awareness of the percept emerged only once it was formed.

The conclusion that Gestalt perception can serve as the trigger for breakthrough may explain a recent study that used CFS as a means of inducing visual learning (Sadil et al., 2019). This study presented visual objects under CFS, with participants terminating each CFS trial at the point of partial breakthrough. After the study phase, participants completed a series of visual tests of their memory for the objects, in which they were given “aperture views” showing small, unrecognizable, circular patches of the objects. One memory test displayed a single aperture part and asked participants to guess the name of the object (part-to-whole). Another test displayed two different aperture parts, in their respective positions, and asked participants whether the two parts belonged to the same object or two different objects (part-to-part). Critically, this second test could be performed without knowing the identity of the object by using a sense of associative familiarity. Remarkably, studying objects under CFS selectively boosted performance in the part-to-part task as compared to the part-to-whole task, and this pattern differed from the pattern following binocular study. In other words, visual learning under CFS allowed the visual system to learn the low-level visual properties of the objects, including the part-to-part associations, but it did not allow learning of Gestalt information (i.e., the higher-level meaning of that that visual information). This lack of learning for Gestalt information is sensible if Gestalt perception is the trigger for breakthrough considering that the CFS study trials were stopped at the point of breakthrough (i.e., time to study the Gestalt was extremely limited).

Gestalt formation is not necessarily an all-at-once process, and it may be that only the final step draws awareness to the suppressed eye. More specifically, Gestalt formation has been characterized as a two-step process: knowing which elements in an array go together (clustering) and then conceiving of that cluster as a whole (shape formation). The initial clustering can happen outside of awareness, while shape formation seems to produce awareness under certain circumstances (Koffka, 1935; Trick & Enns, 1997). Perhaps clustering of object parts can happen under suppression, whereas the second step of shape formation triggers breakthrough. In support of this account, it has been found that forming shape Gestalts while separating them from distractors automatically attracts attention (Kimchi, 2009). The application of this two-step account to CFS would allow unconscious clustering prior to breakthrough, which could explain the part-to-part learning under CFS that occurred in the Sadil et al. (2019) study. In other words, perhaps unconscious clustering enables part-to-part learning.

The formation of a Gestalt is the process of organizing perceptual information into something meaningful. But why should this capture awareness? In general, stimuli that abruptly appear demand attention, because they may indicate some previously unappreciated danger. This explains why the constantly changing new information shown to the dominant eye during CFS maintains suppression for extended periods of time. That is, each jumble of squares in the successively presented Mondrian noise masks constitutes a new visual display, refreshed every 100 ms. However, while each mask is a unique, multi-layered display of overlapping coloured squares, at some higher-level, the Mondrian noise masks are all the same, comprising highly similar visual features with no overarching semantic meaning. Meanwhile, for the information entering the visual system via the suppressed eye, a new higher-level percept emerges at some point (e.g., a face, an object, or, in the present study, a Kanizsa figure: a light rectangle overlapping two black circles) and it is the abrupt onset of this new, meaningful object that demands attention to assess its relevance to current task goals. This account may explain why noise masks that are matched to the visual properties of the suppressed image are the most effective for maintaining suppression (Gayet et al., 2014): if the suppressed image is similar to noise masks, then the formation of a Gestalt for the suppressed image is not such a novel event relative to the new objects that constantly appear with each noise mask. More generally, our results suggest that shifts of awareness with binocular rivalry reflect a constantly evolving process of meaning-making. In this process, whether awareness shifts to the suppressed eye depends on factors such as the abrupt formation of a Gestalt for the image shown to that eye, as well the relative novelty of that Gestalt in comparison to the recent contents of conscious perception.

Notes

1. These three participants were included in the modelling reported in Experiment 3 because they still provided useful data in terms of which of the four biters they reported for each condition.
2. The shapes model is equally compatible with the proposal that awareness is attracted to contiguous regions of brightness (e.g., visual contrast makes the mouths of each biter appear to be brighter and when the mouths are aligned, this produces a connected region of brightness that attracts awareness).
3. In the Salience+Shapes model, breakthrough for all four biters can occur from an eye movement, or from perception of an illusory cross. These possibilities are lumped together and captured by γ_{ALL}. Thus, $\gamma_{ALL} = \gamma_x$ for the both-talk condition, but $\gamma_{ALL} = \gamma_{eye}$ for the other conditions. To ascertain the effect of the illusory cross in isolation, the perceptual salience derived from γ_{eye} can be subtracted from the perceptual salience derived from γ_x, resulting in a perceptual salience difference of .12 for the addition of an illusory cross. This indicates that the illusory cross in the both-talk condition is considerably more likely to be perceived than the illusory rectangle in the mixed conditions (the perceptual salience of an illusory rectangle was .02).

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

This work was supported by funds from the National Institute of Mental Health (grant number RF1MH114277) to Rosemary Cowell and David Huber and from the National Science Foundation (grant number BCS1554871) to Rosemary Cowell.

Data availability statement

Experimental data that support the findings of this study are openly available at the Open Science Framework: https://osf.io/dze98/

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