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Individual differences in continuous flash suppression: Potency and linkages to binocular rivalry dynamics

Randolph Blake[a,b,*], Rachel Goodman[a], Andrew Tomarken[a], Hyun-Woong Kim[c]

[a] Department of Psychology, Vanderbilt University, Nashville, TN 37212, USA
[b] Vanderbilt Vision Research Center, Nashville, TN 37212, USA
[c] Department of Psychology, Korea University, Seoul 02842, Republic of Korea

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ABSTRACT

Binocular rivalry (BR) and continuous flash suppression (CFS) are compelling psychophysical phenomena involving interocular suppression. Using an individual differences approach we assessed whether interocular suppression induced by CFS is predictable in potency from characteristics of BR that are plausibly governed by interocular inhibition. We found large individual differences in BR dynamics and, in addition, in the strength of CFS as gauged by the incidence and durations of breakthroughs in CFS during an extended viewing periods. CFS's potency waned with repeated trials, but stable individual differences persisted despite these mean shifts. We also discovered large individual differences in the strength of the post-CFS shift in BR dominance produced by interocular suppression. While CFS breakthroughs were significantly negatively correlated with shifts in BR dominance after CFS, there were no significant associations between individual differences in alternation rate during pre-CFS binocular rivalry and either breakthroughs during CFS or post-CFS dominance shifts. Bayesian hypothesis tests and highest posterior density intervals confirmed the weak association between these two forms of interocular suppression. Thus, our findings suggest that the substantial individual differences in BR dynamics and CFS effectiveness are modestly related but not entirely mediated by one common neural substrate.

1. Introduction

Over the past forty years binocular rivalry (BR) has steadily risen as a topic of interest within psychology and cognitive neuroscience, a trend documented by the increasing number of publications containing BR in the titles and abstracts of journal papers (Baker, 2010; Hedger, Gray, Garner, & Adams, 2016). One reason for this growing interest in BR is, no doubt, its possible role in elucidating neural concomitants of consciousness, a problem that has achieved widespread legitimacy within the neuroscience community (Koch, 2004; Maier, Panagiotaropoulos, Tsuchiya, & Keliris, 2012; Klink, van Wezel, & van Ee, 2013; Brascamp & Baker, 2013). A second, equally important, reason for BR's popularity is its potential utility as a means for studying visual processing outside of awareness: during BR, a normally visible stimulus may undergo complete phenomenal disappearance for several seconds at a time, making it possible to examine the degree to which that stimulus retains its effectiveness despite its erasure from visual awareness (Blake, 1997). Compared to other psychophysical techniques capable of dissociating physical stimulation from phenomenal awareness, BR stands out in terms of its potency and applicability over a wide range of visual viewing conditions (Kim & Blake, 2005).

Still, BR has limitations as a psychophysical tool for studying unconscious processing. First, the stochastic nature of perceptual state durations during BR (Levelt, 1965; Fox & Herrmann, 1967) makes it impossible to predict precisely how long a stimulus will remain suppressed from awareness before transitioning to dominance; durations of suppression, in other words, cannot be precisely controlled. Second, periods of mixed dominance frequently occur during transitions in awareness from one stimulus to the other, especially when rival stimuli are relatively large and configurally complex. Furthermore, these periods of mixed perception can take on a variety of different appearances that complicate an observer's criterion for categorizing rivalry states (see review by Skerswetat, Formankiewicz, and Waugh (2018)) which, in turn, raises the possibility of partial awareness of a putatively suppressed stimulus.

These two shortcomings of BR – unpredictable transitions and confusing mixed states – were seemingly circumvented, by the development of a modified version of BR termed continuous flash suppression (CFS). First described in a pair of papers published within months of one another (Fang & He, 2005; Tsuchiya & Koch, 2005), CFS entails

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[*] Corresponding author at: PMB 407817, 2301 Vanderbilt Place, Nashville, TN 37240-7817, USA.
E-mail address: Randolph.blake@vanderbilt.edu (R. Blake).

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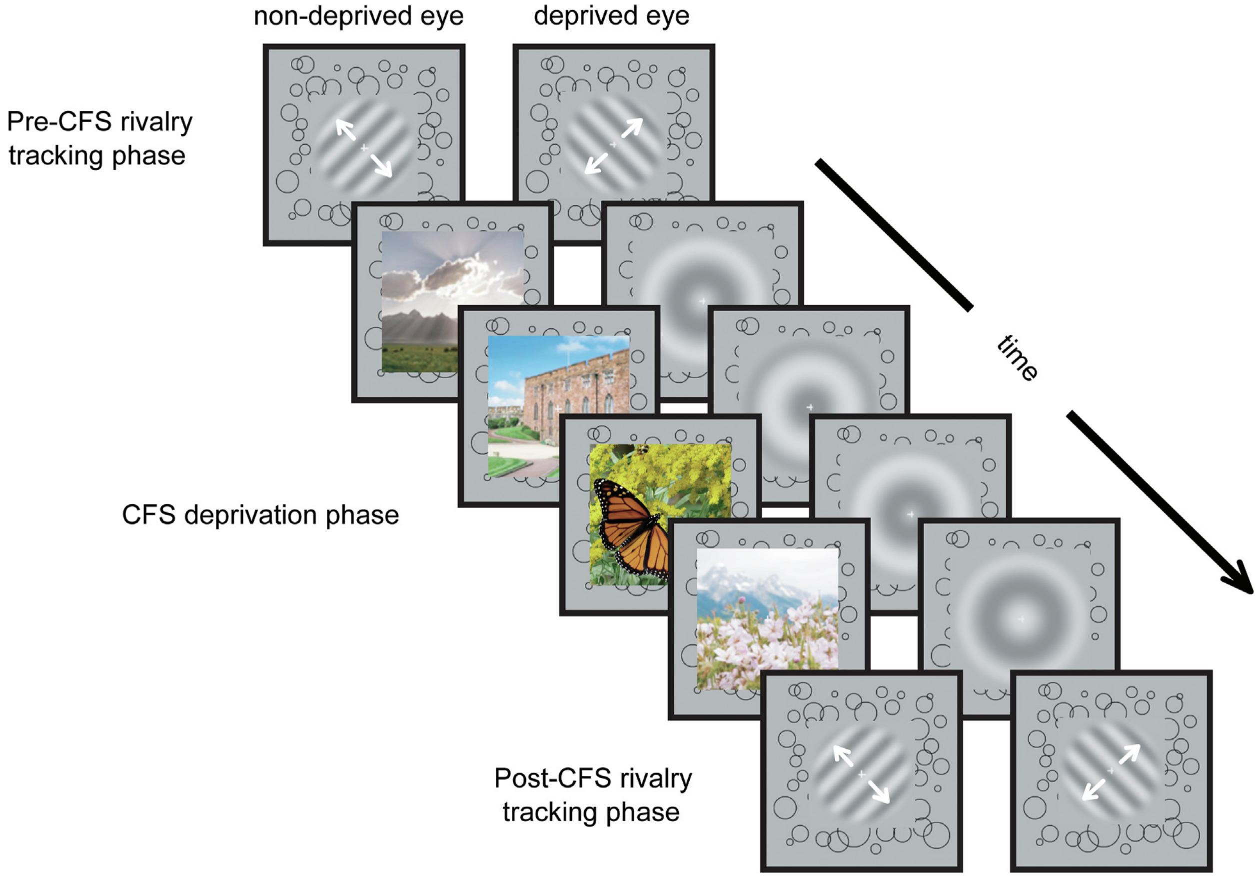

Fig. 1. Schematic of stimulus sequence defining a single trial. Initial pre-CFS rivalry tracking lasted 3-min during which the participant pressed and held buttons to track alternations in rivalry dominance between orthogonally oriented Gabor patches. This was followed by a 6-min phase during which one eye viewed a natural scene CFS sequence and the other eye viewed a bulls-eye pattern with a slow counter-phase oscillatory motion. The participant pressed and held a designated computer key whenever any part of the bulls-eye achieved dominance and pressed another key whenever a butterfly appeared within the CFS sequence. Immediately following this 6-min phase, the participant again tracked rivalry between orthogonal Gabor patches for 3 min.

presentation of a structurally complex, highly dynamic visual mask to one eye paired with more mundane visual stimulus viewed by the other eye. Under these conditions, the CFS mask immediately achieves exclusive dominance that can be maintained for many seconds before one gains any hint of the existence of the contralateral visual stimulus. This exciting advance led immediately to a spike in the popularity of CFS (see Fig. 1, Hedger et al., 2016), with a growing number of studies seeking to identify factors governing the potency and selectivity of CFS (Tsuchiya, Koch, Gilroy, & Blake, 2006; Maruya, Watanabe, & Watanabe, 2008; Hong & Blake, 2009; Zadbood, Lee, & Blake, 2011; Yang & Blake, 2012; Moors, Wagemans, & de-Wit, 2014; Khuu, Gordon, Balcomb, & Kim, 2014; Han, Lunghi, & Alais, 2016; Zhu, Drewes, & Melcher, 2016; Forder, Taylor, Mankin, Scott, & Franklin, 2017; Lunghi, LoVerde, & Alais, 2017; Han, Blake, & Alais, 2018) as well as the extent to which visual processing transpires despite abolishment of awareness of a visual stimulus by CFS (see reviews by Sterzer, Stein, Ludwig, Rothkirch, and Hesselmann (2014), Gayet, Van der Stigchel, and Paffen (2014); Yang, Brascamp, Kang, and Blake (2014), Hedger et al. (2016)).

Descriptively speaking, the stimulus conditions producing BR and CFS are identical: dissimilar monocular stimuli presented separately to the two eyes. But perceptually the two are distinct: durations of interocular suppression are much longer during CFS, and the propensity to experience mixed dominance during CFS is less compared to BR. The two forms of interocular suppression also differ in terms of their impact on the ability to detect probe targets presented during periods of suppression. When one eye views a high-contrast CFS mask, threshold level probes presented to the other eye have to be about 1-log unit stronger when presented during suppression as compared to presentation during dominance. In contrast, probe thresholds are only about 0.3 log-units higher during suppression phases of BR (Tsuchiya et al., 2006). Moreover, BR and CFS do not always lead to the same conclusion concerning aspects of stimulus processing that survive interocular suppression – a point we return to in the Discussion.

In this paper we undertook a theoretically-inspired examination of the relationship between CFS and BR using an individual differences approach that has been fruitfully deployed in other domains of vision (e.g., see reviews by Vogel & Awh, 2008; Kanai & Rees, 2011; Wilmer, 2017; Mollon, Bosten, Peterzell, & Webster, M.A., 2017; Gauthier, 2018). Specifically, we asked whether the potency of interocular suppression gauged by two different indices of CFS effectiveness is predictable based on a key feature of BR that is plausibly governed by strength of interocular inhibition: the briskness with which states of exclusive monocular dominance switch over time during BR, often called alternation rate (AR). The existence of large individual differences in switch rates is well established within the BR literature (Miller et al., 2010; Carter & Pettigrew, 2003; Hancock, Gareze, Findlay, & Andrews, 2012; Fesi & Mendola, 2014; Law, Paon, Riddiford, Gurvich, & Miller, 2015; Dieter, Sy, & Blake, 2017; Sy, Tomarken, Patel, & Blake, 2016; Cao, Wang, Sun, Engel, & He, 2018; Kalyai, He, He & Engel, 2019). This finding is consistent with predictions from neural models of BR in which rivalry fluctuations are controlled, in part, by the strength of reciprocal inhibition between pools of neurons registering the features of competing rival targets (Curtu & Ermentrout, 2001; Wilson, 2007; Klink, Brascamp, Blake, & van Wezel, 2010; Seely & Chow, 2011; Brascamp, Klink, & Levelt, 2015). From this perspective, stronger levels of interocular inhibition should produce slower ARs.

Building on those previous ideas, our study examined the extent to which BR dynamics relate to two measures of CFS potency. We gauged CFS potency in terms of the ability of a monocularly viewed CFS display to induce and maintain exclusive suppression of a monocular target viewed by the other eye, and by the immediate aftereffect of CFS stimulation on dominance experienced during BR. This intriguing, somewhat counterintuitive aftereffect involves a temporary shift in eye dominance during BR following a prolonged period of forced monocular dominance of one eye. The effect was initially described and documented by Lunghi and colleagues in a series of studies using monocular eye patching to achieve forced dominance of one eye (Lunghi, Burr & Marrone, 2011; Lunghi, Burr, & Morrone, 2013; Lunghi & Sale, 2015; Lunghi, Morrone, Secci, & Caputo, 2016). More recently our lab has extended the conditions capable of producing this aftereffect using forced *perceptual dominance* during CFS (Kim, Kim, & Blake, 2017). Both monocular occlusion and prolonged monocular perceptual suppression cause a temporary shift in predominance *in favor of* the previously deprived eye, an aftereffect whose duration depends on the duration of deprivation. In our 2017 study, using the procedure shown schematically in Fig. 1, we were able to show that as little as 3 min of perceptual deprivation induced by interocular suppression from CFS produced a significant shift in predominance towards the suppressed eye that typically returned to pre-CFS baseline levels within a minute or so. We also found within our limited sample of 7 individual's notable differences in the magnitude of this deprivation aftereffect (DAE). In a subsequent pilot study with 34 volunteer participants, we confirmed that there are indeed considerable individual differences in the magnitude and decay of the DAE.

While these initial findings are intriguing, they leave two primary questions unanswered. First, what is the relation between the degree of monocular suppression *during* CFS and DAE immediately *after* CFS? Consistent with the line of reasoning in previous papers (Lunghi & Sale, 2015; Zhou, Baker, Simard, Saint-Amour, & Hess, 2015), we hypothesized that both measures indicate the strength of monocular suppression and thus predicted that more robust suppression during CFS should be associated with larger magnitudes of DAE. More specifically, we hypothesized that the percentage of time that participants experienced intermittent breakthroughs of the suppressed target during CFS (hereafter abbreviated PBT: percentage breakthrough time) would be inversely related to the magnitude of DAE. The second question – and the one that is the primary motivation for the present study – is that of the relation between individual differences in BR and in CFS-induced suppression. Are these two phenomena manifestations of a superordinate individual difference in the strength of perceptual suppression? This possibility would certainly comport with current thinking about underlying substrates of BR (e.g., van Loon, Knapen, Scholte, St. John-Saaltink, Donner, & Lamme, 2013) and CFS (e.g., Shimaoka & Kaneko, 2011). It would also be consistent with a number of models in the areas of personality, psychometric intelligence, and cognitive abilities that posit higher-order individual difference factors (e.g., the general intelligence factor *g*) that account for a substantial proportion of the variance of individual measures and of the covariance between measures (e.g., Guilford, 1967; Markon, Krueger, & Watson, 2005; Reeve & Bonaccio, 2011; Rushton & Irwing, 2011; Spearman, 1927). Recently, Richler et al. (2019) have extended such models to the study of individual differences in object recognition. This collateral evidence would also lead to the prediction that BR and CFS are indeed associated and, more specifically, that AR during BR (a measure thought to be inversely related to strength of suppression) should be positively correlated with PBT during CFS (a measure thought to be inversely related to strength of suppression) and negatively correlated with the magnitude of DAE (a measure thought to directly reflect strength of suppression).

To test these predictions, we recruited a relatively large group of adult participants to perform the task illustrated schematically in Fig. 1, using procedures closely modeled after those developed in our earlier study (Kim et al., 2017). An ancillary goal was to understand the extent to which CFS varies in effectiveness over time during a given exposure, over successive trial repetitions and among different individuals.

2. Methods

2.1. Participants

Forty-seven individuals (26 females), ranging in age from 19 to 30 participated in this experiment; twenty-nine were tested at Korea University (KU) and eighteen were tested at Vanderbilt University (VU). All had normal or corrected-to-normal acuity and good stereopsis, with no reported history of strabismus. Each person gave informed consent prior to beginning the experiment. All aspects of the study were approved by Institutional Review Boards at the respective universities (KU: IRB protocol #1040548-KU-IRB-17-174-A-2; VU: IRB protocol #040915), in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki).

Nine of the participants were excluded from the final data analysis based on a priori rejection criteria: one did not complete the second day session, two had an incidence of extremely long bulls-eye dominance duration (over 200 s) during a CFS phase, four had proportions of mixture states during rivalry exceeding 50% of the total tracking period, and two had unbalanced baseline eye dominance exceeding 70%. Thus our final sample size numbered 38 individuals, a value comparable or even higher than that used in recent published studies on BR and individual differences (Hancock et al., 2012, n = 18; Sy et al., 2016, n = 16).

3. Apparatus

The experimental set-ups utilized at the two test sites were similar. All trial-related events were controlled by a Macintosh Intel-based computer using code written in MatLab and supplemented by routines from the Psychophysics Toolbox (Brainard, 1997). Dichoptic displays were generated on a single, large-screen, gamma corrected CRT monitor (1024 × 768 pixel resolution, 100 Hz refresh rate, mean luminance 81 cd m^2) at VU and on a single gamma corrected CRT monitor (1024 × 768 pixel resolution, 60 Hz refresh rate, mean luminance 40 cd m^2) at KU. Monocularly viewed stimuli were presented on the left- and right-halves of the CRT monitor and were viewed dichoptically through a custom-designed mirror stereoscope with the head stabilized by a head-and-chin rest; the optical path from screen to each eye was 80.5 cm at VU and 64.5 cm at KU. The angles of the stereoscope mirrors and the locations of the two dichoptic images were adjusted using an adaptive, computer-based cover/uncover test to achieve stable binocular overlap of those images, and this alignment procedure was repeated before each testing session. Stable alignment was reinforced by the presence of identically textured fusion frames that surrounded each monocular target (Fig. 1).

4. Stimuli and procedure

The experiment consisted of an initial familiarization phase followed by two test sessions, each lasting approximately 40-min and performed on separate days. The familiarization phase occurred prior to the first test session, and it lasted approximately 15-min during which all aspects of the actual experiment were explained and demonstrated. Practice on all phases of the main experiment were given before moving to the actual test session. Each test session comprised two successive test trials separated by an enforced rest period lasting at least 10-min. A test trial consisted of 3 phases: a pre-CFS rivalry tracking phase, followed by the CFS deprivation phase, followed by a post-CFS rivalry tracking phase.

5. Rivalry phases

The rival stimuli in both the pre- and post-CFS deprivation rivalry phases consisted of a pair of diagonally oriented Gabor patches differing in orientation by 90 angular deg (+45° and −45° from vertical) between the two eyes. Each Gabor patch subtended 2.7 deg visual angle, and its circular border was blurred with a cosine falloff (0.4 deg). Centered within each Gabor patch was a small (0.2 deg) light spot that participants were instructed to fixate during the experiment. To preclude local light adaptation, the spatial frequency of each rival target was modulated back and forth between 1.5 and 2 cycle per degree (cpd) at 0.42 Hz. The Michelson contrast of each Gabor patch was 30%. Gabor patch orientation was counterbalanced between the eyes over trials.

During the 3-min pre- and post-CFS deprivation rivalry phases, participants pressed and held one of two keys on the computer keyboard to indicate which of the two orthogonally oriented gratings was currently dominant exclusively; participants were instructed to press neither key when experiencing periods of mixed dominance (i.e., simultaneous visibility of portions of both rival targets) and, except for no-press durations < 300 msec, those durations were recorded and analyzed; ultra-short no-press durations were deemed too brief to constitute genuine mixture state reports and, instead, were construed to be a consequence of successively releasing one button and pressing another (Sy et al., 2016). Likewise, button press durations lasting $<$ 300 msec were not counted as periods of exclusive dominance. As a safe-guard, we also raised the cut-off value to 500 msec, but found that this had no impact on the resulting estimates of rivalry dynamics.

A small fraction of exclusive dominance states constitute what has been termed return transitions (Brascamp, van Ee, Noest, Jacobs, & van den Berg, 2006; Dieter et al., 2017a,b). These are unique alternation sequences characterized by a period of exclusive dominance of a given stimulus, followed by a transition to the mixture state where portions of the other stimulus are visible, followed next by a transition *back* to exclusive dominance of the previously dominant stimulus. Return transitions raise the question whether to treat those sequences as one episode of dominance or two. For data analyses, we opted to define such instances as two distinct states of exclusive dominance when the intervening mixture state lasted at least 300 msec. When two successive presses of the same button were separated by < 300 msec, those two durations were combined into a single dominance duration.

6. CFS deprivation phase

Following the initial rivalry phase was a 6-minute forced CFS deprivation phase during which one eye viewed a series of rapidly changing, brightly colored natural scene images (3.7 × 3.7 deg visual angle), each presented for 100 ms with no intervening blank intervals (10 Hz) – this constituted the CFS mask. These images were selected from the subset of neutral images in the IAPS image library (Lang et al., 1998) – the RMS contrast of these images averaged 44% (range: 15–83%). Among the sequence of images was the occasional presentation of one of two butterfly images that served as a probe target for the task described below; a total of 20 probe images appeared during the 6-min CFS phase at random, but always separated by at least 10 sec, and error feedback (failure to detect a probe) was signaled by a brief tone. Pitted in rivalry against this dynamic monocular display was a medium-contrast (30%) bulls-eye pattern (3.7 deg in visual angle and 0.7 cpd spatial frequency) undergoing slow (0.125 Hz) counter-phase oscillatory motion to minimize local light adaptation. The circular, outer edge of the bulls-eye pattern was smoothed by steady attenuation of its border contrast using a cosine filter (0.6° in length).

Participants were instructed to press and hold a designated key whenever any portion of the bulls-eye pattern achieved visibility (i.e., either partial or complete dominance). Otherwise, they withheld key presses while only the CFS target was visible, except when a butterfly image was detected within the CFS image sequence in which case the participant tapped another key to denote detection; the inclusion of these infrequent probe presentations was simply to motivate participants to maintain vigilance during what could be construed as a boring, 6-min stream of unrelated images. Whether sustained attention is required for effective CFS remains to be learned, but we do know that attention modulates the dynamics of BR and other forms of bistable perception (e.g., Dieter, Brascamp, Tadin & Blake, 2016).

In the initial instructions to participants, it was stressed that the bulls-eye pattern could appear in its entirety or partially, and they understood that the bulls-eye pattern, when dominant, could appear surrounded within the CFS sequence (as it often was). They were instructed to declare dominance of the bulls-eye whenever any part of it was perceptually visible regardless whether portions of the CFS were also visible. We asked participants to adopt this liberal tracking procedure in order to minimize criterion problems for them and, as well, to obtain a comprehensive record of temporary breaches in CFS.

At the end of the 6-min deprivation period the CFS mask and the bulls-eye target disappeared, and 3 s later the 3-min post-CFS rivalry tracking phase started. Thus each trial lasted approximately 12 min, and the entire experiment consisted of 4 trials. The eye viewing the bulls-eye during the CFS phase (i.e., the 'deprived' eye) was the less predominant eye measured during the first pre-CFS rivalry tracking phase, and was constant in all subsequent trials. We adopted this procedure because other published work on CFS very often assigns target and CFS mask on that basis and, also, because the effect of CFS deprivation is to boost predominance of the deprived eye following the 6-min deprivation period (Kim et al., 2017). During a given session, there was a 10-min break between the first and second trials. The second session was at least 24 h and at most one week after the first session.

7. Results

The rationale for this study rests on the existence of individual differences in BR dynamics and individual differences in the effectiveness of CFS during the perceptual deprivation period. Previous published work prompted our expectation that these differences would indeed exist in our sample of participants, and the following two sections confirm that those expectations were realized.

8. Individual differences in binocular rivalry dynamics

In this section we focus on results from the BR phases of the experiment. As a reminder, dominance durations refer to the individual durations of time that a person presses and holds a given key signifying exclusive dominance of a given rival pattern. It also stands to reason that longer duration key presses create slower rates of alternation in dominance states over time. Thus in the BR literature, one finds rivalry dynamics being indexed in either of two ways: 1) the number of state changes that occur within a given period of time (i.e., alternation rate = AR) (e.g., Carter & Pettigrew, 2003) or, 2) mean duration of dominance during a tracking period as a proxy for rate (e.g., Suzuki & Grabowecky, 2007; et al., 2013).[1] These two indices of BR dynamics are strongly related, because longer dominance durations create fewer state changes. Indeed, in our data set the Pearson and Spearman correlations between number of state changes and average duration of exclusive visibility are −0.89 and −0.94, respectively, i.e., people exhibiting relatively brief dominance durations experience more state changes per

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[1] For each participant we derived AR by taking the average of the AR values associated with each of the four individual 3-min BR tracking periods preceding a CFS episode. Those trial by trial AR values were defined as the number of exclusive dominance states (i.e., key presses), minus 1 (i.e., not the initial dominance state), in a 180 s tracking period, divided by the total duration of that tracking period (i.e., 180 s plus any time added if the final percept extended beyond 180 s).

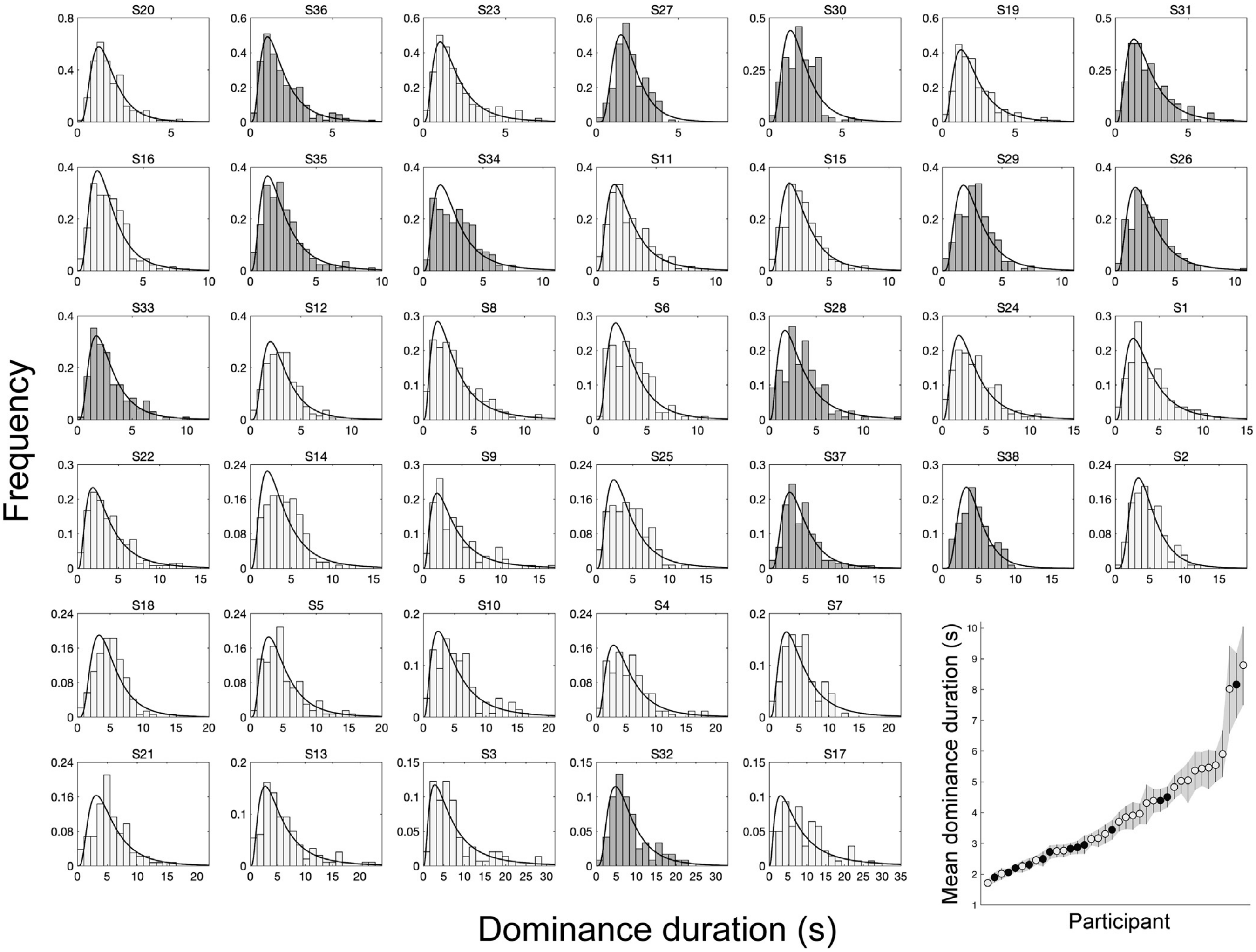

Fig. 2. Histograms of dominance durations (pre-CFS rivalry tracking) for each of 38 participants. Solid lines show best fit log-normal curves. Histograms drawn with light bars are for the 25 participants tested at Korea University (KU) and the histograms drawn with dark bars are for the 13 participants tested at Vanderbilt University (VU). Note that the horizontal and vertical axes are not all to the same scale, which was purposefully done to highlight the relative shapes of the distributions. The left-to-right and top-to-bottom arrangement of those duration histograms is ordered by the average dominance duration for each person (shortest to longest mean durations). The graph at the bottom right of the Figure plots the mean dominance durations for each of these 38 participants, with light- and dark-fill symbols denoting KU and VU individuals, respectively. The vertical bars plot 95% confidence intervals around those means, derived using a bootstrapping procedure (1000 estimates of the mean, with each estimate derived from resampling pre-CFS durations for each individual).

unit time.

9. Binocular rivalry state durations

Fig. 2 shows the distribution of dominance durations for each individual in our study, derived from the four, 180-sec rivalry tracking episodes preceding the CFS deprivation phase. We purposefully omitted the post-CFS rivalry tracking data because of the previously cited evidence that CFS can produce a temporary shift in rivalry predominance in favor of the previously deprived eye. The smooth curve in each plot is the best fit log-normal curve (Brascamp, van Ee, Pestman, & van den Berg, 2005). The shapes of these histograms conform to the characteristic, rightward skew that typifies BR and other forms of perceptual bistability (Levelt, 1965; Fox & Herrmann, 1967; Zhou, Gao, White, Merk, & Yao, 2004; Brascamp et al., 2005; Bosten et al., 2015). Note that the x-axis and y-axis are scaled separately for each individual, because the states of perceptual dominance last considerably longer for some individuals than for others. The insert histogram at the bottom right-hand side of Fig. 2 shows the average dominance duration for each person, ordered from shortest to longest values, and the brackets on each mean symbol show 95% confidence intervals around that mean derived using a bootstrapping procedure applied to each individual's actual dominance durations measured during the four pre-CFS tracking periods. Because the layout of the duration histograms – left-to-right and top-to-bottom – correspond to the order of participants in this summary histogram, readers can easily compare these two sets of data. The range of mean duration values, and by inference the range of AR values, in Fig. 2 closely matches the range of individual differences in binocular rivalry dynamics reported in other studies (Carter & Pettigrew, 2003; Hancock et al., 2012; Fesi & Mendola, 2014; Gallagher & Arnold, 2014; Bosten et al., 2015; Law et al., 2015; Law, Miller, & Ngo, 2017; Sy et al., 2016; Paris, Boddenheimer, & Blake, 2017; Dieter et al., 2017a,b; Kalyal et al., 2019).

To assess the stability of individual differences in BR dynamics across trials, we computed intraclass correlation coefficients (ICCs) (e.g., Shrout & Fleiss, 1979) on pre-CFS mean duration and AR. The ICCs measure what Shrout and Fleiss (1979) termed 'consistency' and are comparable in spirit to Pearson correlations by assessing the degree to which participants' relative rankings were consistent across the four trials. We computed two measures of consistency. The first was what Shrout and Fleiss (1979) termed 'ICC1', representing the proportion of the variability of data assessed on a given trial attributable to stable

Table 1
Intraclass Correlations.

Measure	ICC1	ICC4
Mean Duration	0.70 (0.57, 0.91)	0.90 (0.84, 0.95
Alternation Rate (AR)	0.76 (0.65, 0.85)	0.93 (0.88, 0.96)
Percent Breakthrough (PBT)	0.76 (0.64, 0.85)	0.93 (0.88, 0.96)

N = 38. ICC1 = consistency between pairs of trials. ICC4 = estimated consistency of 4-trial averages. 95% confidence intervals are shown in parentheses.

individual differences among those participants. The second ICC was labeled 'ICC4' and indicates the estimated proportion of variance due to individual differences in aggregate scores averaged across the four trials of a given session. It was computed by applying the Spearman-Brown formula to the ICC1 values. ICC values can potentially range from 0 to 1 with higher values indicating stronger consistency.

As shown in Table 1, both BR measures demonstrated a high proportion of variance due to individual differences, with values for AR being slightly higher than those for mean duration. The ICC4 values for aggregate scores indicate that individual differences account for a very high proportion of the overall variance. We also computed pairwise correlations between Session 1 aggregate scores and Session 2 aggregate scores. These were consistent with the ICCs by indicating strong test-retest stability (average duration: Pearson r = 0.87, Spearman r = 0.87; AR: Pearson r = 0.86, Spearman r = 0.84). Similarly the test-retest correlations between pre-CFS and post-CFS scores were very high (average duration: Pearson r = 0.92, Spearman r = 0.93; AR: Pearson r = 0.76, Spearman r = 0.79). Considered as a whole, these results are consistent with other evidence that duration and AR provide highly stable indices of rivalry dynamics for a given person (e.g., Miller et al., 2010; van Loon et al., 2013). In fact, using a novel non-parametric approach to assess within-subject consistency of rivalry duration distributions, it is possible to classify with high accuracy the single-session performance of individuals based on their subject-specific 'signatures' revealed in the higher-order statistical properties of those distributions (Sy, Tomarken, Patel, & Blake, 2017).

We also assessed the extent to which the pre- and post-CFS BR results differed for individuals, and we looked for possible differences between those individuals tested in Korea (KU) and those tested in the U.S. (VU). We did that by conducting a two (KU/VU) X two (pre-CFS/post-CFS) mixed effects repeated measures ANOVA on both average dominance durations and AR. There were no significant main effects or interactions on either measure (all $ps > 0.10$).

10. Individual differences in CFS effectiveness

The second prerequisite for determining the relation between BR and CFS was to establish the extent to which there exist stable individual differences in the robustness of CFS. To quantify robustness, we indexed the capacity of the bulls-eye target to overcome CFS and, thus, achieve intermittent visibility during the 6-min phase of perceptual deprivation. On this measure of CFS effectiveness, we found substantial individual differences within our sample of 38 participants, as indicated by the histograms in Fig. 3, which plot for each participant the individual durations of epochs during the 6-min CFS period when the bulls-eye was temporarily visible (i.e., episodes of breakthrough from CFS). Plotted at the bottom-right of Fig. 3 are the average PBTs for each person, in the same order as the frequency histograms in the main part of this figure.

The duration histograms in Fig. 3 are pooled over the four CFS phases, but we also confirmed stable individual differences in the cumulative durations of those epochs are stable over the four sessions by performing pair-wise correlations between PBTs over pairs of sessions. Pearson correlation values between sessions 1 and 2 (r = 0.85), sessions 2 and 3 (r = 0.74) and sessions 3 and 4 (r = 0.89) were all highly significant. We construe these high, positive correlation values as confirmation that breakthrough durations and incidence are stable indices of individual differences in CFS strength.

The data in Fig. 3 reveals that during extended viewing the incidence and durations of breeches in CFS vary greatly among individuals. For some participants – but certainly not all – the distributions of breakthrough durations have the unimodal right-skewed shape seen in all of the BR dominance duration histograms in Fig. 2. However, we cannot directly compare those two sets of histograms because the rivalry durations (Fig. 2) represent periods of exclusive visibility of one rival target or the other, while the breakthrough durations (Fig. 3) pertain to periods when any portion of the bulls-eye became visible, not just complete dominance. Moreover, even when the circular bulls-eye was temporarily visible in its entirety, outer border portions of the CFS often remained dominant too. Among the histograms in Fig. 3 are four individuals who reported *no* breakthroughs in CFS during any of the four CFS deprivation phases. These individuals did not exhibit strong eye dominance on the rivalry tracking phases of the experiment, so the complete dominance of the CFS mask cannot be chalked up to pronounced differences in baseline predominance between the eye receiving the CFS mask and the eye viewing the bulls-eye.

These summary results underscore that CFS enjoys varying degrees of success in producing prolonged periods of suppression over a 6-minute observation period, an outcome that echoes the findings and conclusion reached by Gayet and Stein (2017), who focused on a different dependent measure. They performed a *meta*-analysis of data from several CFS studies that employed the popular technique dubbed 'breaking of continuous flash suppression (b-CFS)' wherein the dependent measure is the duration of time elapsing before a suppressed monocular stimulus first overcomes interocular suppression induced by CFS. Gayet and Stein found extensive individual differences in average duration to first breakthrough, leading them to caution against use of raw b-CFS durations for testing hypotheses about processing outside of awareness. They also speculated that those differences may arise, in part, from differences in depth of suppression experienced by different individuals, i.e., the idea that prompted our study before Gayet and Stein's paper had been published. The present study goes beyond that of Gayet and Stein by actually measuring the incidence and durations of perceptual breakthroughs in CFS over an extended viewing period, and we are gratified by the congruence between their *meta*-analysis and our results.

We also calculated the total percentage of time during CFS spent in breakthrough for each participant. This measure, termed PBT below, is defined as the total duration of breakthroughs in each of the four CFS episodes divided by the total duration of each trial (360 s). This measure represents a summary index of individual differences in susceptibility to breakthroughs that reflects the joint contribution of mean duration and incidence of breakthrough episodes and it is the primary index we use in subsequent analyses assessing relations between CFS breakthroughs and other variables. Consistent with the analyses of breakthrough duration and incidence, this measure demonstrated strong individual differences that were stable across sessions. The ICC's presented in the bottom row of Table 1 indicate strong consistency across pairs of trials and strong individual differences in aggregate scores averaged across the four trials. Due to some non-normality on this measure (primarily attributable to some 0 scores), we also conducted Kendall's coefficient of concordance (Kendall, 1948). This index, which ranges from 0 to 1, also indicated strong consistency. Kendall's W = 0.85, $p < .001$.

To our surprise, we also found significant between-site differences in PBTs on both t tests (t(36) = 2.40, p = .02) and Mann-Whitney tests (p = .01). VU participants ($\bar{X}$ = 18.96%) exhibited higher PBT values, on average, than their KU counterparts ($\bar{X}$ = 9.98%). Those between-site differences are evident in lower right-hand corner in Fig. 3, which designates VU and KU participants by the shading of the histogram bars.

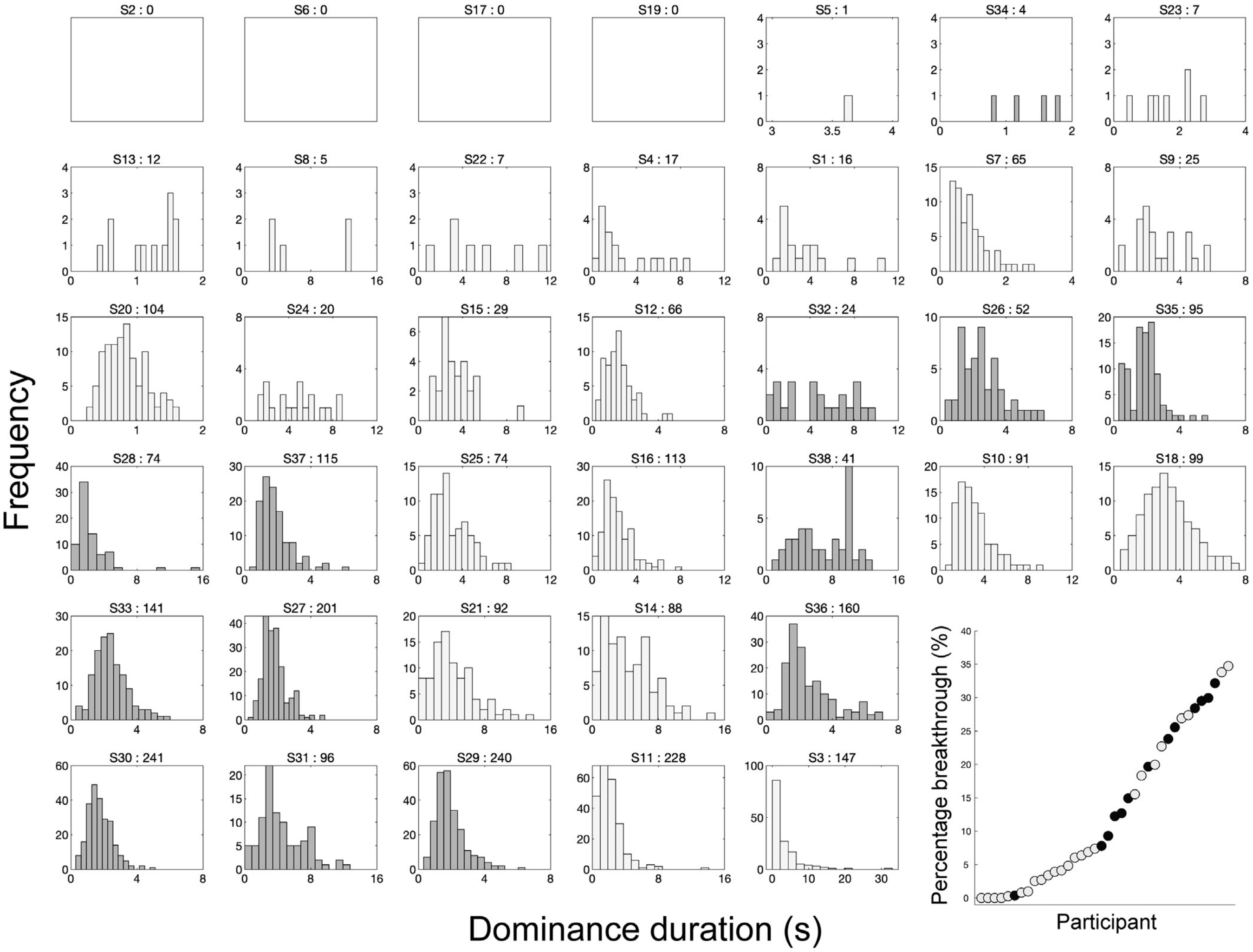

Fig. 3. Histograms of individual breakthrough durations of the bulls-eye, shown for each of the 38 participants, with light and dark bars denoting KU and VU participants respectively. The numbers above each graph give the participant ID number and the total number of bulls-eye dominance episodes for that observer. Empty graphs indicate no incidence of bulls-eye breakthrough. The order of these histograms, left to right and top to bottom, corresponds to the order of individual participants' percent breakthrough values shown in graph inset at the bottom right of this Figure, again with light and dark symbols denoting KU and VU participants, respectively. Percent breakthrough is a single value calculated from all break-through durations over the four CFS phases. Due to the small number of breakthrough episodes for several participants, we did not derive subject-specific confidence intervals using bootstrapping or other approaches.

11. Does CFS effectiveness weaken over time?

Although not the main purpose of our study, our data provide an excellent opportunity to examine whether CFS potency as indexed by percentage of bulls-eye breakthroughs varied over the course of the four prolonged episodes of CFS deprivation. Results from an earlier study involving an adaptive training procedure (Ludwig, Sterzer, Kathmann, Franz, & Hesselmann, 2013) found that a target pitted against a fixed amplitude CFS mask had to be reduced in contrast to maintain "full invisibility" of that target over repeated trials, implying that the strength of CFS wanes over trials. We have looked for direct evidence of this trend in our large sample of participants tested on four successive occasions using the same procedures.

We did indeed find considerable variability among the values of initial duration to first breakthrough. Among the 152 values of initial breakthrough time in our sample (38 participants × 4 trials), the duration values to first breakthrough ranged from 3 to 360 s (the latter value indicating no breakthrough during the entire 6-min CFS period). The median time to initial breakthrough across all trials was 70 s.

Does the propensity for breakthroughs increase with trial number? We addressed this question by assessing whether there was a monotonic trend of the form trial 1 < trial 2 < trial 3 < trial 4 in terms of the percentage of time during which participants reported bulls-eye breakthroughs – this measure is explained and illustrated in Fig. 4, which plots breakthrough episodes for each of the four CFS phases for three observers. To learn whether the breakthrough durations varied systematically, we employed Page's (1963) non-parametric test of monotonic ordering of means that assesses where there is a linear trend across mean ranks (Marascuilo & McSweeney, 1977). The Page test indicated a significant monotonic trend in the predicted direction ($p < .05$), i.e., the pattern of results shown by two of the three participants in Fig. 4. We also found no higher-order quadratic or cubic trends on the ranked data and we reached identical conclusions when we computed more standard linear, quadratic, and cubic trend analyses on the raw data. The significant linear effect ($p < .02$) on the latter suggests that the increasing trend was linear and not just monotonic.

We also conducted supplementary Bayesian order-constrained hypothesis tests (e.g., Hoijtink, 2012, Hoijtink, Mulder, van Lissa, & Gu, 2019; Mulder, Klugkist, van de Schoot, Meeus, & Selfhout, 2009) to compare several more fine-grained hypotheses concerning the pattern of change across trials. We compared the hypothesis of a monotonic trend ($\mu_1 < \mu_2 < \mu_3 < \mu_4$) across all 4 trials to: (1) A less restrictive hypothesis only predicting within-session increases from trial 1 to trial 2 and trial 3 to trial 4 and; (2) A more restrictive and complex

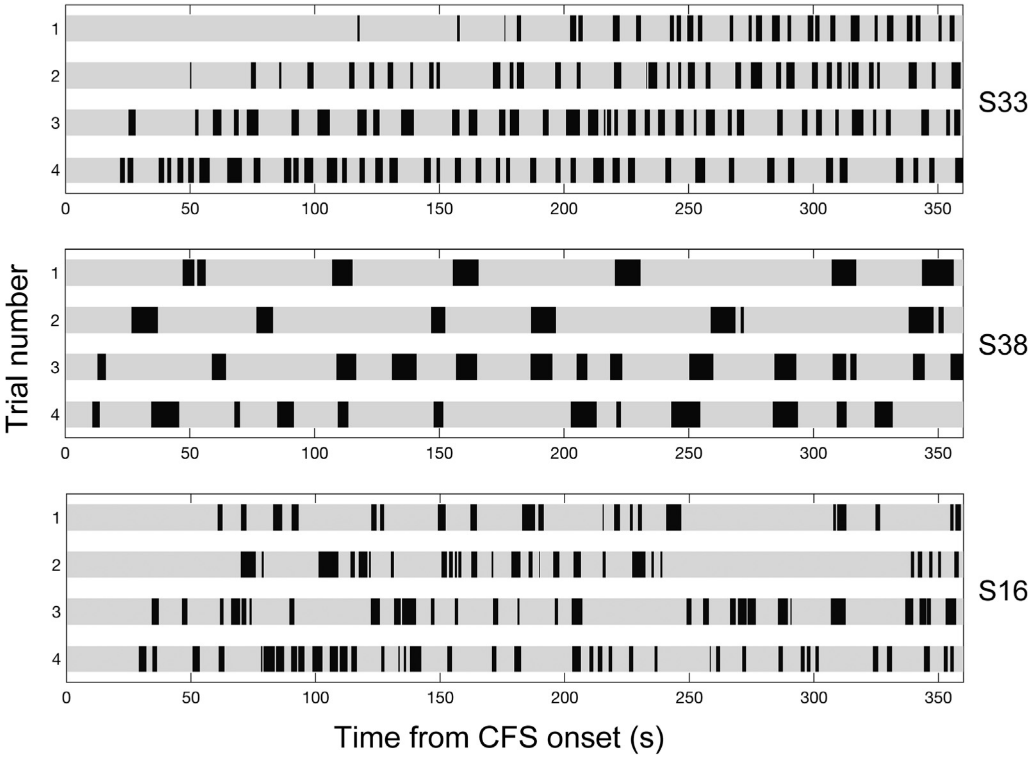

Fig. 4. Time series plots (6-min/plot) for three different observers (#16, 33 and 38 as designated in Fig. 3), with the four series for each observer representing results for each of the four 6-min phases of CFS presented on a given trial. The dark sequences within the time series designate times during which the bulls-eye was partially or completely visible, i.e., CFS was breached. These three observers were selected because they capture several features of those successive phases of breakthrough: 1) for the majority of individuals, the longest period of time elapsing before the first breakthrough occurred on trial 1 (i.e., the pattern of results seen with observers 33 and 38), and 2) the first breakthrough sometimes happened within a very short period of time following onset of CFS. As discussed in the text, the median value of first breakthrough duration was 70 s seconds, and the range was 3 s (almost immediately) – 360 s (i.e., no breakthrough).

hypothesis specifying an overall monotonic trend but smaller increases from trial 2 to trial 3 than between the other adjacent time points. The latter two hypotheses were rooted in the fact that trials 2 and 3 occurred on different days while trials 1 and 2 occurred within the same session, as did trials 3 and 4. Bayes factors (BFs) (e.g., Kass & Raftery, 1995), representing the ratio of the marginal likelihoods of each pair of hypotheses, were computed to select the one with greatest support in the data (see additional discussion of Bayes factors below). Although the BFs obtained were not of sufficient magnitude to allow for a clear winner, the more restrictive trend hypothesis specifying a smaller increase between trials 2 and 3 had marginally better support than the monotonic trend (BF = 1.50) and less restrictive monotonic trend hypothesis (BF = 2.62).[2]

12. Probe detection performance during CFS

While tracking intermittent bulls-eye dominance during the CFS deprivation period, probe targets (pictures of butterflies) were occasionally presented within the 10-Hz stream of natural scene pictures comprising the CFS animation. These probes were included in the experimental design to promote sustained attention during the extended CFS period, not as proxies for breakthroughs from CFS - the incidence of butterfly images was too meager to serve that purpose. Still, we felt it would be interesting to calculate the proportion of probe targets missed during the CFS sequence, to see whether the incidence of detection failures is related to percentage of bulls-eye breakthrough, i.e., PBT. Indeed, those miss rates varied substantially among observers, ranging from 0% to 25% with the average being 12% (i.e., 2.4 misses/CFS phase). As would be expected, the incidence of failures to detect butterfly probes was positively correlated with the percentage of breakthroughs of the bulls-eye (r = 0.74). False alarms (i.e., probe detection responses in the absence of a butterfly image) were negligible (on average, less than one FA during a 6-min CFS phase).

13. Is CFS effectiveness related to BR?

Having established the presence of substantial individual differences in both BR dynamics and CFS effectiveness, we were poised to consider the main question of our study: are the two forms of interocular suppression related? We addressed this question by focusing on the associations among three measures. We have discussed the first two directly above: BR dynamics assessed before CFS and PBT during CFS. As noted earlier, individual differences in rivalry dynamics can be quantified as either average dominance durations or AR (number of state changes per 60 s epoch). We report the results of AR below for two reasons: (1) Consistent with the fact that the two measures are essentially non-linear transformations of one another and have a very high negative correlation, the results of the analyses summarized below were highly similar across the two sets of measures; and, (2) AR tended to have better distributional properties, particularly with respect to univariate normality (e.g., Shapiro & Francia, 1972, test of normality: AR p = .54, average duration p = .004).

14. Quantification of DAE

The third measure that we used was an index of the effectiveness of CFS assessed after the CFS phase: the magnitude of deprivation aftereffect, denoted below as DAE. We used the analytic technique developed by Kim et al. (2017) to quantify the degree to which the 6-min CFS deprivation phase temporarily altered rivalry predominance immediately following the deprivation phase. This procedure entailed computing for each participant a series of successive averages of the deprived eye predominance over the four trials as a function of time from the onset of a given 3-min rivalry tracking phase; this was done

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[2] In addition, in response to a reviewer's suggestion, we assessed whether the duration of dominance episodes systematically changed within each of four 180 sec.CFS trials. We conducted permutation tests to assess whether there was a significant increase or decrease in durations within a trial. Because the analyses did not yield a consistent pattern of effects across trials and because this question was less central to the goals of the present paper, we do not present these analyses in the present paper. More complete summaries of the methods and findings of both the Bayesian order-constrained hypothesis tests and the permutation tests of within-trial changes in duration are available upon request.

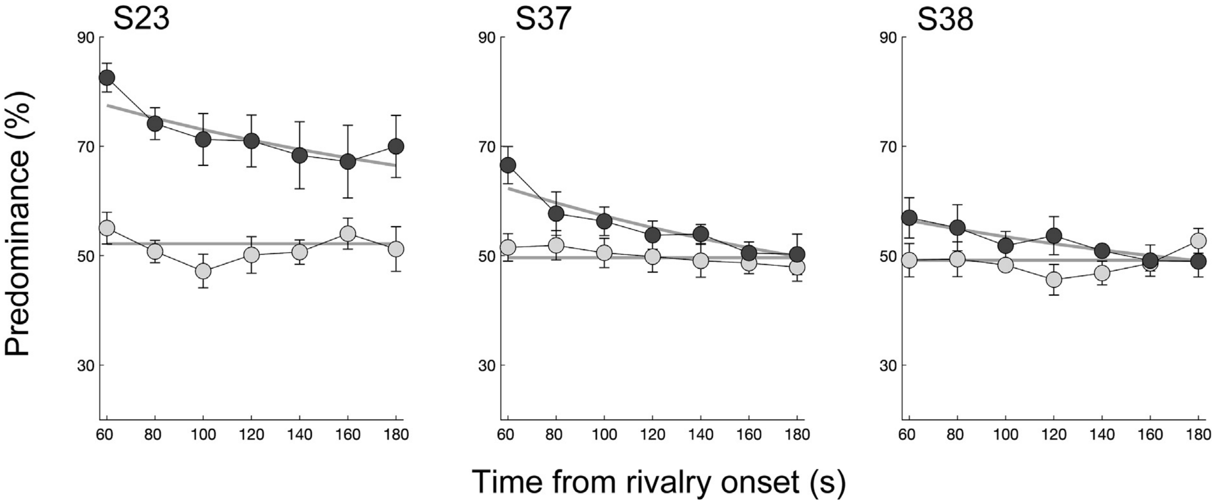

Fig. 5. Plots from three participants showing predominance averaged over successive 20-sec sliding windows, where predominance is the total duration of time that a given eye's rival target was exclusively dominant divided by total duration (excluding mixed dominance durations). The total period of rivalry tracking was 3-min, both before the 6-min CFS deprivation period (light symbols) and immediately after the CFS deprivation period (dark symbols); bars denote ± 1 SE of the mean. The solid lines are best-fit exponential decay curves, as explained in the text.

separately for the period prior to CFS deprivation (baseline predominance) and for the period immediately following CFS deprivation. Each average was calculated over a 60 s window of time, and the window was advanced through the entire rivalry period in increments of 20 s, yielding 7 successive estimates of predominance starting with the phase immediately following deprivation. Three examples of these sliding window calculations of predominance are shown in Fig. 5, one showing a participant with an unusually strong DAE, another showing someone with a moderate DAE, and a third showing a participant with a negligible DAE. Within each panel, the curve plotted with light gray symbols shows results for the 3-min period prior to CFS deprivation and the curve plotted in dark gray symbols shows results for the 3-min period immediately following CFS deprivation. Each data point plots predominance expressed as the percentage of time that the to-be-deprived eye (pre-CFS) and the deprived eye (post-CFS) were dominant during the associated window of time denoted by the x-axis. Each data point shows the average and standard error of predominance for that eye calculated over the four trials. All three cases are characterized by an initial rebound effect in favor of the deprived eye followed by a decline toward a lower asymptote. At the same time, individual differences are evident in both the magnitude of the initial DAE effect and in the dominance percentage ultimately reached in the final window of the interval. Both the consistency and variability of effects across participants were accounted for in our statistical analyses.

To estimate the rebound effect of CFS on BR dominance, we specified a non-linear mixed effects model (NLMM) (e.g., Cudeck & Harring, 2007; Davidian & Giltinan, 1995; Pinheiro & Bates, 2000). The mixed-effects approach allowed us to estimate both average effects across participants and subject-specific effects unique to each participant in the context of one model that combined participants' data. This multilevel approach is generally better than a two-step approach that conducts analyses on each participant's data (i.e, one by one), extracts coefficients and then assesses overall means or associations with external variables in a separate step (e.g., Snijders & Bosker, 2011). By using not just within-subjects data but also between-subjects information to estimate the parameters of a given participant, this approach generally leads to more accurate and efficient estimation (i.e., smaller standard errors) and generation of certain quantities (e.g., standard errors for subject-specific parameters) that can be difficult to estimate accurately using within-subjects data alone.

The NLMM model that we specified is as follows:

$$\mathrm{PD}_{\mathrm{ij}} = ((B_0 + u_{0i}) - (B_1 + u_{1i}) + base_i) \times e^{(-B_2 \times time_j)} + (B_1 + u_{1i}) + e_{ij}, \tag{1}$$

where $\mathrm{PD}_{\mathrm{ij}}$ = Predominance for observer i during time window j, where j is coded

B_0, B_1, and B_2 = fixed-effect parameters denoting DAE, the PD asymptote as time → ∝, and rate of exponential decline, respectively,

$u_{0\mathrm{i}}$ and $u_{1\mathrm{i}}$ = subject-specific random effects for DAE and PD asymptote,

base_i = a constant denoting the average pre-CFS baseline value for each observer, and

e_{ij} = the residual for observer i at time window j

This model specified a pattern of exponential decline (i.e, β_2 parameter) in the predominance of the deprived eye across the 7 time windows[3] and included several additional features. The β_o parameter directly estimated the average DAE as the difference between the predicted predominance value in the initial time window and the baseline value for each observer. In this context, note that when time is coded as 0, $\mathrm{PDij} - \mathrm{base} = \mathrm{B}_0 + \mathrm{u}_0 + \varepsilon_{\mathrm{i,time=0}}$ and $\mathrm{E}[\mathrm{PD}_{\mathrm{ij}} - \mathrm{base}]$ averaged across subjects = B_0 since $\mathrm{E}[\mu_0]$ and $\mathrm{E}[\mathrm{e}_{\mathrm{i,time=0}}] = 0$. The random effect allowed for individual differences in DAE values across observers[4]. As exemplified by participant S23′s results shown in Fig. 5 (left panel), the horizontal asymptote value for some participants' recovery functions was not the pre-CFS baseline value but a different value (greater than the baseline in some cases, less than the baseline in others). For this reason we included the β_1 and μ_1 parameters that denoted, respectively the fixed effect for the average horizontal asymptote across observers and the subject-specific random effect quantifying the deviation of a given participant's asymptotes from the average. We estimated both the fixed effect parameters and the variances of the two random effects. The analysis also generated empirical Bayes estimates of the random effects ($\mu_{0\mathrm{i}}$ and $\mu_{1\mathrm{i}}$) and the approximate standard errors for each observer. We should note that the random effect variance parameters not only allowed us to model and estimate individual

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[3] We also tested models that specified a logistic functional form for the pattern of change over time windows. Information indices indicated better fit for the exponential model.

[4] Preliminary analyses indicated that an additional random effect for the exponential decay parameter failed to improve model fit.

Table 2

Results of Nonlinear Mixed Effects Models on post-CFS Predominance.

Parameter	Estimate	Standard Error	t	p
Base Model				
B_0	8.23	1.06	7.79	< 0.0001
B_1	46.02	0.80	9.63	< 0.0001
B_2	0.11	0.03	3.57	0.001
σ_{u0}^2	38.31	9.79		
σ_{u1}^2	117.93	61.66		
σ_{ϵ}^2	7.67	0.77		
Base + AR				
AR	−0.18	0.26	−0.69	0.50
Base + PBT				
PBT	−0.23	0.08	−2.65	0.01

N = 38. Dependent measure = post-CFS predominance of deprived eye across 6 time windows. B_0 = the magnitude of DAE computed as the difference between the predicted score in the first time window and the average baseline value. B_1 = horizontal asymptote. B_2 = exponential decay parameter. σ_{u0}^2 = variance of random effect of DAE, σ_{u1}^2 = variance of random effect of asymptote. σ_{ϵ}^2 = residual variance. AR = alternation rate during pre-CFS binocular rivalry. PBT = percentage breakthrough during CFS. AR and PBT models were parameterized to assess the effects of each on DAE. Base model parameters changed slightly in models adding AR and PBT. The results of Wald t tests on fixed effects parameters are shown.

differences but also to model the dependence (i.e., correlation) among the observations of a given participant. Normal distributions were specified for random effects and residuals.

We estimated the model described above using the NLMIXED procedure in SAS 9.4 (SAS Institute, Cary NC). Adaptive Gaussian quadrature was used to estimate integrals across random effects and marginal maximum likelihood with dual quasi-Newton optimization was used to estimate model parameters. As summarized in Table 2, the NLMM analysis yielded significant effects for each of the fixed effects parameters. The statistically significant effect of β_0 indicates that, as expected, the deprived eye was more dominant after CFS relative to pre-CFS, with an average increase in percent time of 8%. As indicated by Fig. 6, and by the statistically significant variance component for the DAE parameter yielded by an adjusted likelihood ratio test ($p < .001$), there were substantial individual differences in the magnitude of DAE. Indeed, as indicated by the figure, DAE was, in fact, essentially zero for three participants all of whom exhibited relatively brief dominance durations (S26, S30 and S31 in Fig. 2).

Two additional NLMM models assessed whether AR during rivalry and PBTs during CFS significantly predicted the DAE value during the initial time window. As shown in Table 2, while the regression coefficient for AR was not significant ($p = .50$), a smaller PBT value predicted a larger DAE effect ($p = .01$). This effect was consistent with our expectations that the strength of CFS is inversely related to breakthroughs of the masked stimulus during CFS and directly related to the magnitude of DAE after CFS.

To look at the degree of association among the three measures from a different perspective, we also computed Pearson and Spearman correlations among the AR, PBT, and DAE measures. For the latter, we used the model-predicted values of the predominance measure during the initial time window for each participant that are shown in Fig. 6. We present the results of 1-tailed hypothesis tests because of our priori directional predictions ($r_{AR,PBT} > 0$, $r_{AR,\ DAE} < 0$, $r_{PBT,DAE} < 0$) (see Introduction for rationale). Although there were no significant associations between AR and either of the CFS measures, PBTs during CFS were significantly negatively correlated with the magnitude of DAE (see Table 3). As noted above, this linkage makes sense given the expectation that: (1) a lower frequency of PBTs should indicate more complete suppression during the continuous-flash interval; and, (2) more complete suppression should lead to a larger rebound effect in favor of the non-suppressed eye (i.e., a higher magnitude DAE) during the post-suppression phase.

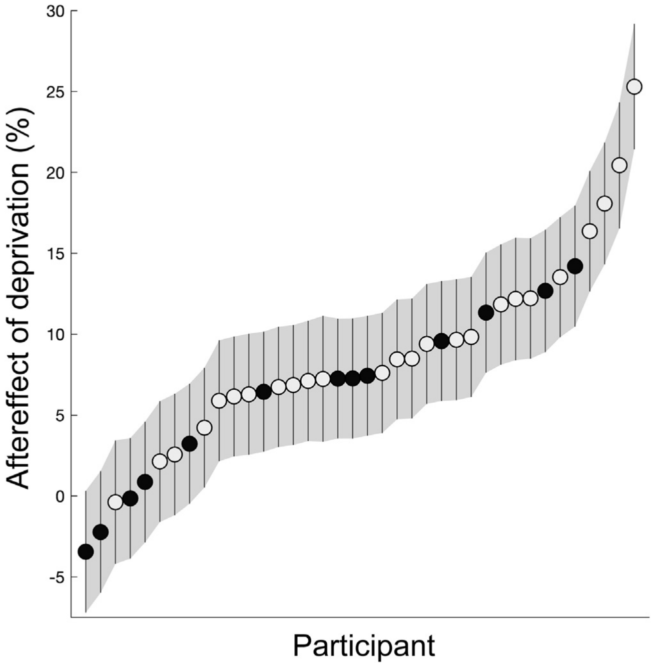

Fig. 6. DAE values during the initial 60 s time window that denote the magnitude of the temporary increase in rivalry predominance in the eye viewing the bulls-eye target during the 6-min CFS period. These values were derived using a nonlinear mixed effects model described in the text. Values are ordered from smallest to largest values across the sample of 38 participants, with light bars and dark bars denoting KU and VU participants, respectively. The bars specify 95% confidence intervals of the estimate of the intercept parameter for each participant.

Recall, however, that there were significant differences between the KU and VU samples in terms of PBT. These effects indicate that correlational results that do not take into account site could be at least partially confounded by between-group mean differences. For example, if two groups differ in the same direction (i.e., group 1 > group 2) on two measures, the two measures could be positively correlated even if the within-group association is 0. The converse can also occur. We addressed this issue by computing partial correlations among our measures of interest. We partialed out a dummy variable denoting site. The resultant partial correlation is an index of the overall within-site correlation between two measures with the effects of between-site mean differences removed. Given that site is binary grouping variable, the adjusted scores are simply group mean-centered residuals (i.e., formed by subtracting each score on a given variable from its group mean). The resultant correlations are pooled within-group correlations assuming that, subject to sampling error, the direction of the association between variables is the same in both sites. We tested this assumption via Z tests of differences in correlations and linear and robust regression analyses that specified interaction terms testing for continuous predictor × site interactions that would indicate between-site differences in regression slopes. There were no significant effects on any of these analyses. As shown in Table 3, across both Pearson and Spearman r's, the partial correlations were generally rather similar to the zero-order r's. While the correlations between PBT and DAE were somewhat lower, both the Pearson and Spearman partial r's were statistically significant (see Table 3).

Although these results are informative, they leave some questions unanswered. As is commonly recognized (e.g., Carver, 1978; Cohen, 1994), conventional null hypothesis testing informs about the probability of the data given the null hypothesis but not the strength of evidence for or against the null or alternative hypotheses. For these

Table 3
Correlations and Partial Correlations.

Variable Pair	Zero-Order r/s		Partial r's (Adjusted for Site)	
	Pearson	Spearman	Pearson	Spearman
Alternation Rate/Percent Breakthroughs	0.15	0.15	0.13	0.10
Alternation Rate/Deprivation After-Effect	−0.11	−0.20	−0.09	−0.18
Percent Breakthroughs/Deprivation After-Effect	-0.39^{***}	-0.38^{***}	−0.32*	-0.33^{**}

N = 38. 1-tailed p values: * = $p < .05$, ** = $p < .025$, *** = $p < .01$ At the two-tailed level, three of the four statistically significant correlations shown in Table 3 are also significant and the fourth is $p < .06$.

reasons, we additionally computed Bayes factors (BFs) (e.g., Jeffreys, 1961; Kass & Raftery, 1995) that allowed us to compute a quantitative index indicating the relative support for the null and alternative hypotheses in the data (e.g., Wagenmakers, 2007). To compute BFs we used the BayesMed package (Nuijten, Wetzels, Matzke, Dolan, & Wagenmakers, 2015; see also Wetzels & Wagenmakers, 2012) implemented in (R Core Team, 2018). We focused on partial correlations due to potential confounding by site differences in means. BFs were computed as the ratio of the marginal likelihood of the alternative hypothesis to the marginal likelihood of the null hypothesis. Marginal likelihoods are essentially a weighted average of the likelihood of the data across the parameter space of a given hypothesis. The weighting factor is the prior density of the parameter(s) specified in advance. We used the Jeffreys-Zellner-Snow mixture of g-prior's specification introduced by Liang, Paulo, Molina, Clyde, and Berger (2008) to compute BFs. The alternative hypotheses (H_1) reflected our directional predictions and were that $\rho_{AR,PBT.Site} > 0$, $\rho_{AR,DAE.Site} < 0$, and $\rho_{PBT,DAE,Site} < 0$, respectively. The null hypothesis (H_0) was that each partial correlation equals 0. In this context, BFs > 1 indicate greater relative support for H_A and BFs < 1 indicate greater relative support for H_0. From a conceptual standpoint, it is important to note that BFs indicate the *change* in the relative probability of the alternative and null hypotheses brought about consideration of the actual data (e.g., Lavine and Schervish, 1998).

Table 4 displays the Bayes Factors for each comparison. Also shown are the posterior probabilities of the alternative hypothesis, the mean of the posterior distribution, and 90% and 95% highest posterior density credible intervals for each partial correlation of interest. It is very clear that the BFs and posterior probabilities are rather low for the partial correlations between AR and PBT and between AR and DAE. According to Raftery (1995) criteria, BFs < 0.33 provide clearly positive support for H_0, and BFs > 3 provide positive support for H_A, although stiffer criteria (e.g., BFs < 1/6 or > 6) could conceivably be invoked. The BFs for the partial correlation between AR and DAE is below the 0.33 threshold and the BF for the partial correlation between AR and PBT is fairly close to it. Both posterior probabilities are about 0.25, thus indicating rather low support for H_A in the data. In contrast, the BF for $\rho_{PBT,DAE,Site}$ is clearly above 1, thus offering support for our directional prediction that $\rho < 0$. We should caution that a BF of this magnitude is generally not considered particularly strong support for the alternative hypothesis. The posterior probability indicates slightly more than a 2/3 probability that H_A is true. Overall, this analysis indicates weak to moderate support for our prediction concerning the correlation between PBT and DAE.

Table 4
Results of Bayesian Analyses of Partial Correlations.

	Variable Pair		
	AR/PB	AR/DAE	PB/DAE
Hypothesis Testing			
H_0	$\rho_{AR,PBT} = 0$	$\rho_{AR,DAE} = 0$	$\rho_{PBT,DAE} = 0$
H_A	$\rho_{AR,PBT} > 0$	$\rho_{AR,DAE} < 0$	$\rho_{PBT,DAE} < 0$
BF (H_0/H_A)	0.40	0.31	2.22
Posterior Probability H_A	0.28	0.23	0.69
Posterior Distribution			
Mean	0.12	−0.08	−0.30
90% HPD	(−0.15.39)	(−0.35, 0.19)	(−0.56, −0.04)
95% HPD	(−0.20, 0.44)	(−0.40, 0.24)	(−0.61, 0.01)

Note: N = 38. AR = Alternation Rate, PBT = Percentage Breakthroughs, DAE = Deprivation After-Effect. BF = Bayes Factor. HPD = Highest Posterior Density. BFs > 1 indicate greater relative support for H_A while BFs < 1 indicate greater relative support for H_0.

15. Discussion

The aims of this study were 1) to assess individual differences in BR dynamics and in CFS effectiveness, and 2) to leverage those individual differences to examine the degree to which these two forms of interocular suppression are related. With respect to aim 1, individual differences in BR have been thoroughly studied over the years, and our results substantiate that those differences exist in our subject population. In contrast, very few earlier studies have focused on individual differences in CFS effectiveness, so our confirmation that such differences exist is important. With respect to aim 2, the results from our study lead us to conclude that CFS and BR, while related forms of interocular suppression, differ in some notable ways. In this Discussion section, we examine potential implications of that conclusion. Toward that end, it is helpful to begin with some comments and observations about CFS.

As mentioned in the Introduction, CFS represents an especially effective means for creating extended periods of invisibility of a normally visible monocular stimulus. CFS can be achieved using a variety of different interocular mask configurations, including sequences of independently generated 2D noise images (e.g., Han & Alais, 2018), arrays of small random-dots (Fang & He, 2005), Mondrian-like colored blocks (Tsuchiya & Koch, 2005), arrays of grey-scale squares and circles (Ludwig, Sterzer, Kathmann, & Hesselmann, 2016) and natural-scene images (Kim et al., 2017), the last of which we used in our study. Generalizing across those various animation formats, an archetypical format for creating CFS emerges: richly contoured, high-contrast stimulus elements that are changing briskly over time. And when appropriately crafted, a monocular CFS display can erase visibility of a complex visual stimulus viewed by the other eye for durations that far outstrip anything achievable by other psychophysical means (Kim & Blake, 2005; Breitmeyer, 2015), including conventional BR. That is why CFS quickly became popular as a tool for studying processing outside of awareness. But, as we have come to learn, it is a tool that does not work with equal effectiveness on everybody (e.g., Ledgeway, McGraw, & Thompson, 2013; Yamashiro et al., 2014; Gayet & Stein, 2017). This conclusion is now amply documented by the present results summarized in Fig. 3: the incidence and durations of breaches in CFS vary substantially among people, as does the amount of time elapsing before the first breach following the onset of CFS. Our results also show that these individual differences are preserved across trials despite mean shifts in the incidence of breaches.

Do those individual differences undermine the original claim that CFS can maintain suppression of a target viewed by the other eye for a minute or longer (e.g., Tsuchiya & Koch, 2005)? Not at all, for the median duration of time elapsing before an initial breakthrough in CFS was 70 sec in our study, a value that is 15 times longer than the median dominance durations measured during the pre- and post-CFS BR phases (see also Yamashiro et al., 2014). In this respect our results are consistent with the widely touted potency of CFS. Our results also reveal that the duration of the initial period of suppression produced following the onset of CFS varies considerably among participants. Those individual differences in CFS effectiveness need to be considered when using the bCFS technique where duration to breakthrough is the dependent variable (cf. Gayet, Paffen, & Van der Stigchel, 2013). Moreover, CFS's potency tends to wane with repeated trials, a trend reported earlier by Ludwig et al. (2013).

It is also worth remembering that CFS effectiveness depends on the contrast (e.g., Ludwig et al., 2016), the spatial frequency content (Yang & Blake, 2012), and the temporal frequency content (Han et al., 2016) of the CFS mask. Moreover, the incidence and timing of breeches of CFS vary depending on the contrast of the to-be-suppressed target viewed by the other eye (e.g., Yuval-Greenberg & Heeger, 2013). Indeed, studies using the bCFS version often elect to start with a very low-contrast monocular stimulus to promote longer durations of suppression, and then to increase the target's contrast steadily to insure eventual breakthrough of suppression (e.g., Jiang. Costello, & He, 2007; Yang, Blake, & McDonald, 2010). That technique places the burden of decision entirely in the observer's hands, so to speak, which raises concerns about how different people interpret 'emergence from suppression' (a point emphasized by Gayet & Stein, 2017). In our study we purposefully selected a moderate, unchanging bulls-eye contrast that, for the vast majority of participants, managed to achieve intermittent dominance during sustained viewing. Still, the question of criterion differences among participants, we realize, can be raised about our study as well. We also acknowledge that the indices of CFS potency that we derived, i.e, PBT and DAE, would likely vary were we to repeat our measurements using a weaker CFS mask (e.g., a stream of low contrast monochrome noise images) or a more robust contralateral target (e.g., a very high contrast, rapidly flickering bullseye target). But we see no reason why those manipulations would impact the pattern of individual differences in DAE that we have documented (Fig. 6).

Moving to the heart of our project, what might be the neural bases for these individual differences in CFS effectiveness and how might that relate to BR? It is tempting to believe that the potency of CFS is governed, at least in part, by the strength of interocular inhibition exerted on the neural signals associated with the other eye's stimulus. Consistent with that belief, Yamashiro et al. (2014) found that weaker neural responses to a monocular probe, measured from extrastriate visual cortical areas using fMRI, were observed in individuals exhibiting longer durations of suppression caused by CFS. Recall that reciprocal inhibition models of BR can account for individual differences in BR dynamics by positing differences in endogenous strength of interocular inhibition. Consistent with this idea, van Loon et al. (2013) found that individual differences in switching rates during BR were correlated with concentration levels of the inhibitory neurotransmitter gamma-amino butyric acid (GABA) within the visual cortex measured using magnetic resonance spectroscopy, with higher concentrations of GABA showing up in people exhibiting longer dominance durations and, by inference, slower rates of switching. In addition, Shimaoka and Kaneko (2011) adopted a computational modeling approach to show that reciprocal inhibition together with neural adaptation, i.e., the lynchpin ingredients of reciprocal inhibition models of BR (e.g., Wilson, 2007), can predict the unusually long suppression durations exerted by CFS on the other eye's stimulus. Our study now adds to these other results another key finding: the effectiveness of CFS to shift rivalry dominance temporarily is related to its effectiveness in maintaining interocular suppression during the prolonged period of CFS mask/target viewing (Table 1).

Considered as a whole, the frequentist and Bayesian analyses that we conducted offered mild to moderate support for the directional prediction that the two within-CFS measures (PBT and DAE) are negatively correlated. The observed magnitude of effect here is best deemed 'medium' according to Cohen (1992) standards for correlations specifying that $\rho = 0.1$ is small, $\rho = 0.3$ is medium, and $\rho = 0.5$ is large. To our surprise, however, we found no evidence for even a mild to moderate relation between individual differences in AR and individual differences on measures that reflect the strength of suppression during (PBT) or immediately after (DAE) CFS. Pearson and Spearman zero-order and partial correlations were consistently low and non-significant. Consistent with these results, Bayes factors, posterior probabilities, and HPD intervals indicated a lack of support for the hypotheses that $\rho_{AR,PBT} > 0$ and that $\rho_{AR,DAE} < 0$ relative to the hypothesis that each correlation equals 0.

We should caution that both frequentist p values and BFs are sensitive to sample size, though in different ways (Held & Ott, 2018). That our sample size ($N = 38$) was sufficient to detect correlations in the ± 0.30 range on significance tests and other indices (e.g., HPD intervals) suggests that the null findings for the correlations of AR with the two CFS measures are not primarily due to small sample sizes. That said, we acknowledge the importance of replicating and extending our results using larger sample sizes and perhaps a broader array of measures of both BR and the effects of CFS. Pending such evidence, however, measures derived from a standard BR paradigm and from CFS do not appear to represent two sides of the same coin. Consistent with this reasoning is the evidence that BR and CFS can differentially impact aspects of visual processing, a point alluded to in the Introduction. For example, visual adaptation to complex spiral motion is disrupted by BR suppression (Wiesenfelder & Blake, 1990) but appears to survive CFS (Kaunitz, 2011). Moreover, semantic information shows no tell-tale signs of being registered during suppression phases of BR (Zimba & Blake, 1983; Cave, Blake, & McNamara, 1998), but several studies report results purporting to demonstrate that semantic information is registered during CFS (Sklar et al., 2012; Zabelina et al., 2013). That conclusion, however, does not receive support from several other recent papers (Kang, Blake, & Woodman, 2011; Shanks, 2017; Kimchi, Devyatko, & Sabary, 2018; Rabagliati, Robertson, & Carmel, 2018; Moors & Hesselmann, 2018). Resolving possible reasons for this controversy concerning the survival of semantic processing during CFS is beyond the scope of our Discussion.

Of course, it is always possible that ancillary factors are differentially affecting BR and CFS, effectively diluting their commonality. For instance, in addition to inhibition strength and adaptation, BR dynamics may also be more susceptible to noise within the input signals to this reciprocal inhibition network (Moreno-Bote, Rinzel, & Rubin, 2007) or more susceptible to noise in the adaptation process itself (van Ee, 2009). It should also be noted that CFS displays, because of their ever-changing format, probably attenuate the impact of neural adaptation relative to that associated with the weaker monocular stimulus viewed by the other eye. By minimizing adaptation, of course, activity-driven inhibition associated with the CFS display can remain relatively strong because of the sustained, robust activation within neurons responsive to that display and, as well, because of the prolongation of weak activation within neurons responsive to the suppressed stimulus. This complex of neural interactions could emerge through modulation of contrast gain control due to the overwhelmingly strong contribution of neural activity produced by the CFS mask to the pooled response governing normalization (Yuval-Greenberg & Heeger, 2013). It remains to be learned whether reciprocal inhibition is, in fact, a common ingredient underlying these two forms of interocular suppression, an ingredient that is diluted when mixed with other factors unique to BR or to CFS.

For now, however, the evidence presented here suggests that BR and CFS, despite their common origins (i.e., dissimilar monocular stimulation), may be more like first degree relatives rather than identical twins. Pending additional evidence, it would seem prudent to maintain an open mind about whether BR and CFS belong in the same immediate family.

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