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Slow and steady, not fast and furious: Slow temporal modulation strengthens continuous flash suppression

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ABSTRACT

Continuous flash suppression (CFS) involves the presentation of a rapidly changing Mondrian sequence to one eye and a static target in the other eye. Targets presented in this manner remain suppressed for several seconds at a time, and this has seen the prevalent use of CFS in studies of unconscious visual processes. However, the mechanisms behind CFS remain unclear, complicating its use and the comprehension of results obtained with the paradigm. For example, some studies report observations indicative of faster, visual masking processes whereas others suggest slower, rivalry processes. To reconcile this discrepancy, this study investigates the effect of temporal frequency content and Mondrian pattern structure on CFS suppression. Our results show predominant influences of spatial edges and low temporal-frequency content, which are similar to binocular rivalry, affording a parsimonious alternative in unifying the two paradigms.

1. Introduction

Understanding the extent to which visual stimuli falling outside of conscious awareness remain effective in visual processing constitutes a key theme in psychology and neuroscience research. Among the wide variety of tools used to suppress images from visual awareness (Alais & Blake, 2005; Breitmeyer, 2014; Kim & Blake, 2005), continuous flash suppression (CFS) has emerged as one of the most effective. In CFS, a dynamic sequence of complex, geometric images presented to one eye at a typical rate of 10 Hz can suppress a static target viewed by the other eye for many seconds at a time (Tsuchiya & Koch, 2005; Tsuchiya, Koch, Gilroy, & Blake, 2006). Similar to binocular rivalry, CFS relies on neural inhibition, triggered when irreconcilable monocular images are viewed dichoptically. Yet, unlike rivalry, the dissimilar monocular images employed to create CFS tend not to alternate frequently, and the initial percept is reliably the dynamic masking pattern which can remain exclusively dominant for remarkably long durations. The reliability and potency of CFS enable easy study of unconscious visual processes, resulting in the frequent use of these Mondrian masking patterns in evaluating the potency of cross-modal and higher-order influences on processing of unconscious stimuli (Fang & He, 2005; Jiang, Costello, & He, 2007; Kido & Makioka, 2013; Lunghi, Verde, & Alais, 2017; Moors, Huygelier, Wagemans, De-Wit, & Van Ee, 2015; Moors, Wagemans, van Ee, & de-Wit, 2015).

Whilst these developments in unconscious perception research are intriguing, the stimulus factors governing the Mondrian masker's potency remain poorly understood. This is concerning, because conclusions drawn from CFS may be driven by factors such as insufficiently rigorous awareness measures and poorly masked stimulus features (Hedger, Gray, Garner, & Adams, 2016). Indeed, studies report that the reliability of CFS suppression varies with feature similarity between the dichoptic images, increasing in

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strength when similar spatial frequencies and speeds are used (Moors, Wagemans, & De-Wit, 2014; Yang & Blake, 2012). Han, Lunghi, and Alais (2016) recently measured the temporal frequency tuning of CFS using temporally narrowband, filtered noise maskers. To control for spatial frequency differences, their noise maskers were spatially filtered to have a 1/f profile to resemble the spatial frequency profile of the target stimuli which, themselves, were natural images. Results from that study revealed a low temporal frequency peak in CFS suppression, which not only corresponded to the low-biased temporal frequency spectrum of the Mondrian masker, but also became more pronounced with high spatial frequency and high contrast. These observations are reminiscent of a parvocellular bias in binocular rivalry (Bossink, Stalmeier, & de Weert, 1993; Carlson & He, 2000; Mueller & Blake, 1989), suggesting a parsimonious interpretation of rivalry and CFS in terms of common interocular suppression mechanisms.

Whilst the temporally filtered noise maskers used in Han et al. (2016) are ideal for examining the temporal frequency tuning of CFS, and the low frequency bias corresponded to the Mondrian's temporal frequency spectrum (see Fig. 1d of Han et al., 2016), noise maskers are spatially random in phase. Consequently, they do not contain coherent spatial patterns and lack the rapidly changing shapes and contours that are the hallmark of dynamic Mondrian maskers. This may be an important difference as coherent spatial phase is known to enhance rivalry suppression (Alais & Melcher, 2007; Baker & Graf, 2009) and the repeating pattern of transient onsets and offsets of shapes and contours in CFS does appear to enhance suppression (Tsuchiya et al., 2006). It is also not uncommon for studies to adapt the spatial form of Mondrian patterns to enhance suppressive strength, e.g., using ellipses instead of rectangles when suppression of face images is required (Stein, Hebart, & Sterzer, 2011; Sweeny, Grabowecky, & Suzuki, 2011). Akin to forms of masking such as the "standing wave of invisibility" (Macknik & Livingstone, 1998) and pattern structure masking (Breitmeyer, 1984; Enns & Di Lollo, 2000), these characteristics pose a paradox in which faster, visual masking processes and slower, rivalry processes both appear to play significant roles in CFS suppression. Thus, the goal of this study is to investigate more closely the low-frequency bias reported by Han et al. (2016) examining how the spatial integrity of the Mondrian pattern interacts with temporal frequency content.

A simple approach would be to manipulate the Mondrian pattern structure and update schedule, since the removal of sharp spatiotemporal edges should reduce the impact of masking (Macknik & Martinez-Conde, 2007; Macknik, Martinez-Conde, & Haglund, 2000; Schiller & Smith, 1966) and reveal the magnitude of rivalry influences. Such manipulations, however, are surprisingly scarce. Previous studies have spatially filtered the Mondrian pattern (Maehara, Huang, & Hess, 2009; Yang & Blake, 2012) and compared the Mondrian masker with filtered dynamic noise (Han et al., 2016), but interpretations with these approaches are complicated by differences in spatial spectral content. Other studies manipulate the update schedule by varying the number of Mondrian patterns presented per second (Kaunitz, Fracasso, Skujevskis, & Melcher, 2014; Zhu, Drewes, & Melcher, 2015), but any resultant change in suppression strength is confounded by simultaneous variations in the number of pattern changes and temporal frequency spectrum of the changes (Fig. 1a). To circumvent these issues, we could temporally filter Mondrian maskers and vary their spatial structural integrity by phase scrambling the Mondrian patterns. As shown in Fig. 1b, these methods afford control over spatiotemporal frequency content without introducing confounds such as the number of pattern changes.

In a bid to thoroughly understand the relationship between the Mondrian pattern and temporal frequency, we first addressed the roles of the Mondrian pattern and its components in Experiments 1–2. In Experiment 1, we asked if the Mondrian pattern acts on the level of target recognition. This was because studies frequently adapt the spatial form of the Mondrian pattern to resemble that of the target (Stein et al., 2011), raising the possibility that any resulting enhancement may be driven by impaired target recognition. Spatially phase-scrambled Mondrian sequences were compared to intact Mondrian patterns, and two judgment types (i.e., location and identity) were collected. Following that, we examined the effects of pattern edges and solid areas in Experiment 2. Spatial edges are known to influence both binocular rivalry (Levelt, 1965; Baker & Graf, 2009; Hunt, Mattingley, & Goodhill, 2012) and masking (Macknik & Martinez-Conde, 2007; Macknik et al., 2000; Schiller & Smith, 1966), and it would be interesting to see if these features have a significant contribution to CFS suppression. We assessed the contributions of the individual pattern components by selectively preserving edges and solid areas, and then studied the relationship between these components by varying the extent to which each component was preserved.

Having revealed keynote features of the Mondrian pattern and its components, we then examined the effects of temporal frequency content and spatial pattern integrity in Experiment 3. We compared temporally low- and high-pass filtered maskers (i.e. < 4 Hz and > 4 Hz respectively), and then evaluated these maskers against unfiltered maskers in Experiment 3. Here is the reasoning behind this approach: matched in RMS contrast, the high-pass filtered masker reveals the suppressive strength of predominant masking influences whereas the low-pass filtered masker would reveal the importance of transients in CFS. Conducting these comparisons would demonstrate the suppressive strength of each of these processes and give us an idea of the dominant process in CFS. We also conducted these comparisons with phase-scrambled and intact Mondrian patterns, thereby allowing us to compare the size of pattern effects for each type of temporal frequency content. To ensure that the low-pass filtered and high-pass filtered maskers fall on either side of the crossover point between low and high temporal frequency channels (~ 4 Hz), respectively (Cass & Alais, 2006), we used a cut-off temporal frequency of 4 Hz. This approach extended the work of Yang and Blake (2012), and provided a suitable comparison to Han et al. (2016). Our results corroborated and extended the findings of Han et al. (2016): we found that suppression was mainly driven by pattern edges and low temporal frequency content. High temporal frequency maskers, on the other hand, provided weak suppression regardless of pattern structure.