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Forum

Continuous Flash Suppression: Stimulus Fractionation rather than Integration

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Recent studies using continuous flash suppression suggest that invisible stimuli are processed as integrated, semantic entities. We challenge the viability of this account, given recent findings on the neural basis of interocular suppression and replication failures of high-profile CFS studies. We conclude that CFS reveals stimulus fractionation in visual cortex.

Awareness and unawareness of visual input has intrigued scientists for decades, if not centuries. A popular line of research has focused on which aspects of stimulus processing can bypass visual awareness. About 10 years ago, a powerful paradigm, known as continuous flash suppression (CFS), was introduced [1]. CFS involves dichoptic stimulation in which one eye is presented with dynamically changing overlapping colored shapes, while a target stimulus is presented to the other eye, yielding reliable suppression of that stimulus (Box 1). Compared to other 'blinding' paradigms such as forward/backward masking, this robust and prolonged suppression has rendered CFS persuasive in shaping our understanding of visual awareness at the behavioral and neural level, resulting in over 200 empirical studies to date (http://www.gestaltrevision.be/s/cfs).

Several CFS studies drew the conclusion that perceptually suppressed stimuli are processed more extensively than implied by previous research on unconscious visual processing, yet in line with earlier views on binocular rivalry as a central, high-level process [2,3]. A nonexhaustive list of these findings includes the processing of subliminal faces and words, of semantic incongruities in invisible scenes and sentences, and even the solving of invisible equations [4].

CFS can be considered as a special case of binocular rivalry. The study of binocular rivalry has strong historical roots, and its neural underpinnings have been thoroughly examined (Box 2). It is currently viewed as a hierarchical process, impacting processing at several levels in the visual hierarchy, starting at but not restricted to monocular channels in visual cortex [5]. Although such a view in principle allows for extensive unconscious processing, we argue here that recent observations give more weight to the stance that processing invisible stimuli during CFS is most likely limited to a fractionated collection of simple visual features derived from representations in visual cortex [6,7]. These observations are as follows: (i) Recent studies have provided converging evidence for interocular suppression to transpire early in the visual processing hierarchy, where low-level features of the visual input are encoded [8–11]. (ii) Several of the early and influential findings using CFS have now been challenged due to replication failures, and alternative interpretations have been advanced based on re-examining the original data [12–15].

Early Suppression in Binocular Rivalry

From the binocular rivalry viewpoint, it might seem surprising that many researchers considered CFS a viable paradigm to study unconscious visual processing of complex, integrated stimulus features. The rationale was that as CFS allows to suppress a stimulus for seconds, this might allow more elaborate processing. We argue that this reasoning falls short because it ignores how a stimulus is represented during perceptual suppression. Amongst others, four recent studies have contributed to the view that the prime locus of interocular suppression resides in low-level visual areas.

(i) de Jong and colleagues [8] used intracranial recordings in occipital cortex and observed that spontaneous and stimulus-induced perceptual changes during binocular rivalry showed similar neural modulations. This suggests that the initiation of perceptual content already happens in early visual cortex, rather than in higher-level frontoparietal areas.

(ii) Zou and colleagues [9] showed that stimuli can still engage in binocular rivalry despite the fact that they are rendered invisible through chromatic flicker fusion. This implies that awareness of perceptual conflict is unnecessary for binocular rivalry to transpire, substantiating an account of interocular competition based on mechanisms in early visual cortex.

(iii) Yuval-Greenberg and Heeger [10] showed that CFS modulates blood oxygenation level-dependent (BOLD) activity in early visual cortex (V1–V3). Invisible stimuli evoked activity that was statistically indistinguishable from activity in stimulus-absent (i.e., mask-only) trials.

(iv) Fang and He [16] suggested that CFS suppresses visual processing in the ventral stream, while leaving the processing of action-relevant stimulus features in the dorsal stream intact. However, the key finding of relatively preserved BOLD activity in dorsal stream areas could not be confirmed in follow-up studies. This suggests that the link between BOLD activity and perceptual (un)awareness is stream-invariant in higher-order visual cortex [11].

Collectively, these studies indicate that perceptual suppression induced by interocular conflict has an early locus in the

Box 1. Continuous Flash Suppression: Implementation and Methods

When dissimilar images are presented to corresponding regions of both eyes, something peculiar happens. Our perception alternates between both images in a seemingly stochastic manner. This phenomenon, known as binocular rivalry, is the basis of continuous flash suppression (CFS). In CFS, a highly salient and dynamic stimulus is presented to one eye, resulting in strong and effective suppression of the stimulus presented to the other eye, rather than unpredictable alternations between stimuli (Figure I).

CFS has been used in two different ways to study unconscious visual processing. In indirect paradigms, a stimulus is perceptually suppressed and one measures adaptation aftereffects, attentional shifts, or priming effects elicited by the suppressed stimulus. Here, a particular challenge is to show that the suppressed stimulus was actually invisible. Therefore, a direct paradigm known as breaking CFS has gained considerable popularity. Here, a trial typically starts with presenting a stimulus at an initial low contrast such that suppression is guaranteed. Subsequently, the contrast of the suppressed stimulus is gradually increased. The time it takes for the stimulus to break suppression (i.e., become detectable) is frequently used as an index of unconscious processing, although the validity of this method to reveal unconscious processing has been questioned.

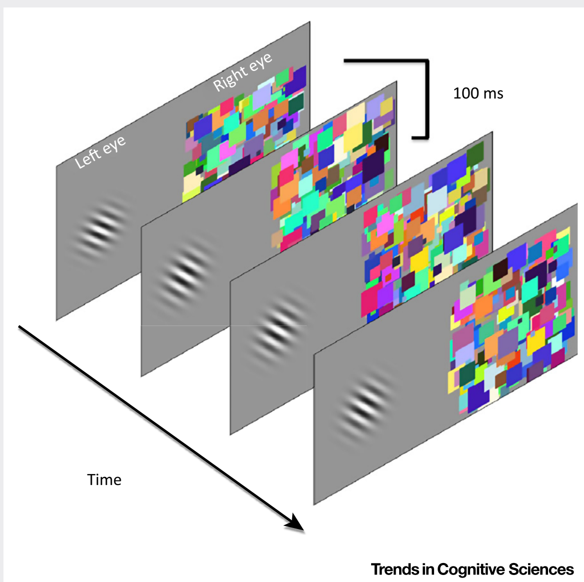

Figure I. An Example of a Typical CFS Setup. The dynamic mask consists of various colored geometric elements and its contents are updated every 100 milliseconds. Here, a grating stimulus is presented to the other eye.

visual system, shifting the early versus late suppression debate more towards the early side (Box 2). Based on these recent data, we argue that it is most likely that the representation of invisible stimuli is fractionated, and limited to their basic, elemental features. This view has also been advanced based on behavioral observations that the presence of or changes in certain stimulus features (e.g., flicker, color) are reportable during CFS, while others are not [6,7].

Box 2. Binocular Rivalry: Historical Roots and Consensus View

Much of the binocular rivalry literature pertains to the (neural) site of perceptual suppression, a discussion dating back to Breese and von Helmholtz, amongst others. Two views can be dissociated in this debate: is suppression a more ‘peripheral’ process situated early in visual processing as a consequence of reciprocal inhibition between monocular channels (eye-based suppression) or does it reflect a more central process happening in downstream areas between stimulus representations rather than eyes [2,3]? Over the years, considerable evidence has accumulated for either stance, inspiring a hybrid model of binocular rivalry in which it is considered to be the consequence of a series of processes playing out at different levels of the cortical hierarchy [5].

Replication Failures of High-Profile CFS Studies

From the previously discussed studies, it seems reasonable to posit that processing during CFS does not involve integrated, semantic features. Nevertheless, two studies had a strong impact on the contrary view. The conclusions from both studies have recently been called into question:

(i) Mudrik and colleagues reported that scenes containing incongruent object–background relations entered awareness faster compared to those containing congruent relations [12]. Moors and colleagues [13] failed to replicate the findings reported in Mudrik *et al*. Through three different replication experiments, a Bayesian analysis, and an analysis of image features, they argued that the reported empirical evidence is more consistent with the absence of a congruency effect.

(ii) Sklar and colleagues reported that semantic incongruities can be detected in short invisible sentences, and that multistep arithmetic operations can be performed for invisible equations [14]. The arithmetic part of the study by Sklar *et al*. has recently been the subject of a critical reanalysis, based on statistical, methodological and theoretical considerations. This reanalysis concluded that the data do not contain sufficient evidence to make claims on the existence of unconscious arithmetic [15].

CFS – Probing Stimulus Representation in Early Visual Cortex

In sum, we conclude that processing of CF-suppressed stimuli reveals how these stimuli are represented at the level of early visual cortex. That is, behavioral and neural correlates of invisible stimulus processing inform us on the default (or current) sensitivity of early visual cortex to input statistics that observers have been exposed to throughout their life. These statistics have shaped the neural representation of the basic features of the input as well as the strength of their connectivity pattern. In turn, this biases stimulus processing towards the effects that are commonly observed in CFS studies. What are the implications of such an account?

(i) The representation of CF-suppressed stimuli is fractionated rather than integrated and restricted to basic features of the visual input – as highlighted by recent studies [6,7]. As such, we submit that processing of integrated, semantic stimulus features during CFS is not possible.

(ii) This view does not exclude modulatory effects of working memory or attention on invisible stimuli as these effects play out at the level at which the stimulus is suppressed.

(iii) Plasticity of the visual system should make it possible to change how the invisible stimulus is represented. Perceptual learning or conditioning paradigms can tap into the dynamics of these changes, and reveal whether awareness of the visual input is needed for learning.

We believe that the stimulus fractionation model of CFS provides the most plausible picture of the current literature on stimulus processing during CFS. Furthermore, it constrains hypothesis generation for future CFS research hopefully resulting in a more consistent literature.

Acknowledgments

P.M., J.W., and R.V.E. were supported by the Methusalem program by the Flemish Government (METH/14/02), awarded to J.W.; G.H. was supported by the German Research Foundation (DFG grant HE 6244/1-2); R.V.E. was supported by the EU HealthPac grant (awarded to J. van Opstal) and FWO-Vlaanderen.

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http://dx.doi.org/10.1016/j.tics.2017.06.005

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Forum

Chinese versus English: Insights on Cognition during Reading

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Chinese reading experiments have introduced important caveats to theories of reading that have been largely informed by studies of English reading – especially in relation to our understanding of lexical processing and eye-movement control. This article provides a brief primer on Chinese reading and examples of questions that arise from its study.

Recent interest in Chinese reading reflects a growing appreciation that the language and writing system can inform our understanding of the perceptual, cognitive, and motor processes involved in reading – an understanding that has largely been informed by studies of English and other Western languages and writing systems [1]. This article will review what is known about the reading of Chinese versus English, focusing on the Chinese logographic writing system and how its properties affect two important aspects of skilled reading – word identification and eye-movement control (for reviews, see [2,3]).

As Figure 1 shows, Chinese is visually denser than English. Unlike English words, which consist of letter strings, Chinese words are composed of 'characters' – the smallest pronounceable and meaningful units in Chinese, corresponding to morphemic syllables having one of four possible tones (in Mandarin). Each character consists of one to 36 overlapping 'strokes' occupying a uniformly sized, two-dimensional box-shaped spatial layout in text. Strokes can be further arranged into 'radicals', some of which can also be characters, but most being within-character subunits. In addition, the words (most of which consist of one to four characters) are not demarcated by clear word boundaries.

As Table 1 shows, with both English and Chinese, factors that increase the length or complexity of words also slow their identification. However, in English, word length and complexity are defined by the number of letters or morphemes, whereas in Chinese, length and