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Exploring the boundary conditions of unconscious numerical priming effects with continuous flash suppression

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ABSTRACT

The scope and limits of unconscious processing are a controversial topic of research in experimental psychology. Particularly within the visual domain, a wide range of paradigms have been used to experimentally manipulate perceptual awareness. A recent study reported unconscious numerical processing during continuous flash suppression (CFS), which is a powerful variant of interocular suppression and disrupts the conscious perception of visual stimuli for up to seconds. Since this finding of a distance-dependent priming effect contradicts earlier results showing that interocular suppression abolishes semantic processing, we sought to investigate the boundary conditions of this effect in two experiments. Using statistical analyses and experimental designs that precluded an effect of target numerosity, we found evidence for identity priming, but no conclusive evidence for distance-dependent numerical priming under CFS. Our results suggest that previous conclusions on high-level numerical priming under interocular suppression may have been premature.

1. Introduction

The scope and limits of unconscious perceptual priming effects have been a central and, at the same time, controversial topic of research in experimental psychology and cognitive neuroscience for the last decades (Holender, 1986; Kouider & Dehaene, 2007). In the course of this scientific endeavor, a wide range of paradigms have been used to present stimuli outside of participants' awareness, particularly within the visual domain (Bachmann, Breitmeyer, & Ogmen, 2007; Kim & Blake, 2005). One emerging view is that not all invisible stimuli are equally invisible, since different paradigms suppress the conscious perception of stimuli at different levels of the neurocognitive architecture (Breitmeyer, 2014; Faivre, Berthet, & Kouider, 2012; Fogelson, Kohler, Miller, Granger, & Tse, 2014).

A paradigm that has recently become very popular for the investigation of unconscious visual processing is continuous flash suppression (CFS): high-contrast dynamic patterns shown to one eye disrupt the conscious perception of a low-contrast stimulus shown to the other eye for up to several seconds (Tsuchiya & Koch, 2005). In contrast to binocular rivalry, onset and offset of stimulus suppression can be deterministically controlled by switching the dynamic CFS masks on and off, respectively. Behavioral and neuroimaging studies using CFS have already produced a large but heterogeneous body of evidence regarding the types of visual information that can be processed during this powerful variant of interocular suppression (Gayet, Van der Stigchel, & Paffen, 2014; Hesselmann, 2013; Sterzer, Stein, Ludwig, Rothkirch, & Hesselmann, 2014; Yang, Brascamp, Kang, & Blake, 2014).

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The findings of a recent study (Bahrami et al., 2010) suggested that numerical processing of small quantities (1–3) can escape CFS and lead to robust numerical priming effects in an enumeration task. In a series of three priming experiments (and two control experiments to assess prime invisibility), the authors showed that unconsciously presented non-symbolic and symbolic primes (sets of Gabor patches and Arabic digits, respectively) induced a priming effect for non-symbolic numerosity targets which was linearly dependent on the numerical distance between target (*t*) and prime (*p*). Specifically, the priming effect signaled "interference" (i.e., slower RTs relative to a prime-absent baseline) for negative *t*–*p* distances (e.g., *t*: 1, *p*: 3), and "facilitation" for positive *t*–*p* distances (e.g., *t*: 3, *p*: 1), while facilitatory priming was relatively small and less robust for zero *t*–*p* distance, i.e., numerically congruent trials (e.g., *t*: 2, *p*: 2). The same priming function was observed for invisible and visible primes. While intriguing and robust across experiments, this pattern of results merits further investigation due to two reasons. First, the results are in disagreement with earlier interocular suppression studies which have shown that binocular rivalry abolishes visual semantic priming (Cave, Blake, & McNamara, 1998; Zimba & Blake, 1983), and that semantic analysis does not occur in the absence of awareness induced by CFS (Kang, Blake, & Woodman, 2011). Second, the specific shape of the observed priming functions is difficult to reconcile with the results from previous numerical priming studies. For example, it has usually been found that when a target is preceded by a prime number, participants' response latencies decrease with decreasing absolute *t*–*p* distance (Dehaene et al., 1998; Koechlin, Naccache, Block, & Dehaene, 1999). This well-established feature of numerosity priming is generally explained by increasing representational overlap between the prime and the target as *t*–*p* distance decreases (Van Opstal, Gevers, De Moor, & Verguts, 2008).

Furthermore, the pattern of priming across *t*–*p* distances has been shown to depend on the notation of the prime: While V-shaped priming (centered on zero *t*–*p* distance) was found for symbolic digit primes, a step-like priming function resulted from trials with non-symbolic dot primes (Roggeman, Verguts, & Fias, 2007). Computational models of number perception often assume two different coding schemes (Dehaene & Changeux, 1993; Verguts & Fias, 2004). V-shaped priming effects are taken as indicative of a place coding scheme. Since numerical magnitude is thought to be represented along a continuum, place coding implies the activation of circumscribed positions (i.e., numbers) along this continuum which in turn leads to the co-activation of neighboring positions (i.e., neighboring numbers). Step-like priming functions are thought to indicate a summation coding scheme. Here, a given numerosity corresponds to the sum of activated nodes along the continuum. That is, a given numerosity activates all nodes up to and including a certain node, thereby leading to step-like priming functions. Surprisingly, Bahrami et al. (2010) reported similar linear priming functions for both non-symbolic and symbolic primes.

Here, we sought to investigate the boundary conditions of the distance-dependent priming effect previously observed under CFS. In the first experiment, we asked whether the linear priming effect, which was originally reported by Bahrami et al. (2010) for primes and targets within the subitizing range (Burr, Turi, & Anobile, 2010; Kaufman & Lord, 1949), generalizes to larger numerosities (>4). It has been suggested that the apperception of small and large numerosities invoke distinct cognitive functions, and more specifically, that subitizing is functionally different from estimation (Revkin, Piazza, Izard, Cohen, & Dehaene, 2008). Experiment 1 closely followed the procedures of the original numerosity priming study (Bahrami et al., 2010) but involved only non-symbolic primes and non-symbolic targets either in a small or large numerosity range.

2. Experiment 1

2.1. Methods and materials

2.1.1. Participants

We determined sample size based on the original study by Bahrami et al. (2010). The authors reported F and p values and degrees of freedom for three independent repeated measures ANOVAs with factor "*t*–*p* distance" (Exp. 2: $N = 17$, $F_{4,64} = 7.72$, $p < .0001$; Exp. 3: $N = 13$, $F_{4,48} = 2.6$; $p = .04$; Exp. 4: $N = 16$, $F_{4,60} = 4.50$, $p = .003$). We calculated the associated effect sizes f (Exp. 2: $f = 0.43$; Exp. 3: $f = 0.28$; Exp. 4: $f = 0.34$) assuming a mean correlation between repetitions of 0.5. Using G*Power 3.1.9 (Faul, Erdfelder, Lang, & Buchner, 2007) we determined that for $f = 0.35$, and $\alpha = 0.05$, a sample size of $N = 14$ was required to achieve a power of 0.90 (actual power: 0.91).

19 observers participated in our experiment, which was conducted with local ethics approval at the Department of Psychiatry and Psychotherapy, Charité-Universitätsmedizin Berlin, Germany. They were recruited from a student pool via email and paid 8 €/h for their participation. Three participants were excluded from further analyses because they showed significant above-chance forced-choice discrimination performance for invisible stimuli in the control experiment (see Section 2.1.10). All remaining 16 participants (9 female, mean age: 22, range: 18–30 years) had normal or corrected-to-normal vision, were naïve to the purpose of the study, and provided informed written consent. GH, ND, and KW collected data.

2.1.2. Apparatus and setup

Participants were seated in a dark environment, the only light coming from the experimental monitor and a second monitor, and viewed the dichoptic images on a 19" CRT monitor (SAMTRON 98PDF; effective screen diagonal: 43.6 cm; refresh rate 60 Hz) via a mirror stereoscope. To stabilize head position the participants placed their heads on a chinrest. The viewing distance from the eyes to the screen (including distances within the mirror system) was 66 cm. All stimuli were generated with PsychToolbox 3 (Brainard, 1997; Pelli, 1997) running under Matlab R2007b (MathWorks Inc., USA).