

# Cogito ergo video: Task-relevant information is involuntarily boosted into awareness

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Only part of the visual information that impinges on our retinae reaches visual awareness. In a series of three experiments, we investigated how the task relevance of incoming visual information affects its access to visual awareness. On each trial, participants were instructed to memorize one of two presented hues, drawn from different color categories (e.g., red and green), for later recall. During the retention interval, participants were presented with a differently colored grating in each eye such as to elicit binocular rivalry. A grating matched either the task-relevant (memorized) color category or the task-irrelevant (nonmemorized) color category. We found that the rivalrous stimulus that matched the task-relevant color category tended to dominate awareness over the rivalrous stimulus that matched the task-irrelevant color category. This effect of task relevance persisted when participants reported the orientation of the rivalrous stimuli, even though in this case color information was completely irrelevant for the task of reporting perceptual dominance during rivalry. When participants memorized the shape of a colored stimulus, however, its color category did not affect predominance of rivalrous stimuli during retention. Taken together, these results indicate that the selection of task-relevant information is under volitional control but that visual input that matches this information is boosted into awareness irrespective of whether this is useful for the observer.

## Introduction

Consciousness is believed to be a prerequisite for demanding tasks (Dehaene, Kerszberg, & Changeux, 1998) that require planning (Crick & Koch, 2003), information integration (Baars, 2002; Faivre & Koch, 2014; Mudrik, Faivre, & Koch, 2014; Tononi & Edelman, 1998), and action selection for novel behavior (Ansorge, Kunde, & Kiefer, 2014; Dehaene & Naccache, 2001; Gayet, Van der Stigchel, & Paffen, 2014b; Kunde, Kiesel, & Hoffmann, 2003). Because of our visual system's capacity limitations, only part of the visual information that impinges on our retinae is selected for conscious experience (e.g., Baars, 1997a, 1997b; Dennett, 1991; Edelman & Tononi, 2000). As a result of this processing limitation, it would seem of ecological significance to quickly separate the wheat from the chaff, such that information that is relevant for subsequent behavior predominates awareness. The aim of the present study was to investigate how such prioritization might transpire.

Our present approach centered on binocular rivalry, a phenomenon that occurs when different images are presented to each eye of an observer, causing perception to fluctuate back and forth between the two images (Wheatstone, 1838; for reviews, see Alais & Blake, 2005; Lin & He, 2009). During binocular rivalry, visual awareness therefore varies independently of physical stimulation, which remains constant. In the present study, we experimentally

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manipulated the task relevance of visual information and measured how this affected perception during concurrent binocular rivalry. We presented observers with a dual task, composed of an encoding phase, during which the task relevance of specific visual features (e.g., the color of a stimulus) is determined, and a perceptual selection phase, in which we measured whether one rivalrous image would predominate over the other, depending on its (mis-)match with the predetermined task-relevant feature. The separation of the encoding phase and the perceptual selection phase allowed for assessing the specific conditions under which the perceptual selection process is affected by the behavioral goals of the observer.

During binocular rivalry, and related forms of interocular competition such as continuous flash suppression (for a review, see Gayet, Van der Stigchel, & Paffen, 2014a), relevant stimuli have been shown to gain preferential access to awareness. This has been demonstrated mostly with socially relevant stimuli. For instance, faces predominate over nonfaces (Bannerman, Milders, de Gelder, & Sahraie, 2008; Engel, 1956; Jiang, Costello, & He, 2007; Stein, Hebart, & Sterzer, 2011; Stein, Peelen, & Sterzer, 2011), emotional faces predominate over neutral faces (Alpers & Gerdes, 2007; Coren & Russell, 1992; Gray, Adams, & Garner, 2009; Gray, Adams, Hedger, Newton, & Garner, 2013; Pasley, Mayes, & Schultz, 2004; Stein, Seymour, Hebart, & Sterzer, 2014; Stein & Sterzer, 2012; Yang, Zald, & Blake, 2007), and faces with directed gaze predominate over faces with averted gaze (Chen & Yeh, 2012; Stein, Hebart, & Sterzer, 2011). In addition, naturalistic images have been shown to predominate over nonnaturalistic images (Baker & Graf, 2009), and looming motion predominates over receding motion (Malek, Mendoza-Halliday, & Martinez-Trujillo, 2012; Parker & Alais, 2007). In these studies, differences in behavioral relevance of different stimuli were inevitably accompanied by differences in visual stimulus characteristics, which are known to affect interocular competition as well (e.g., Levelt, 1965; Yang & Blake, 2012). Thus, instead of high-level cognitive effects (such as gaze direction), lower-level stimulus characteristics (such as the specific conjunction between face curvature and pupil location) might drive the above-mentioned prioritization for awareness (e.g., Chen & Yeh, 2012). Although the approach in these studies offers valuable insights in how different stimulus categories compete for visual awareness, the potential influence of differences in stimulus features between stimulus categories makes it less suitable for directly addressing the question of how relevance per se affects access to awareness. We therefore chose to strictly separate stimulus relevance from physical stimulus properties.

One way to experimentally vary the relevance of stimuli, while keeping the physical stimulation constant, is by manipulating the task instructions, such that, depending on the instruction, the same stimuli are either relevant or irrelevant for the task at hand. A number of studies have manipulated stimulus relevance while keeping the stimulus constant and measured the effect on binocular rivalry. For instance, stimuli that were previously paired with an electric shock (Alpers, Ruhleder, Walz, Muhlberger, & Pauli, 2005) or with a monetary reward (Balcetis, Dunning, & Granot, 2012) more frequently dominated perception at rivalry onset than similar stimuli that were not paired with a shock or reward. Along similar lines, a stimulus feature that was helpful for an auxiliary search task was more frequently dominant at rivalry onset than a stimulus that was not helpful for the search task (Chopin & Mamassian, 2010). Interestingly, although these studies demonstrated that task-relevant stimuli are more likely to gain initial dominance in binocular rivalry, no prolonged effects of task relevance on dominance durations during binocular rivalry were observed. This may be because manipulations of task relevance affect the choice of the initial percept only at rivalry onset, but it is also possible that a stimulus that had been task relevant prior to, rather than during, the binocular rivalry period is no longer subject to enough prioritized processing to affect perceptual selection during binocular rivalry. In sum, given our objective of assessing the influence of task relevance on access to awareness, we opted in our experiments to keep the task relevance in effect throughout the binocular rivalry period.

A particularly fruitful method to manipulate the task relevance of intrinsically neutral stimuli over a prolonged duration is the delayed match to sample task (e.g., Harrison & Tong, 2009; Olivers, Meijer, & Theeuwes, 2006). In this task, participants are presented with two different stimuli that vary on a particular feature dimension, followed by a retro cue that indicates which of these two stimuli should be memorized for a subsequent match to sample task. Consequently, on each trial, one stimulus is made relevant for the upcoming task, whereas the other one is not. This method has two major assets. First, it allows for controlling the period within which the stimulus is relevant for the task at hand (i.e., until the match to sample task). Second, and more importantly, the task-relevant and the task-irrelevant stimuli do not differ in terms of (objective) stimulus characteristics, nor do they differ in terms of initial stimulus processing depth, as it is unknown to the observer, at the time of stimulus presentation, which stimulus will be relevant for the subsequent task and which stimulus will be irrelevant. In the present set of experiments, we combined the delayed match to sample task with binocular rivalry tracking to investigate the role of task relevance in the selection of information for visual awareness.

Rivalrous stimuli that match the task-relevant color category are expected to predominate awareness over rivalrous stimuli that match the task-irrelevant color category. This prediction stems from a number of studies, in which the delayed match to sample task was also used to manipulate task relevance of a stimulus or stimulus category. In these studies, the stimuli matching the task-relevant stimulus category behave as if they were subject to an increase in signal strength, compared with the stimuli that match an irrelevant stimulus category. For instance, stimuli matching the task-relevant color category capture attention (Olivers et al., 2006; van Moorselaar, Theeuwes, & Olivers, 2014) and eye movements (Hollingworth & Luck, 2009; Hollingworth, Matsukura, & Luck, 2013; Schneegans, Spencer, Schöner, Hwang, & Hollingworth, 2014; Silvis & Van der Stigchel, 2014) in search tasks, elicit more pronounced behavioral priming effects under backwards masking (Pan, Cheng, & Luo, 2012), and appear to last longer (Pan & Luo, 2012) than stimuli matching an irrelevant color category. Bistable perception is affected by concurrently retained information as well. The perceived direction of an ambiguously rotating structure from motion sphere was biased by the motion direction of a concurrently memorized unambiguously rotating sphere (Scocchia, Valsecchi, Gegenfurtner, & Triesch, 2013). Along similar lines, interocularly suppressed stimuli broke through continuous flash suppression faster when they matched the task-relevant compared with task-irrelevant color category (Gayet, Paffen, & Van der Stigchel, 2013). This study highlighted the intimate relationship between the task relevance of a stimulus category and the prioritization of matching stimuli for visual awareness. Note that the delayed match to sample task is generally referred to as a manipulation of visual working memory content. In this article, we used the term *task relevance*, as it describes the experimental manipulation per se (i.e., which stimulus is relevant for the subsequent recall task) rather than *visual working memory*, which describes the anticipated behavior of the participant elicited by the experimental manipulation.

The present set of experiments was set up to investigate the way in which the current behavioral goals of the observer affect the selection of information for visual awareness. For this purpose, we used a dual-task paradigm in order to separate the encoding phase, in which task relevance is determined, from the perceptual selection phase, in which the influence of the task-relevant information on selection for awareness is measured. In Experiment 1, we demonstrated the effect of task relevance on perceptual dominance during binocular rivalry per se, consistent with expectations based on the literature summarized above. Rivalrous stimuli that matched the color category of the cued (i.e., task-relevant) stimulus were dominant for a larger portion of the

binocular rivalry period than rivalrous stimuli that matched the color category of the noncued (i.e., task-irrelevant) stimulus. Experiment 2 and Experiment 3 were set up to manipulate task relevance separately for the encoding (memorization) phase and the perceptual selection (binocular rivalry) phase. In Experiment 3, participants were instructed that either the color or the shape of a cued stimulus was relevant for the subsequent recall task. Under these circumstances, the color category of the memorized stimulus biased perception only if color was the volitionally retained feature dimension. That is, when participants had to recall the shape of a stimulus, its color category did not affect perception during concurrent binocular rivalry. This demonstrates that only the task-relevant feature dimension of a stimulus was encoded such that it biased concurrent selection for visual awareness. Altering the feature dimension that is relevant for the perceptual selection task, however, revealed a different pattern of results. Once the task-relevant feature (e.g., the red color category) was determined, matching rivalrous stimuli predominated awareness, both when participants reported the color (Experiments 1 and 3) and the orientation (Experiment 2) of the perceived rivalrous gratings. Importantly, in the latter case, color information per se was irrelevant and could therefore be disregarded to perform the task at hand (i.e., reporting the orientation of the stimuli). Together, these experiments showed that observers can voluntarily determine the task relevance of visual information in the encoding phase. However, once task relevance is determined, it involuntarily boosts concurrently presented matching information into awareness.

A secondary aim of the present study was to elucidate how the effect of task relevance on access to awareness of matching stimuli varied over the time course of the retention interval. This is interesting because thus far, only effects of task relevance on initial dominance have been demonstrated. The present method, however, allowed for maintaining task relevance throughout the entire binocular rivalry period. The results of Experiment 1 showed that the greater predominance of rivalrous stimuli that match the task-relevant versus task-irrelevant color category is stable throughout the entire retention interval. Thus, the faster access to awareness for stimuli matching the task-relevant color category (as shown by Gayet et al., 2013) is not the result of an initial prioritization. Rather, the enhancement of matching information is observed as long as the task relevance is in effect.

## Experiment 1

The goal of Experiment 1 was to investigate whether information that is relevant for a concurrent task will



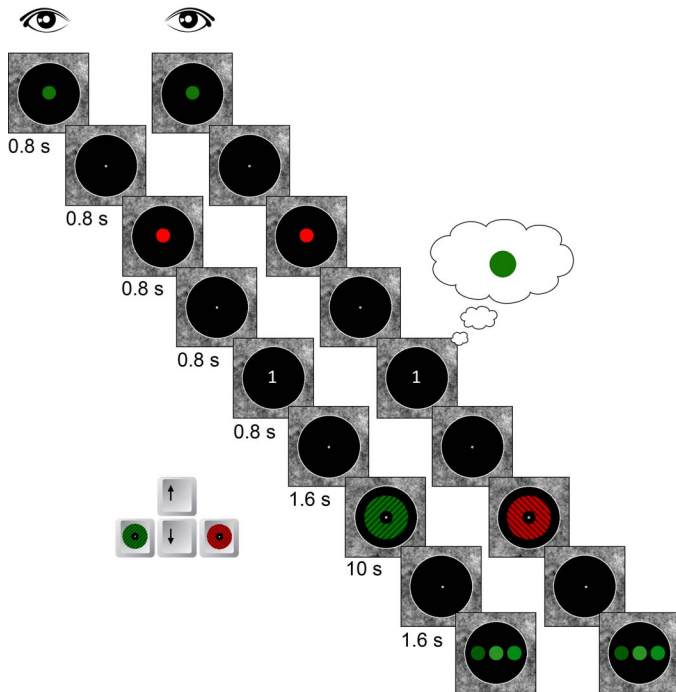


Figure 1. Stimuli and procedure of Experiment 1 and Experiment 2. Participants performed a dual task. For the memory task, participants subsequently viewed two differently colored stimuli and a retro cue (“1” or “2”) that indicated which of the two stimuli should be memorized for subsequent recall. During the 10-s retention interval, participants were presented with a different grating in each eye, such as to elicit binocular rivalry. The rivalrous stimuli could match either the color category of the cued stimulus or the color category of the noncued stimulus. In Experiment 2, the rivalrous stimuli could also be of a third color category that was not used on that trial. Participants were instructed to continuously report the color (Experiment 1) or orientation (Experiment 2) of the rivalrous stimuli.

predominate during binocular rivalry. To this end, participants were presented with a dual task (the full stimulus sequence of a trial is depicted in Figure 1). For the first task, participants were sequentially presented with two stimuli drawn from the color categories red or green and a retro cue (“1” or “2”) that indicated which of the two exact hues should be memorized for subsequent recall. At the end of each trial, participants were required to indicate which of three presented hues, drawn from the color category of the memorized hue, was identical to the one they had memorized at the start of that trial. During the retention interval, binocular rivalry was elicited during a 10-s period, by presenting participants with a differently colored grating in each eye. The length of the retention interval was chosen as a compromise between the trial lengths in binocular rivalry studies that are typically 1 min or more (e.g., Levelt, 1965) and the retention intervals of up to 10 s used in delayed match to sample tasks (e.g., Christophel,

Hebart, & Haynes, 2012; Harrison & Tong, 2009; Serences, Ester, Vogel, & Awh, 2009). Pilot studies revealed that, using the present stimuli, 10 s would suffice for eliciting multiple dominance periods of each of the two gratings. On each trial, one of the rivalrous gratings matched the color category of the task-relevant (i.e., cued) stimulus, whereas the grating presented to the other eye matched the category of the task-irrelevant (i.e., noncued) stimulus. During this binocular rivalry period, participants were instructed to continuously report with button presses whether they perceived a green grating, a red grating, or a transition between the two. The exact hues of the rivaling stimuli were never identical to the hues used in the auxiliary memory task.

## Methods

### Participants

All experiments complied with the ethical principles set out in the Declaration of Helsinki. The participant group for this experiment consisted of 10 undergraduate students from Utrecht University, who participated for course credits or monetary reward after signing informed consent. All participants had normal or corrected-to-normal vision and were tested for color blindness with the Ishihara color blindness test plates (Ishihara, 1917) and tested for stereoscopic vision with the TNO test for stereoscopic vision (12th edition; Walraven, 1972).

### Stimuli and apparatus

The experiment was conducted using an Apple dual 2-GHz PowerPC G5 equipped with a linearized 22-inch LaCie Electron Blue IV CRT monitor (1,024 × 768 pixels; 100-Hz refresh rate) and an Apple keyboard, which was used for response registration. There were no light sources in the experiment room, except for the computer monitor. Stimulus presentation and response collection were managed using the Psychophysics Toolbox 3 (Brainard, 1997; Pelli, 1997) in MATLAB (R2009b; The Mathworks, Natick, MA). A pair of displays was viewed dichoptically through a mirror stereoscope mounted on a chin rest, which kept the effective viewing distance at 57 cm. All stimuli were presented on a uniform black background ( $<1$  cd/m<sup>2</sup>). To facilitate binocular fusion of the two complementary images, we surrounded a circular area of 6.7° of visual angle presented to each eye with a Brownian (i.e.,  $1/f^2$ ) noise frame that subtended 9.9° by 9.9° of visual angle and had a mean luminance of 21 cd/m<sup>2</sup> and a 12% RMS contrast. Also, all frames were composed of a white fixation circle with a diameter of 0.2° of visual angle and a black fixation dot in its center (0.04° of visual angle). The retro cues consisted of the Arabic numerals “1” and “2” in white (48 cd/m<sup>2</sup>) Arial font with a font size of 18.

Color	CIE values*		
	X-value	Y-value	Luminance (cd/m <sup>2</sup> )
Red 1	0.590	0.340	6.08
Red 2	0.542	0.298	5.87
Red 3	0.587	0.365	5.76
Red 4	0.510	0.279	5.84
Red 5	0.562	0.388	6.29
Green 1	0.285	0.441	6.15
Green 2	0.324	0.568	6.14
Green 3	0.262	0.479	6.22
Green 4	0.359	0.544	6.19
Green 5	0.232	0.372	6.04
Blue 1	0.181	0.145	6.09
Blue 2	0.167	0.084	5.81
Blue 3	0.170	0.145	6.22
Blue 4	0.156	0.076	5.99
Blue 5	0.182	0.187	6.28
Saturated blue <sup>†</sup>	0.152	0.071	6.02

Table 1. Overview of the colors used in all experiments. *Notes:* \*CIE values stands for Commission Internationale d’Eclairage values, as measured with a PR-650 SpectraScan colorimeter/telephotometer (Photo Research, Inc.). †The saturated blue was the reference stimulus for the perceptual luminance matching (i.e., heterochromatic flicker photometry; Kaiser & Comerford, 1975; Wagner & Boynton, 1972) with the saturated red and saturated green colors that were used to create the square wave gratings for the binocular rivalry stimuli. Also, the luminance of the saturated blue color served as the basis for the physical luminance matching (by means of a telephotometer) of the 15 color variations for the memory task, which are described in this table.

The color stimuli used for the memory task were identical to those of Gayet et al. (2013). These stimuli consisted of 10 nonsaturated colored circles (five red and five green hues; one of each presented during each memorization phase) that were physically matched to the luminance of the saturated blue rivalrous stimulus (see below) using a PR-650 SpectraScan colorimeter-telephotometer (Photo Research, Chatsworth, CA). The resulting color patches had a mean luminance of 6.06 cd/m<sup>2</sup> ( $SD = 0.17$ ) and a diameter of 1.4° of visual angle. An overview of all CIE-color values is provided in Table 1. The stimuli used for the binocular rivalry task consisted of circular square wave gratings with a diameter of 4.7° of visual angle and a spatial frequency of 10 cycles per stimulus width. The colors used for the peaks of the gratings were saturated red or green. A saturated blue color (6.02 cd/m<sup>2</sup>,  $x = 0.152$ ,  $y = 0.071$ ) was used to obtain perceptual isoluminance of the saturated red and saturated green colors for each subject by means of heterochromatic flicker photometry (Kaiser & Comerford, 1975; Wagner & Boynton, 1972). The pixel intensities of the peaks of the gratings were halved to obtain the pixel intensities for the

troughs of the gratings (i.e., 33% Michelson contrast). The rivalrous stimuli had a circular central recess with a diameter of 1.4° of visual angle, such as to avoid spatial overlap with the colored stimuli used for the memory task and ascertain visibility of the fixation dot.

### Experimental design and procedure

The experimental conditions were fully counterbalanced and manipulated within participants. This included the order in which the color stimuli for the memory task appeared (either red followed by green or vice versa), the retro cue (memorize either the first or the second stimulus), the eyes to which the rivalrous gratings were presented (either red in the left eye and green in the right eye or vice versa), and the orientations of the rivalrous gratings (plus 45° from the vertical in the left eye and minus 45° from the vertical in the right eye, or vice versa). The combinations of these conditions were repeated five times throughout the experiment, accounting for a total of 80 trials. The hues for the memory task were randomly selected in such a way that each of the five hues within a color category was presented equally often during the memorization phase of the memory task. Two factors were randomized without replacement but not counterbalanced. These were the choice of hues for the two distractor stimuli that were presented alongside the target stimulus in the recollection phase of the memory task and the location of that target with respect to these two distractors. Finally, the stimulus-response contingencies for the binocular rivalry task were counterbalanced between participants (i.e., left arrow key for red percept and right arrow key for green percept, and vice versa). The experiment was separated into eight blocks of about 5 min each and was preceded by an eight-trial practice session. Participants were explicitly instructed to maintain fixation and to avoid blinking during the 10-s binocular rivalry period.

### Data analyses

In all analyses of the binocular rivalry data, participants’ reported percepts were separated into those in which the perceived rivalrous stimulus (e.g., the red grating) matched the task-relevant color category (e.g., a red hue was memorized for the memory task) and those in which the rivalrous stimulus matched the task-irrelevant color category (e.g., a green hue was memorized). In addition, all transitory percepts were discarded, such that only exclusive percepts (i.e., the report of seeing either one grating or the other) were included in the analyses. Trials in which participants reported correctly and incorrectly on the memory task were both included in the analyses of the binocular rivalry data. In this method, it is generally assumed (e.g., Olivers et al., 2006;

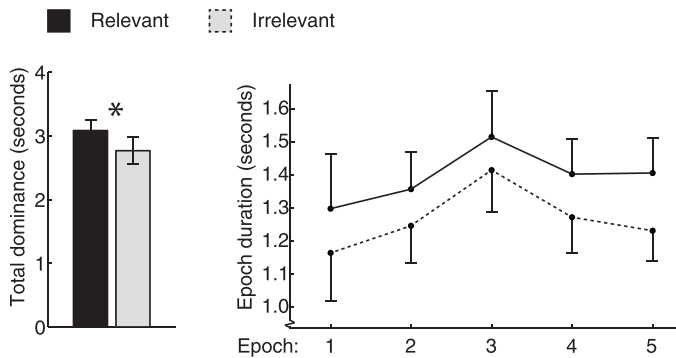


Figure 2. Results of the binocular rivalry task in Experiment 1. Left: Total dominance duration in seconds of the rivalrous stimuli that matched the task-relevant (depicted in black) and the task-irrelevant (depicted in light gray) color categories. Right: Median epoch duration of the rivalrous stimuli that matched the task-relevant (solid line) and the task-irrelevant (dotted line) color categories for the first five epochs of the binocular rivalry period. Error bars represent the standard error of the mean. \* $p < 0.05$ .

van Moorselaar et al., 2014) that incorrect answers on the memory task reflect a failure to report the exact hue (i.e., choosing the wrong hue of green), rather than a failure to memorize the correct stimulus (i.e., having memorized the hue of the red stimulus instead). Because the delayed match to sample task is intrinsically difficult and hence brings about a high number of errors, excluding erroneous trials would drastically reduce our experimental power without increasing the diagnostic power. Compared with other binocular rivalry studies in which rivalrous stimuli are displayed for 1 min or more, the 10-s display time of rivalrous stimuli in the present set of experiments was relatively short. As a result of this, 24.1% ( $SD = 9.2\%$ ) of the percepts were truncated. Therefore, the main analyses in the present set of experiments are the analyses of total dominance durations, which is a more robust method under these circumstances (for a similar approach, see Scocchia, Valsecchi, Gegenfurtner, & Triesch, 2013). The total dominance duration was computed as the summed duration of each rivalrous percept within a trial, separated on the basis of whether they matched the task-relevant or the task-irrelevant color category (i.e., the factor Relevance). In all experiments, planned comparisons were conducted between Relevance conditions. These consisted of paired-samples  $t$  tests that were declared significant if the  $p$  value (two-sided) was smaller than the standard alpha level of 0.05 (after Bonferroni correction, in case of multiple comparisons).

## Results and discussion

In the memory task, participants correctly reported the memorized color on 54.6% ( $SD = 10.3$ ) of the trials,

which is better than the 33% chance level,  $t(9) = 6.553$ ,  $p < 0.001$ . The accuracy on the memory task did not differ between trials in which participants were cued to memorize the first stimulus ( $M = 55.8\%$ ,  $SD = 10.3$ ) and trials in which they were cued to memorize the second stimulus ( $M = 53.5\%$ ,  $SD = 13.7$ ),  $t(9) = 0.560$ ,  $p = 0.590$ . This shows that the task was feasible but demanding, which is an important requirement for delayed match to sample tasks (e.g., Olivers et al., 2006).

First, a planned pairwise comparison was conducted with the two levels of the factor Relevance, to assess whether they differed in total dominance durations (Figure 2, left). This analysis revealed that the rivalrous stimulus that matched the color category of the task-relevant stimulus was dominant for a longer portion of a trial ( $M = 3.08$  s,  $SD = 0.54$  s) than the stimulus that matched the color category of the task-irrelevant stimulus ( $M = 2.77$  s,  $SD = 0.66$  s),  $t(9) = 3.612$ ,  $p = 0.006$ . Next, we wanted to make sure that this effect of Relevance is strictly brought about by the task relevance of the cued stimulus, rather than by the sequence of presentation of the colored stimuli. For this purpose, we conducted a  $2 \times 2$  repeated-measures analysis of variance with the factors Relevance (relevant versus irrelevant) and Retro Cue (i.e., “1” or “2”). In this control analysis, the absence of an interaction between the factors Relevance and Retro Cue on total dominance durations,  $F(1, 9) = 0.229$ ,  $p = 0.644$ , showed that the effect of Relevance, reported above, did not depend on whether the relevant color category was that of the first or the second stimulus. This was corroborated by a main effect of Relevance,  $F(1, 9) = 9.487$ ,  $p = 0.013$ , and the absence of a main effect of Retro Cue,  $F(1, 9) = 0.442$ ,  $p = 0.523$ . These results demonstrate that, over an entire rivalry period, rivalrous stimuli that match a task-relevant color category predominate over rivalrous stimuli that match equally accessible but task-irrelevant color category.

To further investigate this effect, the median dominance duration of individual percepts within a trial (i.e., epochs) was computed. This analysis allows us to ascertain whether the effect found for total dominance durations (a) can be accounted for by a particular subset of epochs (e.g., only the first epoch) and (b) whether this effect changes throughout the retention interval. Again, these data were separated on the basis of whether the percept matched the task relevant or the task-irrelevant color category (Figure 2, right). On average, participants had 4.3 ( $SD = 1.4$ ) exclusive percepts in each 10-s rivalry period. All participants reported at least one exclusive percept on every trial. Participants had at least two exclusive percepts in 98.5% ( $SD = 2.6$ ) of the trials, at least three exclusive percepts in 95.0% ( $SD = 6.7$ ) of the trials, at least four percepts in 82.9% ( $SD = 15.2$ ) of the trials, at



least five exclusive percepts in 63.4% ( $SD = 22.1$ ) of the trials and at least six exclusive percepts in 36.4% ( $SD = 28.4$ ) of the trials. Until the fifth epoch, each condition contained at least 11 data points per participant. In the sixth epoch, however, 50% of the participants had fewer than 10 data points per condition, two of which had only 3 data points per condition. As a result of this rapid decrement in data points for increasing epoch numbers after the fifth epoch, only the first five epochs were included in the next analysis. This analysis revealed a main effect of Relevance,  $F(1, 9) = 12.237$ ,  $p = 0.007$ , which means that epoch durations depended on whether percepts matched the task-relevant color category ( $M = 1.40$  s,  $SD = 0.33$  s) or the task-irrelevant color category ( $M = 1.26$  s,  $SD = 0.34$  s). The absence of a main effect of Epoch number revealed that the different epochs did not differ in duration per se,  $F(1.7, 15.3) = 1.961$ ,  $p = 0.178$  (Greenhouse-Geisser corrected, as the assumption of sphericity was violated,  $p < 0.05$ ). Importantly, the effect of Relevance on epoch duration did not interact with the Epoch number,  $F(4, 36) = 0.285$ ,  $p = 0.886$ . This shows that the increased predominance of the rivalrous stimulus that matches the task-relevant as opposed to task-irrelevant color category mentioned above is maintained throughout the retention interval.

Finally, a measure of initial dominance was obtained by computing the proportion of trials in which participants' first percept of the rivalry period matched the color category of the task-relevant (i.e., cued) stimulus. This revealed no reliable effect of task relevance on initial percept,  $t(9) = 0.236$ ,  $p = 0.819$ . The matching percept was reported as the first exclusive percept in 49.5% ( $SD = 6.7$ ) of the trials. Participants had no strong bias toward reporting the grating presented to one eye more often as the initial percept than the grating presented to the other eye (48% left eye,  $SD = 5.5$ , range = 38.8%–56.2%). There was, however, a slight bias toward reporting the green grating as the first percept more often than the red grating (30.8% red grating,  $SD = 12.5$ , range = 12.5%–51.3%). This bias indicates that isoluminance achieved by means of heterochromatic flicker photometry does not ensure equal-onset dominance probability in binocular rivalry.

Together, these findings demonstrate that the active retention of a color for an auxiliary task causes matching stimuli to predominate during binocular rivalry. Interestingly, the task relevance of a color category did not kick-start the perception of matching rivalrous stimuli, as was demonstrated by the analysis of initial dominance. Rather, as was shown by the analysis of epoch durations, the duration of each individual epoch was lengthened when the percept matched the task-relevant rather than -irrelevant color category.

## Experiment 2

Based on the first experiment, we conclude that visual input that matches task-relevant information predominates awareness over visual input that matches task-irrelevant information. With the next experiment, we addressed two questions. First, we aimed to elucidate whether the effect described above is the result of an increased predominance of the rivalrous stimulus that matches the task-relevant color category or a decreased predominance of the rivalrous stimulus that matches the task-irrelevant color category. For this purpose, a third color condition was added, such that the rivalrous stimuli could now match the color category of the cued stimulus (task relevant) of the non-cued stimulus (task irrelevant), or of a novel color category that had not been used on that trial (task unrelated). This task-unrelated color category acted as a baseline level, against which increases in dominance durations in one condition can be dissociated from decreases in dominance durations in the other condition. Second, we aimed to investigate whether the effect found in Experiment 1 would persist if participants reported the orientation rather than the color of the perceived rivalrous stimulus. This would demonstrate that the effect of a concurrently retained color category affects the perception of rivalrous stimuli based on their color, even if color is an irrelevant feature dimension for the task of reporting rivalry dominance. In addition, requiring participants to report the orientation rather than the color of the rivalrous stimuli makes the task more robust to response biases. That is, irrespective of which grating they perceive, participants might be more prone to responding “green” when they are concurrently memorizing a (different) color from the green color category. It is less likely that memorizing a green color would bias participants toward responding to a particular orientation.

## Methods

### Participants

Fifteen new undergraduate students from Utrecht University participated in this experiment. All inclusion criteria from Experiment 1 applied to Experiment 2 as well. Because this experiment was composed of three trial types rather than one (see below), we increased the number of participants to obtain comparable statistical power as in Experiment 1. Because of below-chance performance on the memory task (i.e., 29% correct at a 33% chance level), one participant was excluded from further analyses and substituted by a new participant.

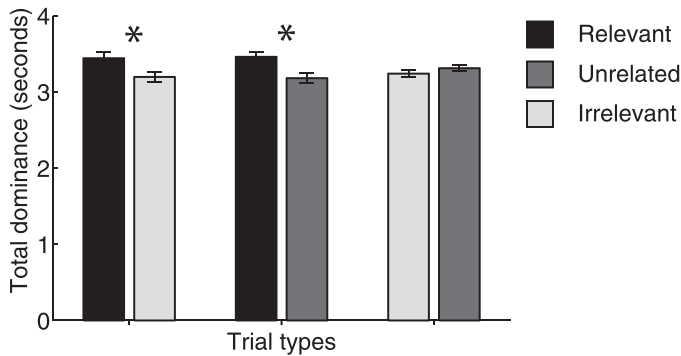


Figure 3. Results of the binocular rivalry task in Experiment 2. The height of the bars represents the total dominance duration of a percept over the 10-s rivalry period, separated into three trial types. The black bars represent rivalrous stimuli that matched the task-relevant color category, the light gray bars represent rivalrous stimuli that matched the task-irrelevant color category, and the light gray bars represent the rivalrous stimuli that matched the task-unrelated color category. Error bars represent the standard error of the mean. \* $p < 0.05$  (Bonferroni corrected).

### Stimuli and design

The stimuli and design of Experiment 2 were identical to those of Experiment 1, except for the following differences. For this experiment, five hues from a blue color category were included (see Table 1). Also, a saturated blue color for the binocular rivalry task was included. As a result of this expansion, a task-unrelated condition could be implemented, in which a rivalrous stimulus matched neither the color category of the cued stimulus nor that of the noncued stimulus. There were now three different trial types: the two stimuli for the binocular rivalry task could match the task-relevant color category and the task-irrelevant color category (this condition was comparable to Experiment 1), they could match the task-relevant and the task-unrelated color category, or they could match the task-irrelevant and task-unrelated color category. All experimental conditions (i.e., trial type, color category of first stimulus, color category of second stimulus, eye of presentation, retro cue) were again fully counterbalanced within participants, adding up to a total of 72 trials (i.e., 24 per trial type). The selection of specific hues for the memory task was identical to that of Experiment 1. In contrast to Experiment 1, however, participants were now instructed to report the orientation of the perceived rivalrous gratings. Participants' key presses could now reflect exclusive perception of either a grating tilted clockwise  $45^\circ$  or tilted counterclockwise  $45^\circ$  or reflect a transitory (i.e., nonexclusive) percept. Again, the stimulus-response contingency was counterbalanced between participants. Because of the smaller amount of trials per condition in Experiment 2 (24) compared

with Experiment 1 (80), the analyses of epoch duration yielded too few data points in each Relevance condition (fewer than five) from the third epoch onwards and was therefore deemed uninformative. As in Experiment 1, the main analyses consisted of the planned pairwise comparisons between total dominance durations of the Relevance conditions, now separated on the basis of trial type.

## Results and discussion

In the memory task, participants correctly reported the memorized color on 59.1% ( $SD = 6.7$ ) of the trials, which is better than the 33% chance level,  $t(14) = 14.973$ ,  $p < 0.001$ . The accuracy on the memory task did not differ between trials in which participants were cued to memorize the first stimulus ( $M = 62.0\%$ ,  $SD = 8.2$ ) and trials in which they were cued to memorize the second stimulus ( $M = 56.1\%$ ,  $SD = 6.7$ ),  $t(14) = 2.040$ ,  $p = 0.061$ .

In the binocular rivalry task, we first aimed to assess whether the effect of Relevance on total dominance duration was different for the three trial types used in this experiment. The two levels of the factor Relevance (e.g., task relevant and task irrelevant), however, differed between the three trial types (see Figure 3, left, center, and right). For instance, in one trial type (e.g., left on Figure 3), the task-irrelevant stimulus condition was assigned to the second level of the factor Relevance, whereas the same stimulus condition was assigned to the first level of the factor Relevance in another (i.e., right on Figure 3) trial type. The outcome of an overall analysis of variance with the three trial types would depend on the contingency that we assigned between specific stimulus conditions (i.e., task irrelevant and task unrelated) and specific levels of the factor Relevance (i.e., Level 1 and Level 2). To circumvent this issue, we computed the absolute difference between the total dominance durations of the two levels of each trial type (e.g., the absolute difference between the task-relevant and the task-irrelevant percepts). Then, we conducted a three-level repeated-measures analysis of variance with the factor Trial Type on this difference measure. This revealed a main effect of Trial Type,  $F(1.357, 19.004) = 6.075$ ,  $p = 0.016$  (Greenhouse-Geisser corrected, as the assumption of sphericity was violated,  $p < 0.05$ ), which indicated that the effect of Relevance was different in the three trial types.

To investigate the specific effect of task relevance on predominance during binocular rivalry, we conducted planned pairwise comparisons between the two levels of Relevance for each of the three trial types. This revealed that rivalrous stimuli that matched the task-relevant color category ( $M = 3.45$  s,  $SD = 3.06$  s) were



dominant for a larger portion of the binocular rivalry period than rivalrous stimuli that matched the task-irrelevant color category ( $M = 3.13$  s,  $SD = 3.17$  s),  $t(14) = 3.189$ ,  $p = 0.007$  (significant at a Bonferroni-corrected  $\alpha$ -level of 0.0167). This shows that the greater predominance for visual input that matches task-relevant information, as found in Experiment 1, persists when a different stimulus dimension is reported (i.e., the orientation rather than the color of the rivalrous grating). Next, these analyses revealed that rivalrous stimuli that matched the task-relevant color category ( $M = 3.58$  s,  $SD = 2.20$  s) were dominant for a larger portion of the binocular rivalry period than rivalrous stimuli that matched the task-unrelated color category ( $M = 3.16$  s,  $SD = 3.30$  s),  $t(14) = 3.829$ ,  $p = 0.002$ . In contrast, rivalrous stimuli that matched the task-irrelevant color category ( $M = 3.23$  s,  $SD = 2.16$  s) and rivalrous stimuli that matched the task-unrelated color category ( $M = 3.27$  s,  $SD = 1.74$  s) were dominant for an equivalent portion of the rivalry period,  $t(14) = 0.650$ ,  $p = 0.526$ . Thus, the greater predominance of visual input that matches task-relevant information, as found in Experiment 1, is not the result of decreased predominance of task-irrelevant information but of increased predominance of task-relevant information.

Finally, we aimed to investigate potential effects of task relevance on perceptual dominance at rivalry onset. We conducted a repeated-measures analysis of variance on the three levels of the factor Trial Type (as for the analysis of total dominance durations above). The absence of an effect of Trial Type,  $F(2, 28) = 1.181$ ,  $p = 0.322$ , showed that potential effects of task relevance on initial dominance were similar across all three trial types. Subsequent pairwise comparisons revealed no significant difference between the rivalrous stimuli matching the relevant ( $M = 50.3\%$ ,  $SD = 12.5\%$ ) and irrelevant color categories,  $t(14) = 0.086$ ,  $p = 0.932$ . Rivalrous stimuli matching the relevant ( $M = 55.6\%$ ,  $SD = 10.2\%$ ) color category tended to be reported more often as the initial percept than those matching the unrelated color categories,  $t(14) = 2.092$ ,  $p = 0.055$ , but this tendency seems spurious when compared with the Bonferroni-corrected  $\alpha$ -level of 0.0167. In addition, the absence of a difference between the rivalrous stimuli matching the irrelevant ( $M = 49.4\%$ ,  $SD = 14.6\%$ ) and unrelated color categories,  $t(14) = 0.147$ ,  $p = 0.885$ , corroborates the idea that the unrelated color category plays no special role in rivalry onset. Thus, the task relevance of a color category, as manipulated by the memory task, had no systematic influence on the perceptual dominance at rivalry onset. Participants had no strong bias toward reporting the grating presented to one eye more often as the initial percept than the grating presented to the other eye (46.0% left eye,  $SD = 14.1\%$ , range = 15.3%–73.6%). There was, however, a slight bias toward reporting the green grating as the

first percept more often than the red grating (28.6% red grating,  $SD = 25.0\%$ , range = 0.0%–83.3%), as well as a bias to report the green grating more often than the blue grating (31.4% blue grating,  $SD = 20.3\%$ , range = 4.2%–79.2%), but no preference in initial dominance was apparent between the blue grating and the red grating (49.7% red grating,  $SD = 20.1\%$ , range = 4.2%–95.8%).

With Experiment 2, we replicated the finding that rivalrous stimuli predominate awareness when they match task-relevant information. This effect was further specified by demonstrating that it was caused by an increase in predominance of the rivalrous stimuli matching task-relevant information as opposed to a decrease in predominance of the rivalrous stimuli matching task-irrelevant information. This is a pattern of findings that is similar to the effect of working memory content on attentional capture (Olivers et al., 2006) and on suppression durations under continuous flash suppression (Gayet et al., 2013). Thus, boosting task-relevant information, rather than suppressing task-irrelevant information, might be a more general manner in which the visual system prioritizes relevant information.

More importantly, the data of Experiment 2 also revealed that the predominance of rivalrous stimuli that match task-relevant color information over those that match task-irrelevant color information persists when another stimulus feature dimension (i.e., orientation) is reported. Aside from eliminating potential strategic biases that participants might entrain, it also demonstrates that the effect of task relevance on perception during rivalry is not selective for the feature dimension that is used during the binocular rivalry task. Indeed, in Experiment 2, color information per se was irrelevant for the binocular rivalry task, which consisted of reporting the orientation of the rivalrous gratings. Nonetheless, the color category that was made relevant for the concurrent memory task still affected perception during binocular rivalry. As such, the task-relevant information captured visual awareness automatically.

### Experiment 3

Experiment 2 showed that a color category that is relevant for the memory task biases the access to awareness of colored stimuli in a concurrent perceptual report task, even when color information is irrelevant for performing that concurrent task and could therefore be disregarded completely. This raises the question whether the ability of a memorized stimulus to bias perception also generalizes to irrelevant features of that memorized stimulus or is specific to the feature dimension that is volitionally memorized. In other words, would the color of a memorized stimulus also

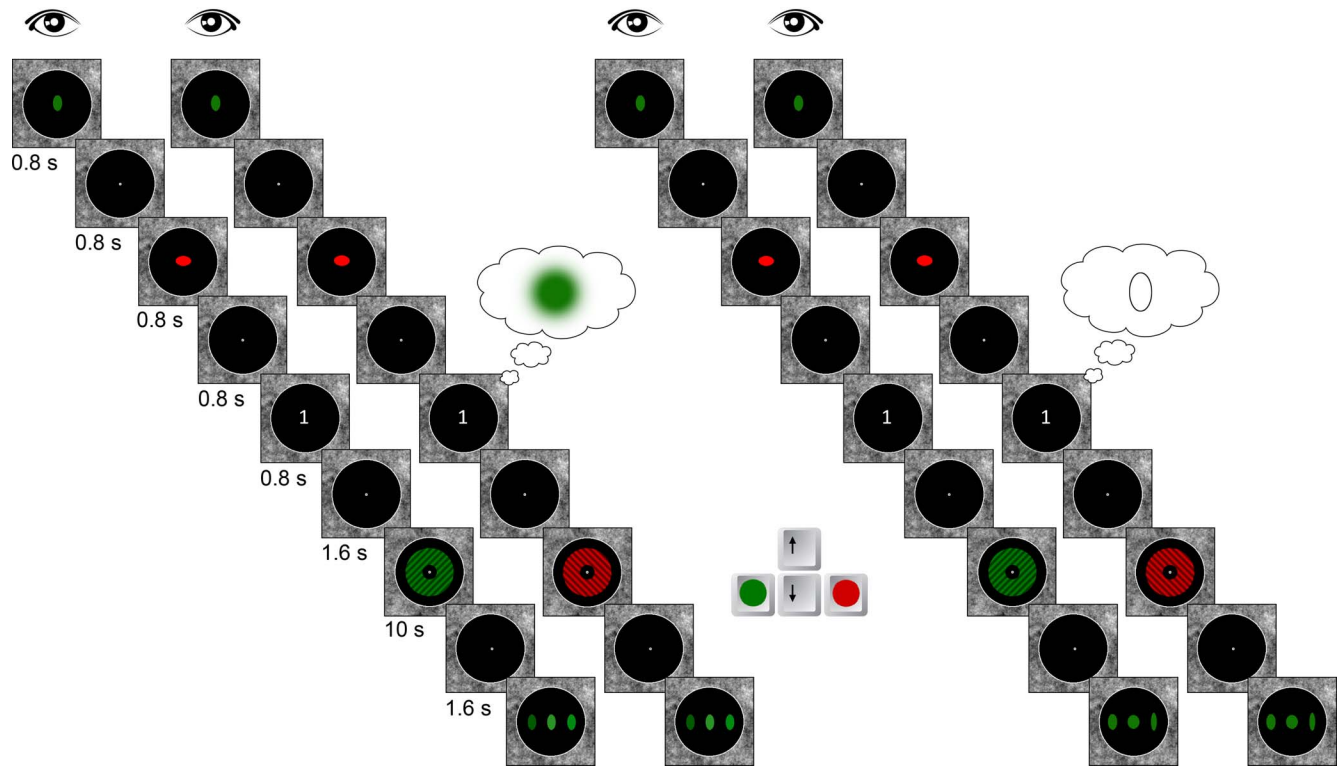


Figure 4. Stimuli and procedure of Experiment 3. Depending on the experimental block, participants were instructed to either memorize the color (left) or the shape (right) of the cued stimulus. In both conditions, participants were instructed to continuously report the color of the rivalrous stimuli.

bias perception if the memory task entailed remembering, say, the shape of the stimulus rather than its color? To test this, we manipulated the aspect ratio (length and width) of the color stimuli used for the memory task and included two types of instructions. In one half of the experimental blocks, participants were instructed to memorize the color of the cued stimulus, making “color” a volitionally retained stimulus dimension, whereas in the other half of the experimental blocks, participants were instructed to memorize the shape of these same stimuli, making “color” an incidental feature of the cued stimulus.

## Methods

### *Participants, stimuli, and design*

Ten undergraduate students from Utrecht University participated in this experiment. All inclusion criteria from Experiment 1 applied to Experiment 3 as well. The stimuli and experimental procedure of Experiment 3 were similar to that of Experiment 1, except for the following addition (see Figure 4). The shape of the memory stimuli were drawn from two categories: either vertical ellipses or horizontal ellipses. In each category, five elliptical shapes were created that varied stochastically between  $1.4^\circ$  and  $1.16^\circ$  of visual angle (with steps of  $0.08^\circ$  of visual angle, i.e., two pixels) while negatively

covarying the orthogonal dimension between 0.76 and 1.0, such that the surface of the ellipses remained constant (as far as allowed for by the screen resolution). During the delayed match to sample phase of the experiment, all three stimuli varied along the critical dimension but were identical to the memorized stimulus with respect to its irrelevant feature dimension. For instance, in the condition in which participants were to memorize the shape of an ellipse of a specific hue, all three stimuli in the recollection phase were of that exact same hue but varied along the shape dimension (and vice versa when participants had to memorize the hue of the cued ellipse).

The experimental design was also identical to that of Experiment 1, except for the two following differences. First, the two shape categories of the stimuli (horizontally or vertically elongated) were fully counterbalanced within participants, along with all conditions already included in Experiment 1 (the red and green color categories of the memory task stimuli, the two retro cues, and the two orientations of the rivalrous gratings). Second, in one half of the experiment, participants were instructed to memorize the exact hue of the cued stimulus (as in Experiment 1), whereas in the other half of the experiment, participants were instructed to memorize the exact shape of the cued stimulus. Both halves of the experimental session were

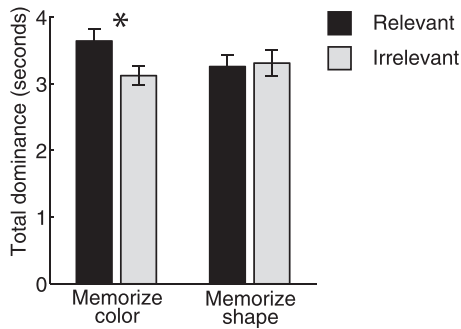


Figure 5. Results of the binocular rivalry task in Experiment 3. The height of the bars represent the total dominance duration of a percept over the 10-s rivalry period, separated on the basis of the two task instructions (memorize the color or the shape of the cued stimulus). The black bars represent rivalrous stimuli that matched the task-relevant color category; the light gray bars represent rivalrous stimuli that matched the task-irrelevant color category. Errors bars represent the standard error of the mean. \* $p < 0.05$  (Bonferroni corrected).

preceded by eight practice trials, to allow participants to get acquainted with the task and the stimulus-response contingencies. The order in which the task conditions were presented (i.e., first the color memory task and then the shape memory task, or vice versa) was counterbalanced between participants. Both halves of the experimental session were divided into four blocks, totaling 64 experimental trials. Because of the smaller amount of trials per condition in Experiment 3 (32) as compared with Experiment 1 (80), the analyses of epoch duration yielded too few data points in each Relevance condition (fewer than 10 from the second epoch onwards and fewer than 5 from the third epoch onwards) and were therefore deemed uninformative. As in Experiment 1, the main analyses consisted of the planned pairwise comparisons between total dominance durations of the Relevance conditions, now separated for both Memory Instruction conditions.

## Results and discussion

In the memory task, participants correctly reported the memorized feature on 58.4% ( $SD = 8.2\%$ ) of the trials, which is better than the 33% chance level,  $t(9) = 8.831$ ,  $p < 0.001$ . The accuracy on the memory task did not differ between trials in which participants were instructed to memorize the color ( $M = 53.8\%$ ,  $SD = 10.6\%$ ) and trials in which they were instructed to memorize the shape of the cued stimulus ( $M = 58.4\%$ ,  $SD = 14.0\%$ ),  $F(1, 9) = 0.628$ ,  $p = 0.449$ . Also, the accuracy on the memory task did not differ between trials in which participants were cued to memorize the first stimulus ( $M = 57.8\%$ ,  $SD = 14.5\%$ ) and trials in which they were cued to memorize the second stimulus

( $M = 54.4\%$ ,  $SD = 8.5\%$ ),  $F(1, 9) = 0.663$ ,  $p = 0.437$ . Finally, there was no interaction between these two factors, suggesting that performance on the memory task did not vary as a function of memory instruction and retro cue,  $F(1, 9) = 0.694$ ,  $p = 0.426$ .

For the analysis of the binocular rivalry data (Figure 5), we first conducted a  $2 \times 2$  repeated-measures analysis of variance on the total dominance duration with the factors Relevance (rivalrous stimulus is related to relevant versus irrelevant color category) and Memory Instruction (memorize the color versus the shape of the cued stimulus). This analysis revealed no main effect of Memory Instruction,  $F(1, 9) = 0.479$ ,  $p = 0.506$ , indicating that total dominance durations of the rivalrous percepts did not depend on whether participants memorized the color or the shape of the cued stimulus. There was, however, a main effect of Relevance,  $F(1, 9) = 9.813$ ,  $p = 0.012$ , which showed that the total dominance duration of a percept depended on whether it matched the color category of the cued stimulus or the color category of the noncued stimulus. The interaction effect between Memory Instruction and Relevance, however, did not reach significance,  $F(1, 9) = 3.592$ ,  $p = 0.091$ . In the present experiment, as in Experiments 1 and 2, we aimed to investigate whether task-relevant information would predominate over task-irrelevant information during binocular rivalry. Our prior hypotheses for the present experiment, however, were explicitly aimed at investigating whether or not this effect would emerge in the two Memory Instruction conditions. As such, we conducted planned pairwise comparisons between the predominance of rivalrous stimuli matching the task-relevant versus the task-irrelevant color category, for both Memory Instruction conditions separately (Figure 5), despite the absence of an interaction effect. These analyses allow for comparing the present results with those of Experiments 1 and 2 where similar planned pairwise comparisons were conducted. When participants were instructed to memorize the color of the cued stimulus, the rivalrous stimulus that matched its color category ( $M = 3.64$  s,  $SD = 0.18$  s) was dominant for a larger portion of the 10-s rivalry period than the rivalrous stimulus that matched the color category of the noncued stimulus ( $M = 3.12$  s,  $SD = 0.15$  s),  $t(9) = 3.096$ ,  $p = 0.0128$  (significant at a Bonferroni-corrected  $\alpha$ -level of 0.025). This replicated the findings of Experiments 1 and 2. In contrast, when participants were instructed to memorize the shape of the cued stimulus, the rivalrous stimulus that matched its color category ( $M = 3.26$  s,  $SD = 0.18$  s) was not dominant for a larger portion of the rivalry period than the rivalrous color that matched the color category of the noncued stimulus ( $M = 3.31$  s,  $SD = 0.20$  s),  $t(9) = 0.309$ ,  $p = 0.764$ . Thus, although the interaction between Relevance and Memory instruction did not



reach significance, the planned comparisons suggest that the main effect of Relevance was fully driven by the condition in which participants had to memorize the color of the cued stimulus. These planned pairwise comparisons, similar to those used in Experiment 1 and 2, demonstrate that when the color of the cued stimulus is memorized, the matching rivalrous stimulus is dominant for about 500 ms longer than the mismatching rivalrous stimulus. However, there is no hint of a difference in dominance durations when the shape of that same stimulus is memorized (about 50 ms shorter). Together, these results show that only the intentionally stored feature dimension of a stimulus has the potency to affect subsequent perception during binocular rivalry.

Similarly to Experiments 1 and 2, we aimed to investigate potential effects of task relevance on the perceptual dominance at rivalry onset. Pairwise comparisons revealed no differences between the rivalrous stimuli matching the relevant ( $M = 49.5\%$ ,  $SD = 4.2\%$ ) and irrelevant color categories,  $t(9) = 0.864$ ,  $p = 0.932$ . When participants were instructed to memorize the color of the cued stimulus, there was no difference in initial dominance between the rivalrous stimulus matching the relevant ( $M = 51.2\%$ ,  $SD = 4.7\%$ ) and irrelevant color categories,  $t(9) = 0.840$ ,  $p = 0.423$ . Similarly, when participants were instructed to memorize the shape of the cued stimulus, there was no difference in initial dominance between the rivalrous stimulus matching the relevant ( $M = 47.8\%$ ,  $SD = 6.8\%$ ) and irrelevant color categories,  $t(9) = 1.023$ ,  $p = 0.333$ . Moreover, these proportions did not differ between tasks,  $t(9) = 0.355$ ,  $p = 0.730$ . Thus, the task relevance of a color category did not affect the initial dominance at rivalry onset. Overall, participants had no strong bias toward reporting the grating presented to one eye more often as the initial percept than the grating presented to the other eye (46.7% left eye,  $SD = 14.8\%$ , range = 32.8%–81.3%). There was, however, a slight bias toward reporting the green grating as the first percept more often than the red grating, both when participants memorized the color (31.9% red grating,  $SD = 20.0\%$ , range = 0.0%–56.3%) and the shape of the cued stimulus (34.1% red grating,  $SD = 22.0\%$ , range = 0.0%–68.8%). This bias was comparable to that found in Experiment 1 and Experiment 2.

## General discussion

In the present set of experiments, we investigated the influence of task relevance on the selection for visual awareness. Task relevance of stimuli was operationalized by a delayed match to sample task, in which one of two stimuli should be memorized, whereas the selection

for awareness was measured by means of binocular rivalry tracking during the retention interval, with stimuli that matched and mismatched the concurrently retained stimulus. All three experiments demonstrated an increased predominance for binocular rivalry stimuli that matched rather than mismatched the color category (i.e., red, green, or blue) of a concurrently retained hue (e.g., a specific blue hue).

The finding that task-relevant stimuli predominate awareness under conditions of binocular rivalry is in line with several other studies that used stimuli with no intrinsic relevance (Alpers et al., 2005; Balcetis et al., 2012; Chopin & Mamassian, 2010). These studies demonstrate that stimuli that match a stimulus category in an auxiliary task are more likely to gain initial dominance in binocular rivalry. Interestingly, Alpers et al. (2005) and Chopin and Mamassian (2010) did not detect an effect on dominance durations, and Balcetis et al. (2012) measured only initial dominance. In contrast, our study demonstrated that task relevance elicited a prolonged predominance of matching stimuli (Experiments 1, 2, and 3) that lasted throughout the rivalry period (Experiment 1). The major difference with the present set of experiments is that in their studies, the stimulus features that were coupled to a relevance condition were not task relevant during the binocular rivalry task. Possibly, a stimulus that is no longer relevant during the binocular rivalry task is no longer subject to enough prioritized processing to affect sustained perception during binocular rivalry. A compelling argument for this view comes from the self-stabilizing nature of binocular rivalry; when one eye's dominance duration is artificially lengthened (e.g., by means of task instructions), this reduces the duration of that eye's next few dominance periods (Blake, Westendorf, & Fox, 1990). As such, unless the manipulation is continuously applied, manipulations of dominance durations will tend to hamper themselves. In the study of Chopin and Mamassian (2010), for example, a cue indicated whether on that trial participants would be required to report percept dominance or whether they were required to perform a search task. The cue onset therefore indicated that the feature that was relevant for the search task was no longer relevant on that trial and could thus be disregarded. In the present set of experiments, in contrast, the relevant stimulus feature had to specifically retain its relevance during the binocular rivalry task for participants to perform the subsequent recall task. In line with this idea, a recent study showed that memorizing a face stimulus for a subsequent recall task caused matching face stimuli to break through continuous flash suppression faster than mismatching face stimuli (Pan, Lin, Zhao, & Soto, 2014). When the recall task was performed just before the suppression task so that the face stimulus was no longer relevant, however, this effect was abolished.

Therefore, it appears that the processing of stimuli under interocular competition is affected to a greater extent by a match with concurrently relevant information compared with information that had been relevant in close temporal proximity. Although these interpretations potentially explain why we did find effects of task relevance on dominance durations, it does not explain why these manipulations had no impact on perceptual selection at rivalry onset in the current study. A difference between our study and the three previously mentioned studies that did find an effect of task relevance on initial dominance (Alpers et al., 2005; Balçetis et al., 2012; Chopin & Mamassian, 2010) is that we offered participants three rather than two options to report their percept during binocular rivalry: They could report seeing either of the two percepts as well as having an ambiguous percept. Although including this third option provides more information on participants' percept during binocular rivalry, it might also hamper the detection of differences in initial dominance compared with a forced-choice paradigm. In addition, we did not provide participants with temporal constraints. Chopin and Mamassian (2010), for instance, restarted the trial if participants had not reported a first percept within 1 s. Alternatively, most of the variance in initial dominance in this study was explained by factors other than whether the rivalrous stimuli matched the color category of the cued stimulus or not. For instance, one participant reported the image presented to the left eye as initially dominant in 85% of the trials, whereas another participant reported the green stimulus as the initially dominant percept in 100% of the trials. In general, preferences in onset rivalry are believed to be relatively stable within participants and very variable across participants (Carter & Cavanagh, 2007). This is made apparent by the large between-subject differences in eye dominance preference and color preference in initial dominance in all three experiments reported here. Such large, systematic differences leave but little room for top-down modulation by task instruction.

The main finding of the current experiments is the asymmetry between top-down control and visual awareness. Experiment 3 revealed that the color category of the actively retained hue affected concurrent rivalry only when color was the volitionally retained feature dimension. In contrast, when color was an incidental feature, that is, when participants had to memorize the shape of a colored stimulus, dominance durations during binocular rivalry were not affected by its color category. Conversely, however, Experiment 2 revealed that prolonged dominance for stimuli matching the color category of the retained stimulus was also observed when participants reported the orientation of the rivalrous stimuli. Thus, the task relevance of a color category affected the selection of information for visual

awareness, even though color information per se was irrelevant and could be disregarded to perform the task at hand. A large number of studies has shown that top-down control could affect dominance during binocular rivalry (Chong & Blake, 2006; Chong, Tadin, & Blake, 2005; Lack, 1978; Meng & Tong, 2004; Mitchell, Stoner, & Reynolds, 2004; Ooi & He, 1999; van Ee, van Dam, & Brouwer, 2005; for reviews, see Dieter & Tadin, 2011; Paffen & Alais, 2011). For instance, attending to a specific feature (e.g., Mitchell et al., 2004) or to a stimulus (e.g., Ooi & He, 1999) presented to one eye increases the predominance of the ipsiocular percept. As such, the results of Experiment 3 could be interpreted as an effect of endogenous feature-based attention on perception during binocular rivalry. In the present study, however, participants ultimately had no volitional control over which of the rivalrous stimuli should predominate. First, because matching color information was propelled into awareness while participants were reporting orientation information (Experiment 2). Second, even in Experiment 1 and Experiment 3, in which participants had to report the color of the rivalrous stimuli, the information that was boosted into awareness was totally irrelevant for the task at hand; it matched only the color category that had been determined to be task relevant beforehand. If anything, when retaining a specific hue for subsequent recall, task performance might be hindered more by prolonged perception of a similar but slightly different stimulus than by prolonged perception of a stimulus from a distinct color category. Arguably, stimuli matching the task-relevant color category captured awareness, irrespective of the current behavioral goals of the observer. From this perspective, the asymmetry between top-down control and visual awareness reported here is in line with the idea that consciousness is required to determine rules that govern novel behavior (e.g., Ansorge et al., 2014; Gayet et al., 2014b; Kunde et al., 2003). Once these rules are in place, they can be implemented in nonconscious processes, in a nonflexible, automated manner. Thus, whereas participants could exert volitional control over which stimulus to retain for subsequent recall (Experiment 3), this retained information then guided the selection for awareness during binocular rivalry in a way that was insensitive to volitional control (Experiment 2).

During interocular competition, visual features of stimuli can be misbound, such that a percept comprises one feature from the stimulus presented to the left eye and another feature from the stimulus presented to the right eye. For instance, awareness of one feature dimension (e.g., flicker) can co-occur with unawareness of another feature (e.g., orientation) of the same stimulus under continuous flash suppression (Mudrik, Gelbard-Sagiv, Faivre, & Koch, 2013; Yang & Blake, 2012; Zadbood, Lee, & Blake, 2011). During binocular

rivalry, a percept can, for instance, comprise the color and motion (Andrews & Blakemore, 1999; Carney, Shadlen, & Switkes, 1987; Creed, 1935), motion and shape (Alais & Parker, 2006), or color and shape features presented to different eyes (Hong & Shevell, 2006; Kang & Shevell, 2008). Color misbinding is particularly likely if, as in the present case, differently colored rivalrous stimuli are isoluminant (Kang & Shevell, 2008). Our Experiment 2 showed that the orientations of rivalrous stimuli that matched the task-relevant color category predominated over the orientations of rivalrous stimuli that matched the task-irrelevant color category. The order of magnitude of this effect (a difference of 310 ms) was comparable with that of Experiment 1 (320 ms) in which the same stimuli were used, but participants reported the color rather than the orientation of the rivalrous gratings. This allows for an alternative perspective on the present results. Experiment 3 showed that the color of the cued stimulus affected concurrent perception only when it was the volitionally retained feature dimension. In contrast, Experiment 2 showed that once the relevance of a color category was determined, it boosted rivalrous stimuli into awareness that were composed of this color category, irrespective of whether color information was necessary to report perception. In this view, task relevancy in the encoding phase is highly selective, such that only the volitionally retained feature dimension affects concurrent perception. During perceptual selection, however, a stimulus matching the task-relevant feature dimension is boosted as a whole, such that all its features (i.e., color and orientation in the present case) gain more perceptual dominance.

At first glance, our results seem at odds with a recent study in which the content of visual working memory did not affect perception during binocular rivalry (Scocchia et al., 2014). In Scocchia et al.'s third experiment, stimuli were used that closely resembled the stimuli that were used in the present set of experiments. Participants were required to memorize the spatial frequency of a gray-scale sine wave grating for a delayed match to sample task. During the retention interval, differently colored orthogonal sine wave gratings were presented to each eye to elicit binocular rivalry. Participants reported the color (red or green) of the perceived grating, which either matched or mismatched the orientation of the memory stimulus. Crucially, the volitionally stored feature dimension of the memorized stimulus was its spatial frequency, whereas its orientation was an incidental feature dimension, which just happened to be part of the memorized stimulus. Our Experiment 3 revealed that only the volitionally retained feature dimension (in our case color; in their case spatial frequency) has the potency to affect concurrent perceptual selection, whereas the same feature does not affect perceptual

selection if it is an incidental feature of the memorized stimulus (in our case color, while shape was memorized; in their case orientation, while spatial frequency was memorized). Our findings are in line with a functional magnetic resonance imaging study by Serences et al. (2009). In this study, participants were instructed to memorize either the color or the orientation of a colored Gabor patch for delayed recall. Only the volitionally retained feature dimension could be reliably decoded from early visual areas, whereas the incidental feature dimension, which just happened to be part of the same object, could not. Consequently, the incidentally stored feature dimension that is not represented by neural activity in the visual cortex lacks the potency to interact with concurrent processing of incoming visual information. In conclusion, the null effect reported in the third experiment of Scocchia and colleagues (2014) is in line with the null effect reported in the Shape Memory condition of our Experiment 3: incidental features of a memorized stimulus do not affect perceptual selection during binocular rivalry.

In the first two experiments of the study by Scocchia and colleagues (2014) discussed above, the memory stimuli were images drawn from the stimulus categories “planes,” “houses,” and “faces.” During the concurrent rivalry tracking task, participants reported the color (red or green) of the dominant percept, which was either an exemplar from the memorized stimulus category or from one of the other two categories. The authors found the same dominance durations for stimuli that matched and stimuli that mismatched the image category of the memorized stimulus. As such, the memory task did not affect perceptual selection during binocular rivalry. In contrast with their third experiment in which they used grating stimuli, dominance durations in the binocular rivalry task (e.g., an airplane and a face) were now measured as a function of their contingency with the volitionally retained feature dimension (e.g., an airplane). Thus, in terms of task instructions, this experiment was equivalent to our Experiment 2, in which we did find an effect of the retained stimulus category on perceptual selection. Taking together our study and that of Scocchia et al. (2014), it appears that only the active retention of lower-level stimulus features (such as color) can bias concurrent perceptual selection, whereas the active retention of more complex stimuli (such as airplanes) cannot.

## Conclusion

The present set of experiments demonstrates how the selection of information for visual awareness is affected by the potential behavioral relevance of that information. On the one hand, this selection process is highly



specific, and thus very efficient; stimuli matching the color category of the cued stimulus predominated awareness only when color was the volitionally retained stimulus dimension. When color was an irrelevant feature dimension that just happened to be part of the cued stimulus, however, its color category did not affect concurrent selection for awareness. On the other hand, this selection process is very rigid. A color category that was previously determined as being relevant affected concurrent perceptual selection even if it was completely uninformative for the task at hand. Taken together, these results indicate that the selection of task-relevant information is under volitional control. Concurrent visual input that matches this information, however, is boosted into awareness, irrespective of whether it is useful for the current behavioral goals of the observer.

*Keywords:* visual awareness, consciousness, binocular rivalry, interocular competition, task relevance

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## References

- Alais, D., & Blake, R. (Eds.). (2005). *Binocular rivalry*. Cambridge, MA: MIT Press.
- Alais, D., & Parker, A. (2006). Independent binocular rivalry processes for motion and form. *Neuron*, *52*, 911–920.
- Alpers, G. W., & Gerdes, A. (2007). Here is looking at you: Emotional faces predominate in binocular rivalry. *Emotion*, *7*, 495–506.
- Alpers, G. W., Ruhleder, M., Walz, N., Mühlberger, A., & Pauli, P. (2005). Binocular rivalry between emotional and neutral stimuli: A validation using fear conditioning and EEG. *International Journal of Psychophysiology*, *57*, 25–32.
- Andrews, T. J., & Blakemore, C. (1999). Form and motion have independent access to consciousness. *Nature Neuroscience*, *2*, 405–406.
- Ansorge, U., Kunde, W., & Kiefer, M. (2014). Unconscious vision and executive control: How unconscious processing and conscious action control interact. *Consciousness and Cognition*, *27*, 268–287.
- Baars, B. J. (1997a). In the theatre of consciousness: Global workspace theory, a rigorous scientific theory of consciousness. *Journal of Consciousness Studies*, *4*, 292–309.
- Baars, B. J. (1997b). *In the theater of consciousness: The workspace of the mind*. New York: Oxford University Press.
- Baars, B. J. (2002). The conscious access hypothesis: Origins and recent evidence. *Trends in Cognitive Sciences*, *6*, 47–52.
- Baker, D. H., & Graf, E. W. (2009). Natural images dominate in binocular rivalry. *Proceedings of the National Academy of Sciences, USA*, *106*, 5436–5441.
- Balcetis, E., Dunning, D., & Granot, Y. (2012). Subjective value determines initial dominance in binocular rivalry. *Journal of Experimental Social Psychology*, *48*, 122–129.
- Bannerman, R. L., Milders, M., de Gelder, B., & Sahraie, A. (2008). Influence of emotional facial expressions on binocular rivalry. *Ophthalmic and Physiological Optics*, *28*, 317–326.
- Blake, R., Westendorf, D., & Fox, R. (1990). Temporal perturbations of binocular rivalry. *Perception & Psychophysics*, *48*(6), 593–602.
- Brainard, D. H. (1997). The Psychophysics Toolbox. *Spatial Vision*, *10*, 433–436.
- Carney, T., Shadlen, M., & Switkes, E. (1987). Parallel processing of motion and colour information. *Nature*, *328*, 647–649.
- Carter, O., & Cavanagh, P. (2007). Onset rivalry: Brief presentation isolates an early independent phase of perceptual competition. *PLoS One*, *2*, e343.
- Chen, Y. C., & Yeh, S. L. (2012). Look into my eyes and I will see you: Unconscious processing of human gaze. *Consciousness and Cognition*, *21*, 1703–1710.
- Chong, S. C., & Blake, R. (2006). Exogenous attention and endogenous attention influence initial dominance in binocular rivalry. *Vision Research*, *46*, 1794–1803.
- Chong, S. C., Tadin, D., & Blake, R. (2005).

- Endogenous attention prolongs dominance durations in binocular rivalry. *Journal of Vision*, 5(11):6, 1004–1012, <http://www.journalofvision.org/content/5/11/6>, doi:10.1167/5.11.6. [PubMed] [Article]
- Chopin, A., & Mamassian, P. (2010). Task usefulness affects perception of rivalrous images. *Psychological Science*, 21, 1886–1893.
- Christophel, T. B., Hebart, M. N., & Haynes, R. (2012). Decoding the contents of visual short-term memory from human visual and parietal cortex. *The Journal of Neuroscience*, 32(38), 12983–12989.
- Coren, S., & Russell, J. A. (1992). The relative dominance of different facial expressions of emotion under conditions of perceptual ambiguity. *Cognition & Emotion*, 6, 339–356.
- Creed, R. S. (1935). Observations on binocular fusion and rivalry. *Journal of Physiology*, 84, 381–392.
- Crick, F., & Koch, C. (2003). A framework for consciousness. *Nature Neuroscience*, 6, 119–126.
- Dehaene, S., Kerszberg, M., & Changeux, J. P. (1998). A neuronal model of a global workspace in effortful cognitive tasks. *Proceedings of the National Academy of Sciences, USA*, 95, 14529–14534.
- Dehaene, S., & Naccache, L. (2001). Towards a cognitive neuroscience of consciousness: Basic evidence and a workspace framework. *Cognition*, 79, 1–37.
- Dennett, D. C. (1991). *Consciousness explained*. Boston: Little, Brown.
- Dieter, K. C., & Tadin, D. (2011). Understanding attentional modulation of binocular rivalry: A framework based on biased competition. *Frontiers in Human Neuroscience*, 5, 155.
- Edelman, G. M., & Tononi, G. (2000). *A universe of consciousness: How matter becomes imagination*. New York: Basic Books.
- Engel, E. (1956). The role of content in binocular resolution. *American Journal of Psychology*, 69, 87–91.
- Faivre, N., & Koch, C. (2014). Temporal structure coding with and without awareness. *Cognition*, 131, 404–414.
- Gayet, S., Paffen, C. L., & Van der Stigchel, S. (2013). Information matching the content of visual working memory is prioritized for conscious access. *Psychological Science*, 24, 2472–2480.
- Gayet, S., Van der Stigchel, S., & Paffen, C. L. (2014a). Breaking continuous flash suppression: Competing for consciousness on the pre-semantic battlefield. *Frontiers in Psychology: Consciousness Research*, 5, 460.
- Gayet, S., Van der Stigchel, S., & Paffen, C. L. (2014b). Seeing is believing: Utilization of subliminal symbols requires a visible relevant context. *Attention, Perception, & Psychophysics*, 76, 489–507.
- Gray, K. L., Adams, W. J., & Garner, M. (2009). The influence of anxiety on the initial selection of emotional faces presented in binocular rivalry. *Cognition*, 113, 105–110.
- Gray, K. L., Adams, W. J., Hedger, N., Newton, K. E., & Garner, M. (2013). Faces and awareness: Low-level, not emotional factors determine perceptual dominance. *Emotion*, 13, 537.
- Harrison, S. A., & Tong, F. (2009). Decoding reveals the contents of visual working memory in early visual areas. *Nature*, 458, 632–635.
- Hollingworth, A., & Luck, S. J. (2009). The role of visual working memory (VWM) in the control of gaze during visual search. *Attention, Perception, & Psychophysics*, 71, 936–949.
- Hollingworth, A., Matsukura, M., & Luck, S. J. (2013). Visual working memory modulates rapid eye movements to simple onset targets. *Psychological Science*, 24, 790–796.
- Hong, S. W., & Shevell, S. K. (2006). Resolution of binocular rivalry: Perceptual misbinding of color. *Visual Neuroscience*, 23, 561–566.
- Ishihara, S. (1917). *Test for colour-blindness*. Tokyo: Hongo Harukicho.
- Jiang, Y., Costello, P., & He, S. (2007). Processing of invisible stimuli: Advantage of upright faces and recognizable words in overcoming interocular suppression. *Psychological Science*, 18, 349–355.
- Kaiser, P. K., & Comerford, J. P. (1975). Flicker photometry of equally bright lights. *Vision Research*, 15, 1399–1402.
- Kang, P., & Shevell, S. K. (2008). The role of luminance edges in misbinding of color to form. *Vision Research*, 48, 2495–2500.
- Kunde, W., Kiesel, A., & Hoffmann, J. (2003). Conscious control over the content of unconscious cognition. *Cognition*, 88, 223–242.
- Lack, L. C. (1978). Selective attention and the control over binocular rivalry. *Perception & Psychophysics*, 15, 193–200.
- Levelt, W. J. M. (1965). *On binocular rivalry* (Unpublished doctoral dissertation). Institute for Perception RVO-TNO, Soesterberg, the Netherlands.
- Lin, Z., & He, S. (2009). Seeing the invisible: The scope and limits of unconscious processing in binocular rivalry. *Progress in Neurobiology*, 87, 195–211.
- Malek, N., Mendoza-Halliday, D., & Martinez-Trujillo, J. (2012). Binocular rivalry of spiral and linear

- moving random dot patterns in human observers. *Journal of Vision*, *12*(10):16, 1–20, <http://www.journalofvision.org/content/12/10/16>, doi:10.1167/12.10.16. [PubMed] [Article]
- Meng, M., & Tong, F. (2004). Can attention selectively bias bistable perception? Differences between binocular rivalry and ambiguous figures. *Journal of Vision*, *4*(7):2, 539–551, <http://www.journalofvision.org/content/4/7/2>, doi:10.1167/4.7.2. [PubMed] [Article]
- Mitchell, J. F., Stoner, G. R., & Reynolds, J. H. (2004). Object-based attention determines dominance in binocular rivalry. *Nature*, *429*, 410–413.
- Mudrik, L., Faivre, N., & Koch, C. (2014). Information integration without awareness. *Trends in Cognitive Sciences*, *18*, 488–496.
- Mudrik, L., Gelbard-Sagiv, H., Faivre, N., & Koch, C. (2013). Knowing where without knowing what: Partial awareness and high-level processing in continuous flash suppression. *Journal of Vision*, *13*(9): 1103, <http://www.journalofvision.org/content/13/9/1103>, doi:10.1167/13.9.1103. [Abstract]
- Olivers, C. N., Meijer, F., & Theeuwes, J. (2006). Feature-based memory-driven attentional capture: Visual working memory content affects visual attention. *Journal of Experimental Psychology: Human Perception and Performance*, *32*, 1243–1265.
- Ooi, T. L., & He, Z. J. (1999). Binocular rivalry and visual awareness: The role of attention. *Perception-London*, *28*, 551–574.
- Paffen, C. L., & Alais, D. (2011). Attentional modulation of binocular rivalry. *Frontiers in Human Neuroscience*, *5*, 105–105.
- Pan, Y., Cheng, Q. P., & Luo, Q. Y. (2012). Working memory can enhance unconscious visual perception. *Psychonomic Bulletin & Review*, *19*, 477–482.
- Pan, Y., Lin, B., Zhao, Y., & Soto, D. (2014). Working memory biasing of visual perception without awareness. *Attention, Perception, & Psychophysics*, *76*, 2051–2062.
- Pan, Y., & Luo, Q. Y. (2012). Working memory modulates the perception of time. *Psychonomic Bulletin & Review*, *19*, 46–51.
- Parker, A., & Alais, D. (2007). A bias for looming stimuli to predominate in binocular rivalry. *Vision Research*, *47*, 2661–2674.
- Pasley, B. N., Mayes, L. C., & Schultz, R. T. (2004). Subcortical discrimination of unperceived objects during binocular rivalry. *Neuron*, *42*, 163–172.
- Pelli, D. G. (1997). The Video Toolbox software for visual psychophysics: Transforming numbers into movies. *Spatial Vision*, *10*, 437–442.
- Schneegans, S., Spencer, J. P., Schöner, G., Hwang, S., & Hollingworth, A. (2014). Dynamic interactions between visual working memory and saccade target selection. *Journal of Vision*, *14*(11):9, 1–23, <http://www.journalofvision.org/content/14/11/9>, doi:10.1167/14.11.9. [PubMed] [Article]
- Scocchia, L., Valsecchi, M., Gegenfurtner, K. R., & Triesch, J. (2013). Visual working memory contents bias ambiguous structure from motion perception. *PLoS One*, *8*, e59217.
- Scocchia, L., Valsecchi, M., Gegenfurtner, K. R., & Triesch, J. (2014). Differential effects of visual attention and working memory on binocular rivalry. *Journal of Vision*, *14*(5):13, 1–15, <http://www.journalofvision.org/content/14/5/13>, doi:10.1167/14.5.13. [PubMed] [Article]
- Serences, J. T., Ester, E. F., Vogel, E. K., & Awh, E. (2009). Stimulus-specific delay activity in human primary visual cortex. *Psychological Science*, *20*, 207–214.
- Silvis, J. D., & Van der Stigchel, S. (2014). How memory mechanisms are a key component in the guidance of our eye movements: Evidence from the global effect. *Psychonomic Bulletin & Review*, *21*, 357–362.
- Stein, T., Hebart, M. N., & Sterzer, P. (2011). Breaking continuous flash suppression: A new measure of unconscious processing during interocular suppression? *Frontiers in Human Neuroscience*, *5*, 167.
- Stein, T., Peelen, M. V., & Sterzer, P. (2011). Adults' awareness of faces follows newborns' looking preferences. *PLoS One*, *6*, e29361.
- Stein, T., Seymour, K., Hebart, M. N., & Sterzer, P. (2014). Rapid fear detection relies on high spatial frequencies. *Psychological Science*, *25*, 566–574.
- Stein, T., & Sterzer, P. (2012). Not just another face in the crowd: Detecting emotional schematic faces during continuous flash suppression. *Emotion*, *12*, 988–996.
- Tononi, G., & Edelman, G. M. (1998). Consciousness and complexity. *Science*, *282*(5395), 1846–1851.
- van Ee, R., van Dam, L. C. J., & Brouwer, G. J. (2005). Voluntary control and the dynamics of perceptual bi-stability. *Vision Research*, *45*, 41–55.
- van Moorselaar, D., Theeuwes, J., & Olivers, C. N. (2014). In competition for the attentional template: Can multiple items within visual working memory guide attention? *Journal of Experimental Psychol-*



- ogy: *Human Perception and Performance*, 40, 1450–1464.
- Wagner, G., & Boynton, M. (1972). Comparison of four methods of heterochromatic photometry. *Journal of the Optical Society of America*, 62, 1508–1515.
- Walraven, J. (1972). *TNO test for stereoscopic vision* (9th edition). Utrecht, the Netherlands: Lameris Instrumenten.
- Wheatstone, C. (1838). Contributions to the physiology of vision. Part the first. On some remarkable, and hitherto unobserved, phenomena of binocular vision. *Philosophical Transactions of the Royal Society of London*, 128, 371–394.
- Yang, E., & Blake, R. (2012). Deconstructing continuous flash suppression. *Journal of Vision*, 12(3):8, 1–14, <http://www.journalofvision.org/content/12/3/8>, doi:10.1167/12.3.8. [PubMed] [Article]
- Yang, E., Zald, D. H., & Blake, R. (2007). Fearful expressions gain preferential access to awareness during continuous flash suppression. *Emotion*, 7, 882–886.
- Zadbood, A., Lee, S. H., & Blake, R. (2011). Stimulus fractionation by interocular suppression. *Frontiers in Human Neuroscience*, 5, 135–135.