Priming makes a stimulus more salient

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The present study used visual prior entry to determine which of two stimuli received attention first. Observers were asked to judge whether two test stimuli across a range of stimulus onset asynchronies (SOAs) were synchronized or not (simultaneity judgment task; SJ), or to report the temporal order of the two test stimuli (temporal order judgment task; TOJ). Before the presentation of the two test stimuli, a single noninformative stimulus that matched the color of one of the test stimuli was presented in the center of the display. The results showed that, in both the TOJ and SJ tasks, the noninformative stimulus caused a shift in the psychometric function such that the test stimulus that had the same color as the preceding noninformative stimulus was seen earlier in time than the test stimulus that had a color that did not match. In other words, the mere processing of the color of a noninformative stimulus, rendered the stimulus having that same color more salient, an effect that we attributed to priming. Because priming made one of the stimuli more salient, it received attention first and accelerated its processing, causing prior entry into awareness. Importantly, when the noninformative stimulus was a color word, no such priming effect was observed. We conclude that a primed test stimulus has the ability to capture attention in an automatic way.

Introduction

In a recent study we demonstrated the limits of top-down attentional selection (Theeuwes & Van der Burg, 2011). In that study, observers searched displays for one of two equally salient color singletons among several nontarget elements. Before each search trial, observers received a word cue (e.g., a word saying "red" or "green") or a symbolic cue (a circle colored red or green) telling them which color singleton to select on the upcoming trial. Theeuwes and Van der Burg (2011) showed that with a word cue, observers could not selectively search for the target color singleton, as the irrelevant singleton captured attention. Crucially, however, when a symbolic cue was used, selection was perfect: there was no capture by the irrelevant color singleton. We attributed this effect to passive automatic priming induced by the cue.

We claimed that the cue showing the color of the to-be-searched-for upcoming target singleton primed one of the colors such that attention was automatically directed to the singleton having that color. A word cue that showed, for example, the word "red" or "green" indicating the color of the upcoming target singleton had no such effect. We argued that this type of symbolic priming changes the salience of the color feature within the priority map making the primed singleton more salient than the nonprimed singleton. Even though salience is typically defined as a physical property expressing how different a particular object is from its surrounding in color, orientation, motion, depth, and so forth (Itti & Koch, 2001), by now several visual search studies have shown that (intertrial) priming has a large effect on the efficiency of visual selection (Maljkovic & Nakayama, 1994; Theeuwes, Reimann, & Mortier, 2006; Theeuwes & Van der Burg, 2007, 2008, 2011; see Kristjánsson & Campana, 2010 for a review on priming). This result is attributed to an increased salience of the primed stimulus (see Pinto, Olivers, & Theeuwes, 2005; Theeuwes, 2010a, 2010b).

Even though the role of priming in a visual search is undisputed, the boundary conditions that result in priming remain unclear. On the one hand, it has been argued that the mere exposure to a stimulus results in priming (Maljkovic & Nakayama, 1994; Theeuwes et al., 2006; Theeuwes & Van der Burg, 2007, 2008, 2011), while others have argued that passive viewing is not enough to obtain priming (e.g., Brascamp, Blake, & Kristjánsson, 2011; Kristjánsson, Saevarsson, & Driver, 2013). For example, in a "priming of pop-out" search display (cf. Maljkovic & Nakayama, 1994), Kristjánsson et al. (2013) had observers either passively view displays

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or actively search for a pop-out target. Before each trial they were cued to either view the display passively or search actively for the oddly colored target (i.e., a diamond) and respond to the location of the cutoff of the diamond (either at the top or bottom). The results showed that target repetition resulted in intertrial priming, while passively looking at the display had no substantial effect on search times. Kristjánsson et al. (2013) concluded that priming is critically dependent on identifying the target; the mere passive exposure to a pop-out display did not result in intertrial priming effects. Even though these results are compelling, they are not consistent with the general notion that priming is usually automatic, that is, not subject to top-down control. As argued by Nakayama, Maljkovic, and Kristjánsson (2004) regarding priming of pop-out search display: "performance cannot be influenced by prior knowledge or expectancy. Whether a subject knows, pays attention to, or completely ignores the sequence of target colors is irrelevant" (p. 403).

One possible explanation for the absence of a priming effect when going from a passive to an active trial in Kristjánsson et al. (2013) may have nothing to do with priming itself. Indeed, it may be related to task switching, that is, going from not responding to the target in a passive trial to responding to the target in a subsequent active trial. This is consistent with Schuch and Koch (2003) as well as Los and Van der Burg (2010) who have shown that responses toward a target stimulus were slower when the preceding trial was a no-go trial than when the preceding trial was a go trial. Regarding the Kristjánsson et al. study (2013), it might have been the case that this task-switching slows observers down when changing from a passive to an active trial, concealing a possible intertrial priming effect. Clearly, this slowing does not occur when observers perform two or more active trials in a row.

The neurophysiological evidence concerned priming is somewhat ambiguous. It has been argued that priming produces a "sharpening" of its cortical representation, possibly making it more salient within its environment (Desimone, 1996). Single cell studies (e.g., Bichot & Schall, 2002) showed that repeating a stimulus changed responses of neurons in the frontal eye field (FEF), a region that has been implicated to be the neural substrate of the salience map (Thompson & Bichot, 2005). We argued that salience is not solely defined by the physical appearance of a stimulus in the outside world, but depends on its representation in the priority map (Awh, Belopolsky, & Theeuwes, 2012). In this view, the processing of a stimulus (as occurs in priming) leads to a change in the representation of that stimulus in the priority map, and this change occurs independently of top-down intentions (see also Hickey, Chelazzi, & Theeuwes, 2010 on reward priming).

The present paper was designed to provide direct evidence for the claim that priming, even when viewed passively, changes visual salience. Instead of using the traditional visual search paradigm, the current study employed two different, but related, psychophysical methods to assess the salience of the primed stimulus. In Experiment 1, we used the traditional temporal order judgment task (TOJ) (e.g., see, Hikosaka, Miyauchi, & Shimojo, 1993; Shore, Spence, & Klein, 2001; Stelmach & Herdman, 1991). In this task, observers report which of two stimuli appeared first. The delay between the two stimuli's onset (the stimulus onset asynchrony, SOA) was systematically varied. In Experiments 2 and 3 we used a simultaneity judgment task (SJ) in which participants had to judge whether two stimuli were presented simultaneously or not (Bushara, Grafman, & Hallett, 2011; Van der Burg, Olivers, Bronkhorst, & Theeuwes, 2008). With both of these tasks, one measures the initial deployment of attention (e.g., Shore et al., 2001). The assumption underlying this so-called "prior entry effect" is that the stimulus that receives attention first accelerates the processing of that stimulus, thereby decreasing the time between the physical onset and its further processing (see Spence & Parise, 2010 for a review on the prior entry effect). For the current experiments, if priming renders a stimulus as more salient, it expected to receive attention first, causing prior entry into awareness.

Recently, Donk and Soesman (2011) provided some evidence that prior entry may be affected by salience. In this study observers were presented with displays containing two tilted-orientation line segments embedded in a background of homogeneously vertical-oriented line segments. One of the target line segments was tilted more strongly than the other line segment, making this line segment stand out more from the background. Both target line segments could change color, and observers had to indicate the temporal order of these color changes. The results showed that a color change that occurred at the more salient (more tilted relative to the background of vertical line segments) target line segment was perceived as occurring earlier in time than a color change that occurred at the less salient (less tilted) target. Donk and Soesman (2011) concluded that the more salient target line segment received attention first, accelerating the processing of that stimulus and causing observers to perceive the color change of the more salient stimulus to occur before the color change of the less salient stimulus. The current study also uses temporal order judgment to assess whether priming renders a stimulus as more salient, causing it to be perceived earlier in time than a stimulus that is not primed.

In Experiment 1, observers were presented with test arrays of two colored circles. Before the presentation of the test array, a single noninformative stimulus was

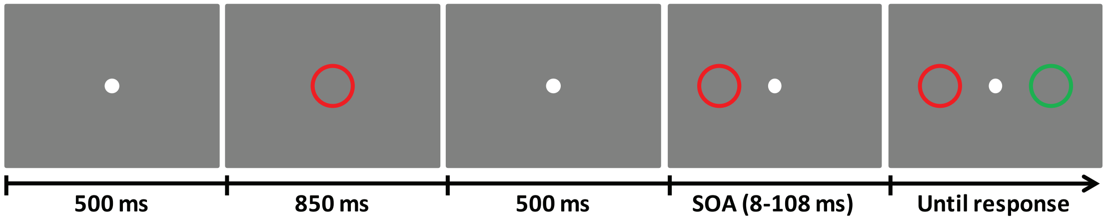

Figure 1. Example of a go trial (not on scale). Observers had to indicate which of the two circles appeared first. The SOA between the two circles was systematically varied. Before the presentation of the test stimuli, a noninformative stimulus (red or green) was presented for 850 ms.

presented in the center of the display. This noninformative stimulus was assumed to prime one of the two stimuli in the test array. We systematically varied, the SOA between the two circles and observers had to indicate which of the two circles was presented first. We then calculated the time interval needed for the observer to see both stimuli as arriving simultaneously (i.e., the point of subjective simultaneity, or PSS). If the noninformative stimulus primes one of the stimuli in the test array, then it is assumed that this stimulus is perceived to be more salient than the other stimulus. If this is the case, we expect that the unprimed stimulus needs to be presented slightly earlier in time than the primed stimulus in order to perceive the two stimuli as being presented simultaneously. This effect will result in a shift in the psychometric function (i.e., a shift in PSS).

Experiment 1

In Experiment 1 we used the same type of symbolic cueing as we used in Theeuwes and Van der Burg (2011). Before each trial, a colored circle was presented as a noninformative stimulus for 850 ms (see Figure 1). Unlike in Theeuwes and Van der Burg (2011) where the cue indicated which target to search for during the upcoming trial, in the current experiment the noninformative stimulus was completely irrelevant for the TOJ task. However, to ensure that observers processed the noninformative stimulus, on 20% of the trials, the noninformative stimulus was presented for 650 ms and then changed its color from red to orange or green to orange. In the case in which it changed color, observers were instructed to refrain from doing the TOJ task (no-go trials), and to press the spacebar after the trial. In the TOJ task, observers indicated (nonspeeded) with one of two keys whether the red or the green circle was presented first.

Method

Observers

Thirty-three students participated in Experiment 1 (18 female, 21.6 years; ranging from 18–33 years). All observers were naive as to the purpose of the experiment and received either course credits or money (€8, or approximately $10.67, per hour) for their participation.

Apparatus

Experiments were run in a dimly lit cubicle. Observers were seated approximately 80 cm from the CRT monitor (19 inch; 120 Hz refresh-rate).

Stimuli, procedure, and design

Each trial began with the presentation of a white (radius = 0.1°; 92.4 cd m^{-2}) fixation dot for 500 ms at the center of a gray screen (9.2 cd m^{-2}). Subsequently, the fixation dot was replaced by a noninformative stimulus for 850 ms. On 80% of the trials (go trials), the noninformative stimulus was either a green (radius = 0.78°; 10.8 cd m^{-2}) or red circle (radius = 0.78°; 15.5 cd m^{-2}), and on the remaining 20% of the trials (no-go trials), after 650 ms the color of the noninformative stimulus changed to orange. After the noninformative stimulus presentation, the fixation dot reappeared for another 500 ms.[1] Then, the first circle was presented either on the left or on the right side of the fixation dot (5.2° from fixation), and followed by the second circle, which appeared on the opposite side of the fixation dot after a randomly determined stimulus onset asynchrony (SOA; −108, −67, −33, −17, −8, 8, 17, 33, 67, 108). Note that one of the circles was green (radius = 0.78°; 10.8 cd m-1) and one of them was red (radius = 0.78°; 15.5 cd m-2), and that a negative SOA indicates that the red circle preceded the green circle and vice versa. Observers were asked to judge the temporal order of the presentation of the two circles (i.e., TOJ task). To ensure that observers processed the noninformative stimulus, observers only performed the temporal order judgment task when it did not change its color (i.e., a go trial); in a case in which the color did change, they were required to refrain from responding (i.e., a no-go trial). After a go trial, observers were asked to make a temporal order judgment about which of the two circles was presented first, by pressing the r-key (red) or the g-key (green) when the red circle or green circle was presented first, respectively (nonspeeded). After a no-go trial, observers were asked to ignore the two circles, and to press the spacebar after the trial.

The color (red or green) and location (left or right of fixation) of the first circle was balanced and randomly mixed within blocks. The color of the noninformative stimulus and the trial type (go vs. no-go trials) were also balanced and randomly mixed within each block. SOA was randomly mixed within blocks. One practice block and five experimental blocks of 100 randomly selected trials each were included.

Psychometric function fitting

In order to compute the PSS, the data from each observer were estimated by fitting the following two-parameter cumulative Gaussian function to each individual's data (see also Van der Burg et al., 2008), through minimizing the RMSE (root mean square error) in Microsoft Excel Solver.

$$P(response|SOA) = \frac{1}{1 + e^{-slope(SOA-PSS)}} \quad (1)$$

Here, SOA reflects the interval between the two circles (between −108 and +108 ms). PSS and slope were estimated.

Results and discussion

Figure 2 presents the proportion of green first responses, as a function of the noninformative stimulus color (red vs. green) and SOA (between −108 and +108 ms) with the fitted psychometric functions (mean RMSE = 0.077). Negative SOAs indicate that the red circle was presented first, whereas positive SOAs indicate that the green circle was presented first. In 4.4% of the trials, observers made a TOJ while they were asked to ignore the two circles (i.e., false alarms). In 1.1% of the trials, observers pressed the spacebar while they were asked to do the TOJ task (i.e., misses). The data from five observers were excluded, since they consistently indicated the color of the noninformative stimulus as the first circle color. This was evident as the overall proportion of green first responses (collapsed over SOA) was 98.5% when the prime was green, and 0.9% when the prime was red. The data from two observers were excluded since their overall performance was 50% over all SOA conditions. The data from another observer was excluded since on 98% of the trials, the observer made a TOJ while he/she was asked to ignore the two circles (i.e., false alarms).

Point of subjective simultaneity (PSS)

The mean PSS and slope for each noninformative stimulus color were subjected to separate two-tailed *t* tests. The overall estimated PSS was 16 ms, suggesting that regardless of a possible effect of priming, the color red was perceived as more salient than green. Such an effect is expected as the color red was more luminant (15.5 cd m^{-2}) than the color green (10.8 cd m^{-2}). As luminance contrast directly affects salience (e.g., Northdurft, 2000), finding such an effect on our PSS measure confirms the notion that the PSS is affected by the relative salience. Crucially, however, on top of this overall salience effect, there was a clear effect of the noninformative stimulus: there was a significant effect of the color of the noninformative stimulus on the PSS, $t(24) = 2.3$, $p < 0.05$, as the PSS was greater when the two circles were preceded by a red-colored stimulus (22 ms) than when the two circles were preceded by a green-colored stimulus (9 ms). The slope failed to reach significance ($p = 0.89$), indicating that the color of the noninformative stimulus had no effect on the TOJ decision.

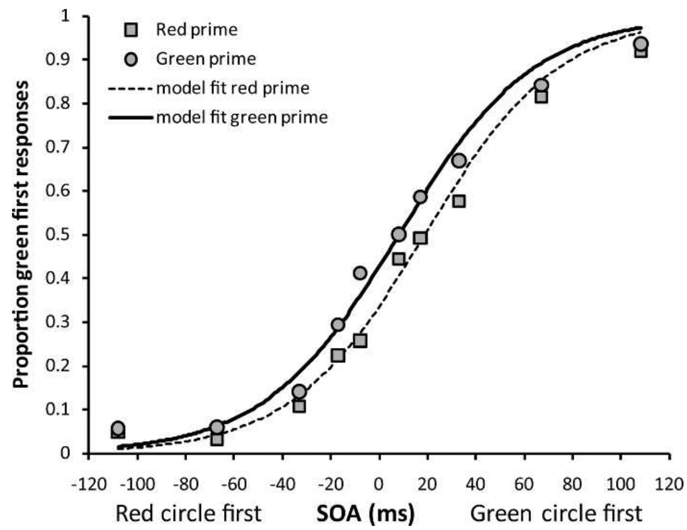

Figure 2. Experiment 1: The mean proportion green first responses as a function of SOA for each color (red and green) when primed by red or by green.

Proportion green first responses

The proportion green first responses were subjected to an ANOVA with noninformative stimulus color and SOA as within subject variables. The ANOVA yielded a reliable main effect of SOA, $F(9, 215) = 54.9$, $p < 0.001$. The main effect of the color of the non-informative stimulus was also reliable, $F(1, 24) = 6.3$, $p = 0.019$, as overall proportion green first responses was greater when the preceding noninformative stimulus color was green (.45) than when it was red (.39). Importantly, the ANOVA yielded a reliable SOA × noninformative stimulus color interaction, $F(9, 216) = 3.2$, $p < 0.005$, indicating that the effect of the preceding color was pronounced primarily for short

SOAs but not for longer SOAs. For the long SOAs, the performance in the TOJ was at ceiling.

The results are clear. The color of the irrelevant stimulus that preceded the test array resulted in a small and reliable shift of the psychometric function. If the two circles were preceded by a green stimulus, then the red circle needed to be presented earlier in time than the green circle to perceive the two circles as being presented simultaneously and vice versa. This shift in the psychometric function indicates that the irrelevant stimulus before the test array caused the circle that had the same color as the preceding irrelevant stimulus to appear earlier in time than the circle that had a color that did not match. In other words, the color of an irrelevant stimulus rendered the stimulus having that same color more salient, an effect that we attribute to priming.

Even though these results are clear, one possible concern is that the reported shift in PSS might be due to a response bias instead of a true change in the PSS. For example, it is possible that when observers did not perceive the order in which the two circles were presented, they simply may have reported the color of the noninformative stimulus that preceded the test array as a default. Clearly, this will result in a shift in the PPS but has nothing to do with an effect of the noninformative stimulus on the *perceived* temporal order. To circumvent this concern, in Experiment 2 we employed a simultaneity judgment task (SJ), which is known to be insensitive to response bias (Santangelo & Spence, 2008; Schneider & Bavelier, 2003; Van der Burg et al. 2008; Zampini, Guest, Shore, & Spence, 2005).

Experiment 2

Experiment 2 was identical to Experiment 1, except that observers were asked to do a simultaneity judgment (SJ) by indicating whether the circles were presented simultaneously or not. Furthermore, in the current experiment, a no-go trial was a trial in which the noninformative stimulus was not a circle but an oval shape instead. In those trials (20%), observers were refrained from doing the SJ task (no-go trials).

Method

Observers

Ten students participated in Experiment 2 (four female, 23.3 years; ranging from 20–27 years). All observers were naive as to the purpose of the experiment and received either course credits or money (€8, or approx. $10.67, per hour) for their participation.

Stimuli, procedure, and design

The noninformative stimulus was always presented for 850 ms. In 80% of the trials (go trials), the noninformative stimulus was either a green or red circle (like in the previous experiment), and on the remaining 20% of the trials (no-go trials), the noninformative stimulus was either a green or red oval (height = 1.56°; width = 1.17°). The randomly determined stimulus onset asynchrony was −108, −67, −33, −17, −8, 0, 8, 17, 33, 67, or 108 ms. Observers were asked whether the two circles were presented simultaneously or not. To ensure that observers processed the noninformative stimulus, the simultaneity judgment task was only required when the preceding noninformative stimulus was a circle (i.e., a go trial); not when the preceding noninformative stimulus was an oval (i.e., a no-go trial). After a go trial, observers were asked whether the two circles were presented simultaneously or not by pressing the j-key (yes) or n-key (no), respectively (nonspeeded).

The color (red or green) and location (left or right of fixation) of the first circle was balanced and randomly mixed within blocks. The color of the noninformative stimulus and its shape (go vs. no-go trials) were also balanced and randomly mixed within each block. SOA was randomly mixed within blocks, with the constraint that there were more simultaneous trials (32 per block) than asynchronous trials (eight of each SOA per block) so that a priori the number of synchronous and asynchronous trials was equal (see also Santangelo & Spence, 2008; Van der Burg et al., 2008; Zampini et al., 2005 for a similar methodology). There was one practice block and five experimental blocks of 136 randomly selected trials each.

Psychometric function fitting

In order to compute the PSS, the data from each observer were estimated by fitting the following a three-parameter Gaussian function to each individual's data (see also Santangelo & Spence, 2008; Van der Burg, Alais, & Cass, 2013; Van der Burg et al., 2008).

$$P(response|SOA) = a \cdot e^{\left[-0.5 \cdot \left(\frac{SOA-PSS}{b}\right)^2\right]} \quad (2)$$

The SOA parameter was equal to the interval between the two circles (−108 to +108 ms). Parameters a (amplitude) and b (Gaussian bandwidth) were estimated ($a > 0$ and $b > 0$).

Results and discussion

Figure 3 presents the proportion simultaneous responses, as a function of noninformative stimulus color (red vs. green) and SOA (between −108 and +108

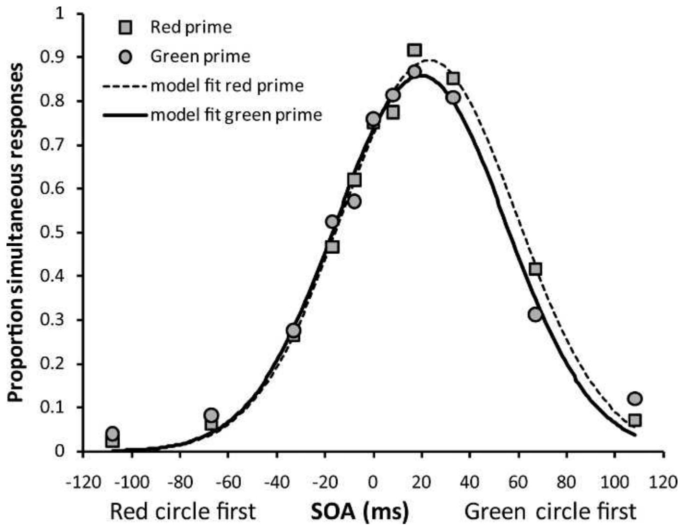

Figure 3. Experiment 2: The mean proportion simultaneous responses as a function of SOA for each color (red and green) when primed by red or green.

ms), with the fitted Gaussian functions (RMSE = 0.07). On 2.6% of the trials, observers made an SJ while they were asked to ignore the two circles (i.e., false alarms). On 0.5% of the trials observers pressed the spacebar while they were asked to do the SJ task (i.e., misses). The data from two observers were excluded, because on 12% of the trials the observers made a TOJ while they were asked to ignore the two circles (i.e., false alarms).

Point of subjective simultaneity (PSS)

The estimated mean PSS was subjected to a separate two-tailed t test. The overall estimated PSS was 20 ms, suggesting that, as in Experiment 1, the color red was more salient than green, regardless of priming. The t test revealed a significant effect of the color of the noninformative stimulus on PSS, $t(7) = 2.5$, $p < 0.05$, as the PSS was greater when the two circles were preceded by a red stimulus (22 ms) than when the two circles were preceded by a green stimulus (18 ms). Overall priming caused a shift of 4 ms of the psychometric function. The other parameters (a and b) failed to reach significance (ps > 0.45), indicating that priming had no influence on the shape of the psychometric function (i.e., its amplitude and Gaussian bandwidth, respectively).

Proportion simultaneous responses

The proportion simultaneous responses were subjected to an ANOVA with noninformative stimulus color and SOA within subject variables. The main effect of SOA was reliable, $F(10, 70) = 37$, $p < 0.001$, whereas the main effect of the color of the noninformative stimulus failed to reach significance ($F <$ 1). As in Experiment 1, the ANOVA yielded a reliable SOA × noninformative stimulus color interaction, $F(10, 70) = 2.0$, $p = 0.05$, suggesting that when the SOA was greater than the PSS (all SOAs greater than 20 ms; i.e., collapsed over 33, 67, and 108 ms), proportion simultaneous responses were greater when the preceding noninformative stimulus was red than when it was green, whereas the reversed effect occurred when the SOA was smaller than the PSS (<20 ms; collapsed over −108, −67, −33, −17, −8, 0, 8, and 17 ms). This was statistically confirmed, $t(7) = 3.9$, $p = 0.006$.

The present results confirm the findings of Experiment 1. As in the first experiment, presenting a noninformative stimulus resulted in priming of one of the two circles, which led to a small and reliable shift of the psychometric function. Because the noninformative stimulus primed one of the two circles, the unprimed circle needed to be presented earlier in time than the primed circle. As outlined, the current results of the SJ task cannot be explained in terms of a response bias (Santangelo & Spence, 2008; Schneider & Bavelier, 2003; Van der Burg et al., 2008; Zampini et al., 2005), as observers responded to the order of the presentation of the circles, and not to the colors of the circles as in the TOJ task of Experiment 1.

Experiment 3

Theeuwes and Van der Burg (2011) showed that a cue such as that employed as a noninformative stimulus in the current experiments was effective in guiding visual search to the relevant target. We attributed this effect on visual search to priming. Experiments 1 and 2 provide elegant evidence for this conception in a task that is very much unlike visual search. Note however, that Theeuwes and Van der Burg (2011) also showed that when the cue is not symbolic (i.e., a circle with the actual color that needed to be searched) but merely a word telling which color needed to be searched (e.g., a word saying "red," or "green"), there was no effect of the cue on guiding visual search. The underlying notion is that a word cue cannot prime the actual color feature. More specifically, Theeuwes (2010a, 2010b) argued that a verbal cue may not be able to affect early perceptual selection processes because a verbal instruction (e.g., "search for red") cannot directly affect the "cycling" of neurons. However, neurons in early visual areas that code for a particular feature (e.g., the color red) may sharpen their cortical representation (e.g., see Desimone, 1996) after these neurons have been exposed to the actual stimulus feature (e.g., neurons need to "cycle" in order to get set for a particular feature).

If in the current experiments we are measuring priming as observed in earlier visual search experiments (e.g., Theeuwes et al., 2006; Theeuwes & Van der Burg, 2007, 2008, 2011), then similarly, a noninformative word cue in the current set-up should have no effect on prior entry. Processing the word preceding the test array should not affect the initial allocation of attention. Experiment 3 was identical to Experiment 2 but instead of a symbolic noninformative stimulus cue, we presented a word ("red" or "green") before the test array. Again, as in Experiment 2, observers had to process this stimulus because in 20% of the trials the stimulus was written incorrectly (e.g., "greon" instead of "groen" [green, in Dutch]) which required observers to refrain from responding in the SJ task.

Method

Observers

Fifteen students participated in Experiment 3 (seven female, 21.6 years; ranging from 18–28 years). The data from one observer was excluded since he or she did not do the task correctly. The present experiment was identical to Experiment 2 except that we replaced the red circle by the word "red" (i.e., "rood" in Dutch) and the green circle by the word "green" (i.e., "groen" in Dutch). Furthermore, to make sure that the observers processed the words, they were asked to do the SJ only when the words were written correctly and to press the spacebar afterwards in the case of the word being written incorrectly (i.e., "roed" or "groon"). All letters were lowercase and presented in white 32-point Times font (92.4 cd m^{-2}; 1.2° in height).

Results and discussion

Figure 4 presents the percentage simultaneous responses, as a function of noninformative stimulus color (red vs. green) and SOA (–108 to +108) with the fitted psychometric functions (RMSE = 0.07). On 3.9% of the trials, observers made an SJ while they were asked to ignore the two circles (i.e., false alarms). On 0.2% of the trials, observers pressed the spacebar while they were asked to do the SJ task (i.e., misses).

Point of subjective simultaneity (PSS)

Overall estimated PSS was 17 ms, again indicating that red was more salient than green. The extracted parameters from the fitted curves in Figure 3 were subjected to separate two-tailed t test. All parameters failed to reach significance ($ps > 0.25$). Crucially, there was no effect of noninformative stimulus color on PSS indicating that the psychometric functions basically overlap.

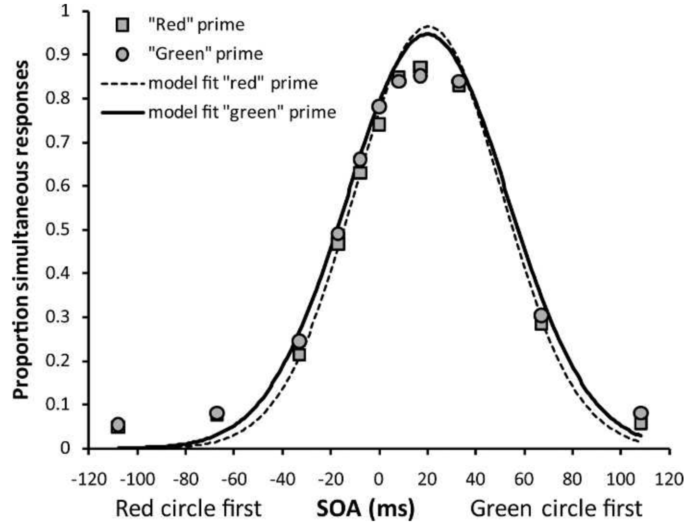

Figure 4. Experiment 3: The mean proportion simultaneous responses as a function of SOA for each color (red and green).

Proportion simultaneous responses

The main effect of SOA was reliable, $F(10, 130) = 67$, $p < 0.001$, whereas the main effect of noninformative stimulus color failed to reach significance, $F(1, 13) = 2.0$, $p = 0.177$. Importantly, the two-way interaction between SOA and noninformative stimulus color was far from significant ($F < 1$), Whereas a colored noninformative stimulus as used in Experiments 1 and 2 did affect the temporal order or perceived simultaneity of the two circles, word noninformative stimulus had no effect whatsoever.

General discussion

The results demonstrate that the processing of the color of a completely irrelevant stimulus results in subsequent automatic selection of the stimulus that has the same color. This effect, which we attribute to priming, occurs automatically, and does not depend on any specific task instructions. Even though the current temporal order and simultaneity judgment tasks did not require selection of any particular target, we show that the initial deployment of attention was directed to the stimulus that was primed, resulting in its prior entry into awareness.

We assume that showing one color before the test array primes this particular color such that the object of this color in the test array appears to be more salient than the other object in the display. Because it is more salient, it captures attention first, causing a prior visual effect as measured by both temporal order judgment and the simultaneity judgment tasks. Even though showing the actual color can have this priming effect, describing a color by a word had no effect on the subsequent processing, suggesting that for priming to occur it is necessary that the particular stimulus feature is processed.

Our claim here is that the mere processing of a stimulus automatically results in priming, which renders one of the stimuli in the test array more salient. We argue that this is an automatic process because the stimulus presented before the test array was completely irrelevant for the task. As argued by, for example, Yantis and Egeth (1999), to establish the existence of automatic, bottom-up processes it must be ensured that there is no incentive for the observer to attend the stimulus. Given the fact that the observer only had to decide which stimulus in the test array was presented first (Experiment 1), or whether the two stimuli were presented in synchrony (Experiment 2), the presentation of the stimulus before the test array had no function whatsoever. According to Schneider and Shiffrin (1977) automatic processing "is activated automatically without the necessity for active control or attention by the subject" (p. 2), a characteristic that also applies to the present situation. Even though this priming effect occurs in an automatic fashion, it does not necessarily mean that observers could have avoided the occurrence of priming. For example, by endogenously directing attention away from the stimulus, the priming effect may be reduced. This is also found with the well-known Stroop effect, which is typically considered to be the hallmark of automatic processing. By directing attention away from the Stroop word, the Stroop effect is significantly reduced (e.g., Treisman & Kahneman, 1981).

Our findings are inconsistent with theories that claim that active processing of a stimulus is required to obtain priming (e.g., Brascamp et al., 2011; Fecteau, 2007; Kristjánsson et al., 2013). Clearly, in the current experiments, the mere viewing of a stimulus that is completely irrelevant for the task caused a shift in PSS, which is attributed to priming. Crucially, the current experiments did not involve active search, search templates, or speeded responses. It is the most simple and direct way to demonstrate that the mere processing of stimulus feature (even when it is completely irrelevant) renders that stimulus feature more salient. These findings are consistent with the notion that priming is a passive automatic effect (Maljkovic & Nakayama, 1994; Nakayama et al., 2004; Theeuwes et al., 2006; Theeuwes & Van der Burg, 2007, 2008, 2011)

The present study employed a somewhat unconventional approach using two psychophysical paradigms (TOJ and SJ) to assess the effect of priming. Importantly, even though the approach is quite different, the results confirm earlier findings obtained with more classic visual search tasks. Even though many findings in visual search are attributed to top-down guidance on the basis of a cue presented before display onset, the current findings (and those of Theeuwes et al., 2006; Theeuwes & Van der Burg, 2007, 2011) indicate that the mere exposure to a color feature before display onset may automatically render one of the features in the display as more salient, thus causing attentional selection priority. Obviously, this automatic effect on salience is not under top-down control, but instead is the result of passive exposure to the stimulus. Note, however, that even though the stimulus that preceded the test array was completely irrelevant for the SJ and TOJ task, by introducing the go or no-go task, we made sure that observers processed the stimulus. The notion that the processing of a completely irrelevant stimulus drives subsequent selection is consistent with findings of Maljkovic and Nakayama (1994), who investigated intertrial effects in feature search. Even when a target on a given trial was 100% predictable (e.g., target definition changed in an AABBAABBAA ... pattern), knowledge-based expectations could not modulate feature-specific intertrial effects. Maljkovic and Nakayama (1994) conclude that their intertrial effects reflect passive priming that are not top-down penetrable, a notion that is consistent with the current findings.

The use of temporal order judgment is a well-established measure to assess the initial deployment of attention (see reviews by Shore et al., 2001; Stelmach & Herdman, 1991). The underlying notion is that attention accelerates the processing of sensory stimuli. Because processing is accelerated, the time between the actual physical onset and its processing is reduced, causing observers to perceive the stimulus as being presented earlier in time than the stimulus without attention. For example, Stelmach and Herdman (1991) showed that observers perceived a spatially cued black dot several milliseconds before the same dot at an uncued location. Shore et al. (2001) showed that the prior entry effect was larger for exogenous cueing (an abrupt onset near the target location) than for endogenous cueing (a central arrow pointing to the likely target location). West, Anderson, and Pratt (2009) did not use a spatial cue to direct attention but instead presented (as in the current study) two stimuli (in their case, faces) on either side of fixation and demonstrated that a face that displayed threat was perceived about 5 to 7 ms earlier in time than a neutral face. The authors concluded that these prior visual entry effects demonstrate that motivationally significant stimuli (such as a threatening facial expression) have the ability to summon attention, a conclusion that is similar to our claim that the mere processing of an irrelevant stimulus feature causes automatic priming that drives prior visual entry. The use of the SJ task in attention research is not often applied even though it has proven to be less sensitive to response bias. Most studies employing the SJ task looked at multisensory processing (e.g., Santangelo & Spence, 2008; Schneider & Bavelier, 2003; Van der Burg et al., 2008; Zampini et al., 2005). The current results show that it does not matter which task (TOJ or SJ) is used, since the results of Experiments 1 and 2 were basically the same. However, the magnitude of the prior entry effect appears to be greater in the TOJ task than in the SJ task, a finding that has been reported before (e.g., see Van der Burg et al., 2008; Spence and Parise, 2010 for a discussion).

The current findings that the mere processing of a noninformative stimulus has an effect on the subsequent deployment of attention is consistent with a whole host of studies investigating the effects of priming on visual search (e.g., Kristjansson, Wang, & Nakayama, 2002; Maljkovic & Nakayama, 1994, 1996; Pinto et al., 2005; Theeuwes et al., 2006; Theeuwes & Van der Burg, 2007, 2008). However, there are also studies that claim that one must actively consolidate the stimulus into working memory before it can have an effect on the deployment of attention (e.g., Downing, 2000; Soto, Humphreys, & Heinke, 2006). Even though it may be the case that actively storing information in working memory will have a large effect on the initial deployment of attention (for a review see Theeuwes, Belopolsky, & Olivers, 2009), it does not necessarily mean that passive priming as we investigate here (and as reported in other priming studies) does not occur as well, especially because, unlike the working memory studies, priming studies typically use rather simple stimuli. Also, priming effects are relatively small and can only be picked up by sensitive dependent measures, such as the TOJ and SJ measures that are currently used.

In sum, we have demonstrated that a primed stimulus receives attention first, suggesting that it captures attention in a bottom-up, automatic way. Our TOJ and SJ tasks that measure the initial deployment of attention without any task set or response bias may prove to be an important tool for future research measuring automatic selection priority. Our findings contribute to a long line of research that point to the limits of top-down selection (for a review, see Awh et al., 2012).

Keywords: priming, temporal order judgment, visual search

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Footnote

[1]We used a relatively long interval of 500 ms between the stimulus and the test array to prevent the occurrence of apparent motion. It is well established that with an interstimulus interval of 200 ms or more, the subsequent displays are perceived as separate events that do not give rise to apparent motion (Kolers, 1972).

References

Awh, E., Belopolsky, A. V., & Theeuwes, J. (2012). Top-down versus bottom-up attentional control: A failed theoretical dichotomy. *Trends in Cognitive Sciences, 16,* 437–443.

Bichot, N. P., & Schall, J. D. (2002). Priming in macaque frontal cortex during popout visual search: Feature-based facilitation and location based inhibition of return. *Journal of Neuroscience, 22,* 4675–4685.

Brascamp, J. W., Blake, R., & Kristjánsson, Á. (2011). Deciding where to attend: Priming of pop-out drives target selection. *Journal of Experimental Psychology: Human Perception and Performance, 37,* 1700–1707.

Bushara, K. O., Grafman, J., & Hallett, M. (2001). Neural correlates of auditory–visual stimulus onset asynchrony detection. *Journal of Neuroscience, 21,* 300–304.

Desimone, R. (1996). Neural mechanisms for visual memory and their role in attention. *Proceedings of the National Academy of Sciences, USA, 93,* 13494–13499.

Donk, M., & Soesman, L. (2011). Object salience is transiently represented whereas object presence is not: Evidence from temporal order judgment. *Perception, 40,* 63–73.

Downing, P. E. (2000). Interactions between visual working memory and selective attention. *Psychological Science, 11,* 467–473.

Fecteau, J. H. (2007). Priming of pop-out depends upon the current goals of observers. *Journal of Vision, 7*(6):1, 1–11, http://www.journalofvision.org/content/7/6/1, doi:10.1167/7.6.1. [PubMed] [Article]

Hickey, C., Chelazzi, L., & Theeuwes, J. (2010). Reward changes salience in human vision via the anterior cingulate. *Journal of Neuroscience, 30,* 11096–11103.

Hikosaka, O., Miyauchi, S., & Shimojo, S. (1993). Voluntary and stimulus-induced attention detected as motion sensation. *Perception, 22*(5), 517–526.

Itti, L., & Koch, C. (2001). Computational modelling of visual attention. *Nature Reviews Neuroscience, 2*(3), 194–203.

Kolers, P. A. (1972). *Aspects of motion perception.* Elmsford, NY: Pergamon Press.

Kristjánsson, Á., & Campana, G. (2010). Where perception meets memory: A review of priming in visual search. *Attention, Perception & Psychophysics, 72,* 5–18.

Kristjánsson, Á., Saevarsson, S., & Driver, J. (2013). The boundary conditions of priming of visual search: From passive viewing through task-relevant working memory load. *Psychonomic Bulletin and Review,* 1–8.

Kristjánsson, Á., Wang, D., & Nakayama, K. (2002). The role of priming in conjunctive visual search. *Cognition, 85,* 37–52.

Los, S. A., & Van der Burg, E. (2010). The origin of switch costs: Task preparation or task application? *Quarterly Journal of Experimental Psychology, 63*(10), 1895–1915.

Maljkovic, V., & Nakayama, K. (1994). Priming of pop-out: I. Role of features. *Memory & Cognition, 22*(6), 657–672.

Maljkovic, V., & Nakayama, K. (1996). Priming of pop-out: II. Role of position. *Perception and Psychophysics, 58,* 977–991.

Nakayama, K., Maljkovic, V., & Kristjánsson, A. (2004). Short-term memory for the rapid deployment of visual attention. In M. Gazzaniga (Ed.), *The cognitive neurosciences III.* (pp. 397–408). Cambridge, MA: MIT Press.

Nothdurft, H. C. (2000). Salience from feature contrast: Temporal properties of saliency mechanisms. *Vision Research, 40,* 2421–2435.

Pinto, Y., Olivers, C. N. L., & Theeuwes, J. (2005). Target uncertainty does not lead to more distraction by singletons: Intertrial priming does. *Perception & Psychophysics, 67*(8), 1354–1361.

Santangelo, V., & Spence, C. (2008). Crossmodal attentional capture in an unspeeded simultaneity judgment task. *Visual Cognition, 16,* 155–165.

Schneider, K. A., & Bavelier, D. (2003). Components of visual prior entry. *Cognitive Psychology, 47,* 333–366.

Schneider, W., & Shiffrin, R.M. (1977). Controlled and automatic human information processing: I. Detection, search, and attention. *Psychological Review, 84*(1), 1–66.

Schuch, S., & Koch, I. (2003). The role of response selection for inhibition of task sets in task shifting. *Journal of Experimental Psychology: Human Perception and Performance, 29,* 92–105.

Shore, D. I., Spence, C., & Klein, R. M. (2001). Visual prior entry. *Psychological Science, 12,* 205–212.

Soto, D., Humphreys, G. W., & Heinke, D. G. (2006). Working memory can guide pop-out search. *Vision Research, 46,* 1010–1018.

Spence, C., & Parise, C. (2010). Prior-entry: A review. *Consciousness and Cognition, 19,* 364–379.

Stelmach, L. B., & Herdman, C. M. (1991). Directed attention and perception of temporal order. *Journal of Experimental Psychology: Human Perception and Performance, 17,* 539–550.

Theeuwes, J. (2010a). Top-down and bottom-up control of visual selection. *Acta Psychologica, 123,* 77–99.

Theeuwes, J. (2010b). Top-down and bottom-up control of visual selection: Reply to commentaries. *Acta Psychologica, 123,* 133–139.

Theeuwes, J., Belopolsky, A., & Olivers, C. N. L. (2009). Interactions between working memory, attention, and eye movements. *Acta Psychologica, 132*(2), 106–114.

Theeuwes, J., Reimann, B., & Mortier, K. (2006). Visual search for featural singletons: No top-down modulation, only bottom-up priming. *Visual Cognition, 14*(4-8), 466–489.

Theeuwes, J., & Van der Burg, E. (2007). The role of spatial and nonspatial information in visual selection. *Journal of Experimental Psychology—Human Perception and Performance, 33*(6), 1335–1351.

Theeuwes, J., & Van der Burg, E. (2008). The role of cueing in attentional capture. *Visual Cognition, 16*(2–3), 232–247.

Theeuwes, J., & Van der Burg, E. (2011). On the limits of top-down control. *Attention, Perception & Psychophysics, 73,* 2092–2103.

Treisman, A., & Kahneman, D. (1981). An early interference effect in visual perception. *Bulletin of the Psychonomic Society, 18*(2), 68–68.

Thompson, K. G., & Bichot, N. P. (2005). A visual salience map in the primate frontal eye field. *Progress in Brain Research, 147,* 251–262.

Van der Burg, E., Alais, D., & Cass, J. (2013). Rapid recalibration to audiovisual asynchrony. Manuscript submitted for publication.

Van der Burg, E., Olivers, C. N. L., Bronkhorst, A. W., & Theeuwes, J. (2008). Audiovisual events capture attention: Evidence from temporal order judgments. *Journal of Vision, 8*(5):2, 1–10, http://www.journalofvision.org/content/8/5/2, doi:10.1167/8.5.2. [PubMed] [Article].

West, G., Anderson, A., & Pratt, J. (2009). Motivationally significant stimuli show visual prior entry: Direct evidence for attentional capture. *Journal of Experimental Psychology: Human Perception and Performance, 35,* 1032–1042.

Yantis, S., & Egeth, H. E. (1999). On the distinction between visual salience and stimulus-driven attentional capture. *Journal of Experimental Psychology: Human Perception and Performance, 25,* 661–676.

Zampini, M., Guest, S., Shore, D. I., & Spence, C. (2005). Audio-visual simultaneity judgments. *Perception & Psychophysics, 67,* 531–544.