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Context-dependent brightness priming occurs without visual awareness

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ABSTRACT

Our visual systems account for stimulus context in brightness perception, but whether such adjustments occur for stimuli that we are unaware of has not been established. We therefore assessed whether stimulus context influences brightness processing by measuring unconscious priming with metacontrast masking. When a middle-gray disk was presented on a darker (or brighter) background, such that it could be consciously perceived as brighter (or darker) via simultaneous brightness contrast (SBC), reaction times were significantly faster to a bright (or dark) annulus than to a dark (or bright) annulus. We further show that context-dependent brightness priming does not correlate with visibility using an objective measure of awareness (Experiment 1) and that context-dependent, but not context-independent brightness priming, occurs equally strongly for stimuli below or above the subjective threshold for awareness (Experiment 2). These results suggest that SBC occurs at early levels of visual input and is not influenced by conscious perception.

1. Introduction

Because of capacity limitations, our visual systems must continuously extract relevant from irrelevant information from our environments to successfully guide behavior. As a result, it is a common notion that we only process and consciously experience a small fraction of visual information at any given time. Compelling evidence now suggests, however, that significant amounts of information can be unconsciously processed to very extensive levels of representations. For example, several studies have demonstrated that an unconscious prime can modulate responses to a subsequent shape (Klotz & Neumann, 1999; Klotz & Wolff, 1995; Neumann & Klotz, 1994; Ro, Singhal, Breitmeyer, & Garcia, 2009), color (Breitmeyer, Ro, & Singhal, 2004; Schmidt, 2002), and even semantic information (Dehaene et al., 1998).

A series of studies from our laboratory has further suggested that unconscious visual information may be represented differently from consciously perceived visual information (Breitmeyer, Ro, Ogmen, & Todd, 2007; Breitmeyer et al., 2004). Using a metacontrast masking procedure (Breitmeyer & Öğmen, 2000, 2006), in which a prime stimulus was rendered invisible by using a spatially adjacent but non-overlapping mask, we demonstrated a dissociation between unconscious and conscious priming. Specifically, we showed that white primes, which were consciously perceived as bluish-white but physically composed of mostly green light on a CRT monitor, produced priming effects resembling green primes when unconsciously presented. These results suggest that priming from unconscious visual stimuli is based on raw, physical features (wavelength), while priming from consciously processed stimuli is percept-dependent.

In the current study, we examined whether such a distinction between conscious and unconscious levels of representation might be demonstrated for another visual property, namely brightness. The perception of brightness, arguably the most

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basic aspect of vision, is produced not only by stimulus luminance (i.e., the physical intensity of the light stimulus), but also by the luminance of other objects in the scene. For example, a gray object on a dark background is perceived brighter than the same gray object on a bright background, an extremely robust and extensively studied phenomenon referred to as simultaneous brightness contrast (SBC). Typically, SBC involves awareness in that it is the subjective perceptual experience of a surface property. However, whether SBC stimuli can be unconsciously processed and produce priming effects similar to those that are consciously perceived remains heretofore unknown. We therefore assessed whether SBC occurs in the absence of awareness or whether only purely luminance-based brightness processing without any influences from stimulus context (i.e., the brightness of the background) occurs unconsciously.

In addition to assessing whether SBC occurs both consciously and unconsciously, we also indirectly assessed the level at which SBC might be occurring. One of the most common explanations of SBC suggests that illusory brightness is a result of early encoding that is based on lateral interactions between cells at the earliest input levels of the visual system (i.e., the retina). However, examples incompatible with this explanation have been constructed (Adelson, 1993; Cornsweet, 1970; Gilchrist, 1977), and some evidence also suggests the involvement of higher order processes that are dependent on experience (Williams, McCoy, & Purves, 1998a, 1998b). Because we manipulated the brightness and visibility of the prime stimulus and evaluated its effects on a trailing metacontrast mask that was either congruent or incongruent in brightness, our experimental design allowed us to distinguish between two different explanations for SBC:

(1) If SBC occurs only with awareness of the stimuli, then priming from unaware stimuli should be based only on physical properties of the primes (i.e., luminance), whereas priming from visible stimuli should reflect context-dependent levels of processing. Such results would be more in agreement with higher level explanations of SBC in that context-dependent effects would only occur with visual awareness.
(2) On the other hand, if SBC is coded at early levels of visual processing prior to presumably later, context-dependent perceptual effects, then we should expect similar priming effects from both visible and invisible stimuli. Such results would be more consistent with low level theories of SBC that do not presuppose influences from higher level perceptual processes that may require visual awareness.

We also used both objective and subjective measures of awareness because of a long standing debate regarding the optimal ways for measuring awareness (Eriksen, 1960; Hannula, Simons, & Cohen, 2005; Holender, 1986; Merikle, Smilek, & Eastwood, 2001; Schmidt & Vorberg, 2006; Wiens, 2007). An objective criterion, based on the ability to discriminate stimuli, is problematic because it requires accepting the null-hypothesis (e.g., chance-level performance). Additionally, it can underestimate unconscious perception; in many circumstances human observers can discriminate above chance while claiming no subjective experience (e.g., as in blindsight, in which patients with visual cortex damage can discriminate visual information without awareness). Because of these shortcomings, many authors emphasize subjective reports (Dehaene & Changeux, 2011; Merikle et al., 2001). Although subjective reports could be influenced by response biases, they better capture the nature of subjective experience, which is what motivates consciousness research in the first place. Our findings reported here therefore rely primarily on subjective measure of awareness, although we provide converging evidence using objective measures. The results from two experiments, which used these different measures for assessing visual awareness, both show that SBC can be processed unconsciously, and they suggest that this illusion occurs at early levels of visual encoding.

2. Experiment 1

Using metacontrast masking we tested whether context-dependent brightness priming requires awareness. In the SBC conditions, a middle-gray priming disk was briefly presented on either a darker or brighter background to induce a context-dependent brightness of the disk via SBC. To assess whether luminance-dependent (non-SBC) brightness processing also occurs without awareness, a dark or bright priming disk was presented on a middle-gray background (constant context). We manipulated the visibility of the prime stimuli by using two different prime-mask intervals: one that ensures optimal masking (low visibility) and one for non-optimal masking (high visibility).

2.1. Method

2.1.1. Participants

Twenty-two subjects (11 female), between the ages of 18 and 36 ($M = 20.6$ years), were recruited from the undergraduate subject pool of The City College of the City University of New York. All observers had normal or corrected to normal vision and participated after informed consent.

2.1.2. Stimuli and apparatus

Two 16″ CRT monitors (Sony Model G220) with a refresh rate of 100 Hz were used for testing. All stimuli were presented at the center of the monitor and consisted of a fixation cross measuring 0.1° of visual angle, disks with a diameter of 0.53° of visual angle, and annulus masks with an inner diameter of 0.53° and an outer diameter of 1.06°. The masks also served as the targets in this experiment. 20% of the trials were catch trials in which no disk and only the mask was presented. To generate the stimuli, we used three levels of luminance (dark = 4.0 cd/m^2; middle-gray = 11.1 cd/m^2; bright = 18.8 cd/m^2 for one monitor and dark = 5.4 cd/m^2; middle-gray = 13.2 cd/m^2; bright = 21.4 cd/m^2 for a different monitor). For the non-SBC conditions, a bright or dark disk was presented on a middle-gray background. The disk was followed by a dark or bright annulus, also presented on a middle-gray background (Fig. 1, left). The four combinations of disks and annuli formed two categories: congruent (a dark or bright disk followed by a dark or bright annulus, respectively) and incongruent (a dark or bright disk followed by a bright or dark annulus, respectively). Note that for the congruent conditions, the disks and masks were identical in luminance and appearance, and this is what we refer to as the non-SBC conditions. Note, however, that non-SBC does not imply that the perception of disk brightness is independent of the background, but rather that the background luminance was always the same and disk brightness was manipulated by changing the actual luminance of the disks.

For the SBC conditions, middle-gray disks that were intermediate in luminance between the bright and dark masks were presented on a bright or dark background followed by a bright or dark annulus presented on the middle-gray background (Fig. 1, right). Although the luminance of the middle-gray disk was the same on either background, the middle-gray disk on the dark background was perceived as bright, whereas the middle-gray disk on the bright background was perceived as dark. The four disk/annulus combinations formed two categories: congruent (middle-gray disk on a dark/bright background followed by a bright/dark annulus on a middle-gray background) and incongruent (middle-gray disk on a dark/bright background followed by a dark/bright annulus).

2.1.3. Procedures

Subjects were seated in a dimly lit, sound attenuated chamber. Chin rests were used to minimize head movements and to fix the eye-to-monitor viewing distance at 57 cm. Each trial started with the presentation of the fixation cross for 1000 ms (Fig. 1). On 80% of the trials, the disk was then presented for 10 ms and the annulus mask (target) for 20 ms at a stimulus onset asynchrony (SOA) of either 40 or 140 ms. These SOAs were chosen based on previous research and pilot experiments that showed that subjects were unaware of the disks at the short SOA (low visibility) and aware of the disks at the long SOA (high visibility). The order of presentation of the two SOAs was randomized within each block. On the 20% of catch trials, no disk was presented, but the mask was presented at the same intervals within the trials as the disk present trials. The subjects participated in two phases of the experiment, which together lasted approximately 45 min. In the first phase, subjects completed five blocks of 90 trials, each with short rest periods between blocks. On each trial, subjects reported whether the mask was bright or dark by pressing one of two response buttons on the mouse as quickly as possible. In the second phase, which was conducted to objectively determine prime visibility, subjects completed five blocks of 90 trials each in which they were asked to report the brightness of the priming disks (dark/bright) by pressing one of two response buttons on a mouse. They were encouraged to guess if necessary. The presentation order of the different disks and annuli combinations was randomized within each block. The response assignments were counterbalanced between the subjects, with half of the subjects using the left mouse button to indicate a bright stimulus and the right mouse button to indicate a dark stimulus and the other half of the subjects using the left mouse button to indicate a dark stimulus and the right mouse button to indicate a bright stimulus.

2.2. Results and discussion

Whereas prime and mask stimuli were presented on the same background in the non-SBC conditions, this was not the case for the SBC conditions. To induce SBC, a middle-gray disk was presented on either a dark or bright background and was followed by a dark or bright mask on a middle-gray background. Catch trials were identical except that no disk was presented. In the SBC conditions, the background alone, which was different from the background on which the masks were

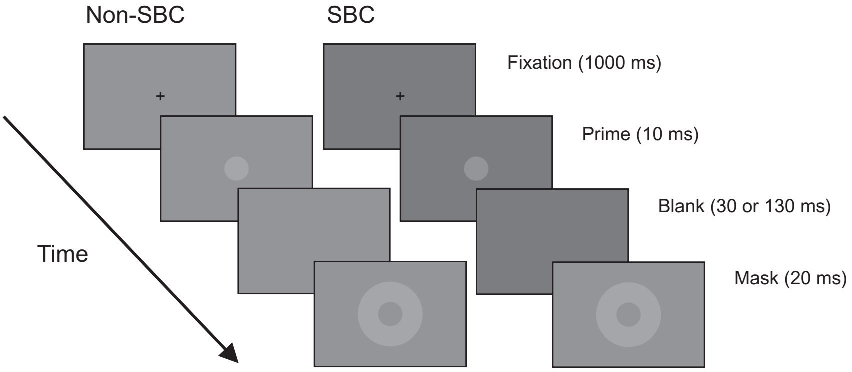

Fig. 1. Schematic showing examples of congruent trials with non-SBC or SBC disks in Experiment 1. Note that the disk in the SBC condition is the same middle-gray used as the background in the non-SBC conditions, but appears brighter because it is presented on a darker background.

presented, could potentially prime responses to the masks. For example, if a middle-gray disk was presented on a bright background, the bright background alone could potentially prime a response to a bright mask. The opposite direction of priming could also be possible; for a middle-gray disk presented on a bright background, the transition to the darker (middle-gray) background of the mask could prime the response to a dark mask. In order to account for any potential effects of the background, we subtracted reaction times (RTs) to the background alone (i.e., catch) trials from RTs to the corresponding disk-present trials using the same backgrounds. Even though the disks in the non-SBC conditions were always presented on the middle-gray background, we nonetheless subtracted RTs on the middle-gray background catch trials from the non-catch trials before all statistical analyses to balance out any biases that this subtraction procedure may have introduced. A complete analysis with uncorrected RTs resulted in the same pattern of results.

Table 1 shows the mean RTs for correct trials and error rates as a function of disk brightness, prime-mask SOA and trial type. Corrected RTs were analyzed in a three-way ANOVA with disk brightness (SBC or non-SBC), SOA (40 or 140 ms) and congruency (congruent or incongruent) as the within-subjects factors. The ANOVA revealed a significant main effect of congruency [$F(1,21) = 192.67$, $MSE = 1353.67$, $p < .001$], with significantly faster RTs for the congruent as compared to the incongruent trials. Although the main effects of disk brightness and SOA and the disk brightness × SOA interaction were not significant, there was a significant SOA × congruency two-way interaction [$F(1,21) = 136.39$, $MSE = 717.28$, $p < .001$]. This interaction is illustrated in Fig. 2, showing that priming was much stronger at the 140 ms SOA for both the SBC and non-SBC disks. This effect of SOA is very likely due to priming effects being larger with longer SOAs, which allow for more extensive prime processing. There was also a significant three-way interaction [$F(1,21) = 6.62$, $MSE = 500.76$, $p = .018$].

Additional two-way ANOVAs (disk brightness × congruency) were conducted for each SOA separately. The main effect of congruency was significant at the 40 ms (i.e., unconscious) SOA [$F(1,21) = 38.39$, $MSE = 510.20$, $p < .001$]. Importantly, significant priming was measured in the SBC conditions (33.4 ms), suggesting that SBC occurs without awareness [$t(21) = 4.19$, $p < .001$]. The main effect of disk brightness and the disk brightness x congruency two-way interaction were not significant at the 40 ms SOA, indicating that both the SBC and non-SBC disks similarly affected RTs to the brightness of the annulus masks. At the 140 ms SOA, however, both the main effect of congruency [$F(1,21) = 217.24$, $MSE = 1560.75$, $p < .001$] and

Table 1
Mean RTs (in milliseconds) and error rates (in percentages) as a function of disk brightness, SOA and trial type in Experiment 1. Standard errors of the mean for RTs are shown in parentheses.

	Disk brightness							
	Non-SBC SOA				SBC SOA			
	40		140		40		140	
	RT	Errors	RT	Errors	RT	Errors	RT	Errors
Disk trial type								
Congruent	453 (11)	4.7	397 (11)	3.6	466 (14)	4.5	417 (14)	4.0
Incongruent	479 (11)	8.3	535 (15)	27.2	507 (11)	9.4	543 (13)	24.5
Catch trial type								
Middle-gray	473 (13)	5.1	464 (13)	5.8	n/a	n/a	n/a	n/a
Congruent	n/a	n/a	n/a	n/a	486 (14)	3.8	476 (11)	4.5
Incongruent	n/a	n/a	n/a	n/a	494 (14)	5.6	491 (14)	6.8

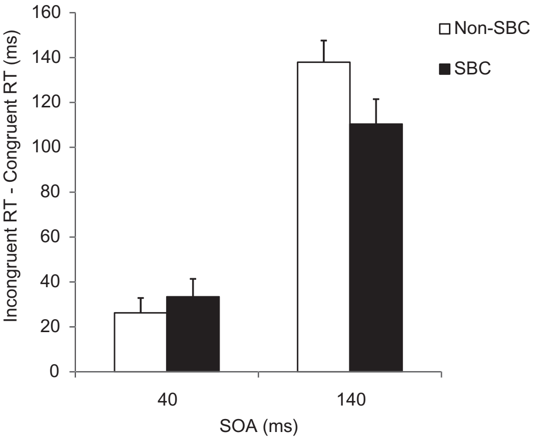

Fig. 2. The priming effects (incongruent minus congruent RTs) measured for non-SBC and SBC disks as a function of SOA in Experiment 1. Bars indicate 1 standard error of mean.

the disk brightness × congruency two-way interaction were significant [$F(1,21) = 5.08$, $MSE = 821.74$, $p = .035$]. This interaction was a result of stronger congruency effects for the non-SBC disks as compared to the SBC disks. Thus, when visibility of the primes was high, the non-SBC disks showed stronger priming effects than the SBC disks; however, when prime visibility was low, the priming effects for SBC disks and non-SBC disks were comparable.

The overall error rates were low, except for the incongruent conditions with high prime visibility, which is likely due to the long SOA (140 ms) allowing for more extensive prime processing and incorrect response activation. Because error rates were lower for congruent as compared to incongruent conditions, our main RT data were not influenced by speed accuracy tradeoffs.

In the objective awareness task, accuracy of prime discrimination at the long, 140 ms SOA was high for both non-SBC (76.87%) and SBC disks (77.92%). At the 40 ms SOA, accuracy was low for both non-SBC (59.16%) and SBC disks (64.37%), but above chance levels [non-SBC disks: $t(21) = 4.24$, $p < .001$; SBC disks: $t(21) = 6.23$, $p < .001$]. Although participants in a pilot experiment reported not being aware of the brightness of the disks at the short SOAs, the subjects in the current experiment were able to guess the brightness of the disks at above chance levels, perhaps unconsciously.

To further explore whether the magnitude of the priming effects was dependent on visual awareness, we performed a correlation analysis between priming and visibility at the 40 ms SOA. For each subject we calculated the magnitude of priming for both non-SBC and SBC disks and the corresponding prime discrimination accuracy. A significant positive correlation would demonstrate that priming increases with prime visibility and would suggest that the priming effects at the 40 ms SOA were a result of conscious prime processing. However, we found that priming was unrelated to the magnitude of visibility for both non-SBC [$r = .2$, $p = .38$] and SBC disks [$r = .29$, $p = .19$]. Our analyses thus show a dissociation between priming effects and awareness.

The results from this first experiment suggest that SBC can occur without awareness. Furthermore, the equivalent magnitudes of priming for the non-SBC and SBC disks at the short SOA but larger priming effects for the non-SBC disks as compared to the SBC disks at the long SOA suggest a potential dissociation between unconscious and conscious representations of brightness. However, there were several complicating factors in this experiment that make these conclusions tentative. First, some subjects may have been aware of some of the disks at the short SOA, as indicated by the slightly, yet still significant above chance performance levels in the prime discrimination task. Although the correlation analysis that we performed addresses this complication, it might still be the case that even for subjects with overall chance levels of discrimination, there may have still been a few trials on which the subjects were aware of the brightness of the disk. These few aware trials alone could have contributed to the "unconscious" priming effects at the short SOA. Second, awareness was confounded with SOA, which may have allowed for more extensive disk processing at the longer SOA, regardless of visual awareness. This longer processing time likely contributed to the larger priming effects at the longer as compared to the shorter SOA, especially for the non-SBC disks. Because our results in Experiment 1 were based on objective awareness measures, with subjects performing above chance, albeit most likely without awareness in the prime discrimination task, we tested whether SBC can occur without awareness using subjective awareness reports in the second experiment.

3. Experiment 2

In Experiment 2, we used only one intermediate level SOA so that approximately half of the disks were perceived. Subjects reported on every trial after the speeded response to the mask whether they perceived the brightness of the disk. This procedure allowed us to examine brightness priming from non-SBC and SBC disks under both aware and unaware states that are based on differential subjective reports but under identical stimulus presentation conditions.

3.1. Method

3.1.1. Participants

Twenty-two subjects (12 female), between the ages of 18 and 33 ($M = 20.1$ years), were recruited from the undergraduate subject pool of The City College of the City University of New York. All observers had normal or corrected to normal vision and participated after informed consent.

3.1.2. Stimuli and apparatus

The stimuli were identical to those used in Experiment 1, but the timing parameters were modified. On the non-catch trials, the disks, presented for 10 ms as in the first experiment, were followed by the annulus masks at a constant 60 ms SOA. The mask was then presented for 20 ms. This SOA setting was determined based on a pilot experiment that resulted in subjects being unaware of the disks on approximately 50% of the trials.

3.1.3. Procedures

Subjects participated in one 45 min session in which they were seated in a dimly lit, sound attenuated chamber. Chin rests were used to minimize head movements and to fix the eye-to-monitor viewing distance at 57 cm. On each trial, the subjects first reported the brightness (dark/bright) of the mask by pressing one of two mouse buttons as quickly as possible and then reported (yes/no) whether they were able to perceive the brightness (dark/bright) of the disks (i.e., a trial-by-trial subjective report procedure was used in this experiment). This procedure allowed us to separate aware from unaware trials under identical stimulus conditions. At the beginning of the experimental session, subjects received a block of 30 practice trials. Each subject then completed nine experimental blocks of 60 trials, for a total of 540 trials, with short rest periods between each block. The presentation order of the different disks and mask annuli combinations was randomized within each block. The button response assignments for both the brightness and the subjective reports were completely counterbalanced between the subjects.

3.2. Results and discussion

Subjects were aware of the brightness of the disk on 57% of the trials (SD = 16%). The mean RTs for correct trials and error rates as a function of disk brightness, awareness and trial type are shown in Table 2. We first corrected for any effects of the background by using the same background subtraction procedure for the RTs described for Experiment 1. The data were then analyzed in a three-way ANOVA with disk brightness (non-SBC or SBC), awareness (aware or unaware) and congruency (congruent or incongruent) as the three within-subject factors. The priming effects were consistent with the data from the first experiment (Fig. 3). There was a significant main effect of congruency [$F(1,21) = 15.11$, $MSE = 3973.16$, $p = .001$], as well as a marginally significant awareness × congruency two-way interaction [$F(1,21) = 3.45$, $MSE = 441.74$, $p = .078$], with slightly stronger priming in the aware condition. There was also a marginally significant disk brightness × awareness × congruency three-way interaction [$F(1,21) = 3.81$, $MSE = 712.71$, $p = .064$]. None of the other main effects or interactions approached significance.

The disk brightness × awareness × congruency three-way interaction was primarily driven by differences in the magnitude of priming as a function of awareness for the non-SBC and SBC disks. Follow-up two-way ANOVAs were conducted separately for the non-SBC and SBC disk trials, with awareness and congruency as the two within subject factors. The awareness × congruency two-way interaction for non-SBC disks was significant [$F(1,21) = 6.80$, $MSE = 610.73$, $p = .016$], with larger congruency effects for the aware as compared to the unaware conditions. In contrast, however, this was not the case for the SBC disks, in which the priming effects were identical regardless of whether subjects were aware or not of the disks [$F(1,21) = 0.16$, $MSE = 543.71$, $p = .695$].

Table 2
Mean RTs (in milliseconds) and error rates (in percentages) as a function of disk brightness, awareness and trial type in Experiment 2. Standard errors of the mean for RTs are shown in parentheses.

	Disk brightness							
	Non-SBC				SBC			
	Unaware		Aware		Unaware		Aware	
	RT	Errors	RT	Errors	RT	Errors	RT	Errors
Disk trial type								
Congruent	579 (34)	4.1	567 (37)	2.2	590 (34)	4.4	594 (34)	3.0
Incongruent	600 (27)	11.2	616 (31)	5.6	645 (29)	10.9	645 (30)	8.9
Catch trial type								
Middle-gray	583 (34)	2.9	n/a	n/a	n/a	n/a	n/a	n/a
Congruent	n/a	n/a	n/a	n/a	597 (31)	2.8	n/a	n/a
Incongruent	n/a	n/a	n/a	n/a	611 (34)	4.3	n/a	n/a

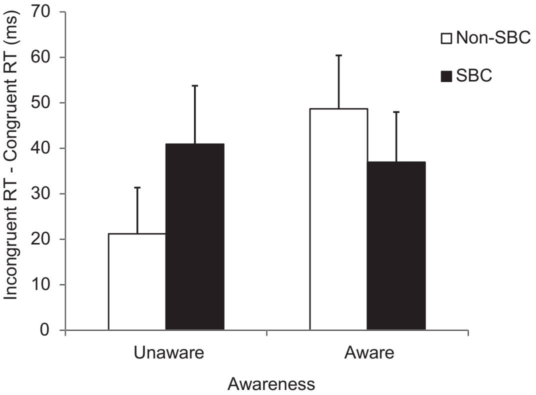

Fig. 3. The priming effects (incongruent minus congruent RTs) measured for non-SBC and SBC disks as a function of disk awareness in Experiment 2. Bars indicate 1 standard error of mean.

To assess whether the magnitude of the priming effects differed depending on the disk brightness condition (non-SBC vs. SBC), two additional two-way ANOVAs were conducted separately for the aware and unaware trials. For the aware conditions, although the non-SBC disks produced numerically larger priming effects than the SBC disks, as in Experiment 1, the congruency × brightness type two-way interaction was not significant [$F(1,21) = 1.04$, $MSE = 728.74$, $p = .32$]. In the unaware trial conditions, however, the congruency × disk brightness two-way interaction approached significance [$F(1,21) = 3.22$, $MSE = 664.41$, $p = .087$], with stronger priming effects for the SBC disks as compared to the non-SBC disks.

These results, in conjunction with those from Experiment 1, demonstrate that priming occurs for SBC disks under conditions of unawareness. They further show that SBC is processed to the same extent regardless of whether subjects are aware of the stimuli but that awareness increases the magnitude of priming for brightness differences that do not depend on SBC. Thus, unconscious priming from SBC disks is at least comparable to, if not stronger, than priming for non-SBC disks.

4. General discussion

In two experiments, we tested whether simultaneous brightness contrast occurs without awareness. The results from the first experiment, in which visibility of the primes was manipulated by using different prime-mask SOAs, showed that under conditions of low visibility, brightness priming effects were comparable for both non-SBC and SBC disks. We also demonstrated that priming effects do not correlate with discrimination accuracy. To circumvent the various problems associated with objective measures of awareness, including the possibility that awareness on some trials was driving the priming effects in Experiment 1, we used a subjective measure of awareness in the second experiment. Participants reported whether they were aware of the brightness of the disk on each trial. Similar to the first experiment, the same magnitude of brightness priming from SBC disks occurred regardless of whether subjects were aware or not of the disks, and was at least comparable, if not stronger, to those for non-SBC disks under the unaware conditions. The second experiment also controlled for confounding effects of different prime processing times by having one fixed SOA. The results from these two experiments together show that SBC occurs without awareness, that unconscious SBC priming is as strong as conscious SBC priming, and suggest that priming from invisible primes may be stronger for SBC disks than for non-SBC disks.

In addition to shedding some light on the differences between conscious and unconscious visual representations, our results may also be informative regarding the mechanisms underlying SBC, for which there are several competing hypotheses. Some hypotheses attempt to explain SBC in terms of lower level processing, whereas others posit higher level, complex computations. One still predominant hypothesis, offering a low level account, is championed by Mach (1886) and Hering (1874) and is based on lateral interactions early in the retina. This hypothesis suggests that a target embedded in a region of higher luminance will be perceived as darker than the same target embedded in a region of a lower luminance because the surround of the on-ganglion cells located at the edge of the target will be inhibited more in a region with higher luminance compared to the same target in a region with lower luminance. However several illusions have been constructed that challenge this account. For example, in White's illusion (Fig. 4, (White, 1979), a target surrounded by a region of predominantly higher luminance looks brighter than an identical target embedded in a region of lower luminance. (Note that this is the opposite of SBC, in which targets appear brighter when presented on a dark as opposed to a bright background.) The multi-scale spatial filtering theory (Blakeslee & McCourt, 2004), which is another low-level account, offers an explanation for these phenomena based on responses in V1, using a set of filters, which resemble receptive fields in early visual cortex. In contrast to these low-level accounts of SBC, a different perspective is embodied by a set of hypotheses that suggest the involvement of higher level processes, such as inferred illumination (von Helmholtz, 1867) or local and global anchoring of lightness values (Gilchrist et al., 1999).

Our results are consistent with accounts that are based on fast lateral processes occurring in V1 or as early as in the retina in that they demonstrate that SBC occurs without awareness and very rapidly (i.e., at the short SOAs and with the very brief presentation durations used in these experiments). Given these fast processing times, extensive computations, inferences, and anchoring (i.e., extraction of higher-order scene information) seem unlikely to play a role in the unconscious SBC effects measured in these experiments. However, our results do not allow us to exclude the possibility that more subtle aspects of brightness perception do require some higher level processes.

On a related note, it is possible that only simple brightness illusions such as SBC are coded unconsciously and early during visual processing. Fast, more local, intra-areal computations performed during the initial feedforward stages of processing (Lamme & Roelfsema, 2000; Ro, Breitmeyer, Burton, Singhal, & Lane, 2003) might be sufficient for unconscious representations of simple brightness illusions. However, more complex brightness illusions that combine objects from more extended

Fig. 4. White's illusion. Even though the gray segments falling on the black bars (left half) are identical to those falling in between the black bars (right half), the gray segments on the left appear brighter than those on the right.

regions of visual space may require inter-areal computations, which likely require lateral and feedback connections and multiple iterative loops between different visual areas. Future research using different and more complicated brightness illusions will be necessary to more precisely assess which aspects of brightness perception rely upon higher-level processing mechanisms and whether longer processing times and conscious vision is necessary to process them.

In the current study, we sought to show unconscious SBC using both an objective (Experiment 1) and a subjective (Experiment 2) measure. Although some argue that assessing awareness with objective criteria is a more optimal, conservative approach, it requires that exclusivity (it should be sensitive to conscious information only) and exhaustiveness (a measure should be exhaustive for all conscious information) assumptions are met (Reingold & Merikle, 1988). These assumptions are highly problematic because it is not possible to demonstrate conclusively that any measure will meet them. As a consequence, objective criteria have a tendency to overestimate conscious perception. Another drawback is that it requires researchers to prove a true null sensitivity, which is an impossible feat. On the other hand, subjective measures of awareness tap directly into phenomenal experience. Importantly, in some paradigms and experimental designs, as in the one used in the second experiment, subjects report on stimulus visibility on every trial, allowing for separation of trials with identical stimuli parameters but with different conscious experiences. The downside of subjective reports is that they can be contaminated with response biases. It is important to note however, that objective and subjective measures are generally in strong agreement (Del Cul, Dehaene, & Leboyer, 2006; Del Cul, Dehaene, Reyes, Bravo, & Slachevsky, 2009), as in our two experiments, and although objective measures are more conservative, when all factors are taken into account, subjective reports provide a better measure of awareness (Dehaene & Changeux, 2011; Merikle et al., 2001).

If unconscious information is represented at more basic, lower levels and conscious information is percept-dependent, as our previous results suggest (Breitmeyer et al., 2004), one would expect little to no unconscious priming for SBC compared to non-SBC disks when prime visibility was low. However, the current results showed priming effects for the SBC disks that were the same regardless of whether subjects were aware or not of the disks and priming effects at least as large as those for the non-SBC disks in the unaware conditions. On the other hand, in the aware conditions we measured larger priming effects for the non-SBC (significantly in Experiment 1, but only numerically in Experiment 2) as compared to the SBC conditions. Because the SBC disks did not appear as dark or bright as the dark and bright disks on middle-gray backgrounds, these results further suggest that priming in the aware conditions may have been percept-dependent and that some visual information may be represented differently when we are conscious of them.

In summary, we demonstrate in two experiments that used different parameters and measures of awareness that SBC occurs without awareness. Our results further suggest that unconscious visual representations differ from conscious ones and that SBC occurs early during visual processing, most likely within the initial feedforward sweep of visual information processing.

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