

RESEARCH ARTICLES

Knowledge alters visual contrast sensitivity

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Research has shown that the visual system's sensitivity to variations in luminance (*visual contrast*) within a particular area of the retina is affected in a bottom-up fashion by the ambient contrast levels in nearby regions. Specifically, changes in the ambient contrast in areas surrounding the target area alter the sensitivity to visual contrast within the target area. More recent research has shown that paying attention to the target or target area modulates contrast sensitivity, suggesting a top-down influence over contrast sensitivity that is mediated by attention. Here we report another form of top-down influence over contrast sensitivity that is unlikely to be mediated by attention. In particular, we show that knowledge and/or expectations about the levels of visual contrast that may appear in upcoming targets also affect how sensitive the observer is to the contrast in the target. This sort of knowledge-driven, top-down contrast sensitivity control could be used to preset the visual system's contrast sensitivity to maximize discriminability and to protect contrast-sensitive processes from a contrast overload. Overall, our results suggest that existing models of contrast sensitivity might benefit from the inclusion of top-down control mechanisms.

Abrupt changes of luminance within a static visual display almost always occur at borders between an object and its background, and the change of pattern of luminance across the surface of an object is often a cue as to the texture of the surface and to the object's identity. Hence, the ability of the visual system to detect local changes in luminance (*visual contrast*) is important for object perception. The visual system, however, faces a particular challenge in the processing of luminance contrasts: The range of ambient contrast levels is larger than the range of contrasts that a cortical contrast-sensitive neuron is able to represent at one time. A contrast-sensitive unit responds to changes in luminance across its receptive field (the area of the retina that provides input to these units). Low levels of contrast do not activate the unit until its threshold value is reached. As contrast is raised above the threshold value, the unit's rate of firing increases until it saturates, with the range between threshold and saturation (the unit's dynamic range) typically being 1/10 to 1/5 as large as the range of contrasts typically found in visual scenes (Albrecht & Hamilton, 1982; Frazor & Geisler, 2006). Therefore, if the dynamic range of a contrast-sensitive neuron were to be fixed, it would be unable to process most of the contrasts that would fall into its receptive field when the observer was scanning the visual scene.

How then does the visual system operate over the entire range of contrasts present in the environment when it is composed of neurons whose dynamic range is much smaller? At least part of the answer can be found in the remarkable ability of the visual system to adjust the sensitivity of contrast-sensitive neurons to the local ambi-

ent contrast level close to the unit's receptive field. For example, if the local ambient contrast level changes from high to low, the visual system increases the sensitivity of the contrast-sensitive neurons. In other words, the unit's contrast sensitivity is adjusted to permit it to function effectively over a large range of ambient contrasts. A number of studies, both behavioral (e.g., Boynton & Foley, 1999; Foley, 1994; Ross & Speed, 1991; Wilson & Humanski, 1993) and neural (e.g., Albrecht & Geisler, 1991; Albrecht & Hamilton, 1982; Gardner et al., 2005; Ohzawa, Sclar, & Freeman, 1982), have found evidence for the existence of a contrast sensitivity control mechanism. They have demonstrated that contrast sensitivity in a confined region of the visual field is modulated by the spatial and temporal frequency composition of nearby stimuli (see, e.g., Foley, 1994, for details on the mechanism). Hence, local stimulus features are assumed to induce changes in contrast sensitivity in a bottom-up fashion.

Another bottom-up process that has been shown to affect contrast sensitivity is contrast adaptation. Prior presentation of a grating in the receptive field of a simple cell in the visual cortex elevates that unit's contrast threshold and shifts its contrast sensitivity function toward higher contrasts (e.g., Carandini & Ferster, 1997). Similar effects have also been found for behavioral measures of contrast sensitivity (e.g., Gardner et al., 2005; Pestilli, Viera, & Carrasco, 2007). Hence, the visual system's response to a grating is affected by its recent history of exposure to different levels of contrast.

More recently, several studies have shown that focusing attention on a target affects contrast sensitivity. When par-

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ticipants are asked to detect an increment in the contrast of a Gabor pattern superimposed on a pedestal, the psychometric function relating detectability to the increment in contrast shifts toward lower contrasts when exogenous attention is directed to the target rather than away from the target (Carrasco, Ling, & Read 2004). Huang and Dobkins (2005) found contrast discrimination to be reduced in a dual-task situation. They attributed the difference in discrimination performance between these two conditions to “poor” attention in the dual-task condition. Similar effects of attention on contrast perception have been shown on a neuronal level in physiological studies with monkeys (Martinez-Trujillo & Treue, 2002; Reynolds, Pasternak, & Desimone, 2000). These results suggest that contrast sensitivity is under attentional influence. Presumably, such attentional influence facilitates the processing of the portion of the visual field that is of the highest interest to the observer.

It is interesting to note that contrast sensitivity is improved not only when attention is directed to the target by a sudden external transient cue (exogenous attention), but also when there is a conscious shift of attention (endogenous attention) (Ling & Carrasco, 2006). The enhanced contrast sensitivity that was found with endogenous attention indicates that contrast sensitivity, in addition to being driven by local stimulus features (ambient contrast or the provision of a visual cue), is under the influence of higher order, more central cognitive processes, such as those responsible for a shift in endogenous attention. Contrast sensitivity seems to be, therefore, under a top-down influence when it is mediated by attention.

Testing for a Top-Down Influence Over Contrast Sensitivity

Top-down influence implies that not only attention, but also a priori knowledge and/or expectations concerning what may appear in the visual field, should be capable of modulating contrast sensitivity. Consequently, a top-down influence over contrast sensitivity should be able to alter contrast sensitivity without attentional mediation. Such top-down influence could be of substantial benefit to observers scanning a familiar (known) visual scene because it allows for the rapid adjustment of the contrast sensitivity in foveal spatial-frequency channels to reflect the level of luminance contrast that is likely to be encountered after a saccade. In other words, knowledge of the contrasts that the visual system is likely to encounter could alter the contrast sensitivity before these contrasts are experienced. For example, an observer could take advantage of the fact that different regions of a scene (e.g., ground, sky) differ in terms of their average contrast level (e.g., the average contrast is lower for the sky than for the ground; see Frazor & Geisler, 2006). When moving their eyes from one of these regions to another, observers should be able to anticipate the direction of the average contrast change and, therefore, be able to adjust their contrast sensitivity accordingly. That is, the visual system could use the knowledge about a familiar environment to enhance contrast sensitivity.

What other advantages might accrue from top-down influence over contrast sensitivity? One might be protec-

tion against saturating or overloading contrast-sensitive mechanisms. Figure 1 plots the response of a hypothetical contrast-sensitive unit to stimulus contrast. At very low levels of stimulus contrast (below the unit’s threshold), the unit responds at its baseline rate. However, at medium levels, the unit’s response increases with stimulus contrast until it reaches a saturation point, at which further increments in stimulus contrast are ineffective at increasing the response of the unit. Consequently, a unit such as this could not discriminate effectively among targets whose contrasts were above the saturation point or below threshold. Note that we assume that when the range of contrasts the unit is likely to encounter is small, the visual system adjusts its sensitivity (shifts the position of the response-intensity function shown in Figure 1), so that the stimulus contrasts fall in the region between threshold and saturation. The question then arises as to how the unit responds when targets can be either very low or very high in contrast. We suggest that the system adjusts its contrast so that the highest contrast that it is likely to encounter remains below the saturation point. Otherwise, if the highest contrast exceeds the saturation point, a contrast overload occurs that possibly leads to a malfunction of higher order processes. Hence, we assume that the visual system prevents a contrast overload by reducing the unit’s contrast sensitivity (shifting the response-intensity function to the right), thereby ensuring good discriminability among high-contrast stimuli. More detailed reasons as to why the visual system should prevent a contrast overload are provided below.

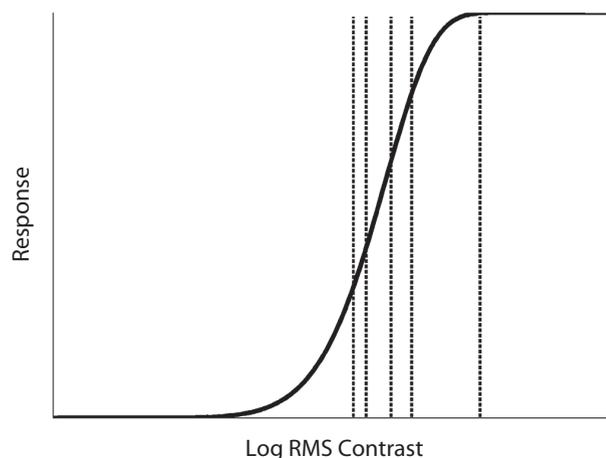


Figure 1. Schematic outline of a hypothetical contrast response function (solid line) along with the contrast values used in Experiment 1 (dashed lines). The function relates stimulus contrast to the response of a contrast-sensitive unit. Low contrasts do not elicit a response change (left tail), whereas high contrast causes a response saturation (right tail). The response that a given contrast triggers within this unit is the y-value of the intersection of the contrast’s corresponding dashed line with the contrast response function. The optimal strategy in absence of a contrast overload would be to shift the contrast response function along the x-axis so that the four contrasts fall into the linear portion. Then the difference between the responses that the four contrasts trigger within this unit would be maximal. The fifth high contrast would also be clearly distinguishable from the other ones since it is the only contrast that causes a saturated response.

A similar mechanism that parallels the adjustment of contrast sensitivity to the highest contrast value has been suggested for lightness perception. Gilchrist et al. (1999) argued that, for simple stationary images, the visual system “anchors” the perceptual scene by always perceiving the area of the image with the highest luminance as white, with the perceived reflectance (PR) of other areas being given by the following formula

$$PR = L_t/L_h \times 90\%, \quad (1)$$

where L_t is the luminance of the target area, and L_h is the highest luminance in the region. Hence, independent of the actual luminance of the brightest part of the field, the range of perceived lightness, according to this theory, always has a fixed upper limit ($PR = 90\% = \text{white}$). If the visual system operates in this mode, it protects against saturated responses of lightness-sensitive mechanisms (lightness overload) by setting PR at 90% of its saturation value. If we apply this principle to the contrast of simple gratings, the area of the visual field with the highest contrast should be perceived as white ($PR = 90\%$), whereas areas of lesser contrast should appear darker. We show that, if this principle applies to stimuli that might be encountered over time (rather than being distributed over space), it effectively ensures good discriminability among high-contrast stimuli, which is one of the functions of an overload protection mechanism.

Why should the visual system adjust its contrast sensitivity to protect against overload (or, alternatively, to anchor perception to the brightest part of the visual field) rather than adjust its sensitivity to maximize discriminability among low-contrast stimuli (i.e., anchoring perception to the darkest part of the visual field)? Although this issue has not been thoroughly explored, several suggestions have been advanced. Graham and Sutter (2000) proposed that a visual contrast sensitivity control mechanism may prevent higher order mechanisms from overload to avoid processing malfunctions. Porciatti, Bonanni, Fiorentini, and Guerrini (2000) suggested that a lack of contrast sensitivity control is correlated with photosensitive epilepsy. The notion here is that the inability to regulate contrast gain could disrupt the efficient functioning of more central visual processing, leading to a seizure. Hence, regulating the responsiveness of contrast-sensitive mechanisms to prevent an overload may help prevent the malfunctioning of these and/or higher order processes.

Generally, the notion of an overload protection is not new in psychological research. A similar mechanism is assumed to exist in the auditory domain. Here it has been suggested that the function of a nonlinear intensity control mechanism is to maximize discriminability and protect the auditory system from an overload. Specifically, Parker, Murphy, and Schneider (2002) showed that one function of auditory gain control, the auditory analogue of visual contrast sensitivity control, is to protect the auditory system from an intensity overload.

The intention of the present study was twofold: to demonstrate that visual contrast sensitivity control is under knowledge-driven top-down influence and to provide evidence that this contrast gain control mechanism effec-

tively increases discriminability for high-contrast stimuli by protecting the visual system from the effects of contrast overload. For reasons clarified below, instead of the standard detection threshold paradigm, we used a new paradigm that was employed by Parker et al. (2002) to show that auditory-intensity control, the auditory analogue to visual contrast sensitivity control, is under top-down influence. In particular, we combined an absolute identification task with a cuing paradigm.

In Experiment 1, participants had to identify the stimuli of a fixed stimulus set by means of their contrast (for details, see the Method section). In the baseline condition of this experiment, participants were requested to identify which of four possible low-contrast stimuli were presented on a trial. This condition provided a baseline for establishing discriminability among these four low-contrast stimuli in the absence of other stimuli. In two other conditions, the stimulus set consisted of the same four low-contrast stimuli of the baseline condition and an additional high-contrast stimulus. In all three conditions, a trial began with the presentation of a fixation stimulus (“+” or “H”). The association between the fixation stimulus and the contrast level present on each trial was random for the baseline condition. Hence, the kind of fixation stimulus presented could not be used to identify the contrast level of the low-contrast grating that followed it, and consequently participants could not use the fixation stimulus as a cue for the upcoming contrast level. In one of the two conditions with the added high-contrast grating, there was also no association between the type of fixation stimulus (“+” or “H”) and the contrast level that followed it. This is referred to as the *invalid-cue condition*, because the type of fixation stimulus did not inform participants about the occurrence of a high-contrast grating. Participants, therefore, could not use the fixation stimulus as a cue for the upcoming contrast level. In the second of the two conditions with the high-contrast grating, the “H” fixation stimulus always preceded the high-contrast grating, whereas the “+” stimulus always preceded a low-contrast grating. This is referred to as the *valid-cue condition*, because the type of fixation stimulus reliably informed participants about the occurrence of a high- or low-contrast grating. Hence, participants could use the fixation stimulus as a cue for the upcoming contrast level. Note that the invalid-cue condition differed from the baseline cue condition only in that its stimulus set included a high-contrast stimulus. The only difference between the valid- and invalid-cue conditions was that the fixation stimulus predicted the occurrences of high- and low-contrast stimuli in the valid-cue condition, but not in the invalid-cue condition.

We assume that contrast sensitivity is adjusted to protect against sensory overload. Hence, if participants knew that only low-contrast stimuli would occur, as in the baseline condition, the contrast sensitivity of the visual mechanisms could be set to high to optimize discriminability among the set of low-contrast stimuli (see Figure 1). However, in the invalid-cue condition, which included a high-contrast grating in addition to the four low-contrast gratings found in the baseline condition, the sensitivity of the visual mecha-

nism might be lowered to protect against the unpredictable occurrence of the high-contrast stimulus on 20% of the trials. Consequently, in the invalid-cue condition, the ability to identify the four low-contrast stimuli would be adversely affected by this decrease in contrast sensitivity. We therefore expected reduced identification performance and discriminability of the four low-contrast stimuli in the invalid-cue condition. (Note that, in both the baseline and invalid-cue conditions, the fixation point was not predictive of contrast of the grating that followed it.) Finally, if top-down influence over contrast sensitivity control is fast acting (i.e., changes in contrast sensitivity would occur within a fraction of a second), we would expect little or no decrement in either identification performance or in the discriminability of the four low-contrast stimuli when the occurrence of the high-contrast stimulus was predictable. The visual system should use the visual cue to prepare for the high contrast by decreasing contrast sensitivity on that trial. Moreover, when the cue indicated that a low contrast would be presented, the visual system should increase contrast sensitivity to enhance discriminability and identification performance. Hence, better identification of the low-contrast stimuli in the valid- as opposed to the invalid-cue condition would suggest top-down control over contrast sensitivity. Finally, a comparison of identification performance on the low-contrast stimuli between the valid and the baseline condition should provide a measure of the effectiveness of the top-down control. That is, this comparison assessed the degree to which top-down adjustment over contrast sensitivity could compensate for the occurrence of a high-contrast stimulus.

EXPERIMENT 1

Method

Participants. Nine University of Toronto undergraduate students and one of the authors (S.d.l.R.) participated in the experiment (age range, 17–34). All participants had normal or corrected-to-normal vision and enjoyed good ocular health as per self-report. Participants had normal Snellen acuity and contrast sensitivity as measured with either the Pelli–Robson charts or the Optec 6500P. All participants gave consent to participate in the experiments. All participants except for the author received credits toward their course grade for compensation. The experiment was conducted in line with the ethical guidelines of the University of Toronto.

Apparatus and Stimuli. The stimuli were generated with a VSG graphics card from Cambridge Research and were presented on a Sony GDM-F520 color monitor with a refresh rate of 120 Hz and a spatial resolution of $1,024 \times 800$ pixels. The monitor was gamma corrected before each session. A chinrest was used to minimize head movements and to help maintain fixation at a viewing distance of 52 cm. Participants' responses were collected with a PC keyboard using keys 1–5.

The gratings spanned $5^\circ \times 5^\circ$ of visual angle (VA) and had a spatial frequency of 4 cpd. All gratings had a phase of 0° , were vertically oriented, and were presented on a gray background (luminance, 55.16 cd/m²) in the center of the monitor.

The gratings in the baseline condition were four low-contrast gratings with 5%, 12%, 19%, and 26% contrast (Contrasts 1, 2, 3, and 4, respectively). These contrast values provided an approximately 75% identification performance in pilot experiments. In the invalid- and valid-cue conditions, this set was extended by including a grating with 100% contrast (Contrast 5). Each grating was shown 25 times in every

Table 1
The Frequency of Assignment of the Two Fixation Stimuli (H and +) to Each Stimulus in the Three Experimental Conditions

Stimulus	Condition					
	Baseline		Valid Cue		Invalid Cue	
	H	+	H	+	H	+
1	7	18	0	25	5	20
2	6	19	0	25	5	20
3	6	19	0	25	5	20
4	6	19	0	25	5	20
5	–	–	25	0	5	20

condition. Thus, there were 100 trials in the baseline condition and 125 trials apiece in the valid- and invalid-cue conditions. Participants were instructed to always assign lower numbers to lower contrasts.

The association between the type of fixation stimulus and the stimulus contrast that followed it was random in both the baseline and invalid-cue conditions, but 100% predictive of the occurrence of a high-contrast grating in the valid-cue condition. The specific assignment of “H” to each contrast stimulus in each of the three conditions is shown in Table 1. In summary, the “H” was not predictive of the occurrence of the high-contrast grating in the invalid-cue condition (cue validity was at chance level), whereas it was 100% predictive of the occurrence of a high-contrast grating in the valid-cue condition. Finally, the “H” was not predictive of the contrast level in the baseline condition.

Procedure. We used an absolute identification task. In an absolute identification task, there is a fixed set of n stimuli. These stimuli differ in magnitude along only one stimulus dimension—for example, luminance contrast. On a given trial, one of the stimuli is randomly selected from the set and presented to the observer. The observer then identifies the stimulus with a number (1– n), where 1 = lowest magnitude in the set and n = highest.

The participant was admitted to the darkened testing chamber and adjusted to the dark surroundings for about 5 min before being seated in front of the apparatus. The participant was shown a paper that had each grating printed on it along with its corresponding number (which gratings were shown depended on the condition tested). The participant received the following instructions: “The computer randomly picks one of these gratings and will present it on the monitor screen. The task is to identify the grating by typing in the corresponding number of the grating and to assign lower numbers to gratings with lower contrast.” The participant was informed that, after a response had been given, the correct answer would be displayed. Participants were informed that, in the baseline condition, a block comprised 100 stimulus identifications and that, in the valid- and invalid-cue conditions, a block comprised 125 stimulus identifications. Furthermore, participants were told that they had to complete four of these blocks for each condition (baseline, valid cue, and invalid cue). It was pointed out to the participant that each trial could start with a fixation cross or with an “H.” Participants were informed about the validity of the “H” cue at the beginning of each block. All participants began with four blocks of the baseline condition. The testing order of the valid- and invalid-cue conditions was counterbalanced across participants. For half of the participants, the baseline condition was followed first by four blocks of the valid-cue condition and then by four blocks of the invalid-cue condition. For the other half of the participants, the baseline condition was followed first by four blocks of the invalid-cue condition and then by four blocks of the valid-cue condition.

Except for presentations of the fixation point, the stimulus grating, and the response feedback, the screen was kept at a uniform gray level. At the beginning of the session, the fixation sign (“+” or “H”) appeared in the middle of this gray screen (see Figure 2). The fixation sign remained on until the participant pressed the space bar.

In signal detection theory, repeated presentations of a stimulus are assumed to give rise to a normal distribution of sensory events along a sensory continuum (such as perceived contrast). For any pair of stimuli, the difference between their mean responses along this sensory continuum ($\mu_2 - \mu_1$), divided by their standard deviation, is referred to as d' and is a bias-free measure of how discriminable these gratings are. Specifically,

$$d' = \frac{\mu_2 - \mu_1}{\sigma}$$

where μ_2 and μ_1 are the mean responses along the sensory axis corresponding to Stimuli 2 and 1, and σ is the distributions' standard deviation (here we assume equal standard deviations for all distributions). Likewise, d' can be calculated for (μ_3, μ_2) and (μ_4, μ_3) .

Consider the case in which an unpredictable high-contrast grating is added to the previous set of four low-contrast gratings, as in the invalid-cue condition. Because the occurrence of the high-contrast stimulus is unpredictable, we would expect the visual system to reduce its overall contrast sensitivity to protect against the unpredictable occurrence of a high-contrast grating. This reduction in contrast sensitivity should reduce the difference in response rates to pairs of stimuli and, therefore, their discriminability (assuming that d' is proportional to differences in response rates to the two stimuli). Hence, we would expect d' values

for adjacent pairs of contrasts to be lower in the invalid-cue condition than in the baseline or valid-cue condition. Moreover, if contrast sensitivity control was fast acting in the valid-cue condition, the contrast sensitivity could be adjusted to accommodate the contrast to be presented. Hence, there should be no change in discriminability between the baseline and valid-cue conditions.

To compare average stimulus discriminability across conditions, we calculated d'_{12} , d'_{23} , and d'_{34} separately for each condition and participant. For each d' calculation, we used a reduced confusion table that contained only responses to the two stimuli in question. For example, for d'_{23} , we treated Answers 1 and 2 as hits when Grating 2 was presented. A *false alarm* occurred when the participant saw Grating 3 but answered 1 or 2 (Macmillan & Creelman, 2005). The difference between the z -transformed hit rate and the z -transformed false alarm rate yielded the d' value. In the instances in which the hit rate was 100%, the hit rate was set to $1 - 1/(2n)$, where n is the number of trials (as Macmillan & Creelman recommended). When the false alarm rate was 0%, the false alarm rate was set to $1/(2n)$.

The individual data are presented in Table 2. We compared the d' values in a two-way repeated measures ANOVA, with d' as the dependent variable and experimental condition (baseline, valid cue, invalid cue) and adjacent pairwise discriminations (S_1S_2 , S_2S_3 , and S_3S_4) as factors.

Table 2
 d' Values of Experiments 1, 2A, and 2B, Listed for Each Participant, Experimental Condition, and Discriminability Comparison

Experiment	Participant	Condition								
		Baseline			Invalid Cue			Valid Cue		
		d'_{12}	d'_{23}	d'_{34}	d'_{12}	d'_{23}	d'_{34}	d'_{12}	d'_{23}	d'_{34}
1	1	3.15	1.73	1.61	3.70	1.51	1.09	2.99	2.18	1.27
	2	4.90	2.12	2.75	3.80	1.26	1.40	4.65	2.32	2.45
	3	2.70	2.13	1.56	2.15	1.42	1.12	2.88	1.65	0.97
	4	3.20	2.35	2.17	2.82	1.98	1.39	3.44	2.56	1.83
	5	2.34	1.95	1.51	3.39	1.62	1.13	3.98	2.13	1.67
	6	3.46	2.93	2.39	3.53	2.78	1.60	3.11	2.46	1.90
	7	3.73	2.07	1.57	4.21	1.86	1.17	5.15	1.74	1.51
	8	3.36	1.91	2.08	4.38	1.58	1.61	4.21	2.04	1.84
	9	3.93	2.05	1.58	2.32	1.96	1.15	3.09	1.90	1.26
	10	3.70	2.76	2.08	3.61	3.06	1.46	4.21	2.29	1.96
2A	1	2.05	2.02	1.48	2.36	1.01	0.74			
	2	2.73	2.59	2.17	3.41	1.39	0.77			
	3	3.46	2.20	1.61	3.61	1.93	0.78			
	4	2.36	1.95	1.59	3.61	1.53	1.43			
	5	3.16	1.18	1.33	2.96	1.54	0.89			
	6	3.61	1.99	1.84	3.62	2.12	1.23			
	7	4.38	2.39	1.05	4.38	1.46	1.83			
	8	3.31	1.72	0.83	3.31	1.43	1.03			
	9	3.34	1.60	1.66	2.15	1.74	0.51			
	10	3.46	1.42	1.33	3.46	1.13	1.42			
2B	1	0.99	1.64	2.02	1.61	2.36	2.09			
	2	1.48	1.64	1.29	2.05	2.05	1.42			
	3	1.43	1.72	2.40	1.64	2.16	1.54			
	4	1.05	1.48	1.50	1.70	1.49	0.73			
	5	1.36	1.42	1.70	0.69	1.68	0.82			
	6	1.48	2.18	1.83	1.56	1.99	1.56			
	7	0.44	1.28	1.33	0.77	1.91	1.64			
	8	1.55	0.94	0.78	1.08	1.12	0.61			
	9	1.05	2.75	1.33	1.30	2.26	1.29			
	10	1.99	2.46	1.92	1.06	2.07	0.88			

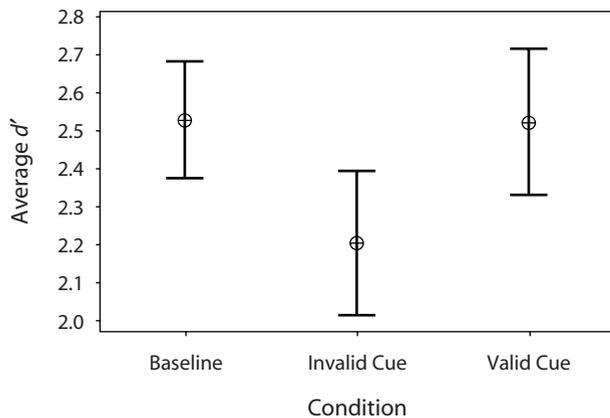


Figure 4. Mean d' values for the three conditions of Experiment 1. Bars indicate ± 1 SE from the mean.

The value of d' differed significantly across experimental conditions and adjacent discriminations [$F(2,18) = 5.48, p = .014$, and $F(2,18) = 70.77, p = .000$, respectively]. The mean d' s for the three experimental conditions are shown in Figure 4. The interaction of experimental condition and adjacent pairwise discriminations, however, did not quite reach statistical significance [$F(4,36) = 2.58, p = .054$]. In line with the idea that reduced accuracy in the invalid-cue condition goes along with reduced discriminability, paired t tests showed that the baseline and the valid-cue conditions were significantly different from the invalid-cue condition [$t(9) = 2.61, p = .028$, and $t(9) = 3.17, p = .01$, respectively], but the baseline and valid-cue condition were not significantly different [$t(9) = 0.03, p = .973$]. We further found that all adjacent discriminations differed significantly (paired t tests) [S_1S_2 vs. $S_2S_3, t(9) = 6.67, p = .000$; S_1S_2 vs. $S_3S_4, t(9) = 12.26, p = .000$; S_2S_3 vs. $S_3S_4, t(9) = 4.04, p = .003$]. Specifically, discriminability decreased with increasing stimulus contrast (see Figure 5). Overall, these results suggest that the decrease of accuracy in the invalid-cue condition went along with a decrease in discriminability.

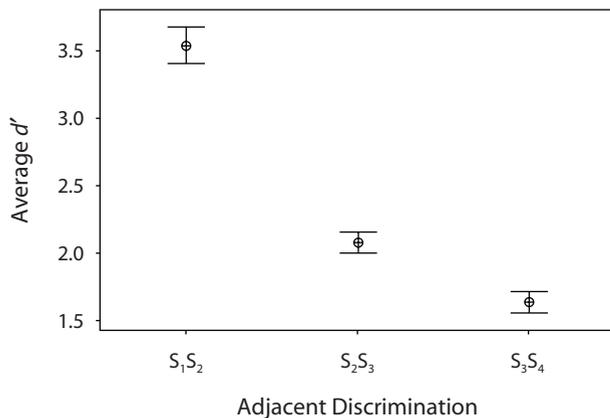


Figure 5. Mean d' values for the discrimination of the three pairs of adjacent contrast stimuli (S_1S_2, S_2S_3 , and S_3S_4) in Experiment 1.

Finally, we note that all participants were instructed to always focus on the center of the screen, where the stimuli were presented in all conditions. Hence, we assume that spatial attention was directed to the stimuli in all conditions. Furthermore, since the stimuli consisted of only one spatial frequency in all conditions, we also find it unlikely that differences in feature-based attention might account for the observed effects. Consequently, it seems unlikely that the observed differences in performance across conditions were due to attentional effects, rather than to a knowledge-based top-down influence over contrast sensitivity.

EXPERIMENT 2 Testing for Overload Protection

Because there is very little evidence in the literature, aside from the study by Porciatti et al. (2000), that contrast sensitivity control might be used to protect subsequent mechanisms (e.g., processes underlying shape recognition) from overload, we decided to further investigate the degree to which the results of Experiment 1 were consistent with a contrast sensitivity control mechanism that protects against contrast overload.

When we added a high-contrast grating to a set of four low-contrast gratings, we increased the overall contrast range in the experiment. It was possible, then, that the effect of adding the high-contrast stimulus was due simply to an increase in the overall range of contrasts. This is precisely what the model of Braida and Durlach (1972) would predict. According to their model, the variance of the underlying sensory representations of the stimuli increases with increases in stimulus range. If the effect were due solely to stimulus range, we would expect a similar decrement in performance if participants were asked to identify four high-contrast gratings while a fifth low-contrast grating was presented occasionally and randomly. If one of the functions of contrast sensitivity control is to protect against sensory overload, however, the addition of a low-contrast grating to a set of high-contrast gratings should not affect performance, because the contrast sensitivity would already be set to optimize performance among the high-contrast gratings, which would also protect against sensory overload. Hence, no further adjustment would be required.

Experiment 2 was conducted in order to discriminate between these two theories.

Method

The method was the same as in Experiment 1, except for the changes noted below.

Participants. Another 10 University of Toronto at Mississauga undergraduate students participated in Experiment 2A, and an additional 10 participants participated in Experiment 2B. All had normal or corrected-to-normal vision and normal contrast sensitivity (as measured by Pelli-Robson charts). All gave consent to participate in the experiments and received credits toward their course grade for compensation. The experiment was conducted in line with the ethical guidelines at the University of Toronto.

Apparatus and Stimuli. The gratings in the baseline condition of Experiment 2A were four low-contrast gratings with contrast levels of 5%, 12%, 19%, and 26% (the same as in the baseline con-

dition of Experiment 1). In the experimental condition of Experiment 2A, a grating with 100% contrast was added to the baseline set. In Experiment 2B, the baseline set consisted of four gratings with contrast levels of 79%, 86%, 93%, and 100%. The contrast values resulted in an approximate 75% correct identification performance in pilot experiments. A fifth grating with 5% contrast was added in the experimental condition. In both experiments, each grating was shown 25 times in every condition. Thus, in both Experiments 2A and 2B, there were 100 trials in the baseline condition and 125 in the experimental condition. Moreover, in both experiments, participants were instructed to assign lower numbers to lower contrasts. As a result, the assignments of numbers to the contrast values switched in Experiment 2B from the baseline to the experimental condition because 4 indicated 100% contrast in the baseline condition (which had four different contrasts in total) but 5 indicated 100% in the experimental condition (which had five different contrasts in total).

Procedure. Participants completed the baseline and experimental conditions twice in Experiments 2A and 2B. Participants always started off with two blocks of the baseline condition. The fixation sign was a fixation cross in all conditions.

Results and Discussion

As in Experiment 1, in Experiment 2A, because we were primarily interested in whether Grating 4 was distinguishable from Gratings 1, 2, and 3, we planned to count keystrokes of 4 or 5 in the experimental condition as a correct identification when Grating 4 was presented. However, Grating 4 was never identified as Grating 5, so this correction was not necessary. Likewise, in Experiment 2B we planned to count keystrokes of 1 and 2 in the experimental condition as a correct identification when Grating 2 occurred. However, there were no instances in which Grating 2 was identified as Grating 1.

The results of Experiment 2A clearly show that adding a fifth high-contrast grating to the base set of four low-contrast gratings resulted in fewer gratings being iden-

tified correctly (Figure 6). A paired *t* test revealed that performance was significantly lower in the experimental condition than in the baseline condition [$t(9) = 3.03$, $SE = 1.97$, $p = .014$]. The results of Experiment 2B were very different: The addition of a fifth low-contrast grating to a set of four high-contrast gratings had no effect on identification performance for the four high-contrast gratings (Figure 6). The lack of any significant effect was confirmed by a paired *t* test, which showed no significant difference between the two conditions [$t(9) = 0.5$, $SE = 2.29$, $p = .628$].

We conducted a signal detection analysis on the data to examine whether the decreased identification performance in the experimental condition of Experiment 2A goes along with a decreased discriminability. We calculated d'_{12} , d'_{23} , and d'_{34} for each condition and participant separately, as in Experiment 1 (see Table 2 for individual data). For Experiment 2A, an ANOVA with experimental condition (baseline, experimental) and stimulus comparisons (S_1S_2 , S_2S_3 , S_3S_4) as within-subjects factors indicated that there was an effect of experimental condition [$F(1,45) = 4.23$, $p = .046$] and a significant effect of stimulus comparison [$F(2,45) = 108.6$, $p = .000$], but no interaction between the two [$F(2,45) = 2.18$, $p = .125$]. However, for Experiment 2B, where a low-contrast grating was added to a set of high-contrast gratings, there was no effect of experimental condition [$F(1,45) = 0.17$, $p = .681$]. There was a significant effect of stimulus comparison [$F(2,45) = 9.48$, $p = .000$], but there was no significant interaction [$F(2,45) = 2.39$, $p = .103$]. These results suggest that the addition of a high-contrast grating to a set of low-contrast gratings reduces the discriminability of the low-contrast gratings. However, this does not hold for the addition of a low-contrast grating to a set of high-contrast gratings. These results are consistent with the notion of top-down contrast sensitivity control that protects the visual mechanisms from overload.

Finally, the results of Experiments 2A and 2B cannot be accommodated within a contrast range model of identification and discrimination that parallels the range model developed by Braida and Durlach (1972) in the auditory domain, because such models predict that performance should decrease as the contrast range increases. However, increasing the range to 5%–100% by adding a high-contrast grating (100%) to a set of low-contrast gratings (5%, 12%, 19%, 26%) reduced identification accuracy and discriminability, whereas increasing the range to the same extent by adding a low-contrast grating (5%) to a set of high-contrast gratings (79%, 86%, 93%, 100%) did not.

GENERAL DISCUSSION

The purpose of the present study was twofold. First, we investigated whether a top-down influence over contrast sensitivity exists that is based on expectations. Second, we examined whether contrast sensitivity control is used for overload protection.

Previous research has shown that contrast sensitivity is controlled by stimulus properties in a bottom-up fashion and by higher order mechanisms such as selective at-

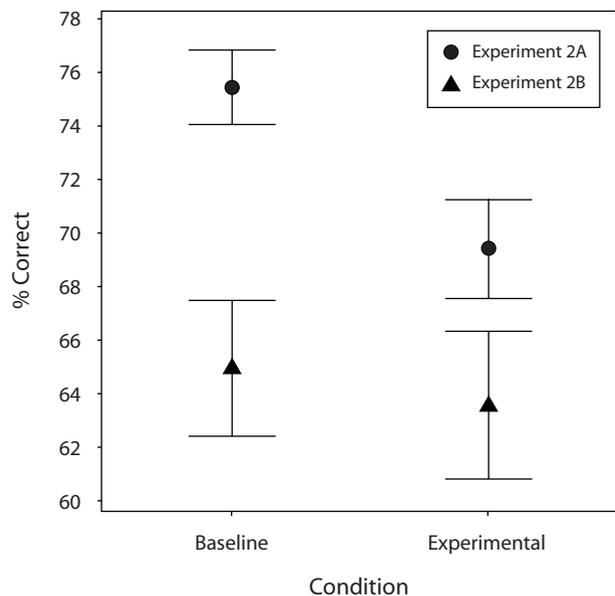


Figure 6. Mean percent accuracy in the baseline and experimental condition in Experiments 2A and 2B. Bars indicate ±1 SE from the mean.

tention. Here, we examined whether contrast sensitivity control is also under knowledge-driven top-down influence that is not mediated by attention, using an absolute identification paradigm combined with a cuing paradigm. In Experiment 1, we investigated whether immediate prior knowledge of the contrast to be presented would permit the observer to rapidly adjust contrast sensitivity between stimulus presentations. We found that, when a high-contrast grating was added to a set of four low-contrast gratings, identification performance and discriminability were reduced only when participants had *no* prior knowledge about the occurrence of the high-contrast stimulus. Hence, the results of Experiment 1 are consistent with the existence of knowledge-driven top-down influence over contrast sensitivity. Because participants were instructed to focus always on the center of the screen in all conditions, it seems unlikely that attention was employed differently across conditions. We therefore suggest that contrast sensitivity is controlled in a top-down manner, *in addition* to bottom-up control.

In Experiment 2, we provided evidence that one of the functions of top-down influence over contrast sensitivity is to protect the visual system from overload. Hence, the discrimination of four low contrasts should be affected by the occasional presentation of a very high contrast. However, the discrimination of four high contrasts should not be affected by an occasional presentation of a very low contrast. Our results were in line with this suggestion.

Can Bottom-Up Models Account for the Effects of Knowledge on Contrast Sensitivity Control?

It is difficult to see how models in which contrast sensitivity is controlled only in a bottom-up fashion can account for the pattern of results found in Experiments 1 and 2. First, assume that bottom-up adjustments in contrast sensitivity are fast acting (occur within 1 sec). Because a uniform gray screen was present between trials in the present experiments and for 500 msec, when the fixation sign was turned off before the presentation of the stimulus, the participant should have been fully adapted to the gray screen, and his or her contrast sensitivity function should have been optimally adjusted for detecting low-contrast stimuli, independently of the occasional presentation of a high-contrast stimulus. Hence, performance on low-contrast stimuli should not have been affected when a high-contrast stimulus was added to the set, independently of whether its occurrence was preceded by a valid cue. However, performance is affected when the occurrence of high-contrast gratings is unpredictable.

If, on the other hand, bottom-up adjustments are slow acting (>1 sec), participants should have performed best when only low-contrast gratings were presented, because they would experience only low levels of contrast throughout a session. However, the addition of occasional high-contrast gratings could change the adaptation level, thereby worsening identification performance for low-contrast gratings because of a change in adaptation level. Indeed, the addition of an unpredictable high-contrast

grating does worsen identification and discrimination. However, the addition of predictable high-contrast gratings does not. The only way that we can imagine obtaining such results in a slow-acting, bottom-up model would be that the participants would have paused much longer in the valid-cue condition than they did in the invalid-cue condition, so that they became adapted to the gray level in the valid-cue condition but not in the invalid-cue condition. We therefore expected participants to have longer reaction times (RTs) and/or longer intertrial times (the time that a participant waited to initiate the next trial) in the valid-cue condition than in the invalid-cue condition. However, we found that participants did not differ across conditions in their RTs. A one-way repeated measures ANOVA showed no significant differences in RTs across the experimental conditions in Experiment 1 [$F(2,18) = 1.18, p = .329$]. We were not able to calculate the intertrial times from all valid- and invalid-cue sessions. However, we were able to calculate the average intertrial time for the last session of each participant. Because we counterbalanced the testing order, we had five average intertrial times for the invalid-cue condition and five average intertrial times for the valid-cue condition. There was no significant difference between the intertrial times in the valid- and invalid-cue conditions [$t(7) = 0.01, p = .992$]. The mean waiting times in the valid- and invalid-cue conditions were 1,023 and 1,022 msec, respectively. Moreover, we compared the overall waiting time (RT + intertrial time) of the valid- and invalid-cue conditions using the last session of each participant. This overall waiting time was slightly higher in the invalid- than in the valid-cue condition (197.7 vs. 187.9 sec). However, this difference was not significant [$t(7) = -0.38, p = .992$]. Additionally, it did not appear to the experimenter that participants paused longer between trials in the valid-cue condition than in the invalid-cue condition. It therefore seems unlikely that a slow-acting bottom-up mechanism was responsible for the pattern found in Experiment 1.

Is It Possible to Explain the Results Without Employing a Contrast Overload Protection?

We think that it is difficult to explain the results of Experiments 1 and 2 without assuming contrast overload protection. To see why this is so, assume for a moment that contrast overload does not exist—that is, that there is no upper contrast limit for the input to a contrast-sensitive mechanism. Remember that the presentation of an unpredictable high contrast was interspersed randomly with the presentation of one of four low-contrast gratings in the invalid-cue condition of Experiment 1. If the high contrast caused no overload of the input to a contrast-sensitive mechanism, there would be no need to adjust contrast sensitivity in this condition. Hence, the best strategy for the visual system would be to adjust its contrast sensitivity so that the four low contrasts could be optimally discriminated. This could be achieved by, for example, positioning the sigmoidal contrast response function of the mechanism in such a way that the low contrasts would fall in the linear portion of the response curve (see Figure 1).

As a result, the contrast-sensitive unit would have a different response to each of the four low-contrast gratings. The high-contrast grating would then most likely cause a saturated response within this contrast-sensitive unit. Overall, this response behavior of the contrast-sensitive unit should grant an optimal discrimination of all gratings: a graded response for the four low contrasts and a saturated response for the high contrast. Consequently, one would not expect a decrease of performance in the invalid-cue condition in comparison with the baseline condition. However, this is not what we have found. We have also argued that a range effect does not explain the results of Experiment 2 and that the asymmetrical contrast range effect is best understood in terms of an overload protection. In summary, we therefore suggest that the results of the two experiments are best understood by assuming that an upper limit for the input to a contrast-sensitive mechanism exists and that the visual system acts to keep the input below that limit.

It is important to note in this respect that a generalization of anchor theory (Gilchrist et al., 1999), under certain restricted conditions, can be viewed as a means of protecting against contrast overload. First, we must assume that the visual system assigns the perception of white to the highest luminance that it might encounter in a temporal series of unpredictable simple images (such as the gratings presented here). Hence, the area of highest luminance in a temporal series of unpredictable images is assigned a PR of 90%, according to Equation 1. Hence, in any of the conditions in this series of experiments, the brightest part of the grating with the highest contrast in the set of stimuli is assigned a PR of 90%. The PR of both bright and dark parts of each of the gratings in the entire set is then assigned a value according to Equation 1, where L_h is the luminance of the brightest portion of the grating with the highest contrast in the set. If we now assume that the effective contrast (EC) between the lightness of the bright and dark portions of the grating is given by $PR_{\text{bright peak}} - PR_{\text{dark peak}}$, then it can be shown that EC for the stimuli in a set is

$$EC = (180 C_s) / (100 + C_{\text{Max}}), \quad (2)$$

where C_s is the contrast of the grating in question, and C_{Max} is the maximum contrast in the set of stimuli. This model predicts a reduction in discriminability among the baseline set of stimuli when a high-contrast grating is added to a set of low-contrast gratings, but not when a low-contrast stimulus is added to a set of high-contrast stimuli (see the Appendix for details). Hence, this version of a contrast overload mechanism readily predicts the results of Experiment 2. However, it should be noted that if PR for the bright and dark stripes is computed for each stimulus, without regard to the stimulus in the set with the highest contrast (i.e., the anchor effect operates only within the image itself), then discriminability will not be affected by the addition or subtraction of stimuli from the set (this version of the theory is outlined in Gilchrist et al., 1999). Moreover, if EC is defined as $(PR_{\text{bright peak}} - PR_{\text{dark trough}}) / (PR_{\text{bright peak}} + PR_{\text{dark trough}})$, EC reduces to 0.9 times stimulus contrast in all cases. Therefore, the an-

chor theory can predict the results of Experiment 2 only when maximum luminance is computed with respect to all of the stimuli in the set and EC (within anchor theory) is defined as in Equation 2. Finally, an anchor theory of lightness cannot easily explain why the effect of adding a high-contrast stimulus to a set of low-contrast stimuli disappears when the occurrence of the high-contrast stimulus is predictable.

Top-Down Control Over Low-Level Visual Processes

There are previous indications that prior knowledge affects low-level visual processes. For example, Ciaramitaro, Cameron, and Glimcher (2001) found improved luminance discrimination when more reliable information (i.e., knowledge) about the possible spatial location of the discriminative stimulus (DS) was provided to participants. The present study extends these findings of a top-down control over low-level visual processes by demonstrating that contrast sensitivity is also under top-down control.

We believe, however, that top-down control over low-level visual processes was not mediated in the same way in Ciaramitaro et al.'s (2001) and our studies. In particular, we suggest that Ciaramitaro et al.'s results might have been mediated by attention, whereas ours were not. This attentional mediation of top-down knowledge is well understood in terms of a slightly modified version of Rose and Pardhan's (2000) model of early binocular vision. Assume that several perceptual channels exist that are broadly tuned to a stimulus property (e.g., orientation or spatial frequency) and to stimulus location and that attention can be directed to one or more perceptual channels at a time. Note, further, that directing attention to a channel improves the processing within the attended perceptual channel. The strength of this effect depends on the amount of attentional resources allocated to this channel. A priori knowledge can be assumed to have affected performance in Ciaramitaro et al.'s experiments, because it reduces the uncertainty about a visual stimulus's property (in their study, spatial location) and allows focusing of attention on the appropriate perceptual channel. For example, when little information was provided concerning the spatial position of the DS in Ciaramitaro et al.'s study, it can be presumed that the visual system distributed its attention over several spatial-location-selective perceptual channels. Then, as the knowledge about the spatial location of the DS increased, the visual system could improve its performance by allocating more attentional resources to the perceptual channel most likely to process the DS. Hence, top-down control over luminance discrimination might be mediated by how attention is distributed among perceptual channels.

For what kind of stimulus properties are perceptual channels likely to exist? Davis, Kramer, and Graham's (1983) results speak in this regard. They showed that, when gratings of different spatial frequencies were intermixed within a block, providing the participant with a cue signaling the grating's spatial frequency improved its detectability in a two-alternative forced choice paradigm.

Presumably, a priori knowledge of the grating's spatial frequency allowed the participants to focus their attention on the appropriate spatial frequency channel. Similar results were found for spatial position but not for stimulus contrast. Note that the latter finding suggests that separate channels for contrast might not exist.

Because attention cannot be directed to a particular contrast channel if contrast channels do not exist, it seems unlikely that a priori knowledge about the upcoming stimulus contrast was mediated by attention in Experiment 1. We suggest that attention was always directed to the same perceptual channel in all of our conditions in Experiment 1, because only one target was employed and that target was always presented in the same portion of the visual field. Therefore, we think it unlikely that changes in attention might have been responsible for the results observed in Experiment 1. Note further that, if separate perceptual channels for low- and high-contrast stimuli existed, we would have expected a different performance in Experiment 1 from what we observed, because the optimal strategy for the visual system to optimize contrast discrimination performance is to focus attention on the lower part of the contrast sensitivity range in which the four low-contrast stimuli would fall. Hence, we would expect the same performance in all conditions, independent of whether the cue was valid. Therefore, it is more likely that a priori knowledge affects contrast by changing the gain control in that perceptual channel.

Overall, our results are important for previous models of visual contrast sensitivity control (e.g., Foley, 1994). These models typically assume that contrast sensitivity is controlled by stimulus parameters solely in a bottom-up fashion. Our results suggest that, to make accurate predictions about the contrast sensitivity of the visual system, these models should also take higher order processes into consideration.

In conclusion, our results suggest that contrast sensitivity is modulated by expectations and by knowledge about what levels of contrast are likely to be encountered. The results support a model in which the function of top-down contrast sensitivity control is to optimize performance while protecting against overload. In this regard, it is similar to the top-down control mechanism proposed by Parker et al. (2002) for auditory intensity. We suggest that contrast sensitivity is controlled in a top-down manner in addition to bottom-up control.

AUTHOR NOTE

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APPENDIX

Let L_{low} , L_{ave} , and L_{high} represent the luminance of the trough, average luminance, and peak luminance of a grating. Note that all gratings have the same average luminance. Let L_{Max} be the maximum luminance obtained by any grating in the set. Finally, let C represent a grating's contrast measured as a percentage. Now, note the following:

$$\begin{aligned}
 L_{low} &= L_{ave} - \Delta L, \\
 L_{high} &= L_{ave} + \Delta L, \\
 C &= 100 \frac{\Delta L}{L_{ave}}, \\
 \Delta L &= \frac{C * L_{ave}}{100}, \\
 L_{low} &= \left(1 - \frac{C}{100}\right) L_{ave}, \\
 L_{high} &= \left(1 + \frac{C}{100}\right) L_{ave}, \\
 L_{Max} &= \left(1 + \frac{C_{Max}}{100}\right) L_{ave}, \\
 PR_{low} &= \frac{L_{low}}{L_{Max}} 90 = 90 \left(\frac{100 - C}{100 + C_{Max}}\right), \\
 PR_{high} &= \frac{L_{high}}{L_{Max}} 90 = 90 \left(\frac{100 + C}{100 + C_{Max}}\right), \\
 EC &= PR_{high} - PR_{low} = \frac{180C}{100 + C_{Max}}.
 \end{aligned}$$

If we now compute the effective contrast (EC) for the four low-contrast stimuli alone, the ECs are 7.14%, 17.14%, 27.14%, and 37.14% for stimulus contrasts of 5%, 12%, 19%, and 26%, respectively. If we now compute the ECs when the 100% contrast stimulus is added to this set, we have ECs of 4.5%, 10.8%, 17.1%, 23.4%, and 90% for stimulus contrasts of 5%, 12%, 19%, 26%, and 100%, respectively. For the high-contrast set, the ECs are 4.5%, 71.1%, 77.4%, 83.7, and 90% for stimulus contrasts of 5%, 79%, 86%, 93%, and 100%, respectively. Note that the addition of a low-contrast stimulus to a high-contrast set does not change the EC according to this model.

Note also that if we define EC as

$$EC = \frac{(PR_{high} - PR_{low})}{(PR_{high} + PR_{low})},$$

the EC of a stimulus is simply 0.9 times stimulus contrast. Hence, the only way an anchor theory can predict the results is if EC is defined as

$$EC = (PR_{high} - PR_{low}),$$

and L_{Max} refers to the highest luminance value in the set of stimuli.

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