

Attention alters decision criteria but not appearance: A reanalysis of Anton-Erxleben, Abrams, and Carrasco (2010)

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Paying attention to a stimulus affords it many behavioral advantages, but whether attention also changes its subjective appearance is controversial. K. A. Schneider and M. Komlos (2008) demonstrated that the results of previous studies suggesting that attention increased perceived contrast could also be explained by a biased decision mechanism. This bias could be neutralized by altering the methodology to ask subjects whether two stimuli were equal in contrast or not rather than which had the higher contrast. K. Anton-Erxleben, J. Abrams, and M. Carrasco (2010) claimed that, even using this equality judgment, attention could still be shown to increase perceived contrast. In this reply, we analyze their data and conclude that the effects that they reported resulted from fitting symmetric functions that poorly characterized the individual subject data, which exhibited significant asymmetries between the high- and low-contrast tails. The strength of the effect attributed to attentional enhancement in each subject was strongly correlated with this skew. By refitting the data with a response model that included a non-zero asymptotic response in the low-contrast regime, we show that the reported attentional effects are better explained as changes in subjective criteria. Thus, the conclusion of Schneider and Komlos that attention biases the decision mechanism but does not alter appearance is still valid and is in fact supported by the data from Anton-Erxleben et al.

Keywords: attention, appearance, contrast perception, psychophysical methods

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Introduction

Whether paying attention to a stimulus enhances its perceived intensity has been debated since the earliest days of experimental psychology and is still controversial today. Carrasco, Ling, and Read (2004) presented the strongest psychophysical evidence to date that attention does alter appearance, showing that when their subjects were forced to choose which of two visual stimuli had higher luminance contrast (“comparative judgment”), subjects tended to choose the stimulus that had been preceded by a transient cue, shifting the psychometric function and the inferred point of subjective equality (PSE) toward higher contrasts, as if the involuntary attentional reorientation evoked by such cues causes subjects to perceive cued stimuli as having higher than veridical contrast. However, Schneider (2006) and Schneider and Komlos (2008) suggested the alternative hypothesis that the cues did not actually alter the perceived contrast of the stimuli but instead merely increased their salience and in doing so created a bias for subjects to choose them. Indeed, using the comparative judgment methodology, a bias in the decision criterion would alter the PSE in exactly the same manner as would an actual change in stimulus appearance. Carrasco et al. had performed several experiments to rule out simple response biases, but the possibility remained that attention acted to bias the decision mechanism. To test this, Schneider and Komlos replicated Carrasco et al. using

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the same stimuli but added a same–different judgment in which subjects were forced to choose whether the two stimuli were equal in contrast or not (“equality judgment”). The advantage of this task is that changes in the subjects’ decision criteria are orthogonal to and, thus, can be distinguished from actual changes in appearance. The results of this study showed that the attentional cues had no effect on the determination of the PSE in the equality judgment task, and we concluded that the cues only affected the decision mechanism and did not actually alter the appearance of the stimuli. In response to this, Anton-Erxleben, Abrams, and Carrasco (2010) attempted to replicate Schneider and Komlos and reported that the equality judgment task systematically underestimated the PSE but, nonetheless, could be used to show that attention did alter appearance and not just response criteria. In this reply, we reanalyze their data and find it actually to be consistent with Schneider and Komlos’ conclusion that attention does not alter appearance.

Methods

Original methodology

The present study focuses on Experiment 3 in Anton-Erxleben et al. (2010), which was partially a replication of the main equality judgment experiment in Schneider and

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Komlos (2008). The methodology of the two studies was similar but not identical. The differences are important because they caused the stimuli of Anton-Erxleben et al. to be substantially less visible than those of Schneider and Komlos, which likely explains the prevalence of the low-contrast asymmetries occurring in Anton-Erxleben et al.'s data but not in Schneider and Komlos' data. In both experiments, a transient visual cue appeared 120 ms before the onset of two Gabor targets, which were located 4° to the left and right of the fixation point. The two targets varied in luminance contrast, and the task of the subject was to determine whether or not the two targets had the same or different contrast. One of the targets was a "standard" contrast, which was 26% contrast in Anton-Erxleben et al. and was either 15, 20, 25, 30, or 35% contrast in Schneider and Komlos. The contrast of the other "test" target was drawn from a range spanning that of the standard target. In Schneider and Komlos, the transient cue was always located near the standard target, whereas in Anton-Erxleben et al., there were three cuing conditions: the cue could be located near the standard or test targets or in a neutral location near the fixation point.

The target stimuli used in Anton-Erxleben et al. (2010) differed in size and orientation from those used in Schneider and Komlos (2008), as depicted in Figure 1. The more important difference is that the Gaussian envelope of the Gabor targets in Anton-Erxleben et al. had a full width at half maximum (FWHM) of 1° , whereas those in Schneider and Komlos had a standard deviation (σ) of 1° . Since $\text{FWHM} = 2\sqrt{2\log 2}\sigma$, an FWHM of 1° gives $\sigma \approx 0.42^\circ$; therefore, the stimuli in Anton-Erxleben

et al. were less than half as large as those in Schneider and Komlos. Stimulus visibility strongly depends on stimulus size. For example, for 4-cpd gratings (used in both studies; Schneider and Komlos, 2008 also used 2-cpd stimuli), decreasing the radius of a stimulus from 1° to 0.5° , comparable to the difference between the stimuli in Anton-Erxleben et al. and Schneider and Komlos, reduces contrast sensitivity by a factor of approximately 2.5 for vertical gratings or 1.75 for oblique gratings (Díaz-Otero, Caballero, Lorenzo, & Sigüenza, 1995).

The second difference between the stimuli in the two studies is orientation. The Gabors in Anton-Erxleben et al. (2010) were oriented at $\pm 45^\circ$, whereas the stimuli in the main conditions in Schneider and Komlos (2008) were oriented vertically. It is a well-known effect that obliquely oriented stimuli are less visible than horizontal or vertical stimuli (Tootle & Berkley, 1983). For 4-cpd gratings, contrast sensitivity is approximately 20% less for oblique than vertical gratings (Díaz-Otero et al., 1995).

Despite these profound differences in visibility, we verified that the stimuli used in Anton-Erxleben et al. (2010) were indeed above threshold, using a detection experiment similar to Carrasco, Fuller, and Ling (2008).

Analysis methodology

Katharina Anton-Erxleben provided us with the equality judgment data from Experiment 3 in Anton-Erxleben et al. (2010), and we fit three different functions to the individual subject data for each of the three experimental

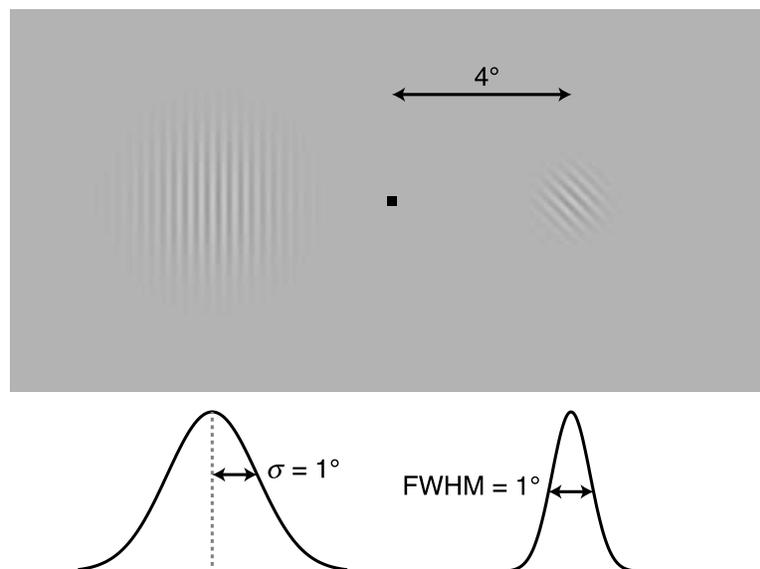


Figure 1. A scale diagram comparing the stimuli sizes between the two studies. The Gabor on the left of the fixation point corresponds to those used in Schneider and Komlos (2008), which were oriented vertically and had a spatial frequency of 2 (not shown) or 4 cpd and a Gaussian envelope with a standard deviation (σ) of 1° . The Gabor on the right corresponds to those used in Anton-Erxleben et al. (2010), which were oriented obliquely and had a spatial frequency of 4 cpd and an envelope with a full width at half maximum (FWHM) of 1° , corresponding to $\sigma \approx 0.42^\circ$. In both studies, the stimuli were located at 4° eccentricity.

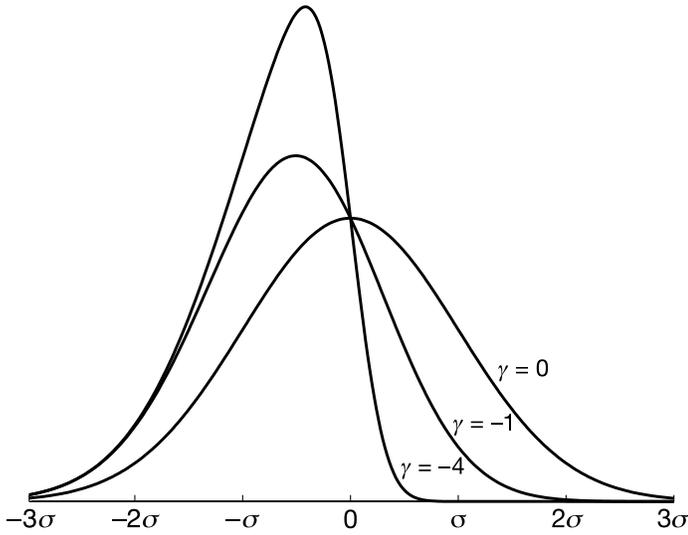


Figure 2. The skew normal distribution. The skew normal function is plotted for three different values of the skew parameter (γ). For larger magnitudes of skew, the function is more asymmetric.

conditions (test stimulus cued, neutral cue, and standard stimulus cued). The three fitted functions were given as follows:

$$f_1(\Delta c) = \Phi\left(\frac{\tau - \Delta c - \alpha}{\sigma}\right) - \Phi\left(\frac{-\tau - \Delta c - \alpha}{\sigma}\right), \quad (1)$$

the equality judgment function described in Schneider and Komlos (2008), where $\Phi(x) \equiv \int_{-\infty}^x \varphi(u) du$ and $\varphi(x) \equiv \frac{1}{\sqrt{2\pi}} e^{-x^2/2}$ are, respectively, the cumulative normal distribution and normal probability density functions, τ is the subjective equality criterion (subjects report that the two targets have equal contrast if the absolute difference in perceived contrast is less than τ), Δc is the actual difference in contrast between the two target stimuli, α is the hypothesized attentional boost in the perceived contrast of the cued target, and σ^2 is the variance of the perceived contrast difference;

$$f_2(\Delta c) = 2\sqrt{2\pi}h\varphi\left(\frac{\Delta c - \alpha}{\sigma}\right)\Phi\left(\gamma\frac{\Delta c - \alpha}{\sigma}\right), \quad (2)$$

a scaled skew normal function (after Azzalini, 1985), where h is a scale factor, and γ is a skew parameter (Figure 2); and

$$f_3(\Delta c) = \Phi\left(\frac{\tau - \Delta c}{\sigma}\right) - \Phi\left(\frac{-\tau - \Delta c}{\sigma}\right) + g\Phi\left(\frac{\mu_g - \Delta c}{\sigma_g}\right), \quad (3)$$

the equality judgment function (with $\alpha = 0$) plus a non-zero asymptote or “guessing rate” g at low contrast,

applied with a threshold μ_g and slope σ_g . In fitting this third function, the σ , μ_g , and σ_g parameters were linked across conditions, so that only the subjective criteria τ and g were free to independently vary among the conditions; there were nine free parameters in total to fit the data from the three conditions for each subject.

For each model, R^2 was computed over all subjects and conditions as $R^2 \equiv 1 - \frac{SS_{\text{err}}}{SS_{\text{tot}}}$, where the residual sum of squares $SS_{\text{err}} = \sum_{i=1}^{N_{\text{sub}}} \sum_{j=1}^{N_{\text{exp}}} \sum_{k=1}^{N_c} (y_{ijk} - f_{ijk})^2$ for the N_{sub} subjects, N_{exp} conditions, N_c contrast levels, data y , and model function f , and the total sum of squares $SS_{\text{tot}} = \sum_{i=1}^{N_{\text{sub}}} \sum_{j=1}^{N_{\text{exp}}} \sum_{k=1}^{N_c} (y_{ijk} - \bar{y}_{ij})^2$, where $\bar{y}_{ij} = \frac{1}{N_c} \sum_{k=1}^{N_c} y_{ijk}$. The root mean square error (RMSE) was calculated as $\text{RMSE} = \sqrt{SS_{\text{err}}/N_{\text{sub}}N_{\text{exp}}N_c}$.

Results

To get an overall impression of the data and to replicate Figure 4A in Anton-Erxleben et al. (2010), we first fit the equality judgment function (f_1 , Equation 1) to the mean data across subjects, as shown in Figures 3 (overlapping) and 4 (separated). Directly comparing the three conditions in Figure 3, the most prominent feature is that the subjects relaxed their subjective equality criteria during the neutral condition compared to the other two conditions, such that they were more likely to report the targets having equal

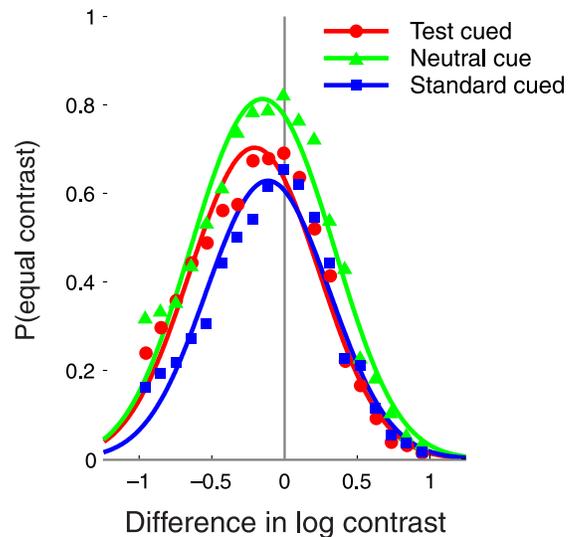


Figure 3. Equality judgment data. The mean data across subjects from Experiment 3 in Anton-Erxleben et al. (2010) are plotted here (as in their Figure 4A), along with fits of the equality judgment function (f_1 , Equation 1), for each of the three attentional cuing conditions, which are plotted together for comparison purposes.

contrast, increasing the response amplitude. Another feature to note in this figure is that the peaks of the fitted functions in all three conditions are shifted to the left, toward the low-contrast test stimuli, with the peak of the fit to the “test cued” data shifted to a lower contrast than was the peak of the fit to the “standard cued” data. The location of the peak of the fitted function is governed by the hypothesized attentional contrast boosting parameter (α), and therefore, the significant difference in α between the “test cued” and “standard cued” conditions was interpreted by Anton-Erxleben et al. (2010) as supporting their hypothesis that attention enhances perceived contrast.

However, we note that the mean data between these two conditions completely overlap for the high-contrast (positive Δc) test stimuli and differ only for the low-contrast (negative Δc) test stimuli. Subjects were more likely to report that a test and standard stimulus had equal contrasts when the test stimulus had lower contrast than the standard, compared to when the absolute difference was the same but the standard stimulus had the lower contrast. This asymmetry between the high- and low-contrast data means that fitting a symmetric function, such as the equality judgment function (f_1 , Equation 1) used here, or the scaled Gaussian used in Anton-Erxleben et al. (2010), results in large systematic errors, as can be seen in the residuals in Figure 4. It is also important to note that the test stimulus contrast that subjects were most likely to report equal in contrast to the standard was in fact the standard contrast ($\Delta c = 0$); however, the maximum of the fitted function is shifted to the left of this, such that the maximum of the data is underestimated by the function, as

the fit attempts to accommodate the significant tail in the data at low contrast. This appears not only in the mean data but also in the individual subject data. A single typical subject is shown in the first row of Figure 5, all of the subjects and the fitted function parameters are shown in Supplementary Figure S1, and the mean residuals across subjects from their individual fits are shown in Figure 6. Our interpretation of these data is that subjects perceived the veridical contrast, independent of the cuing condition, but that their response data deviates from the response model for the low-contrast test stimuli due to the addition of some non-zero asymptotic phenomenon.

To better characterize the data and to explore to what extent its asymmetric nature is responsible for the significant cuing effects reported by Anton-Erxleben et al. (2010), we fit the data to a scaled skew normal function (f_2 , Equation 2; Figure 2). As seen in the single subject in Figure 5 (second row), all of the subjects in Supplementary Figure S2, and the mean residuals across subjects in Figure 6, the addition of a skew parameter improves the fits considerably, eliminating the systematic errors. Unlike the equality judgment function that was derived from signal theory (see Schneider & Komlos, 2008), the scaled skew normal function is merely descriptive and does not provide insight into the response mechanism. However, comparing the skew (γ) from these fits to the hypothesized attentional effect (α) from the equality judgment fits, as shown in Figure 7, we see a very strong correlation ($r = 0.54$, $p = 0.0039$) between the two—the stronger the skew in the data, the more the optimal fitted function must be pulled to the left to

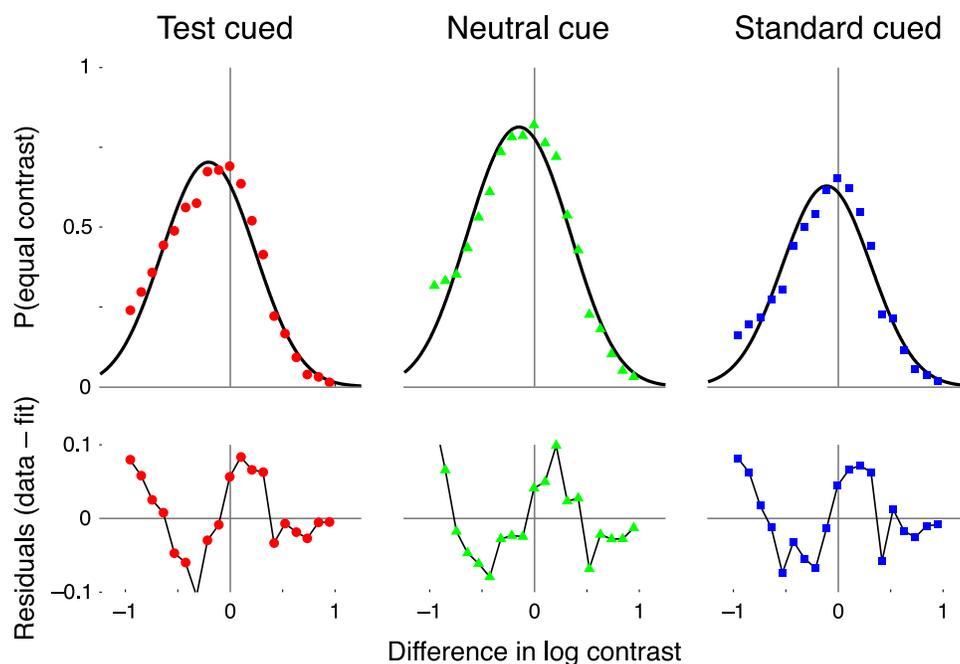


Figure 4. Equality judgment data. In the top row, the mean data across subjects and equality judgment function (f_1 , Equation 1) fits are replotted, as in Figure 3, but separated by condition. The residuals between the fits and the data are shown in the bottom row.

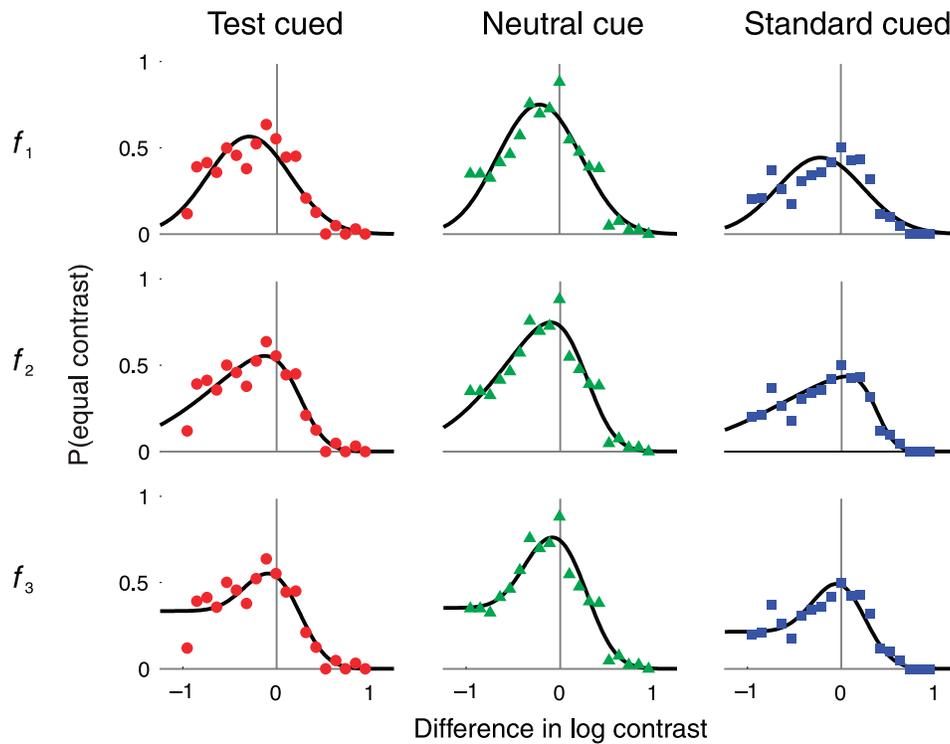


Figure 5. Individual subject data. The responses from an individual typical subject (S2) are shown. Each column represents a different attentional cuing condition, and each row represents the same data but a different function fit (see [Methods](#) section): equality judgment (f_1 , [Equation 1](#)), scaled skew normal (f_2 , [Equation 2](#)), and the equality judgment function with $\alpha = 0$ plus a non-zero asymptote at low contrast (f_3 , [Equation 3](#)).

accommodate the low-contrast asymmetry and, therefore, the stronger the deviation of the fitted symmetrical function away from veridical contrast perception.

Although the scaled skew normal function (f_2 , [Equation 2](#)) fit the data very well, it is difficult to interpret since it is merely a descriptive function rather than a mechanistic

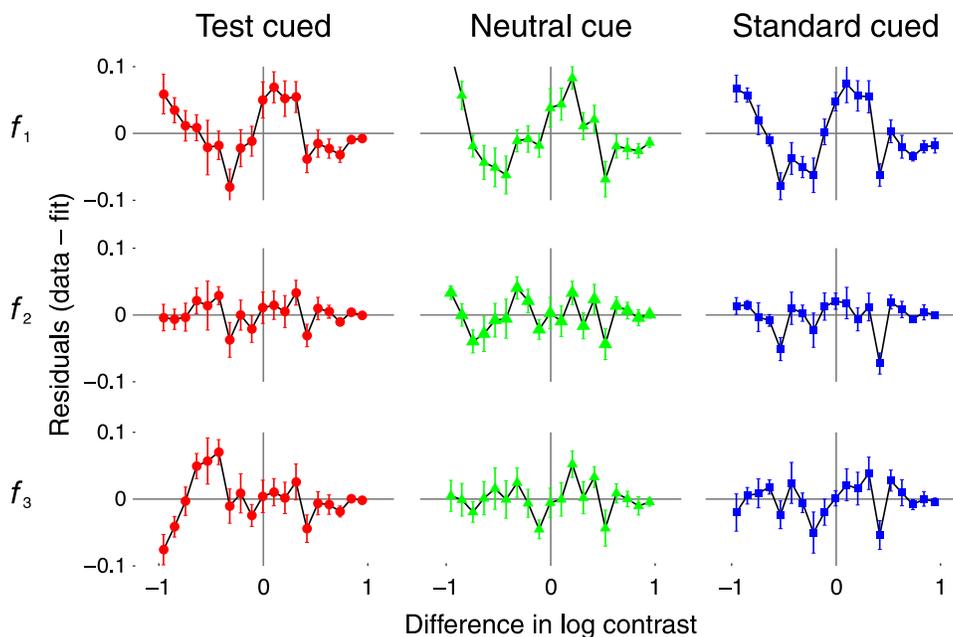


Figure 6. Mean residuals. The mean residuals across all subjects are shown for each of the attentional cuing conditions and fitting functions. Abbreviations as in [Figure 5](#).

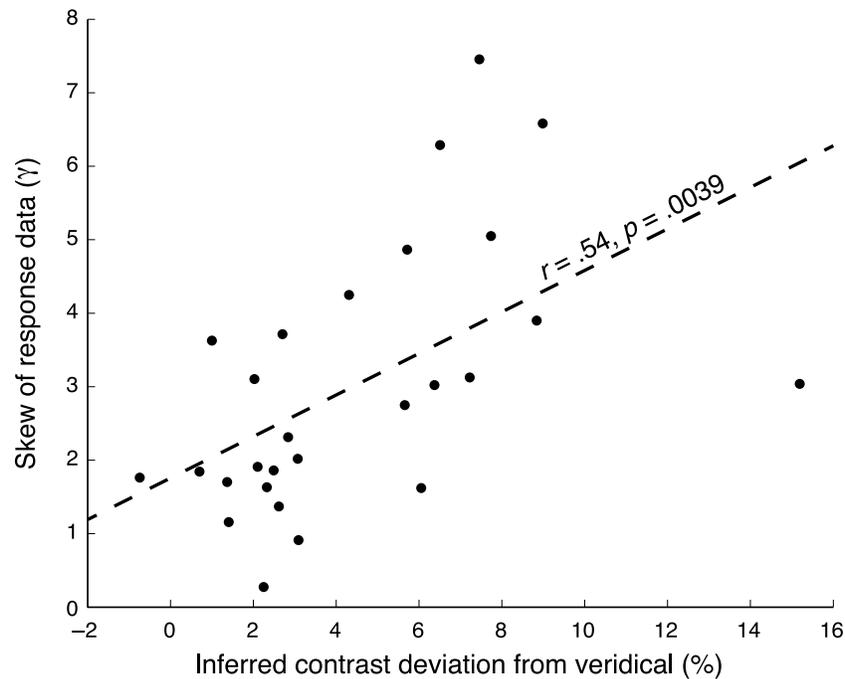


Figure 7. Correlation between reported attention effect and skew. The skew parameter (γ) from the scaled skew normal function (f_2 , Equation 2) fit is plotted as a function of hypothesized attentional boosting factor (α , converted to percent contrast) from the equality judgment (f_1 , Equation 1) fit, for each attentional condition and each subject. The dashed line is the linear regression line.

model. Because the process that caused the skew is unknown, it is impossible to determine whether or not the attentional cues altered perceived contrast. To rectify this, we fit the data to a third function whose parameters can be directly interpreted. Because the low-contrast data appeared in many subjects to asymptote to a non-zero value, and given the reduced visibility of the stimuli used in Anton-Erxleben et al. (2010) compared to those used in Schneider and Komlos (2008; see Methods section), we hypothesized that the asymmetries between the low- and high-contrast data likely resulted from a noise process occurring in the low-contrast regime. Although the low-contrast stimuli might be visible, there might be a threshold below which the subjects might lack sufficient information to properly perform the equality judgment and might, therefore, resort to a default behavior of responding that the two targets had equal contrast with probability g . The third function we fit incorporated this low-contrast noise into the equality judgment function (f_2 , Equation 3). For this third set of fits, to strongly test the hypothesis posited in Schneider and Komlos that attentional cues affect subjective decision criteria but do not alter perceived contrast, we forced $\alpha = 0$, i.e., no attentional effect upon perceived contrast was allowed, and also assumed that the underlying distribution of perceived contrast was identical among the three conditions (σ was linked among the conditions).

As can be seen in the third rows of Figures 5 and 6, plus the individual fits in Supplementary Figure S3, this third model (f_3 , Equation 3), which assumes that only the

subjective criteria τ (the equality threshold) and g varied among the attentional cue conditions, had $R^2 = 0.94$ and $\text{RMSE} = 0.16$ and fit the data better (smaller residuals and reduced systematic error) than the simple equality judgment function (f_1 , Equation 1), with $R^2 = 0.92$ and $\text{RMSE} = 0.19$, that permits the attentional cues to alter objective parameters. Both models used nine free parameters for each subject across the three experimental conditions and fit the data worse than the scaled skew normal function (f_2 , Equation 2), which used twelve free parameters and had $R^2 = 0.95$ and $\text{RMSE} = 0.14$.

Conclusions

The significant effects of attention upon perceived stimulus contrast reported by Anton-Erxleben et al. (2010) were caused by their use of a symmetric function to fit asymmetric response data. Among the individual subjects, the skew of the data was strongly correlated with the magnitude of the reported attentional effect. Cuing the test stimulus versus the standard primarily affected the subjects' responses for low-contrast test stimuli, but this difference could be accounted for by introducing a low-contrast asymptotic noise parameter to the response model. A model (f_3 , Equation 3) that assumed a constant distribution of perceived contrast across attentional cuing conditions was able to explain the subjects' responses, with differences among the conditions only requiring

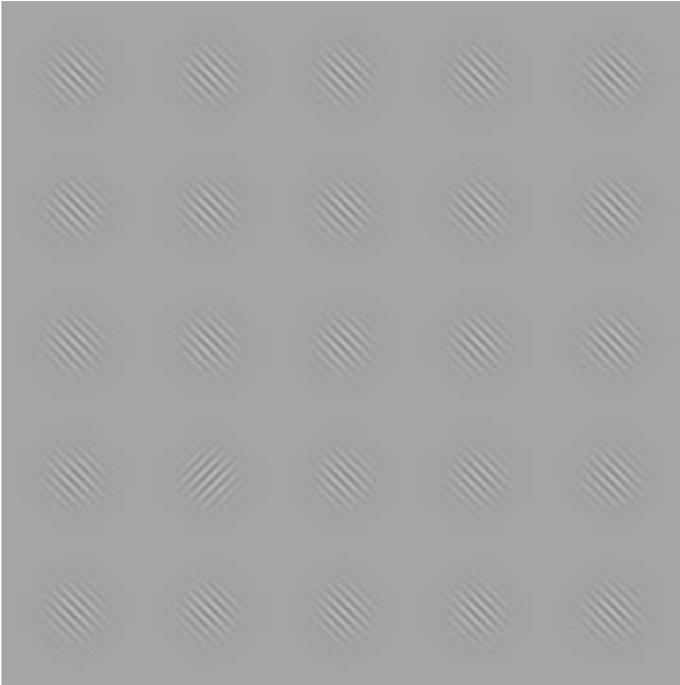


Figure 8. A demonstration that increased salience does not imply increased contrast. One of the Gabor patterns has a unique orientation and, thus, pops out from (is more salient than) the others. However, this Gabor does not appear to have higher contrast than the others.

changes in the subjective equality threshold criteria and the low-contrast asymptotic behavior. Therefore, we conclude that the data reported by Anton-Erxleben et al. were in fact consistent with Schneider and Komlos' (2008) hypothesis that attention alters subjective decision criteria but not perceived contrast.

It is not clear why such significant skew was often observed in Anton-Erxleben et al.'s (2010) data, while no prominent low-contrast asymmetries similarly affected the data fitting in Schneider and Komlos (2008). One reason could be the stimulus differences noted in the [Methods](#) section: their smaller size and oblique orientation made the stimuli used in Anton-Erxleben et al. significantly less visible than those in Schneider and Komlos. In addition, the context in which the stimuli were presented differed, because one of the two stimuli on each trial was always the same standard contrast (26%) in Anton-Erxleben et al., whereas the contrasts were less predictable in Schneider and Komlos, perhaps encouraging more scrutiny of the stimuli. Another possibility is that the quality of the observers varied. Some subjects exhibited a larger skew than others, and the subjects with the smallest skew also exhibited veridical contrast perception, unaffected by the attentional cue. Such differences in precision among subjects have been observed previously (Kerzel, Zarian, Gauch, & Buetti, 2010).

While the present results demonstrate that the difference in conclusions reached by Anton-Erxleben et al. (2010)

and Schneider and Komlos (2008) results from the use of a symmetrical function to fit data that is significantly skewed, Anton-Erxleben et al. suggest that the discrepancies between the two studies might be explained by (1) differences in statistical power or (2) the systematic underestimation of the PSE by the equality judgment, as observed in their Experiment 1. Claim 1 is dubious because adding more points to the psychometric function only weakly improves the estimation of the PSE, and the error in the group PSE is determined primarily by the between-subjects error rather than the error in fitting the psychometric function to each individual subject's data. The estimations by the equality judgments in Schneider and Komlos were almost exactly zero and there is no reason to expect undersampled data to be biased. Claim 2 seems equally unlikely, because, even if the systematic underestimations of the PSE reported in Anton-Erxleben et al. were not simply due to low-contrast noise, as suggested by the present study, and therefore might have actually occurred in Schneider and Komlos, it would be hard to imagine that such underestimations, which were constant over contrast in Anton-Erxleben et al., would have exactly canceled out the effects of the cue that varied with contrast in Schneider and Komlos, being larger for the lower than the higher contrasts.

Not only do the perceptual judgment data, when free of decision biases, not show that attention alters appearance, there is no other data or theoretical reason to think that it should. The notion that attention might be identical to an actual increase in stimulus contrast became popular when it seemed that a contrast gain model of attention explained single unit responses (Reynolds, Pasternak, & Desimone, 2000). Now, however, it is clear that contrast gain is a subset of the possible effects of attention (Reynolds & Heeger, 2009) and that attention and contrast are encoded separately in the cortex, with some neurons more strongly modulated by attention than others (Pooresmaeili, Poort, Thiele, & Roelfsema, 2010). Indeed, it would not be desirable for attention to interfere with veridical perception in our visual systems, because the consequences of attention altering the perception of velocity or other stimulus attributes could be severe. A more reasonable position is that attention enhances the salience of a stimulus without affecting the veridical perception of its features. As an example, the uniquely oriented Gabor pattern in [Figure 8](#) does not appear to differ in contrast from its neighbors, even though it is certainly more salient.

Technical notes

1. Anton-Erxleben et al. (2010) discuss at length the significant correlation they observe between the amplitude and standard deviation parameters in the scaled Gaussian function they used to fit the

equality judgment data. The equality judgment response function (f_1 , Equation 1) used in Schneider and Komlos (2008), which was derived from a signal theory model, contains no explicit amplitude parameter. Instead, the independent parameters are τ , the subjective equality criterion, and σ , the standard deviation. As noted in Schneider and Komlos, the contrast at which the response function is maximum is independent of τ . The response amplitude at this contrast is a function of τ and σ , namely $\Phi(\tau/\sigma) - \Phi(-\tau/\sigma)$, and it is, therefore, not surprising that this amplitude is correlated with σ . Anton-Erxleben et al. are, thus, incorrect in stating that the independence of the equality judgment parameters is not justified, as claimed by Schneider and Komlos. This issue also affects their discussion of Valsecchi, Vescovi, and Turatto (2010).

- Anton-Erxleben et al. (2010) criticize the equality judgment response model (f_1 , Equation 1) in Schneider and Komlos (2008) because “it allows for ill-defined, plateau-like peaks, which renders PSE estimation unreliable.” However, these plateau-like peaks do occur in subjects’ data when τ/σ is large (e.g., see Subjects S5 and S7 in Supplementary Figure S1), which is the reason the response model was originally developed in Schneider and Bavelier (2003). The PSE can be reliably determined even when τ/σ is large as long as a sufficiently large range of test stimuli contrasts is used to sample the slopes on either side of the plateau. The scaled Gaussian function used by Anton-Erxleben et al. is a reasonable approximation to the equality judgment function when τ/σ is small.

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