A three-response task reveals how attention alters decision criteria but not appearance

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Whether attention alters appearance or just changes decision criteria continues to be controversial. When subjects are forced to choose which of two equal targets, one of which has been pre-cued, has a higher contrast, they tend to choose the cued target. This has been interpreted as attention increasing the apparent contrast of the cued target. However, when subjects must decide whether the two targets have equal or unequal contrast, they respond veridically with no apparent effect of attention. The discrepancy between these comparative and equality judgments is explained by attention altering the decision criteria but not appearance. We supposed that when subjects are forced to choose which of two apparently equal targets has the higher contrast, they tend to proportion their uncertainty in favor of the cued target. To test this hypothesis, we used a three-response task, in which subjects chose which target had the higher contrast but also had the option to report that the targets appeared equal. This task disentangled potential attention effects on appearance from those on the decision criteria. We found that subjects with narrower criteria about what constituted equal contrast were more likely to choose the cued target, supporting the uncertainty stealing hypothesis. Across the population, the effects of the attentional cue are explained as changes in the decision criteria and not changes in appearance.

Introduction

Does paying attention to a stimulus alter its appearance or merely influence the decisions we make about it? This question traces its roots to the beginnings of experimental psychology and still intrigues us today. The most recent support for the hypothesis that attention does alter appearance was provided by Carrasco, Ling, and Read (2004). They conducted a study in which two Gabor patches on either side of fixation were presented to subjects. One of the patches was preceded by an exogenous attentional cue that compelled the subjects to covertly orient their attention to that target. The subjects then performed a comparative judgement, deciding which of the two targets appeared to have the higher luminance contrast. Carrasco et al. (2004) reported that attention increased the perceived contrast of the cued target. Unfortunately, although this result fit nicely with contrast gain model of attention that was prominent at the time (Reynolds, Pasternak, & Desimone, 2000), it has not weathered well under the scrutiny that ensued (Itthipuripat, Chang, Bong, & Serences, 2019; Kerzel, Zarian, Gauch, & Buetti, 2010; Linares, Aguilar-Lleyda, & López-Moliner, 2019; Schneider, 2006; Schneider & Komlos, 2008; Zhou, Buetti, Lu, & Cai, 2018). The problem with the comparative judgment task is that it is impossible to disentangle decision effects from real changes in apparent contrast because in the response models, the decision criterion is degenerate

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with apparent contrast (Schneider, 2006; Schneider & Komlos, 2008). Changing the decision threshold has exactly the same effect on subjects' psychometric response functions as does changing the contrast. To distinguish the two, it is necessary to use a different task.

For an alternate task, we previously used the equality judgment, in which subjects report whether the targets have the same or different contrast (Schneider, 2006; Schneider & Komlos, 2008). If attention altered the contrast appearance of stimuli, then it would make two equal-contrast targets appear unequal, and it also could make two unequal targets appear equal by boosting the lower contrast target. But these two scenarios never occurred. In fact, attention had no effect at all on appearance when subjects performed the equality judgment task. In the response model for this task, the decision criterion is orthogonal to the hypothesized boost in perceived contrast due to attention. From these experiments it seemed clear that the purported attentional effects on appearance were merely an artifact of the decision process.

The main motivation for the present study is to investigate how attention influences the decision process. In the comparative judgment, the subjects' decisions are most susceptible to bias when they are the most uncertain and thus most difficult (Fechner, 1860)—when the attended and unattended targets are indistinguishable. When the subjects perceive the two targets as equal in contrast, they must nonetheless still choose one of the two targets. If unbiased, subjects would randomly report one or the other target as having the higher contrast, resulting in the uncertainty being evenly parcellated between the choices. However, when one target is attentionally cued, that target might be prioritized in the decision and be chosen in a larger fraction of the uncertain trials. Beck and Schneider (2017) hypothesized that an attentional cue does not alter the appearance of its target but increases its salience and thus biases its selection.

In the present study, we sought to measure the process of uncertainty allocation between the cued and uncued targets directly, using a three-response task that has been shown to eliminate the confound between biases and perceptual effects (García-Pérez & Alcalá-Quintana, 2012). In this task, subjects had three response options: (1) the uncued target had the higher contrast, (2) the two targets had equal contras, or (3) the cued target had the higher contrast. An additional benefit of this task is that the subjects perform the comparison and equality judgments simultaneously, instead of in separate trials, and thus cannot be criticized as differing in sensitivity, precision, difficulty, or attentional strategy.

We found no significant effects of attention on appearance in this task. However, we did find that subjects with narrower criteria about what constituted equal contrast were more likely to choose the cued target as having higher contrast: the subjects' propensities for choosing the cued target were highly correlated with their decision criteria. In the comparative judgment task, this tendency might be interpreted as attention increasing perceived contrast, but the addition of the equal response option allows us to determine that subjects were merely disproportionately allocating a greater percentage of their responses to the cued target, when they were forced to choose between targets of apparently equal contrast.

Decision mechanism and the "uncertainty stealing" hypothesis

To analyze the three-response task, we used the same three-parameter model used to analyze the comparative and equality judgements in previous studies (Schneider, 2006; Schneider & Bavelier, 2002; Schneider & Komlos, 2008). The difference in contrast between the cued target (c_1) and the uncued target (c_2) is modeled as a normal distribution with mean α, upon which a subject's decision mechanism operates. If the difference in contrast (Δc) is less than a decision criterion τ, the subject is unable to determine which contrast is higher and will respond that the two contrasts are equal ($c_1 = c_2$, blue shaded region in Figure 1A). If $\Delta c < -\tau$, the subject will judge that the uncued target had the higher contrast ($c_1 < c_2$, green shaded region in Figure 1A), and if $\Delta c > \tau$, the subject will judge that the cued target had the higher contrast ($c_1 > c_2$, red shaded region in Figure 1A).

Under the "uncertainty stealing" hypothesis, the attentional cue biases subjects to shift their decision criteria so that, when uncertain, they tend to choose the cued target (red hashed region, Figure 1A). As a result, the attentional cue asymmetrically alters the window of equality, causing the cued target to be more frequently reported as having a higher contrast, and apparently shifting the mean of the underlying contrast distribution, $\alpha > 0$, as shown in Figure 1B. Figure 1C shows the results of uncertainty stealing on a subject's response in the three-response task. The solid lines show a subject's natural responses uninfluenced by attention. The dashed lines show the effects of the attentional cue, changing the decision mechanism by reducing the decision criterion τ and thereby apparently increasing the mean α of the underlying contrast distribution. The result is that the cued target is more often reported as having a higher contrast, and the fraction of "equal contrast" responses is reduced.

In the three-response task, actual changes in contrast appearance can be distinguished from changes in the decision criterion based on the pattern of responses in

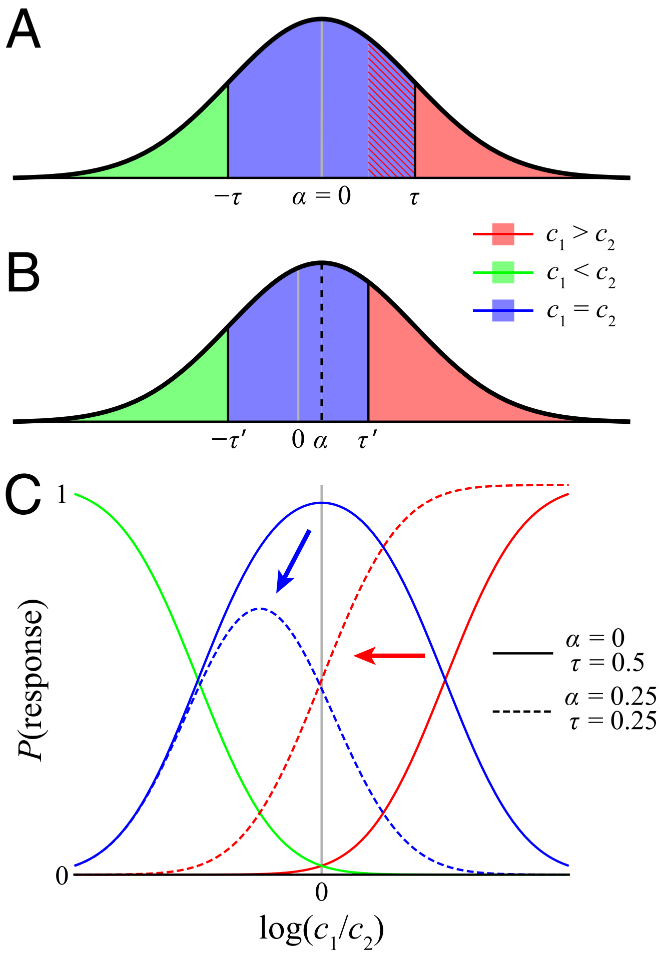

Figure 1. Decision mechanism and "uncertainty stealing." (A) The difference in contrast between the cued target (c_1) and the uncued target (c_2) is modeled as a normal distribution with mean α, on which a subject's decision mechanism operates. If the difference in contrast (Δc) is less than a decision criterion τ, the subject is unable to determine which contrast is higher and will respond that the two contrasts are equal ($c_1 = c_2$, blue shaded region). If $\Delta c < -\tau$, the subject will judge that the uncued target had the higher contrast ($c_1 < c_2$, green shaded region), and if $\Delta c > \tau$, the subject will judge that the cued target had the higher contrast ($c_1 > c_2$, red shaded region). Under the uncertainty stealing hypothesis, the attentional cue biases subjects' decision criteria so that, when uncertain, they tend to choose the cued target (red hashed region). (B) The attentional cue asymmetrically shift the window of equality, causing the cued target to be more frequently reported as having a higher contrast, and apparently shifting the mean of the underlying contrast distribution, $\alpha > 0$. C. The results of uncertainty stealing on a subject's response in the three-response task. The solid lines show a subject's natural responses uninfluenced by attention. The dashed lines show the effects of the attentional cue, changing the decision mechanism by reducing the decision criterion τ and thereby apparently increasing the mean α of the underlying contrast distribution. The result is that the cued target is more often reported as having a higher contrast, and the fraction of "equal contrast" responses is reduced.

the population. In Figure 2, the four plots show different possible response patterns. The green lines model the responses for which a subject indicates that the uncued target (c_2) had a higher contrast ($c_1 < c_2$), the blue lines model the responses in which the subject perceives the two contrasts as equal ($c_1 = c_2$), and the red line models the responses for which the subject indicates the cued target (c_2) had a higher contrast ($c_1 > c_2$). One of the difficulties in analyzing this task across subjects is that the decision criteria can vary considerably across subjects. We recruited a moderate number (20) of subjects to take advantage of this variability by comparing across subjects the decision thresholds to the modeled boosts of attention. Figures 2A and 2C show responses for two subjects with a liberal (Figure 2A) and narrower (Figure 2C) threshold for reporting contrast equality (τ), but no apparent effect of attention on apparent contrast ($\alpha = 0$). If attention changed appearance and not the decision criterion, we would observe a lateral shift in the responses but no changes in amplitude (α and τ independent in the population), as in from Figures 2A → 2B or 2C → 2D. However, if attention changed the decision criterion as in the uncertainty stealing hypothesis, then we would observe a lateral shift coupled with a decrease in amplitude due to the narrowed τ threshold, as in Figures 2A → 2D (α and τ correlated in the population). The result is that the cued target is more often reported as having a higher contrast, and the fraction of "equal contrast" responses is reduced. Although we cannot measure this shift in individual subjects, because removing the cue would change the decision process, we can distinguish the two scenarios based on the pattern of responses across subjects. If the shifts in the comparative judgment are due to actual changes in perceived contrast, then the α and τ parameters should be independent in the population. However, if the shifts are due to changes in the decision criterion and not actual changes in perceived contrast, then we should expect the α and τ parameters to be correlated, with the subjects exhibiting large α also having small τ.

Methods

Subjects

Thirty-two subjects (11 female), mean age 24.6 years (range 19–43), were paid to participate in the study. Two subjects were excluded after not being able to perform the practice task, and no data were collected from them. We aimed to recruit 20 subjects and kept enrolling subjects until we had 20 who passed the inclusion criterion of the fit parameter $\sigma < 1$ (see below) in their data. This is an objective measure of the precision of their responses. Ten subjects did not

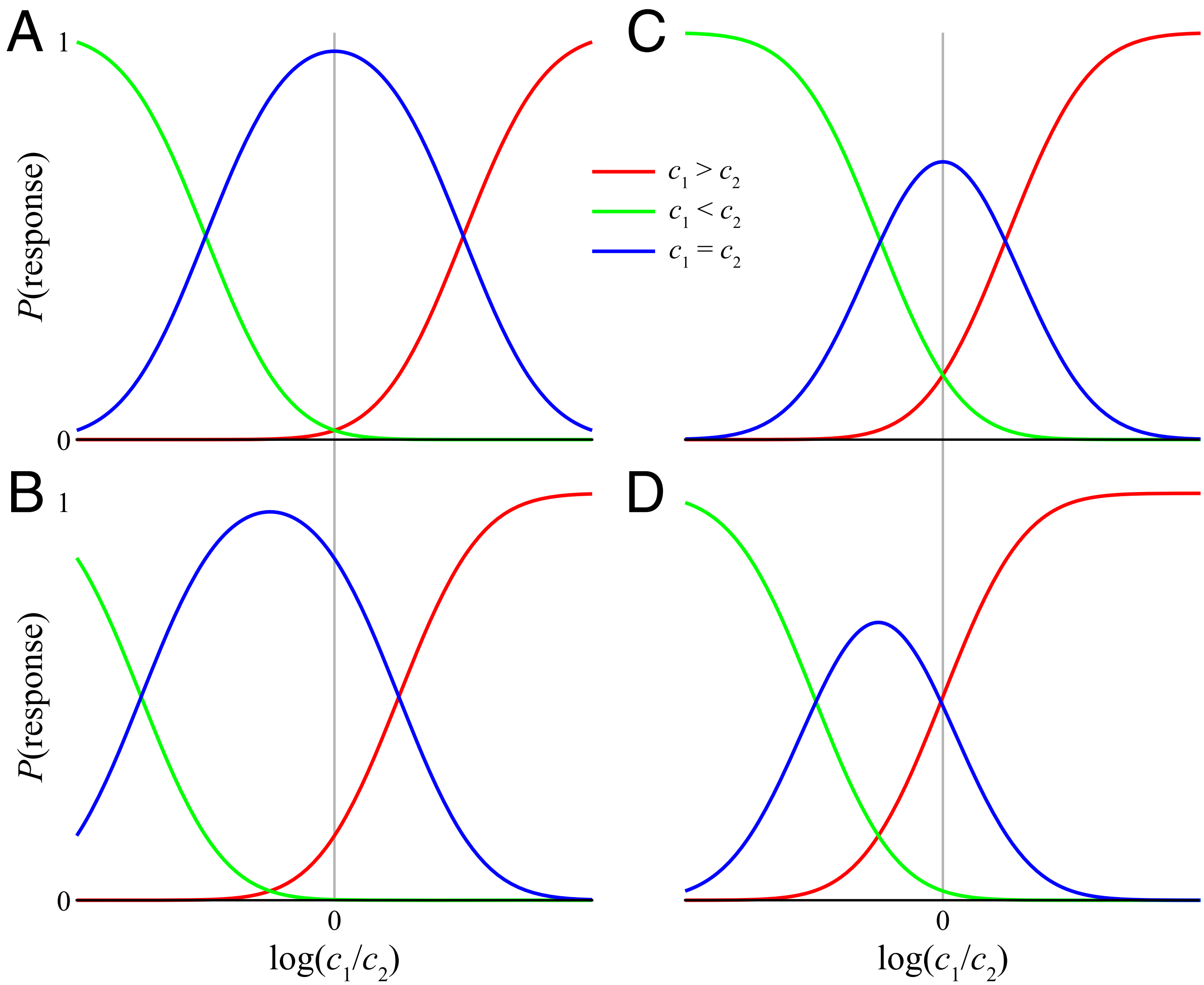

Figure 2. Models of response possibilities. The four plots show different possible response patterns. The green lines model the responses for which a subject indicates that the uncued target (c_2) had a higher contrast ($c_1 < c_2$), the blue lines model the responses in which the subject perceives the two contrasts as equal ($c_1 = c_2$), and the red line models the responses for which the subject indicates the cued target (c_2) had a higher contrast ($c_1 > c_2$). Different subjects naturally have a different decision criterion. A and C show responses for two subjects with a liberal (A) and narrower (C) threshold for reporting contrast equality (τ), but no apparent effect of attention on apparent contrast ($\alpha = 0$). If attention changes appearance and not the decision criterion, then we would observe a lateral shift in the responses but no changes in amplitude (α and τ independent in the population), as in from A $\rightarrow$ B or C $\rightarrow$ D. However, if attention changes the decision criterion as in the uncertainty stealing hypothesis, then we would observe a lateral shift and also a change in amplitude, as in A $\rightarrow$ D (α and τ correlated in the population).

meet this criterion and were excluded after their data were collected—many subjects were not performing the task and appeared to be responding randomly. Because of the unusually high number of exclusions, we show the data from all subjects, including these 10 excluded subjects, in Appendix B. There is a clean separation of the included and excluded subjects using σ as the criterion. The included subjects had σ values well below 1 (the largest being 0.79 at one contrast), and the excluded subjects had σ values well above 1 (no $\sigma < 1$ at any contrast, and at least 1.72 in one or more of their 3 contrast levels tested). The excluded subjects' responses only weakly depended on the stimuli. These subjects performed normally during the training runs while they were being observed by the experimenter, but when they were alone in the testing room, they seemed to respond haphazardly. It should be noted that excluding the subjects with large σ parameters does not limit the maximum amplitude of the "equal" response. This maximum value is governed by both the σ and τ parameters, but primarily τ. For example, note that S19 and S28 (excluded subjects shown in Appendix B) have a very high probability of the "equal" response (blue dots and line) even though they have large σ, because they also have large τ.

All subjects had normal or corrected-to-normal visual acuity, gave their written, informed consent under a protocol approved by the York University Human Participants Review Committee, were naïve to the purpose of the experiment, and were compensated for their participation in the one-hour session (except S1, a research assistant who was an author but initially naïve as to the purpose of the experiment, was not compensated, and participated in 3 sessions during piloting, over which the data were aggregated).

Apparatus

The stimuli were generated on a Macintosh Pro computer (Apple, Inc., Cupertino, CA) using the Matlab (The Math Works, Inc., Natick, MA) programming language and displayed using Psychophysics Toolbox 3 functions (Brainard, 1997; Kleiner, Brainard, Pelli, Ingling, Murray, & Broussard, 2007; Pelli, 1997) on a ViewSonic P225fb monitor (ViewSonic Corp., Walnut, CA) with a refresh rate of 119.6 Hz. The stimuli durations reported below were constrained by the refresh rate and were rounded up to an integral multiple of the 8.4 ms frame rate. The output channels of the video card were combined with a video attenuator device (Video Switcher, Xiangrui Li, Los Angeles, CA, USA) to enable 12-bit precision in the gray-scale luminance values (Li, Lu, Xu, Jin, & Zhou, 2003). The gamma function and luminance of the monitor were measured using an LS-100 photometer (Konica Minolta Photo Imaging USA, Mahwah, NJ, USA).

Visual stimuli

A diagram of the stimulus sequence is shown in Figure 3. Two Gabor stimuli targets, 4 cpd sine gratings, oriented vertically, zero phase and Gaussian envelopes with a standard deviation of 1°, were simultaneously presented for 40 ms on a uniform gray field. The centers of the targets were located 4° eccentricity to the right or left of the fixation point. At 120 ms before the onset of the targets, a 0.3° diameter black dot was presented for 67 ms at the location 1.5° directly above the center of one of the two targets. The luminance contrasts of the two targets were distinct and were defined as $\frac{L_1-L_2}{L_1+L_2}$, where L_1 is the maximum luminance of the sine wave component of the Gabor and L_2 is the minimum. The mean luminance of the sine wave components equaled the background luminance, 85 cd/m^2. The contrast of the cued target was 20%, 25%, or 30%, and the contrast of the uncued target was chosen from 21 different evenly distributed logarithmic range of contrasts spanning ± 1 natural log units relative to the cued target contrast.

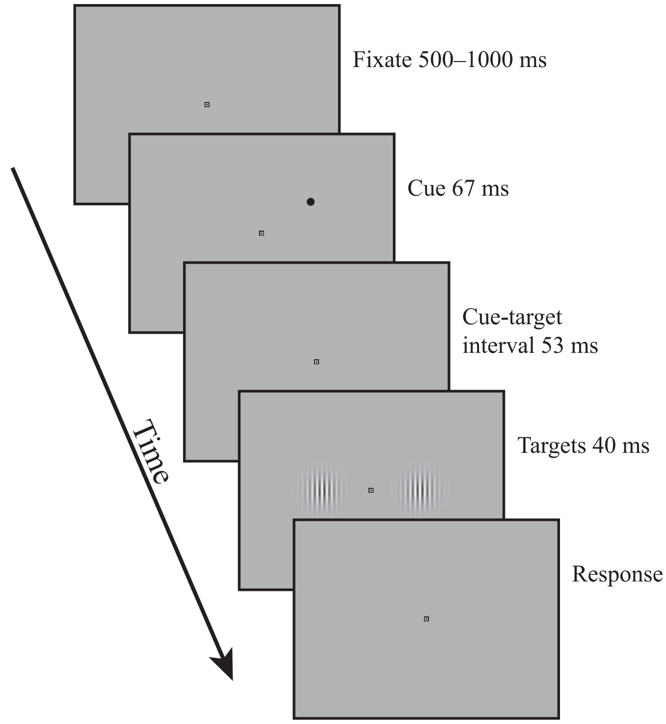

Figure 3. Stimulus sequence. Subjects fixated for 500–1000 ms, after which a cue appeared at 4° eccentricity on the left or right. The cue disappeared after 67 ms and 120 ms after the cue onset, two Gabor grating stimuli appeared centered at the same eccentricity, one of which was slightly below the location where the cue had appeared. After 40 ms, the stimuli disappeared, and subjects reported their relative contrasts.

Procedure

Subjects were seated in a dark room and viewed the display unrestrained from 50 cm. The cue stimulus appeared randomly on the left or right for each trial. Each of the 63 combinations of three contrast levels of the cued target and 21 relative contrast levels of the uncued target was repeated 20 times (60 for S1 across three sessions), for a total of 1260 trials (3780 for S1). The pairs of target contrasts were randomly interleaved throughout the experimental session.

The task of the subjects on each trial was to determine whether the two targets had equal contrast, or if not, which target had the higher contrast. Subjects pressed the left arrow key on the keyboard to indicate that the target on the left had the higher contrast, the up arrow to indicate that the two targets had equal contrast, or the right arrow to indicate that the target on the right had higher contrast. Subjects had unlimited time to respond. The cue stimulus for the next trial appeared 0.5 to 1 s after the response was made. The experimental sessions lasted approximately one hour, during which the observers were automatically allowed to rest and break fixation after every 50 trials, resuming the experiment when ready.

In pilot experiments, subjects were reluctant to use the "equal" response, meaning that their τ criterion was very small, essentially collapsing the three-response options into two, resulting in a two-response comparative judgement. We determined that the two-response task was easier and faster for the subjects. Therefore, to encourage the subjects to perform the three-response task and utilize all three response options, the subjects in the main experiment were encouraged to respond "equal" unless they were certain which target had the higher contrast. This sort of manipulation of subjects' criteria is common in psychophysics, for example, in tasks where there may be a tradeoff between speed and accuracy. The instructions were successful in getting subjects to use this response option and resulted in an expanded range of τ criteria across the population. Subjects were also instructed to respond as accurately as possible, but to give their first impression, and that perseverating on their response would not help.

Each subject began the experiment with a practice run, consisting of 55 trials, with the cued contrast of 25% and five repetitions each for 11 different uncued contrasts, equally spanning the contrast range within ± 1 natural log units relative to the cued target contrast.

Data analysis

The equivalent contrasts of the cued targets were determined by fitting the subjects' three responses to a three-parameter model combining the comparative and equality judgment models (Schneider, 2006; Schneider & Bavelier, 2002; Schneider & Komlos, 2008):

$$P(c_1 > c_2) = 1 - \Phi\left(\frac{\tau - \Delta c - \alpha}{\sigma}\right)$$
$$P(c_1 < c_2) = \Phi\left(\frac{-\tau - \Delta c - \alpha}{\sigma}\right)$$
$$P(c_1 = c_2) = 1 - P(c_1 > c_2) - P(c_1 < c_2)$$

where $\Phi(x) \equiv \frac{1}{2\pi}\int_{-\infty}^{x} e^{-u^2/2} du$ is the cumulative normal distribution, τ is the contrast difference criterion, Δc is the actual difference in contrast between the cued target (c_1) and the uncued target (c_2), σ^2 is the variance of the contrast difference and α is the hypothesized attentional boost in perceived contrast of the cued target relative to the uncued target. Each parameter has units of logarithmic contrast. The variances of the estimates of the model parameters were derived for each subject by assuming that the likelihood function is distributed in parameter space approximately normal near the optimal parameters (MacKay, 1992), and these variances were used to compute the weighted mean of each model parameter across subjects (Schneider, 2006). The perceived contrast was calculated from the model fit as $c' = ce^{\alpha}$ for each actual contrast level c of the cued target.

As previously noted, the α parameter is orthogonal to the σ and τ parameters in the model (Schneider & Komlos, 2008). Changing the σ and τ parameters can alter the amplitude and width of the equality judgement, but it will not affect its central tendency (α). Likewise, changing α will move the entire set of curves to the left or right, but will not change the amplitude or slope of the functions. The parameters in this model are not highly intertwined. This means that in the fitting procedure, a change in one parameter is not well able to compensate for changes in another to yield the same curve fit. We analytically computed the Hessian matrix at the fit point to determine the standard errors of the fit parameters. As shown in Appendix A, the standard errors are small and the model fits the data well. The dependency of a fit parameter on the others can be calculated by holding the other parameters constant (Motulsky, n.d.). We found that the mean dependencies across contrasts and subjects for α, σ, and τ were .34, .47, and .35, respectively. These are very low values, meaning it is difficult for one parameter to compensate in the fit for changes in the other parameters, as they are describing quite different aspects of the curve.

The model parameters for each subject and contrast level were entered into a mixed-effects repeated measures regression, to determine the effect of σ and τ on α, with contrast as the within-subject effect, and subject as the random effect. These statistics were computed using JMP Pro 15.2.0 for Mac (SAS, Cary, NC, USA).

Results

The three-parameter model fit the three response functions well, as seen in the individual subject data in Appendix B. The modeled effect of attention on perceived contrast across subjects is summarized in Figure 4. In this figure, we plot the equivalent contrast that the subjects report, as derived from the response model, for each of the three contrast levels tested. There was an obvious trend across the three cued target contrast levels tested for the perceived contrast of the cued target to be higher than the veridical contrast, however this trend was not significant at any of the levels tested, although nearly so ($p = 0.054$) for the 30% contrast stimuli.

It might seem that attention changed perceived contrast, but the main objective of this study was to determine whether this result was due to an actual

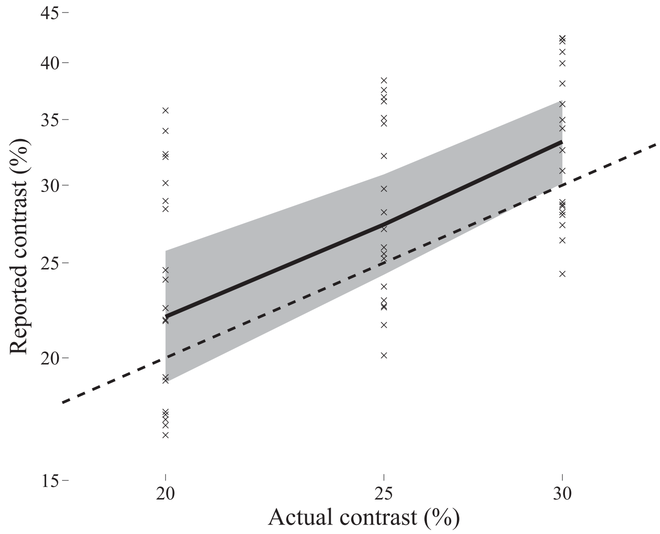

Figure 4. Equivalent contrast. The equivalent contrast as determined by the response model is plotted as a function of actual contrast, $c' = ce^{\alpha}$. Each $\times$ symbol represents a single subject. The solid line is the equivalent contrast calculated from the weighted average of the α parameters across subjects. The shaded region shows the extent of the 95% confidence interval.

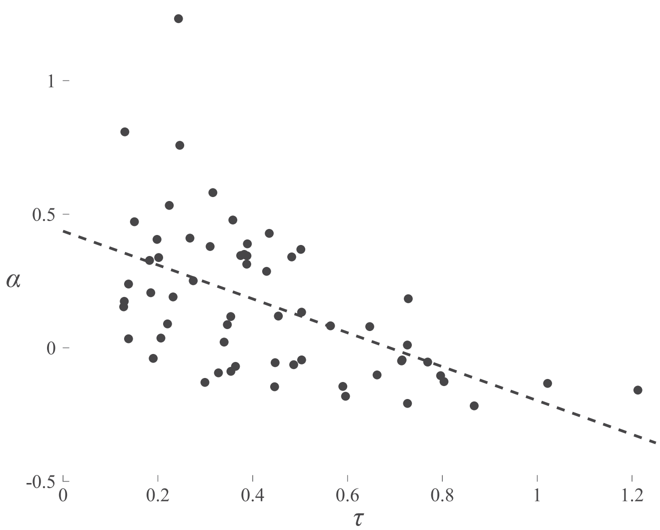

Figure 5. α and τ correlation. Each dot represents the α and τ parameters derived from the fit to a single subject and single cued target contrast. The dashed line is the linear fit. The correlation was $r = -.54$, $p \leq 0.0001$. See text for the full statistical analysis.

change in perception or rather a change in the subjects' decision criteria. We sought to test whether the decision criterion would vary with the modeled perceived contrast, and this is shown to clearly be the case in Figure 5. There was a highly significant correlation, $r = -0.54$, $p < 0.0001$, between the α and τ parameters, such that the higher the modeled α, the smaller the modeled τ. However, this simple correlation does not take into account the high degree of correlation of the parameters within a subject across the three contrast levels, and so the p value is inflated. To properly verify the effect, we computed a mixed-effects repeated measures regression, to determine the joint effects of σ and τ on α, with contrast as a within-subject effect, and subject as the random effect. The fixed effects parameter estimate for τ on α was -0.57, $F_{1,52} = 25.8$, $p < 0.0001$. The effect of contrast was also significant, $F_{1,37.6} = 9.0$, $p = 0.0006$, with the effect at 30% contrast being weaker. We then calculated the correlation for each contrast separately, $r = -0.64$, -0.63 and -0.39, $p = 0.0026$, 0.0033, and 0.093 for the 20%, 25%, and 30% cued target contrasts (α was not correlated with σ, $p =$ 0.89, 0.56, and 0.94).

Subjects reporting veridical contrast (α near zero) tended to have a more liberal threshold for judging the two targets as equal in contrast (larger τ, on the right side of the plot in Figure 5), whereas subjects who exhibited a greater attentional effect (larger α) tended to have a stricter equivalence threshold (smaller τ, left side of Figure 5). This supports the uncertainty stealing hypothesis, that when the subjects are uncertain which target has the higher contrast, that uncertainty is preferentially parceled to the cued target response. This is a change in the decision criterion τ and does not reflect an actual change in perceived contrast caused by the cue.

Discussion

The results of this study directly demonstrate attention changing the decision criterion and not altering perceived contrast. The subjects' decision criteria were strongly correlated with their tendency to choose the cued target, with the subjects reporting the largest effects of attention also exhibiting the strictest decision threshold. If using a simple comparative judgement test, the effects of attention on the perceived contrast could not be distinguished from changes in the decision criterion, and so such changes in the decision criterion have mistakenly been attributed to an alteration of contrast appearance by attention (Carrasco et al., 2004).

The results of the present study are consistent with the results of previous studies that have used a equality judgment to disentangle changes in perceived contrast from changes in the decision criterion (Schneider, 2006; Schneider & Komlos, 2008) and also studies that have explicitly measured response biases in the comparative judgment (Itthipuripat et al., 2019). This latter study did report an effect of attention on appearance at low contrasts using an equality judgment (though see Schneider, 2020). Anton-Erxleben, Abrams, and Carrasco (2010) tried to replicate Schneider & Komlos (2008) using equality judgments and claimed that they did show that attention increased perceived contrast, but they used a much smaller stimulus and as a result, the subjects' equality judgment psychometric curves were skewed at low contrast; when this was taken into account, the effects of attention on appearance disappeared (Schneider, 2011). Anton-Erxleben, Abrams, & Carrasco (2011) claimed that attention still had an effect on contrast at which the psychometric functions were maximum, but Beck & Schneider (2017) pointed out that this maximum point was still dependent on the low-contrast skew and was not an independent measure of attention. Another study used somewhat different stimuli and procedures and showed opposite effects of attention on high vs. low contrast stimuli, demonstrating the profound effect of the task and subjects' decisions (Zhou et al., 2018).

There is considerable variation among the population in the extent of the decision bias. Some subjects are very precise in their judgements and report the veridical contrast even in the presence of an attentional cue, whereas other subjects exhibit large attentionally-driven biases. Kerzel, Zarian, Gauch, and Buetti (2010) showed that the less precise the subjects were in their judgments, in terms of the variance of their responses (the σ parameter of our model and not the threshold τ), the larger effects they exhibited in the comparative judgment task. They also concluded that attention changes the decision criteria and not perceived contrast.

The problem with the forced choice comparative judgment is well known that the decisions biases occur most often in trials in which the subject is uncertain, i.e. when the two stimuli look identical (Fechner, 1860), and methods have been proposed to counteract it (Jogan & Stocker, 2014) or to explicitly model the indecision (García-Pérez & Alcalá-Quintana, 2011). Including the third "equal" option as we have done in this study has been previously shown to allow the effects of biases and perception to be distinguished (García-Pérez & Alcalá-Quintana, 2012).

As we noted in the Methods section above, subjects in pilot testing were naturally disinclined to use the "equal" option, and to ensure that the subjects were performing the three-response task and utilizing the "equal" response option. When τ is very small, the three-response task collapses into a two-response comparative judgment, and when τ is large, the three-response task resembles the equality judgment. We needed to alter the instructions of the task to ensure that, across the population, subjects exhibited a range of τ criteria. Thus, we were able to examine the continuum of results spanning between the comparative judgment, which appears to show an effect of attention on appearance, and the equality judgment, which does not. The uncertainty stealing hypothesis discussed herein thus explains the discrepancy between these two types of judgments, and the range of τ criteria demonstrates the evolution of the decision bias in the comparative judgment, as τ approaches zero. The results show that the effects of attention upon perceived contrast can be entirely explained by changes in decision criteria, and there is no residual effect on the actual stimulus properties that can be observed.

Although early neural recordings seemed to show that attention operated through a contrast gain mechanism (Reynolds et al., 2000), and thus it was natural to assume that attention would operate similarly to increase perceived contrast, more recent neural recordings show that contrast gain is generally not the mechanism by which attention operates (Lee & Maunsell, 2010; Williford & Maunsell, 2006) and that attention and contrast are separable codes in visual cortex (Pooresmaeili, Poort, Thiele, & Roelfsema, 2010). Our empirical observations that attention does not alter appearance therefore are supported by the neural recordings, and our findings support the notion that cognition in general does not affect perception (Firestone & Scholl, 2015).

It is clear from the many results that attention does affect the decision process, because eliminating attention, for example lengthening the cue lead time or displaying the cue after the target, also eliminates the decision effects; but *why* attention affects the decision is less clear. In Beck and Schneider (2017) we discussed the salience account (see also Kerzel, Schönhammer, Burra, Born, & Souto, 2011; Schneider, 2011; Schneider & Komlos, 2008), by which attention enhances the salience of a stimulus without altering its appearance. The cued target is more compelling, as for example a singleton pop-out stimulus would be in a search array, but it does not actually *look* any different. When subjects are uncertain as to which target has the higher contrast, for example when the targets are in fact identical in contrast, but they are still forced to choose one of the targets, they tend to choose the cued target because it is more salient. This salience account is thus parsimonious with the uncertainty stealing mechanism described herein.

Conclusions

The results of this study demonstrate that, rather than actually increasing the perceived contrast of a cued target, attention changes the decision mechanism such that subjects, when uncertain which of two targets had the higher contrast, tend to allocate this uncertainty to the cued target. This explains why, in a comparative judgment in which subjects are forced to choose between two apparently equal targets, that the cued target is chosen more frequently, shifting the psychometric function towards the cued target even though its apparent contrast is unaltered. Since the effects of attention upon the decision mechanism cannot be distinguished from an actual change in perceived contrast using a comparative judgement, it is necessary to use an equality judgement or to include a third "equal" response as we have done here, to accurately account for subjects' perceptions and decisions.

Keywords: attention, appearance, contrast, psychophysics, vision

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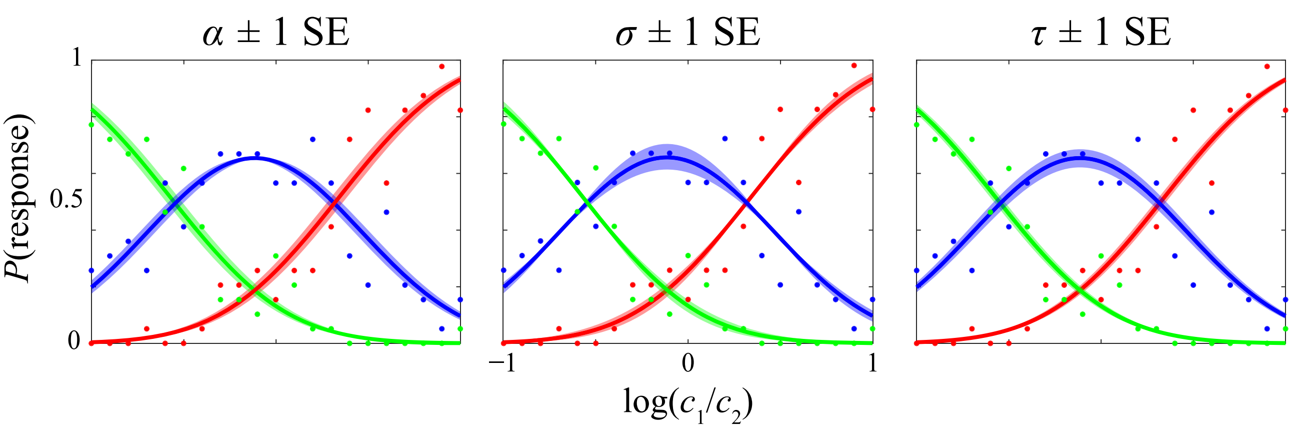
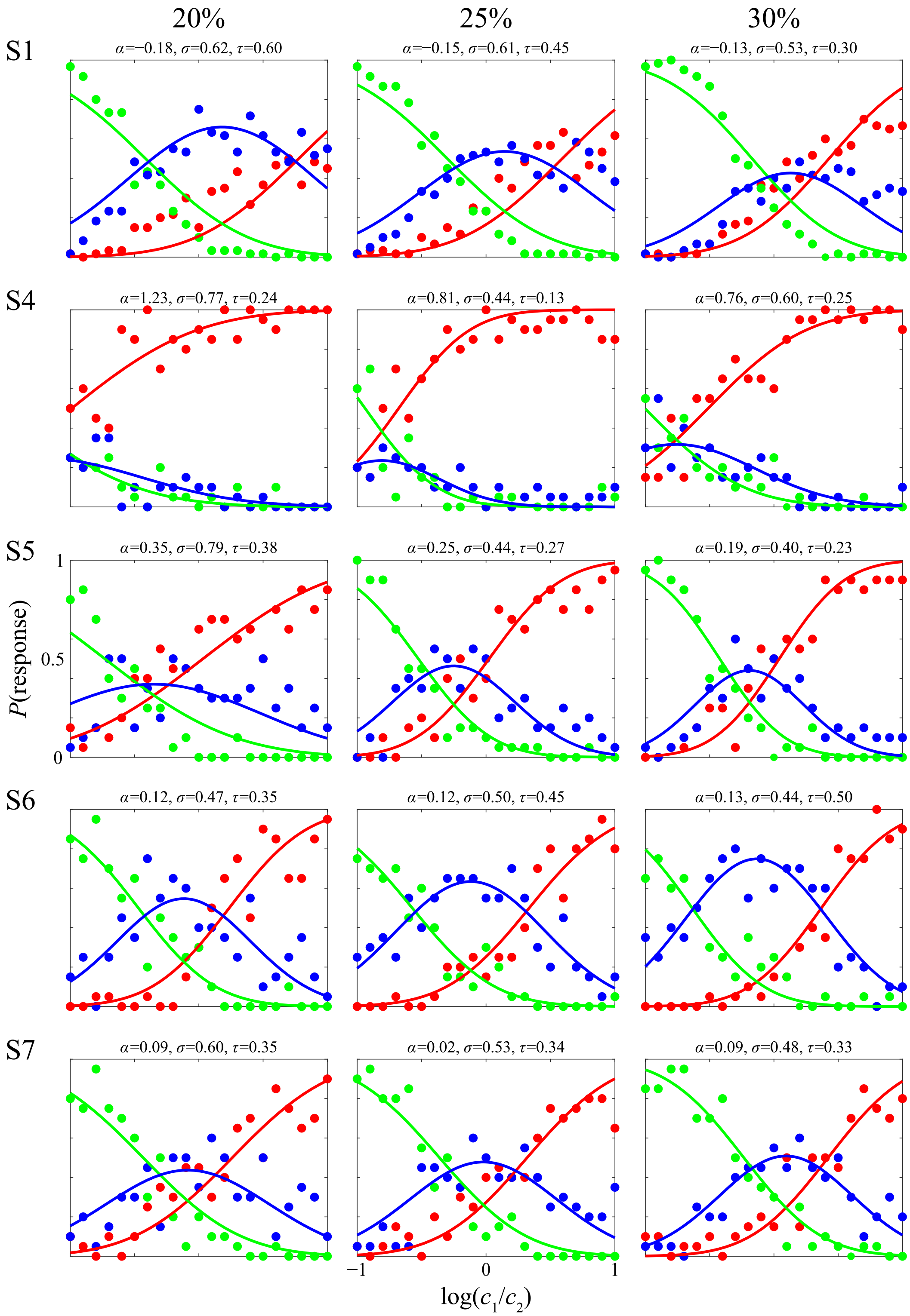
Appendix A

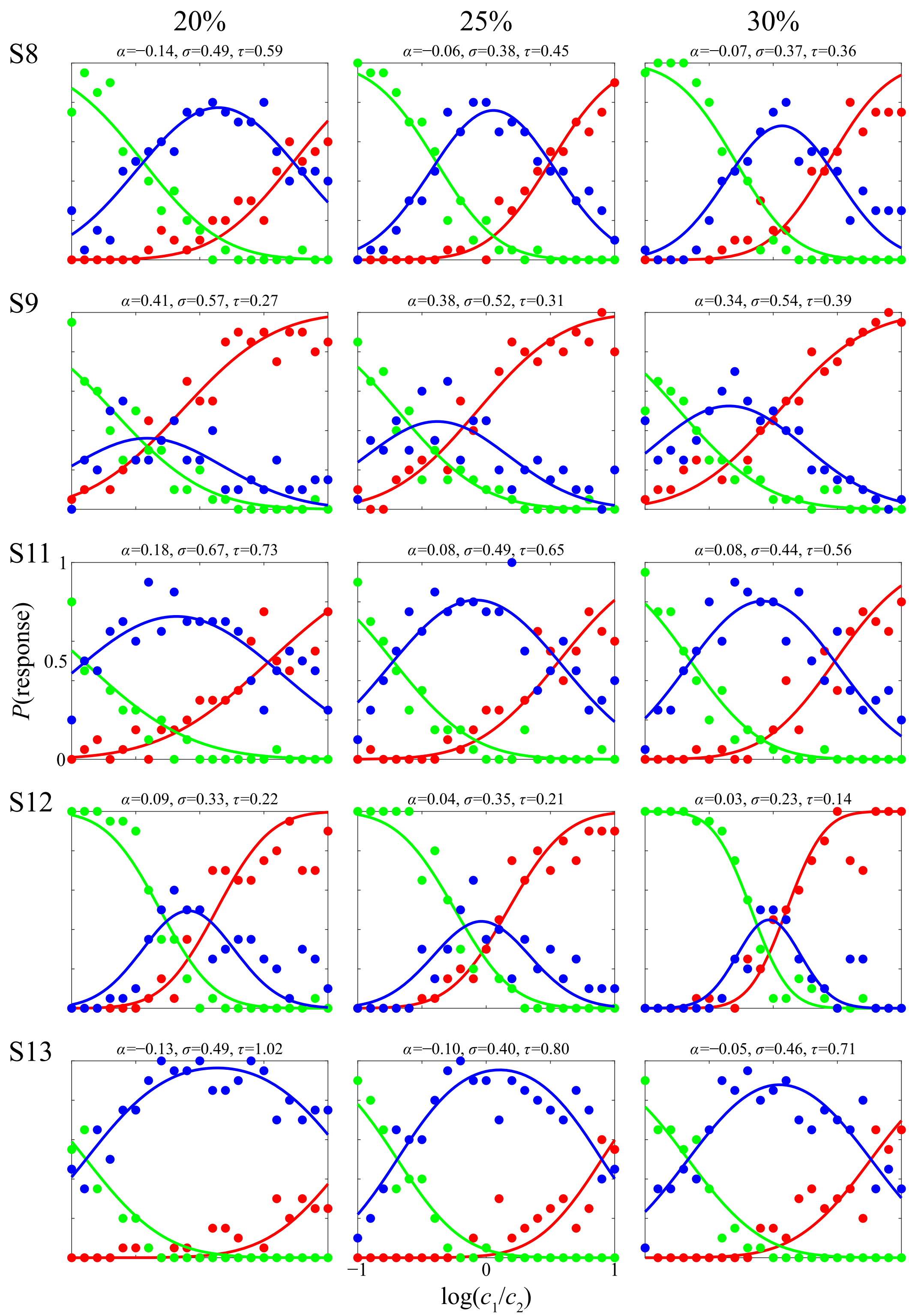


Appendix 1. A plot of the data and fit for a typical subject (S6 at 25% contrast), showing the fits that result in the range of ±1 standard error (SE) for each of the three fit parameters. As noted in the Methods, the α and τ parameters are orthogonal in the model, they are not highly intertwined in the fit, and the magnitude of the fit error is much smaller than that of the variance among subjects. The correlations between parameters that we observe in this study cannot be a result of these issues.

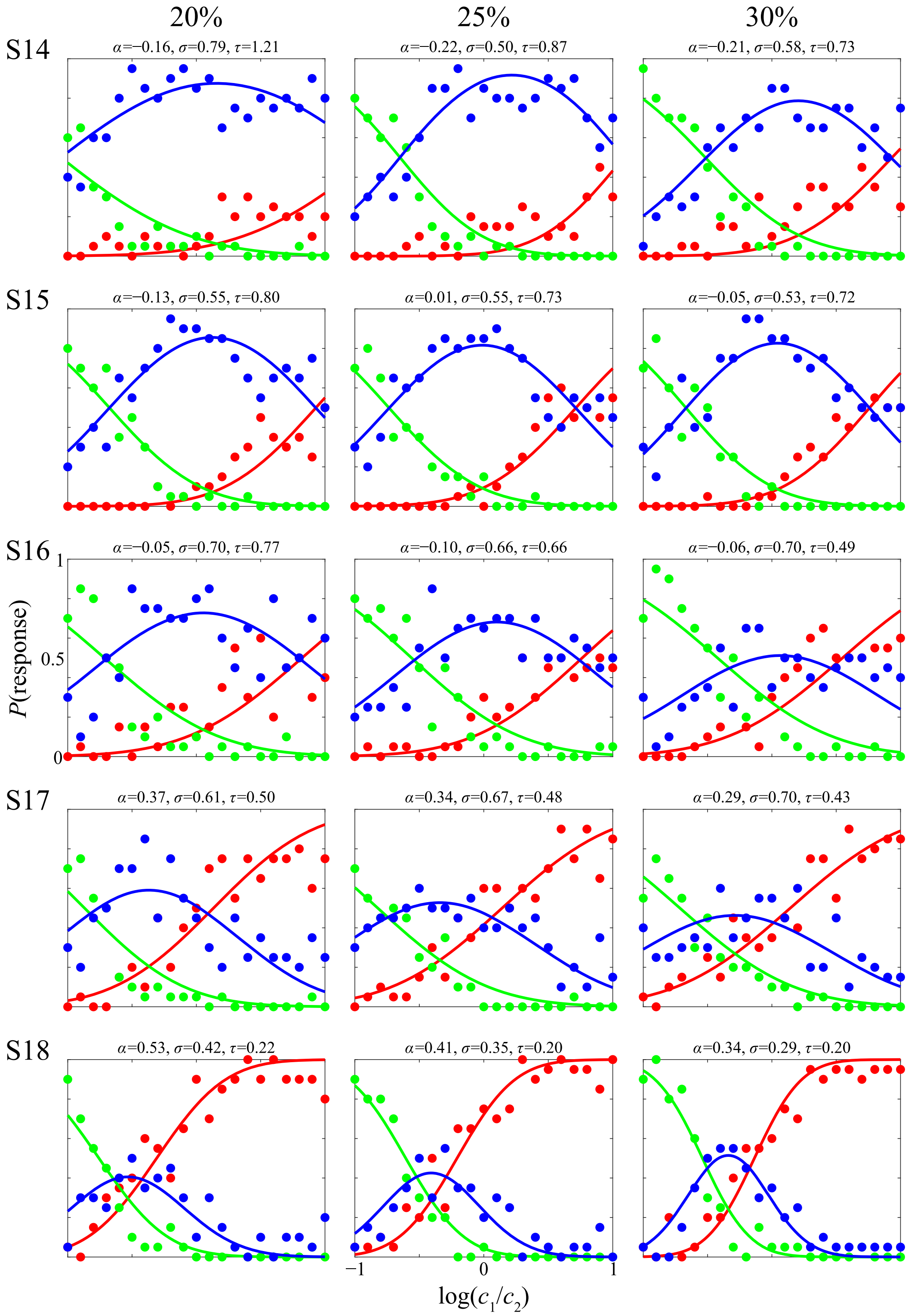
Appendix B



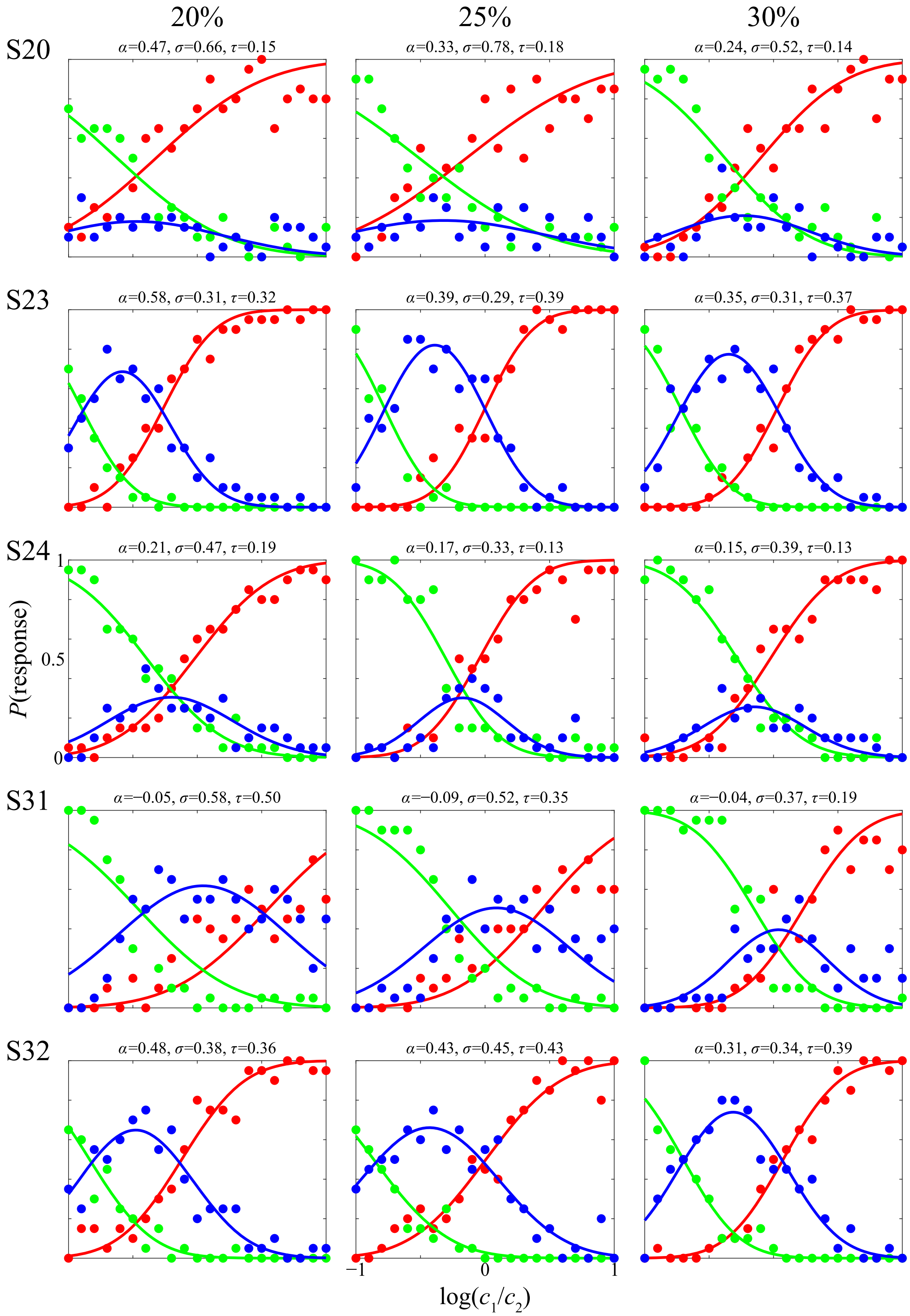
Appendix 2. The individual data for all subjects are shown. The three plots in each row belong to the same subject. The three columns represent the three different cued target contrasts (20, 25 or 30%). The filled circles plot the probability of each response for each cued target contrast (c_1) and uncued target contrast (c_2), and the solid lines are the three-response model fits. The fit parameters are shown at the top of each sub-plot. The first 20 subjects shown were included in the study, and the last 10 subjects were excluded, as they did not meet the inclusion criterion of $\sigma < 1$ for any of their model fits (see Methods).



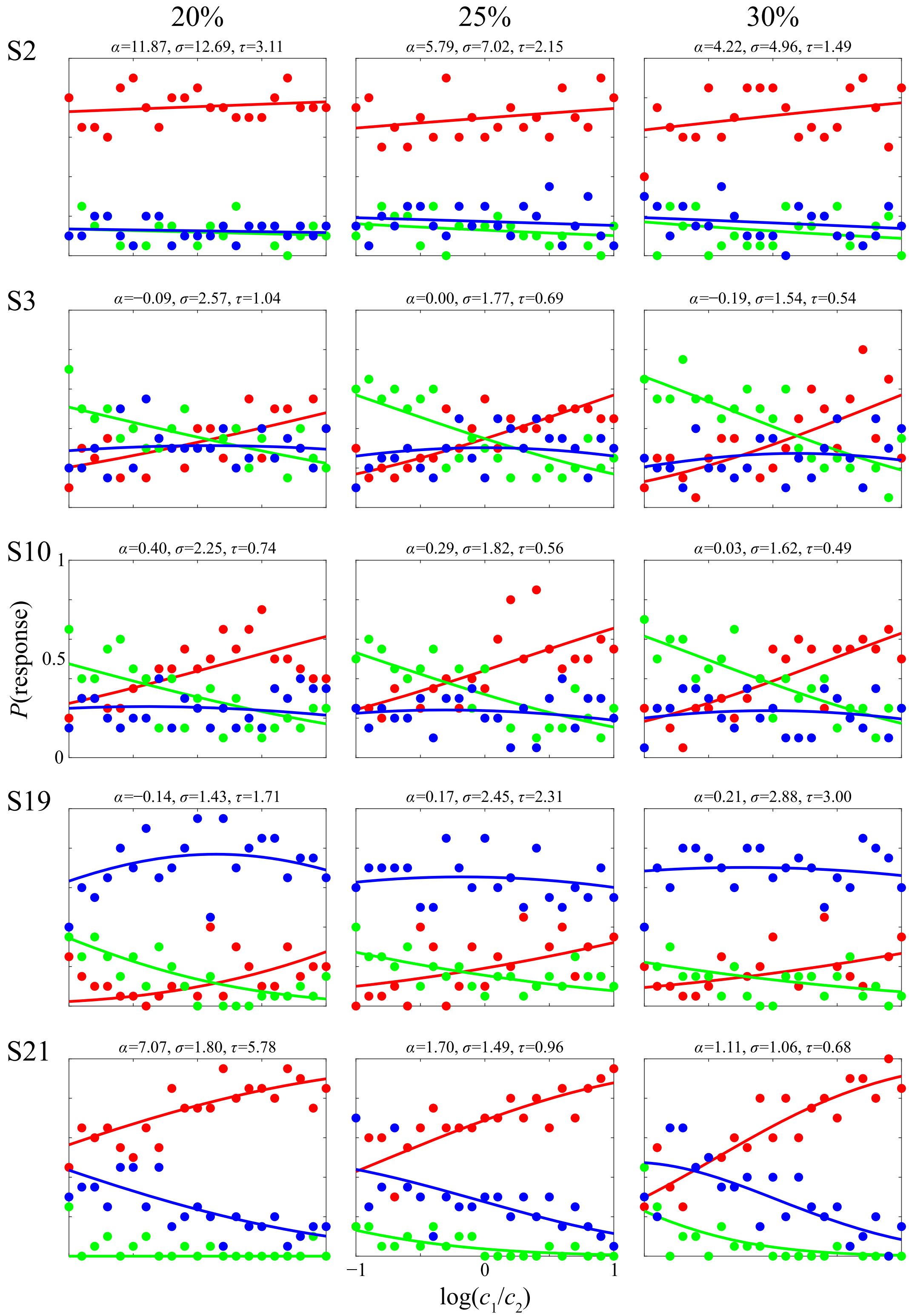
Appendix 2. Continued



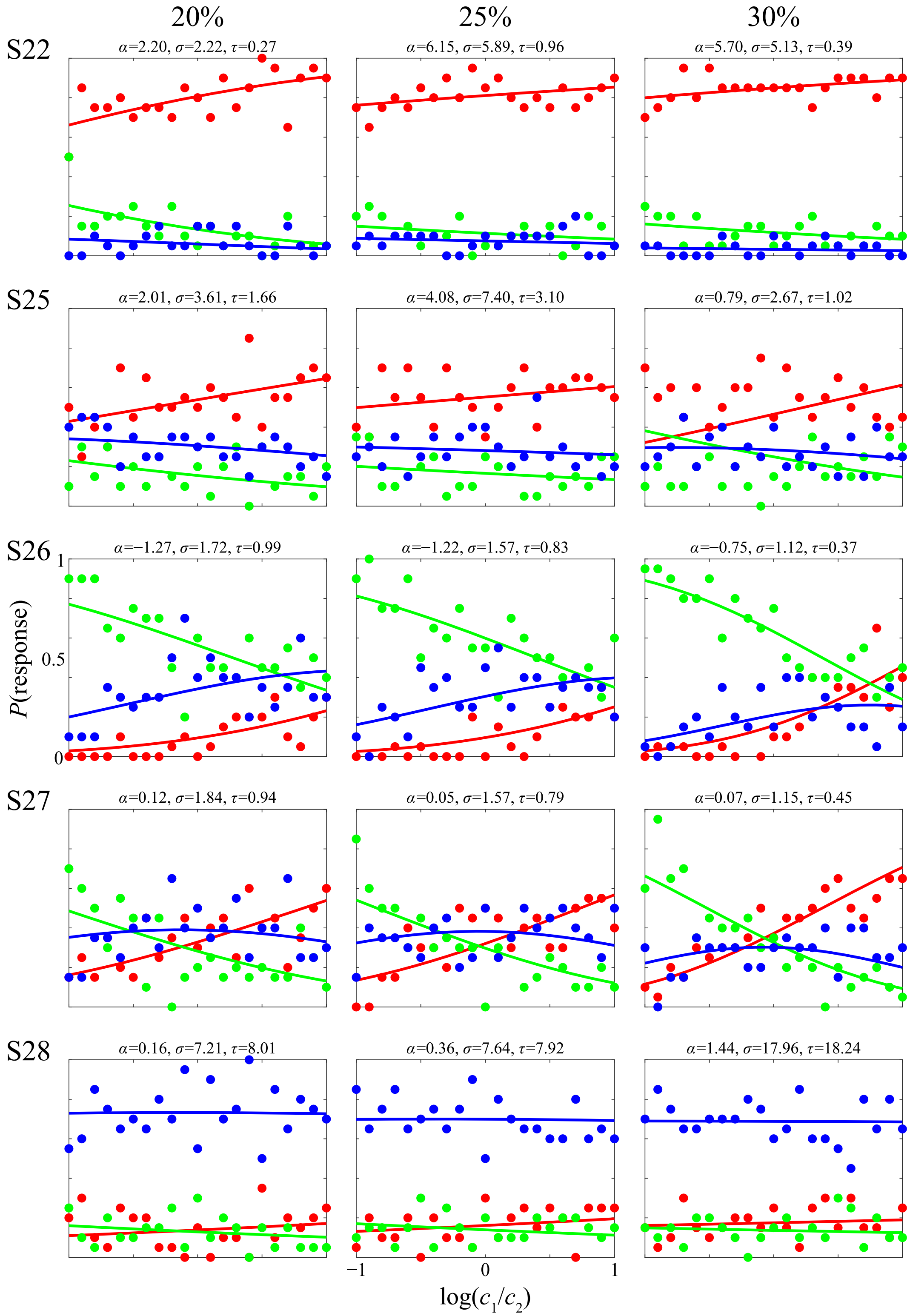
Appendix 2. Continued



Appendix 2. Continued



Appendix 2. Continued



Appendix 2. Continued