Perceptual Learning in Contrast Detection: Presence and Cost of Shifts in Response Criteria

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Contemporary theoretical accounts of perceptual learning typically assume that observers are either unbiased or stably-biased across the course of learning. However, standard methods for estimating thresholds, as they are typically used, do not allow this assumption to be tested. We present an approach that allows for this test, specific to perceptual learning for contrast detection. We show that reliable decreases in detection thresholds and increases in hit rates are not uniformly accompanied by reliable increases in sensitivity (d'), but are regularly accompanied by reliable liberal shifts in response criteria (c). In addition, we estimate the extent to which sensitivity could have increased in the absence of these liberal shifts. These results pose a challenge to the assumption that perceptual learning has limited or no impact on response criteria.

Perceptual learning is defined as an improvement in performance due to repeated sensory experience (e.g., Fine & Jacobs, 2002; Gibson & Walk, 1956). Studies of perceptual learning date to the origins of sensory science (see discussions in Ahissar & Hochstein, 1998; Sinha & Poggio, 2002), and improvements have been demonstrated in a variety of tasks (e.g., Ball & Sekuler, 1987; Fendick & Westheimer, 1983; Karni & Sagi, 1993; McKee & Westheimer, 1978), including contrast detection and discrimination (DeValois, 1977; Dorais & Sagi, 1997; Fiorentini & Berardi, 1981; Mayer, 1983; Sagi & Tanne, 1994; Sowden, Davies & Roling, 2000; Yu, Klein & Levi, 2004). Given often high degrees of stimulus specificity, theoretical accounts of perceptual learning have tended to emphasize low-level, feed-forward mechanisms (although see, e.g., Ahissar & Hochstein, 2002; Petrov, Dosher & Lu, 2005).

The present study considers an alternative hypothesis. Specifically, we concern ourselves with the possibility that changes in response bias play a role in the acquisition of perceptual skill. This study replicates and extends earlier work (Copeland & Wenger, 2003, 2005; Rasche & Wenger, 2004; Wenger & Rasche, 2005) which documented liberal shifts in response bias in perceptual learning for both contrast detection and discrimination. To the extent that decisional factors are playing a role in perceptual learning (either in addition to or instead of changes in perceptual sensitivity), there is the need to consider influences, mechanisms, and cortical circuits that extend beyond those considered in most models of perceptual learning (e.g., Dosher & Lu, 1999; Gold, Bennett & Sekuler, 1999; Petrov, Dosher & Lu, 2005), which typically assume that decisional criteria are not influenced by practice. The work reported here documents the need to consider these possibilities and provides estimates of the extent to which shifts in decisional criteria actually produce levels of perceptual performance that are systematically lower than what would be the case otherwise (see also Seitz, Nanez, Holloway, Koyama & Watanabe, 2005).

Methodological and Conceptual Issues

To our knowledge, prior to our earlier work (Copeland & Wenger, 2005) there have been no systematic investigations of the possible role of shifts in decisional criteria in perceptual learning. This is not reflective of any ignorance of the issue by investigators: indeed, most work has attempted to carefully control stimulus and response situations in an attempt to minimize the effects of bias (e.g., Dosher & Lu, 1999; Lu & Dosher, 2004). In particular, a standard approach in this literature has been to rely on experimental methods (such as two-alternative forced choice methods, see e.g., Klein, 2001; Leek, 2001; Macmillan & Creelman, 2005) that, by design, are assumed to obviate the role of decisional bias. However, there are three potential problems with this assumption. First, as it is typically applied to *detection*, it confounds bias in the labeling of the target stimulus property with bias in distinguishing between its presence or absence. For example, in a two-interval detection task (e.g., Bonneh & Sagi, 1999; Danilova & Kojo, 2001; Kontsevich & Tyler, 1999; Tanaka & Sagi, 1998; Wehrhahn & Dresp, 1998), the target property will always be present in one of the two (spatial or temporal) intervals. In this design, while it is possible

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to estimate an observer's bias for choosing one of the two intervals, there are no data available to allow an estimate of bias for distinguishing between presence and absence,[1] since it is unclear whether the choice of the incorrect interval is a false alarm or a miss. Second, even as concerns identification responses, the design does not guarantee an absence of bias (see in particular Macmillan & Creelman, 2005; Nisbett & Wilson, 1977). Finally, as it is atypical to include trials on which the target property is absent from all response intervals, there are to our knowledge no data (aside from our own, Wenger & Rasche, 2005) that speak to the validity of the assumption with respect to distinguishing presence from absence. The importance of being able to assess observers' bias in distinguishing presence from absence comes from the fact that most models of contrast detection (as reviewed in Silverstein, Carney & Klein, 2001), and prominent models of perceptual learning (in particular Dosher & Lu, 1999; Gold et al., 1999; Petrov et al., 2005) assume that observers are either unbiased or stably biased.

Our initial investigation compared performance of observers in contrast detection and discrimination tasks in both a staircase procedure and a modified version of the method of constant stimuli (Copeland & Wenger, 2003). The use of the method of constant stimuli allowed us to add target-absent trials, equal in number to the target-present trials, and thus allowed us to estimate the signal detection theory measures of sensitivity (d') and bias (c) (e.g., Green & Swets, 1966; Wickens, 2002; Macmillan & Creelman, 2005), along with estimates of detection and discrimination thresholds (obtained from the psychometric function). Improvements in performance (reliable reductions in threshold) were obtained for both tasks, using both experimental methods, at levels comparable to or exceeding those in other studies of learning for contrast detection (e.g., Sowden et al., 2002). Critically, the data from the condition using the method of constant stimuli showed liberal shifts in response criteria along with reductions in threshold.

The approach developed in the earlier work, and refined in the present, is based on the idea of repeatedly applying the method of constant stimuli in order to obtain multiple psychometric functions. The range of stimuli is shifted across sessions with the goal of placing the stimuli in the most sensitive range of the observer (following, e.g., Levitt, 1971, see Figure 1). The stimulus range used in session n yields a psychometric function from which two contrasts (corresponding to criterial levels of accuracy λ_1 and λ_2) are chosen in order to determine the range to be used in session $n+1$. Each session's psychometric function, which is estimated on the basis of performance in target-present trials, is used to estimate two values. The first is the detection threshold, estimated by determining the contrast value that corresponds to a criterial value of accuracy (λ_3 = 0.79 in the present study, following Dosher & Lu, 1999). The second is the hit rate associated with the level of contrast at the median of the psychometric function from the initial session. The data from the target-absent trials are used to obtain the false alarm rates, and the two sources of data are used together to estimate d' and c.

Method

Participants

Five female and four male students were recruited as paid participants. All had corrected-to-normal vision and unencumbered use of their hands, and all were naive to the task.

Materials

The stimuli were monochromatic Gabor patches, with luminance at each x,y location in the display being described by

$$l(x,y) \quad = \quad l_0 \left\{ 1.0 + c \sin\left[2\pi f(\cos\theta \pm y \sin\theta)\right] \exp\left[-\frac{x^2+y^2}{2\sigma^2}\right] \right\} \quad (1)$$

where l_0 is the mean luminance, c is stimulus contrast (the amplitude of the sine-wave component), f is the center frequency of the sine-wave component (2.3 c/d), θ is the tilt of the patch (90°), and σ is the standard deviation (0.385°) of the Gaussian component. All parameters except c were held constant. The overall range of contrasts was 0.05 to 0.8. A target-present trial contained a Gabor patch of a given contrast, centered on a 2.0° × 2.0° square whose luminance was 75 cd/m^2. The background screen luminance was set at 46 cd/m^2. A target-absent trial consisted only of the 2.0° × 2.0° square. Viewing distance was fixed at 76 cm. Stimuli were viewed through tachistoscopic goggles (Milgram, 1997); responses were made using two buttons of a custom eight-button response box. Stimulus display and response timings were all accurate to ±1 ms (Forster & Forster, 2003).

Procedure

Participants completed up to 10 blocks of trials within a two-week period, with a single block of 600 trials completed on each day. A total of 300 target-present and 300 target-absent trials were presented in each block. The 300 target-present trials were composed of 30 trials at each of 10 levels of contrast. Order of presentation was randomized across all trials in each session.

On the first day of the experiment, the contrasts presented in the target-present trials ranged from 0.1 to 0.8. The range of contrasts used in the second and all subsequent sessions was determined by the contrasts corresponding to 0.05 (λ_1) and 0.95 (λ_2) of the estimated psychometric function from the immediately preceding session (see Figure 1). Each trial began with a blank period whose duration was normally distributed ($\mu = 300$ ms, $\sigma = 100$ ms, per general suggestions in Luce, 1986), followed by a white fixation cross whose duration was normally distributed ($\mu = 500$ ms, $\sigma = 100$ ms). A blank screen of 500 ms followed the offset of the fixation cross. The test display was then presented for 20 ms. Positive responses were made using the index finger of the observer's dominant hand, and negative responses were made using the

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[1] Note that this is not a requisite property of 2AFC designs, as it is possible to include trials on which the target property is absent from both intervals (as in Wenger & Rasche, 2005).

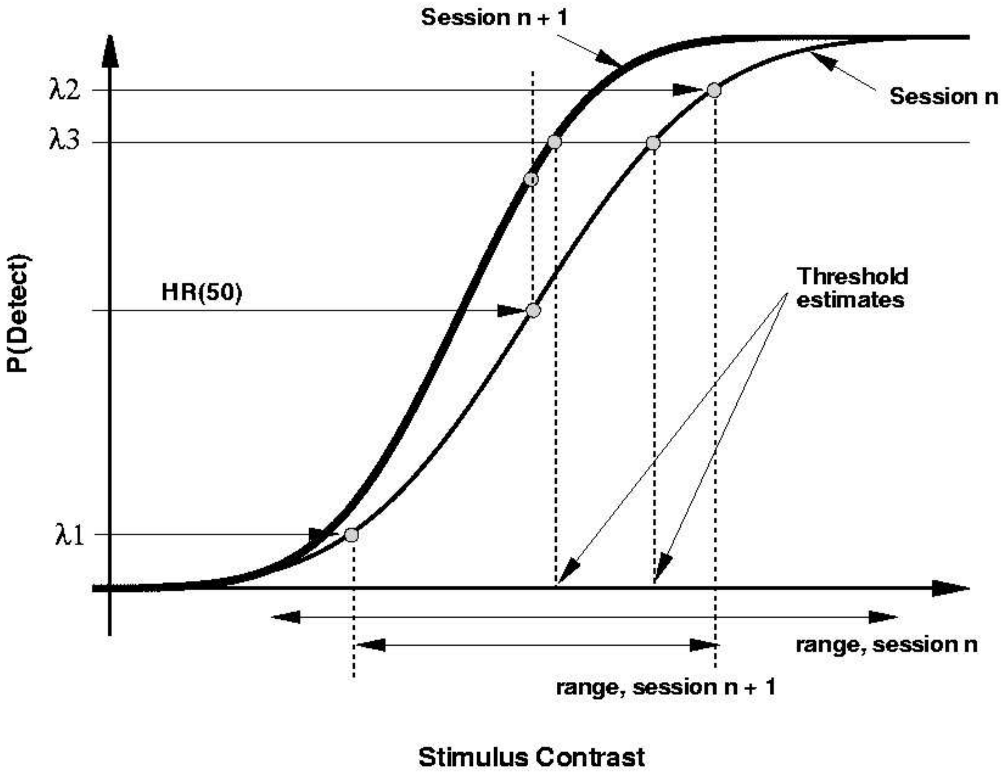

Figure 1. Schematic representation of the experimental method—a modification of the method of constant stimuli—used in the current study. Shown are two psychometric functions at two levels of practice (sessions n and $n+1$). See text for details.

index finger of the non-dominant hand. No feedback was provided.

Results

A psychometric function, relating response accuracy to stimulus contrast, was estimated separately for each observer for each block of trials. Psychometric functions were estimated four different ways: (a) fitting a two-parameter version of the Weibull cdf using non-linear regression, (b) using probit analysis (e.g., Finney, 1971), (c) using bootstrap methods (e.g., Wichmann & Hill, 2001), and (d) by fitting a linear version of the Weibull cdf using linear regression. This method of estimating the psychometric function with these data consistently provided the best description of these data (i.e., largest proportion of variance accounted for). The detection threshold for a given session was defined as the contrast that corresponded to the 79th percentile of the estimated psychometric function.

The psychometric function for the initial session was used to estimate levels of contrast corresponding to the 25th and 50th percentiles. These contrast values were then used to obtain the estimated hit rates for those contrast levels from the psychometric functions estimated in each of the subsequent sessions; these values will be referred to as HR(50) and HR(25). These two hit rates, along with the overall false alarm rate for each session, were used to obtain two corresponding estimates of d' and c. Statistical reliability of any changes due to practice was assessed for all of the dependent measures using linear regression, separately for each observer; an α-level of 0.05 was used for all analyses. A summary of the analyses is presented in Table 1. None of the analyses of the data involving hit rates at the 25th quantile of the estimated psychometric functions were reliable; consequently, these results are omitted.

Standard measures of perceptual learning

Standard evidence for perceptual learning comes by way of statistically reliable decreases in threshold values and/or statistically reliable increases in hit rates (see, e.g., Sowden et al., 2002; Yu et al., 2004). Six of the nine observers in the present study showed reliable[2] decreases in detection

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[2] All evidence in support of reliable results is reported in Table 1.

Table 1
Results of the linear regression analyses of the performance of each of the nine observers (Obs), with respect to changes in estimated detection threshold (in units of contrast), hit rates at the contrast corresponding to the median of the initial session's psychometric function (HR(50)), false alarm rate (FR), d' based on HR(50) and FR (d'(50)), and c based on HR(50) and FR (c(50)). Provided for each observer and each measure are the estimated parameter for the effect of practice (β) and the standard error (SE) of that estimate. $^* = p < 0.05, \dagger = p < 0.01$.

	Threshold		HR(50)		FR		d'(50)		c(50)	
Obs	β	SE	β	SE	β	SE	β	SE	β	SE
1	-.0541*	.0172	.0642*	.0167	.2877*	.0693	.1457*	.0369	-.0547*	.0131
2	-.0344	.0442	.0219	.0102	.0069	.0323	.2845	.1280	-.0219	.0102
3	-.0952*	.0283	.0788*	.0203	.0645	.1191	.0869*	.0191	-.0889*	.0186
4	-.0249*	.0054	.0361	.0047	.1725*	.0364	.0030	.0168	-.0753*	.0238
5	.0053	.0151	.0024	.0142	.0161	.0341	.0091	.0508	-.0225	.0567
6	-.0681†	.0159	.0442†	.0115	.0418	.0483	.1881†	.0515	-.0564*	.0218
7	-.0276*	.0095	.0537*	.0144	.3431*	.1079	.0200	.0574	-.1464*	.0474
8	-.0703*	.0209	.0417*	.0113	.0527	.0547	.0059	.2765	-.0692*	.0210
9	-.0254	.0130	.0077	.0132	.1588*	.0460	.0947	.0653	-.2438	.0636

thresholds across the course of the experiment, consistent with the range of individual differences typically observed in perceptual learning studies (e.g., Fine & Jacobs, 2002; Herzog & Fahle, 1997). Figure 2(a) plots the change in relative threshold (estimated threshold for each session divided by the initial threshold) for these six observers. On average, these observers reduced their detection thresholds by approximately 60%, a level of change consistent with our earlier work (Copeland & Wenger, 2005), larger in magnitude than other studies of perceptual learning for contrast detection (e.g., Sowden et al., 2002), and at approximately the same level of change observed in studies of perceptual learning for contrast discrimination (e.g., Yu et al., 2004). In addition, these same six observers showed statistically reliable increases in hit rates for the contrast associated with the median of the psychometric function from the initial session (HR(50), see Figure 2(b)). Overall, these observers increased their hit rates by more than 30%, a level of change that is consistent with or exceeds levels of change documented in other studies of contrast detection (e.g., Sowden et al., 2002).

Sensitivity and bias

The present study departs from modal practice by including target-absent trials, allowing us to estimate false alarm rates and, as a consequence, signal detection measures of sensitivity (d') and bias (c). Consider first the false alarm rates as a function of practice. For the majority of the observers, the false alarm rate did not change reliably, although all of the estimated regression coefficients were positive (see Table 1). Three of the six observers who showed reliable decreases in threshold also showed reliable increases in false alarm rates.

Changes in d' (sensitivity to the presence of contrast) were estimated for each session using these false alarm rates and the hit rates for the contrast associated with the median of the psychometric function from the initial session (HR(50)). Of the six observers who showed reliable decreases in detection threshold, only three showed reliable increases in d' (see Figure 2(c)). In contrast, all six of these observers showed reliable liberal shifts in c (see Figure 2(d)).

The cost of shifts in response bias

Inspection of the results in Table 1 gives an indication of why we obtained limited evidence for increases in sensitivity and consistent evidence for liberal shifts in response bias as a function of practice. None of the observers who showed improvements with target-present stimuli (i.e., increases in hit rates) showed improvements with target-absent stimuli (i.e., decrease in false alarm rates).[3] This runs counter to the expectation for a "mirror effect" implied by the assumption of an unbiased observer: increases in hit rates accompanied by proportional decreases in false alarm rates (e.g., Fine & Jacobs, 2002; Murdock, 1998; Sikstrom, 2001).

This implies that, had there been decreases in false alarm rates, there would have been larger increases in d'. To check this possibility, we estimated two d' values for each session using the observed hit rates, and both the observed false alarm rates and the false alarm rates that would have been obtained given a mirror effect. Specifically, for each observer, we estimated the false alarm rate that would have been obtained in each session had they changed in a manner inversely and equally proportional to the relative change in the hit rates.

Figure 3 presents these estimates for the six observers who showed reliable decreases in their detection threshold. Had false alarm rates decreased—that is, had observers been unbiased, as is typically assumed (e.g., Dosher & Lu, 1999; Fine & Jacobs, 2002; Gold, Bennett & Sekuler,

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[3] A reviewer raised the question of whether the obtained changes in false alarm rates might be reversed should observers be returned (at the end of practice) to the original range of contrasts. While there are no data from the present experiment that speak to this possibility, we do have pilot data from earlier work in which we added this condition, and found that expanding the range back to its original values had no reliable effects on false alarm rates and, by extension, the bias measure (c).

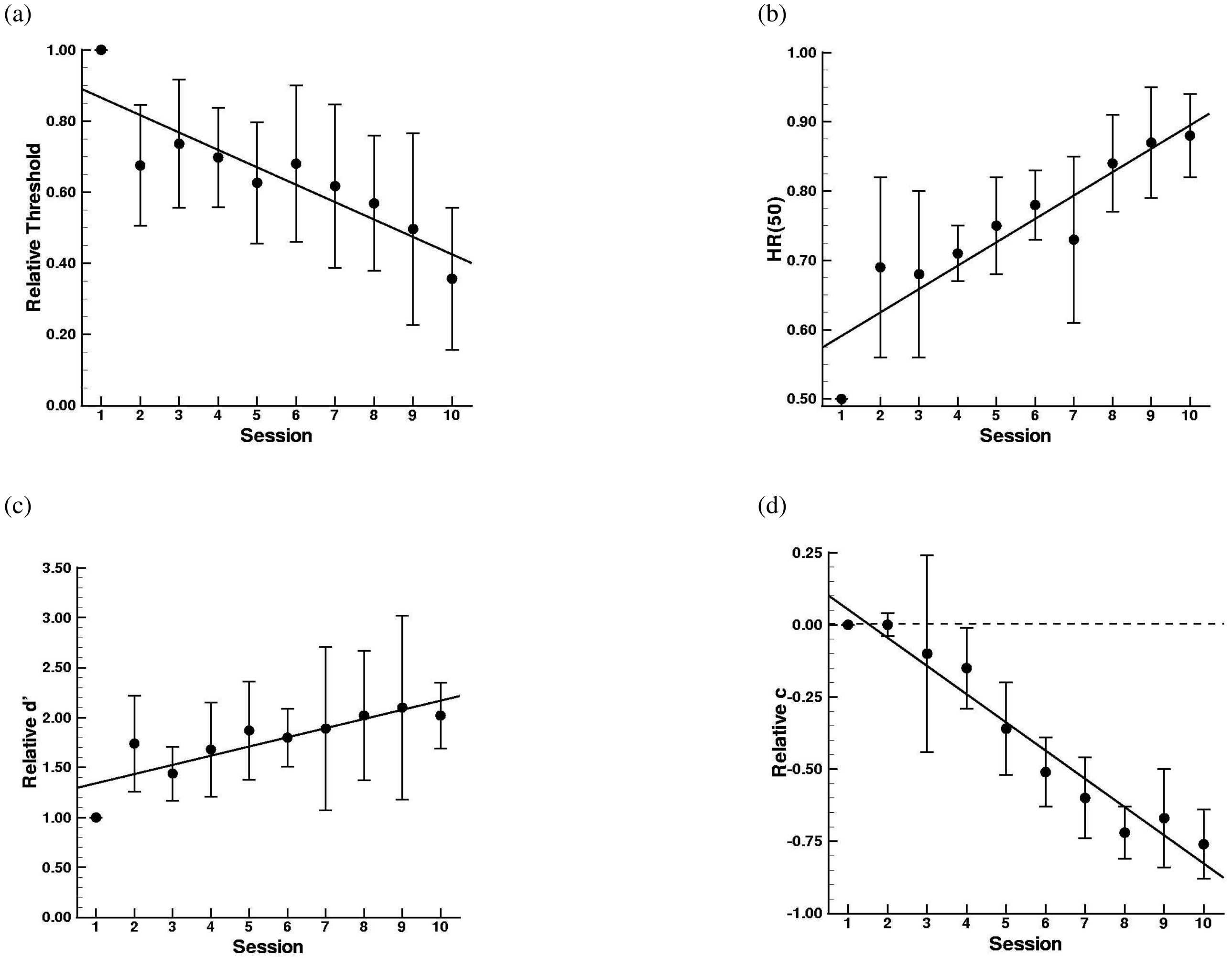

Figure 2. (a) Changes in detection thresholds as a function of session, for the six observers who showed reliable reductions. The vertical extent of each bar represents the range of values (across the six observers), with the central line in each bar representing the median of the six values. The line represents the best-fitting linear regression model for the median values. (b) Changes in hit rates at the contrast value corresponding to the median of the psychometric function of the initial session (HR50), as a function of session, for the six observers who showed reliable increases. (c) Changes in d' as a function of session, for the six observers who showed reliable decreases in detection threshold. (d) Changes in c as a function of session, for the six observers who showed reliable decreases in detection threshold. Note: $c = 0$ indicates unbiased responding, $c < 0$ indicates liberal responding, and $c > 0$ indicates conservative responding.

1999)—the increases in hit rates would have produced increases in d' that would have been roughly 50-60% greater than what was observed on the last session. Thus, the failure to improve performance on target-absent trials has the predictable cost of diminishing perceptual sensitivity (see also Seitz et al., 2005).

Discussion

Theoretical accounts of the changes associated with perceptual learning generally assume that observers are either unbiased or stably-biased across learning. Unfortunately, experimental methods as they are generally used in this domain do not allow for empirical tests of this assumption. In this study, we used a method that allowed us to test this assumption relative to perceptual learning for contrast detection. We obtained the standard evidence for perceptual learning—decreases in threshold and increases in hit rates, equal to or greater in magnitude than other studies in the literature (e.g. Sowden et al., 2002)—while also producing evidence that speaks directly to changes in perceptual sensitivity (d') and bias (c). These measures revealed that changes in sensitivity were more limited than what might have been inferred from the threshold measures, and that observers showed consistent and reliable liberal shifts in response criteria. Further, we estimated that, absent these shifts in response criteria, sensitivity would have been approximately 60% higher than what was actually observed.

An important implication of this work, and the work that

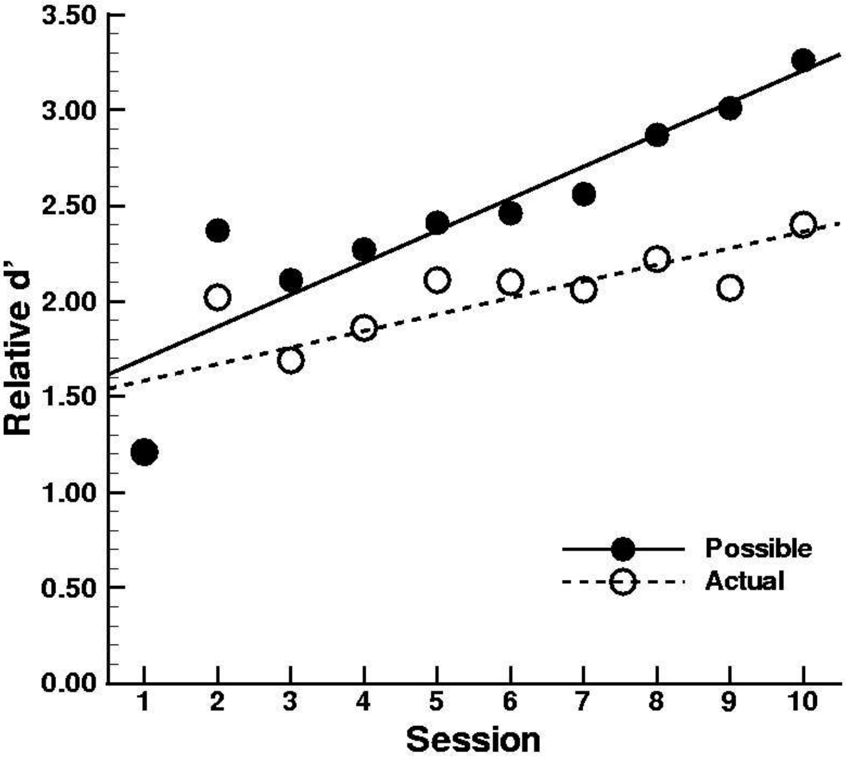

Figure 3. Comparison of the values of d' estimated from the data with values that would have been possible had false alarm rates reduced in a manner proportional to the increase in the hit rates. The "actual" data are the means of the $d'(50)$ values across the six observers who showed reliable decreases in detection thresholds.

motivated it (Copeland & Wenger, 2005), is that the current empirical and theoretical characterizations of of perceptual learning may be incomplete. Specifically, standard methods have not been used in a way that allows the assumption of an unbiased or stably-biased observer to be empirically tested, with this assumption being critical to prominent theoretical accounts of perceptual learning (e.g., Dosher & Lu, 1999; Gold et al., 1999; Petrov et al., 2005) and contrast detection (e.g., Silverstein et al., 2001).

This is not to say that existing work has in any way *ignored* the possibility of response bias. Indeed, most work has been exceedingly careful to balance response alternatives (e.g., Dosher & Lu, 1999; Lu & Dosher, 2004; Zenger-Landolt & Koch, 2001) in order to minimize the potential effects of response bias. Unfortunately, with specific respect to questions of *detection*, those alternatives typically have not included the complete absence of the critical stimulus property (i.e., the target property is always present on each trial). As such, and as noted earlier, in these cases it is not possible to distinguish a bias with respect to response alternative from a bias with respect to presence or absence. We are currently in the process of completing work examining the extent to which these two types of response bias can be empirically distinguished in contrast detection, with our data suggesting that observers can be simultaneously unbiased with respect to the choice of response alternatives, while developing a liberal bias with respect to the presence/absence judgment (Wenger & Rasche, 2005).

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