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Criteria interactions across visual attributes

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Abstract

Judgmental interference in dual tasks has been demonstrated in conditions where the detection or discrimination of different contrast increments applied to two stimuli presented simultaneously or in sequence. The present work demonstrates such interference for changes along two distinct visual features, namely contrast and orientation, when simultaneously applied to the same or to two distinct objects (Gabor-patches). The interference reveals itself in the use of quasi-equal decision criteria for both dimensions, in conflict with an optimal behavior requiring that criteria be proportional to the sensitivities for the distinct changes. The quasi-equality of the criteria assessed for contrast and orientation changes implies the equality of the internal noises characterizing the respective detection process, hence suggesting that they are limited at the decision level. Among the conceptual consequences of this limitation are the existence of a meta-attribute decisional dimension (tantamount to that of a "central executive system") and the questionable merits of probability summation over spatial channels. In addition, the data show a significant sensitivity drop in the dual- with respect to the single-task conditions, all the more so when the modulated features belong to two objects rather than to the same object. While the sensitivity drop in dual tasks is the standard trademark of distributed attention, it is argued that decisional interference is yet another aspect of it.

Keywords: Decision; Sensitivity; Signal detection theory; Internal noise; Dual task; Attention

1. Introduction

In 1999 we presented data supporting the notion that in a multi-decision visual task involving different strength (i.e. contrast), non-interfering stimuli presented simultaneously, observers behave non-optimally: instead of independently modulating their response behavior in accordance with the specifics of the stimuli they report upon (as required by Signal Detection Theory; Green and Swets, 1966), their decision behavior exhibits strong criteria interactions (Gorea and Sagi, 1999, 2000, 2001, 2002a,b). More specifically, with stimuli differing in strength but with equal probability of occurrence, our results indicated that response criteria shifted to higher and lower values for the less and the more salient stimuli, respectively, as if *attracted* by each other. Criteria attraction was observed in a number of experimental conditions involving detection (Gorea and Sagi, 2000, 2002b), discrimination (Gorea and Sagi, 2001) and suprathreshold matching experiments (Gorea and Sagi, unpublished) for both simultaneously and sequentially presented stimuli (Gorea and Sagi, unpublished, 2003). We interpreted this *criteria attraction* as the consequence of a *unitary internal representation* of the (physically) distinct events along the dimension under study (i.e. contrast). This *judgmental interference* is close to intuition: in multiple stimulus environments, the weaker (less visible) stimuli are reported less and the stronger (more visible) ones are reported more frequently than when they are presented in isolation. Such a behavior fits well

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within the wide spectrum of older (for a review see Boring, 1942) and more recent (e.g. Adelson et al., 2000; Gilchrist et al., 1999) context theories including Gestalt (Koffka, 1935, fourth print, 1955), adaptation-level (Helson, 1964) and other anchoring effects.

To date, all the experimental conditions yielding criteria attraction involved one single visual attribute (contrast), with its different values "attached" to spatially (for simultaneous presentations), or temporally (for sequential presentations) distinct visual objects. The purpose of the present study is to test the generality of criteria attraction over distinct visual attributes belonging to either the same object or to two distinct visual objects.

The issue of limitations in the co-processing of distinct (visual) attributes has been addressed from at least two different perspectives. One relates to the capacity of short term (or working) memory originally addressed by Miller (1956) and recently updated by Luck and Vogel's work (Luck and Vogel, 1997; Vogel et al., 2001). The main observation to be drawn from that literature and relevant to the present inquiry is that the number of attributes that can be stored at a time depends on how they are distributed over distinct visual objects: this number can be substantially increased when more than one attribute is "attached" to the same object. The second perspective put forth by Duncan (1984) bears on the *attentional* limitations in visual processing as they relate to the number of attributes one can attend to and report on depending on whether or not they belong to the same visual object. Quite recently, Han et al. (2003) have shown that, with low-noise stimuli, sensitivity deficits in dual- (as compared to a single-) attribute reports are observed only if the two attributes are different *and* belong to distinct objects; equivalent dual-attribute deficits were also observed with high-noise stimuli for distinct attributes belonging to the same object.

There are two ways in which the literature above is relevant to the present study. On the one hand, it encompasses the issue of *objecthood* which is critical to our inquiry as it pertains to the problem of judgmental interference within and across visual attributes and objects. The general question at hand is whether or not the notion of a visual dimension/attribute can be confounded with that of an object, namely a spatially and temporally limited visual entity. On the other hand, it connects to our previous account of judgmental interference as an attentional relaxation process (Gorea and Sagi, 2003, 2005). While attentional limitations in general and in dual-task conditions, in particular, are typically assessed in terms of sensitivity losses (e.g. Han et al., 2003), we have proposed that they may also be quantified in terms of criteria attraction (i.e. judgmental interference). In view of Han et al.'s (2003) work, it is legitimate to ask whether criteria attraction (hence "attention relaxation") across attributes can be equally observed within and across visual objects.

2. Methods

The specific purpose of the present study is the assessment of sensitivity (d') and decision criterion (c') in a task where observers have to decide on the presence of one (contrast *or* orientation; *single* task) or two (contrast *and* orientation; *dual* task) changes applied to one or two visual objects. The main question to be answered regards the putative interference between the decisions made on each of these attributes. Decisional interference (in the dual task) is to be assessed in terms of "criteria attraction" which can be evidenced only inasmuch as the *absolute* criteria (c'; see Fig. 2 and section "Data format and operationalization") assessed in the single tasks are unequal (Gorea and Sagi, 2000). Achieving such a c' inequality requires that the potentially decisionally interfering stimuli yield different sensitivities. Hence, the contrast and orientation changes used here were each applied at two distinct levels yielding d' values of about 1 and 2.

2.1. Stimuli

They were Gabor patches presented on a Philips monitor (1024×750 px) with a 100 Hz raster under the control of a PC. The mean luminance of the screen was 48 cd/m^2. The Gabors had a spatial frequency of 3.8 cpd and a standard deviation of 0.26° at 100 cm from the observer's eyes. They were presented either at fixation (Experiment 1) or ±1.6° to the left and to the right of a small (0.4° diameter) fixation white circle (Experiment 2). The spatial phase of the Gabors' carrier was randomized across trials. The *reference* Gabors were vertical and had a contrast of 20%. The *target* Gabors could differ from the reference ones in contrast (increments), in orientation (clockwise rotations), or in both. They were chosen for each observer so as to yield discrimination (from reference) d' values close to 1 and 2. This was done based on preliminary experiments where discrimination performances were independently assessed for a range of contrast increments and orientation rotations. Black or white (see below) circles 1.3° in diameter and 1 pixel thick circumscribed the targets and were displayed until the observer's response. Reference and target Gabors were each presented for 80 ms.

2.2. Procedure

Sensitivities (d') and response criteria (c') were assessed by means of a standard Yes/No procedure where observers had to decide whether or not the target differed from the reference either in contrast (C) *or* in orientation (O).

Experiment 1: Two attributes, one object. In this experiment only one reference and one target were displayed in succession at fixation, with the latter

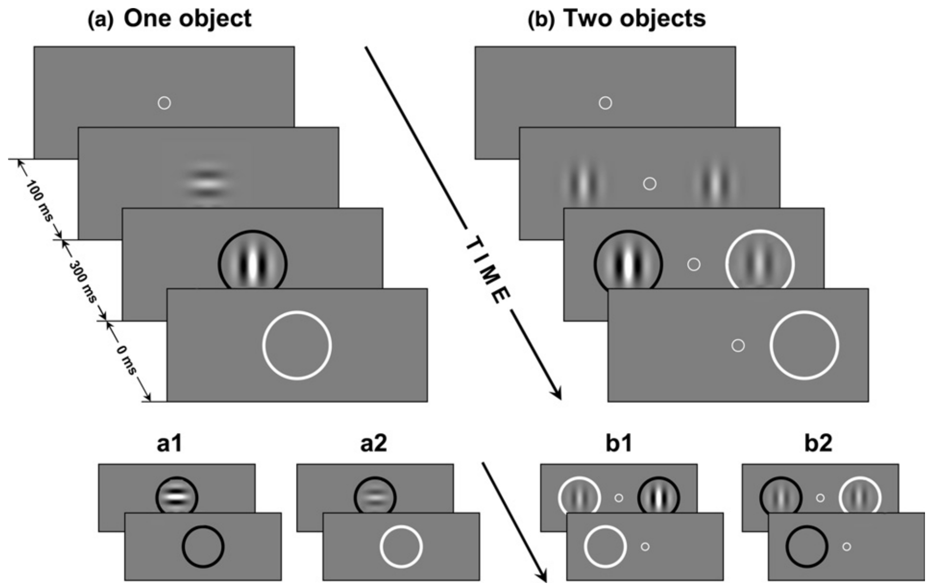

Fig. 1. One trial sequence in Experiments 1 (a; two attributes, one object) and 2 (b; two attributes, two objects). In temporal order, the four frames show (1) the fixation circle, (2) the reference(s) Gabor(s), (3) the target Gabor(s) within black and/or white circles and (4) the post-cue circle whose color indicated the attribute to be reported on (black: contrast; white: orientation). Numbers indicate inter-stimulus intervals in ms. Reference and target Gabors were displayed for 80 ms, while the post-cue circle lasted until observer's response. *Single* and *Dual* conditions were strictly identical with the exception that in the former only one attribute (only one post-cue color) was tested throughout a session, while the tested attribute was randomized over trials in the latter. In a and b target(s) differ from reference(s) in both attributes. a1–b1 and a2–b2 show the last two frames in a sequence where target(s) differed from reference(s) only in contrast and only in orientation, respectively. Cases were no difference was present had a probability of 0.25. In the two objects case, the location (left–right) of the contrast and orientation increments was randomized across trials.

potentially exhibiting (relatively to the reference) a C change, an O change, or both. In sessions of the *Single* type, observers were told in advance that they were to judge only one of the two attributes (C or O) with the color of the post-cue kept constant throughout the session (see below). In sessions of the *Dual* type, observers were told that they were to be tested randomly across trials on either of the two attributes as indicated by the changing color of the post-cue. The temporal specifics of one trial (Fig. 1a) were as follows: (1) display of a white fixation circle; (2) 100 ms after the observer's click, the fixation circle was replaced by the reference Gabor for 80 ms; (3) 300 ms after the reference offset (preventing that observers base their judgment on an apparent motion cue for the case of an orientation change), the target Gabor appeared together with a black circumscribing circle for 80 ms; (4) the circumscribing circle persisted until the observer's response while either preserving its color or changing it to white with this final color (post-cue) indicating whether the observer had to judge a contrast (black) or orientation (white) change. For any single trial the probabilities that the target differed from the reference in either C or O were independent and set at 0.5 (the probabilities of no change at all and of a simultaneous C and O change were thus 0.25). As noted above, C and O changes were chosen to yield d' values around 1 and 2 and are hereafter denoted as C1, C2, O1 and O2. One experimental condition (and block of trials) was characterized by the pairing of the two potential changes and by the fact that observers judged only one of the two attributes, *Single* (S) case (200 trials per block), or any of the two, *Dual* (D) case (400 trials per session). There were six S block types, **C1**O1, C1**O1**, **C1**O2, **C2**O1, C2**O1**, C1**O2**, with the bold characters denoting the attribute (and its magnitude) to be judged; for the **C#** cases, the post-cue remained black during the whole block; for the **O#** cases, the post-cue switched to white for each trial in the block. Only three D-conditions were studied, i.e. **C1O1**, **C1O2**, **C2O1**.[1] For the D case, the attribute to be judged remained unknown until the post-cue whose color remained black (C judgment) or switched to white (O judgment) on a random basis from trial to trial.

Experiment 2: Two attributes, two objects. This experiment differed from Experiment 1 on a frame by frame basis as follows (see Fig. 1b): (1) the fixation circle remained present throughout the trial; (2) there were two reference Gabors symmetrically displayed to the left and to the right of fixation; (3) two targets circumscribed one by a black, the other by a white circle replaced the two references; each of the two targets could differ from its reference *only* in Contrast and *only* in Orientation, with the colors of the circles indicating which of these changes could be applied; the location of the colors

[1] In view of the question asked in the present study, the C2O2 condition was not judged critical and was dropped.

(and hence of the denoted changes) was randomized across trials; (4) both targets and one cue circle disappeared with the persisting circle (post-cue) denoting the target and the attribute to be judged. Experiment 2 also included 6 S and 3 D block types. In the S-conditions, the observer was told in advance which attribute he will be judging throughout the session and the color of the persistent post-cue was correspondingly fixed during the whole session. In the D-conditions the color of the persistent circle was randomized across trials so that the observer did not know which attribute he'll be asked to judge over trials.

For each of the two experiments, the order of the nine experimental conditions was randomized across observers with each condition repeated two or three times so that the final d'-s and c'-s were computed from a minimum of 400 and a maximum of 600 trials. The assessment of two C and two O values yielding d'-s close to 1 and 2 (for each observer) was performed under S-conditions, started with at least four training sessions (800 trials) per attribute and continued with four to six C and O values. All in all, the preliminary stage involved an average of 3400 trials per observer for each Experiment. The preliminary and main phases of each Experiment were run over one to four weeks for each observer.

2.3. Observers

They were four for each experiment. The two first authors and one naïve observer were run in both experiments. The remaining observer was also naïve and different across experiments. All observers had normal or corrected to normal vision.

3. Data format and operationalization

The main question asked here concerns the putative *attraction* of response criteria across contrast (C) and orientation (O) attributes characterizing one (Experiment 1) or two distinct objects (Experiment 2) when they are to be discriminated from a reference within the same trial. Criteria equality represents an extreme attraction case. Here we define the criterion as usually (see Gorea and Sagi, 2000, 2001, 2002a,b, unpublished), namely as the decision point on the sensory continuum measured with reference to the mean of the noise (Fig. 2); this is but the (negative) z score of False Alarms, $-z$FA. Under standard Signal Detection Theory (SDT; Green and Swets, 1966), the zFA of an optimal observer (for a signal probability of 0.5) should equal half his sensitivity, i.e. $z\text{FA} = d'/2$. It follows that the zFA ratio for any arbitrary pair of independent stimuli, 1 and 2, should equal the corresponding d' ratio

$$\frac{z\text{FA}_1}{z\text{FA}_2} = \frac{d'_1}{d'_2} \quad (1)$$

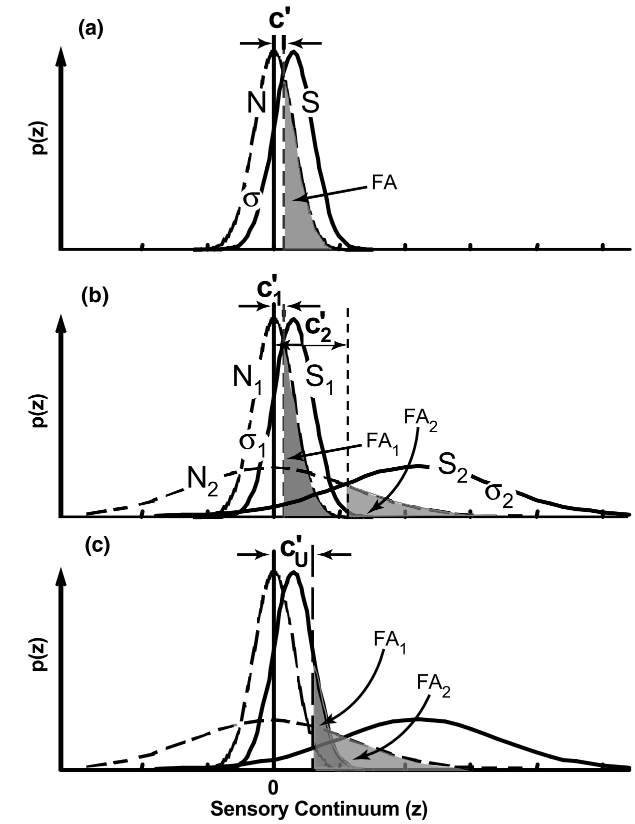

Fig. 2. Signal Detection Theory (SDT) and the unique criterion illustrated for equally likely Signal (S) and Noise (N) trials. All plots represent the probabilities (ordinates) of the internal responses (represented as standard z-scores on the sensory continuum; abscissae) evoked by N and S trials (dashed and continuous Gaussians). Continuous and dashed vertical lines show the mean of the N distribution(s) and the location of the absolute response criteria (c'). Hatched areas show the cumulated probabilities of False Alarms. (a): The case for one S; (b) and (c): the case for two S of unequal variances (σ_1, σ_2). For equally likely N and S trials, an optimal observer places his c' at the intersection of the N and S Gaussians, whether tested with one (a) or two different S (b), provided that the two S are unambiguously labeled. A departure from this optimal behavior is shown in (c) where the observer uses a unique criterion (c'_U) located somewhere in-between the optimal criteria.

In contrast, a *unique criterion* (uc) behavior requires that $z\text{FA}_1 = z\text{FA}_2$. As zFA scores are given in unknown noise units (σ), the proper expression of the uc is given by

$$\sigma_1 z\text{FA}_1 = \sigma_2 z\text{FA}_2 \quad (2)$$

which is equivalent to

$$\frac{z\text{FA}_1}{z\text{FA}_2} = \frac{\sigma_2}{\sigma_1} = k \quad (2')$$

Eq. (2′) is useful as it allows comparison of criteria across stimuli addressing perceptual processes with unknown noise (in the present case those underlying contrast and orientation discrimination). What is more, an observed constancy of the zFA ratio (i.e. its independence of the d' ratio) also specifies the noise ratio, k, between these processes.

Under the specific format of the present experiments, Eq. (2′) translates into

$$\frac{z\mathrm{FA}_{\mathrm{C}i}}{z\mathrm{FA}_{\mathrm{O}j}} = \frac{\sigma_{\mathrm{O}}}{\sigma_{\mathrm{C}}} = k \qquad (2'')$$

with i and j the two sensitivity levels used when pairing C and O increments in the Dual task, namely conditions **C1O1**, **C1O2** and **C2O1** as defined in the Procedure section.

The present data are hence presented as the zFA ratios of the paired (D condition) and of the corresponding unpaired (S condition) stimuli as a function of the corresponding d' ratios. SDT predicts a linear function of slope 1 for both S and D conditions. The uc behavior is applicable only to the latter for which it predicts a slope of 0. For the purpose of the regression analysis, these ratios were transformed into their log equivalents.

4. Results

4.1. Criteria ratios vs. sensitivity ratios

The data obtained in Experiments 1 and 2 are presented in Fig. 3a and b under the format just described. The open and solid symbols represent the logarithms of the zFA vs. d' ratios for the S and D conditions, respectively. Each ratio (experimental point) is based on 800–1200 trials (i.e. on 400–600 trials for the numerator and denominator). Different symbols are for different observers. Dotted straight lines with slopes 1 and 0 are predictions of the SDT and of the uc behavior (respectively). Dashed and solid straight lines are linear regressions fit to all the S and D data, respectively (their slopes, intercepts and correlation coefficients are given in the insets).

Linear regression analyses performed on the zFA- vs. d'-log ratios in Experiments 1 and 2 are summarized in Table 1a and b. They confirm the observations one can make by mere inspection of Fig. 3a and b. The S-data support the SDT prediction: for both experiments, they yield a slope virtually equal to 1 and highly significant correlation statistics (see Table 1). In contrast, the D-data yield slopes of 0.31 and 0.17 with non-significant correlation statistics. The fact that the D-data slopes are larger than 0 (with the correlation statistics for Experiment 1 skimming the significance threshold) indicates that criteria attraction is not "perfect" (i.e. unique criterion).

The average zFA ratios in the D-condition are 0.84 and 1.04 for Experiments 1 and 2 (white digits on the horizontal dotted lines in Fig. 3). As discussed in the previous section, these ratios are supposed to reflect the ratio of noises in the orientation and in the contrast discrimination mechanisms. Hence, the observed average ratio of 0.84 (Experiment 1) would imply that O coding is 16% less noisy than C coding. Nonetheless, the equivalent ratio observed in Experiment 2 indicates strictly identical noises between the C and O processors. Taken together, the observed ratios are suspiciously close to 1.

4.2. Criterion vs. sensitivity

In order to gain more insight into how the observers' decision behavior in a multi-decision environment tends toward the unique criterion, Fig. 4 presents the C1O2 and C2O1 data (see notation in the Methods section) of Experiments 1 (a) and 2 (b), with criteria, c', shown as a function of sensitivity, d'. The data are averaged

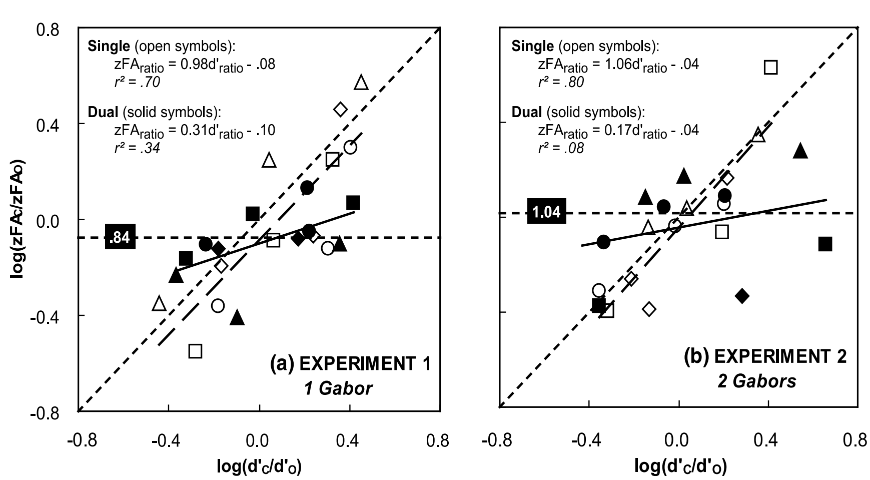

Fig. 3. Criterion (c') vs. sensitivity (d') log ratios for contrast and orientation attributes in the *Single* and *Dual* tasks (open and solid symbols, respectively) in Exps. 1 and 2 (left and right panels). Different symbols are for different observers. Diagonal and horizontal dotted lines show SDT and unique criterion predictions, respectively. Dashed and solid straight lines are linear regressions fitted to the *Single* and *Dual* data (see insets). White digits on the horizontal dotted lines are the mean $z\mathrm{FA_C}/z\mathrm{FA_O}$ ratios in the Dual conditions.

Table 1
Linear regression analyses for the Single and Dual zFA- vs. d'-log ratios in Experiments 1(a) and 2(b)

(a) SINGLE

n	12
R2	0.70
Adjusted R2	0.67
SE	0.2029
95% CI	0.50 to 0.95
2-tailed p	0.0007

Term	Coefficient	SE	p	95% CI	
Intercept	-0.0845	0.0616	0.2000	-0.2217	to 0.0527
Slope	0.9832	0.2038	0.0007	0.5290	to 1.4374

Source of variation	SSq	DF	MSq	F	p
Due to regression	0.957	1	0.957	23.26	0.0007
About regression	0.412	10	0.041		
Total	1.369	11			

(a) DUAL

n	11
R2	0.34
Adjusted R2	0.26
SE	0.1258
95% CI	–0.03 to 0.88
2-tailed p	0.0606

Term	Coefficient	SE	p	95% CI	
Intercept	-0.0991	0.0380	0.0283	-0.1850	to -0.0131
Slope	0.3090	0.1441	0.0606	-0.0170	to 0.6350

Source of variation	SSq	DF	MSq	F	p
Due to regression	0.073	1	0.073	4.60	0.0606
About regression	0.142	9	0.016		
Total	0.215	10			

(b) SINGLE

n	12
R2	0.80
Adjusted R2	0.78
SE	0.1411
95% CI	0.67 to 0.97
2-tailed p	<0.0001

Term	Coefficient	SE	p	95% CI	
Intercept	-0.0442	0.0409	0.3054	-0.1353	to 0.0469
Slope	1.0640	0.1659	<0.0001	0.6943	to 1.4337

Source of variation	SSq	DF	MSq	F	p
Due to regression	0.819	1	0.819	41.13	<0.0001
About regression	0.199	10	0.020		
Total	1.018	11			

(b) DUAL

n	9
R2	0.08
Adjusted R2	-0.05
SE	0.2269
95% CI	–0.47 to 0.80
2-tailed p	0.4574

Term	Coefficient	SE	p	95% CI	
Intercept	-0.0441	0.0782	0.5901	-0.2291	to 0.1408
Slope	0.1750	0.2225	0.4574	-0.3511	to 0.7010

Source of variation	SSq	DF	MSq	F	p
Due to regression	0.032	1	0.032	0.62	0.4574
About regression	0.360	7	0.051		
Total	0.392	8			

over the four observers and shown separately for the C and O attributes (top and mid panels) as well as for their combinations ("C + O", bottom panels). Since C and O attributes were never paired with themselves, the C and O plots in Fig. 4 were obtained by pairing zFA_C and zFA_O scores *across* experimental conditions, that is zFA_{C1} (from C1O2) with zFA_{C2} (from C2O1) and zFA_{O1} (from C2O1) with zFA_{O2} (from C1O2). For the "C + O" format, criteria and sensitivities for a given sensitivity level, i, were geometrically averaged [i.e. $(zFA_{Ci} \times zFA_{Oi})^{0.5}$ and $(d'_{Ci} \times d'_{Oi})^{0.5}$].[2] This data processing was separately applied to the results obtained in S (open circles and dashed lines) and D (solid circles and solid lines) conditions. Under this format, c' for an optimal SDT observer should vary linearly with d' with a slope of 0.5 ($zFA = 0.5d'$; dotted oblique lines in each panel), while the uc behavior predicts a slope of 0 (dotted horizontal lines). Note that this latter prediction for the cross-sessions C and O plots in Fig. 4 depends critically on the d' equality across the two attributes. Inspection of Fig. 4 shows that the actual d' values for C and O plots in the S condition have been indeed satisfactorily though not perfectly matched. Such d' variations may account in part for deviations from the expected uc behavior under D conditions. Still, while Fig. 4 shows a close to optimal behavior under S conditions (in both experiments), it also demonstrates strong departures from it in the direction required by uc under D conditions (particularly so in Experiment 1). Fig. 4 also shows an important overall d' drop (of about 20%) under D conditions which appears to be more pronounced for the high than for the low d' values (clearly so in Experiments 1). These observations are supported by three-way ANOVAs [with attribute (C, O), attribute-level combination (C1O2, C2O1),[3] and experimental condition (Single, Dual) as factors] independently run on the criteria and sensitivity estimates of Experiments 1 and 2.[4] In addition, the estimated c' vs. d' slopes in the S- and D-conditions (Fig. 4) were contrasted with

[2] The reason of the geometrical averaging follows from Eqs. (2)–(2″). Under the uc hypothesis, c' values obtained in the **C1O2** and **C2O1** dual conditions (see notation in the Methods section) should respect the following equalities : $\sigma_C zFA_{C1} = \sigma_O zFA_{O2}$ and $\sigma_C zFA_{C2} = \sigma_O zFA_{O1}$; hence $\sigma_C zFA_{C1} \times \sigma_O zFA_{O1} = \sigma_C zFA_{C2} \times \sigma_O zFA_{O2}$.

[3] In the absence of the C2O2 condition (not run), condition C1O1 was excluded from this analysis so as to obtain a balanced experimental plan.

[4] Because the groups of subjects run in Experiments 1 and 2 were partly different (they shared 3 out of 4 subjects), a different ANOVA was run for each experiment.

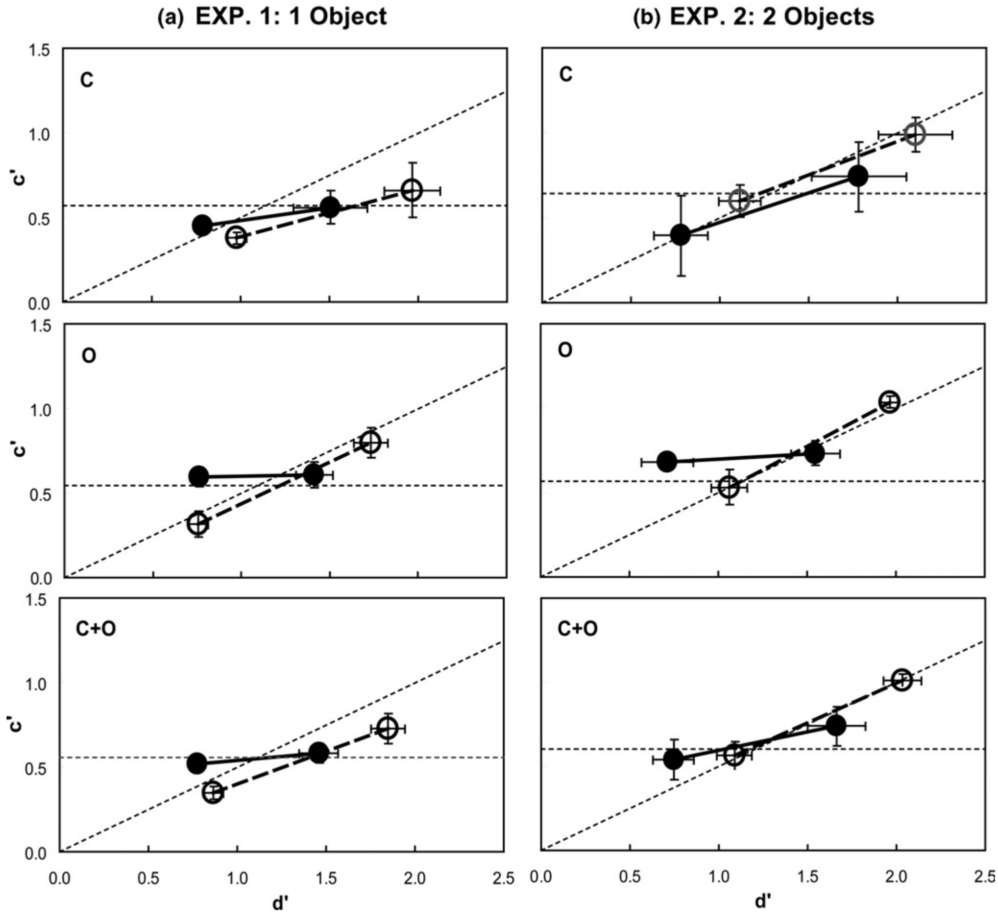

Fig. 4. Criterion (c') vs. sensitivity (d') for *Single* (open circles and dashed lines) and *Dual* (solid circles and solid lines) conditions in Exps. 1 and 2 (left and right panels). Data are shown separately for the Contrast and Orientation attributes (upper and middle panels) as well as for their combination (bottom panels). Dotted diagonal and horizontal lines show where the datum points should have lain had observers been optimal (in the SDT sense), or had they behaved in accordance with the unique criterion. Vertical and horizontal bars show ±1SE.

the SDT (0.5 slope) and *uc* (0 slope) predictions by means of t-tests.

As expected, (1) the dependence of c' on d' in the S-condition is close to the standard SDT prediction, namely a slope of 0.5 [c' vs. d' slopes, *Single*; Experiment 1: for C: 0.30 ± 0.07, $t(3) = -2.94$, ns; for O: 0.48 ± 0.01, $t(3) = -1.61$, ns; Experiment 2: for C: 0.39 ± 0.05, $t(3) = -2.14$, ns; for O: 0.56 ± 0.05, $t(3) = 1.01$, ns]; the fact that these functions (essentially for Experiment 1) lie slightly below the theoretical 0.5 slope (dashed lines) indicates that all four observers adopted a slightly conservative decision behavior. (2) In contrast with the S-condition, the c' vs. d' slopes in the D-condition are, with one exception (out of four cases; italics below), not significantly different from the unique criterion prediction, i.e. 0 slope [c' vs. d' slopes, *Dual*; Experiment 1: for C: 0.14 ± 0.07, $t(3) = 2.07$, ns; for O: −0.03 ± 0.11, $t(3) = -0.248$, ns; Experiment 2: for C: 0.33 ± 0.06, $t(3) = 5.58$, $p = 0.011$; for O: 0.03 ± 0.08, $t(3) = 0.35$, ns]. The exception observed for the C attribute in Experiment 2 (Fig. 4, upper panel) requires qualification. Since C and O attributes were never paired together, the C and O plots in Fig. 4 were obtained by pairing c' (and d') values for C and O *across* experimental conditions (see the beginning of this section). As a consequence, the apparent lack of attraction observed in Experiment 2 for the C attribute alone implies in fact that the criteria associated with the C discrimination task were less "attracted" by the criteria associated with the O discrimination task than the reverse. The reason for this unbalanced attraction between C and O remains unclear. (3) Criteria attraction is also indicated by the significant interaction between the "attribute-level combination" (C1O2, C2O1) and the "experimental condition" (S vs. D) factors in both experiments [$F_{\mathrm{Exp1}}(1,3) = 10.28$, $p = 0.049$; $F_{\mathrm{Exp2}}(1,3) = 10.78$, $p = 0.046$]. Partial comparisons reveal that criteria *increments* in the D vs. S condition at the lower d' levels are statistically significant for Experiment 1 [$F_C = 57.34$; $p = 0.0048$], but not for Experiment 2 [$F = 1.91$; $p = 0.26$]. Criteria *decrements* for the higher d' levels are not significant for any of the two experiments. This unbalanced attraction has been discussed by Gorea and Sagi (2002a,b, unpublished) in relation to what they coined "natural extinction" (criteria increment) in the absence of "counter-extinction" (criteria decrement). (4) A global d' drop (of about 20%) in the D with respect to the S condition is confirmed in both experiments [$F_{\mathrm{Exp1}}(1,3) = 52.53$, $p = 0.005$; $F_{\mathrm{Exp2}}(1,3) = 9.98$, $p = 0.050$]. The statistical analysis reveals no significant interaction between sensitivity level and experimental condition. Such an interaction was expected on the logical ground that d'-s in the S and D conditions are bound to meet at their origin so that their difference, if any, should be larger at higher d' values. Such an imbalanced d' drop at low and high d' values is indeed observed in Experiment 1 but it is less marked in Experiment 2 (Fig. 4).

In short, the data of Figs. 3 and 4 and their statistical analysis point to the fact that decisions bearing on two distinct features characterizing either one or two distinct stimuli (a) interact as long as they occur within the same experimental block of trials, (b) that this *decisional* interaction translates into a tendency to use a unique decision criterion across features and (c) that this criteria attraction in the D condition is accompanied by a significant drop in sensitivity.

Gorea and Sagi (2000) have drawn attention to the fact that criteria interaction does not merely result from the presence of two different sensitivity stimuli but that it requires that judgments be performed on both these stimuli. Partial comparisons performed with the two ANOVAs detailed above between *Single* blocks where the non-tested ("companion") attribute was set at the lower sensitivity level (i.e. **X1**Y1, short for **C1**O1 and C1**O1**; see the notation convention in the Procedure section), on the one hand, and at the higher sensitivity level(**X1**Y2, short for **C1**O2 and C2**O1**), on the other hand, confirm this observation: they yield no significant difference in either d' or c' [Experiment 1: $F_{d'}(1,3) = 2.36$, $p = 0.22$; $F_{c'}(1,3) = 6.61$, $p = 0.08$; Experiment 2: $F_{d'}(1,3) = 3.45$, $p = 0.16$; $F_{c'}(1,3) = 0.00$, $p = 0.99$]. That a *dual judgment* is a necessary condition for criteria attraction and a d' drop strongly points or is tantamount to an attentional involvement.

4.3. Single vs. Dual task sensitivity for one and two objects

The statistical analysis above has shown for both experiments a significant d' drop in the D relative to the S condition. Here we have a closer look at whether or not this drop is stronger for the case where observers attended to two (Experiment 2) rather than to one object (Experiment 1). Fig. 5 displays Single/Dual d'-ratios obtained in the two-object case against those obtained in the one object case for the three subjects having been run in both experiments. In line with previous studies (e.g. Duncan, 1984; Han et al., 2003), the Single/Dual sensitivity ratios for the two objects case are, in average, 1.32 times larger than for the one object case. This difference is statistically significant [$t(46) = -2.34$, $p = 0.02$].

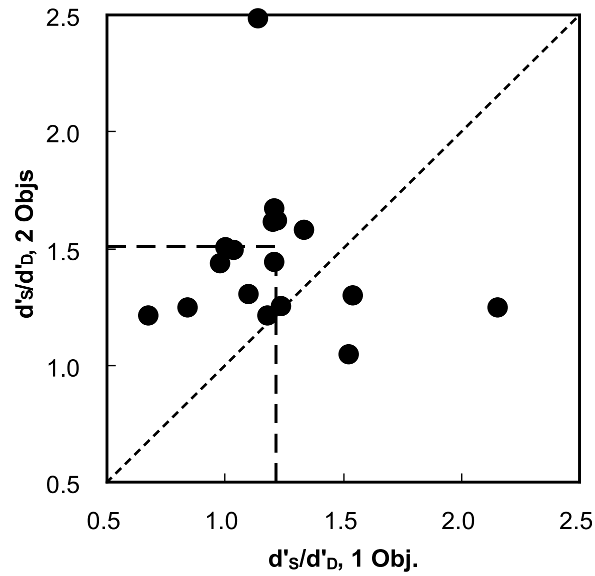

Fig. 5. $d'_{\mathrm{Single}}/d'_{\mathrm{Dual}}$ ratios for one (Exp. 1) vs. two attended objects (Exp. 2). Only data of the three observers having passed the two experiments are considered. Vertical and horizontal dashed lines show the mean ratios for 1 and 2 objects, respectively. Had sensitivity in the *Dual* task been equally degraded (with respect to the *Single* task) for 1 and 2 attended objects the experimental data (circles) should have lain along the dotted diagonal.

5. Discussion

We have previously shown that criteria attraction and particularly its extreme manifestation, the unique response criterion is in quantitative agreement with predictions based on the notion that observers represent a multi-stimulus environment as a unitary internal distribution (uir) to which each stimulus contributes proportionally to its probability of occurrence (Gorea and Sagi, 2000). The present data demonstrate that criteria attraction (but not necessarily a full-fledged unique criterion) also occurs between distinct *attributes* of objects (here contrast and orientation), hence extending the generality of the uir concept. Critically, the present data show that criteria attraction occurs equally between attributes belonging to a unique object as to two distinct objects. Hence, the uir we had originally put forth to account for criteria attraction in a multi-*object* environment should be more appropriately referred to a multi-*decisional* space whether or not this space matches a multi-object environment. The statistical analysis confirms our previous observation that criteria interference does not result from the mere presence of two different stimuli within an experimental session but requires that decisions be taken on each of them (Gorea and Sagi, 1999, 2000).

The present data also bear on the general issue of the *sensory* interference (i.e. as assessed via d' measurements) between visual attributes. Many studies having used single-task conditions evidenced the separability and independent processing of spatial frequency and orientation features at the detection threshold (for a recent review see Shimozaki et al., 2002), but not at suprathreshold levels as long as the two features are spatially overlapping or contiguous (Olzak and Thomas, 1992; Thomas and Olzak, 1990, 1996). Separability and independent sensory processing of contrast and orientation have also been demonstrated for suprathreshold stimuli (such as those used here; see Gorea and Papathomas, 1999). An absence of *decisional* interference for spatial frequency and orientation in a dual categorization task was demonstrated by Chua (1990). This author looked at decisional biases for a given task when performed concurrently with another task, that is, at the dependency of decision boundaries on the magnitude of concurrent stimuli or, equivalently, on their evoked internal responses. Our unique internal representation model is mute concerning such a bias, but is certainly consistent with its absence, as it refers to decision biases resulting from changes in the statistical properties of the stimuli and not from the momentary sensory event. Be it as it may, the present data are the first to our knowledge to show that *decisional interference* (i.e. criteria attraction) occurs between two sensory independent visual attributes and that the strength of this interference is independent of these attributes' belongingness to one or more objects. Taken together with our previous results showing decisional interference within the same attribute distributed over two objects (Gorea and Sagi, 2000, 2002a,b, unpublished, 2003), the present data bear with the notion that, for the decisional system, an *object* is a volatile concept determined by the nature of the task.

The present results show that contrast and orientation processing yields practically identical noise sources (see Fig. 3 and related discussion). Whether the equivalence of the C and O (and, for that reason, of any other attribute) related noises is likely or not is debatable. The literature may surely be sampled so as to provide equal support to the former (e.g. Wiener et al., 2001) as to the latter (e.g. Asaad et al., 2000). The fact is that the issue of the processing noise variability across tasks and cortical areas has not been addressed explicitly. Basing our argument on the observation that, contrary to the neurophysiologically assessed neural noise dependency on the baseline response frequency (Itti et al., 2000), the inferred noise characterizing a contrast discrimination task is independent of the baseline contrast, we have previously argued in favor of a unique limiting noise at the decision level (Gorea and Sagi, 2001). This is pretty much tantamount to posing the existence of a central executive system in charge with all (within modality) decisions (see Pashler, 1998, Chapter 8). Within this context, the presently observed criteria attraction between unrelated dimensions suggests that these attributes can be represented at a unifying *meta-attribute* level, a reminiscence of Stevens' (1969) unifying metric for cross-modal matching experiments. It is interesting to note that the existence of a unique internal noise limiting detection at a central level would render the concept of probability summation over distinct detectors inappropriate. Indeed, probability summation (Graham and Nachmias, 1971; Watson, 1979) requires that the noises associated with different stimulations be uncorrelated. While the present data do not have a direct bearing on probability summation within a single attribute (particularly on contrast summation over space and time at the detection level), they do strengthen the doubts raised about the merits of this concept by a number of recent studies (Bonneh and Sagi, 1999; Tyler and Chen, 2000).

The present data also confirm some basic knowledge on *divided attention* (as it pertains to dual-task experiments; see a review in Pashler, 1998, Chapter 3). They demonstrate a significant sensitivity drop of about 20% in the Dual vs. Single conditions and show that this drop is more pronounced (by about 30%) when attention is "distributed" over two objects rather than one (see Fig. 5). Other studies have reached similar conclusions (Duncan, 1984; Han et al., 2003).

The criteria attraction presently observed for both one and two objects conditions adds a new angle in the way one may interpret the attentional process. Criteria attraction has been successfully modeled as the consequence of the merging of the internal response distributions evoked by the distinct stimuli—the unitary internal representation hypothesis (Gorea and Sagi, 2000). Such a merging testifies to observers discarding information relevant to achieving an optimal decision behavior. This is another way to say that observers' decisional behavior reflects an ineffective *selective attention* process (Gorea and Sagi, 2005). The fact that criteria attraction between two features occurs equally whether they belong to the same object or not, together with previous findings showing the same attraction effect for the same feature distributed over two objects (Gorea and Sagi, 2000, 2001, 2002b) implies that, for the selective attention operator, features and objects are equivalent entities. Obviously, the relationship between the sensory and decisional aspects of distributed/selective attention remains a question for future research.

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