# Orthogonal stimulus variation and attention in dimensional contrast

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These experiments examined one way in which the allocation of attentional resources can change performance during a visual discrimination task. Pigeons were trained to discriminate visual forms under conditions that produced dimensional contrast. In three experiments, negative training stimuli differed from positive stimuli either along a primary physical dimension alone or along both a primary dimension and an orthogonal dimension. When a negative stimulus differed from positive stimuli along two dimensions, discrimination of that negative stimulus improved. For one type of visual form, discrimination of the positive stimuli declined with orthogonal variation in a negative stimulus, whereas for other visual forms, there was no decline in performance. These results are consistent with a model of dimensional contrast that suggests that differences in the allocation of attentional resources determine discrimination performance. The results also indicate that the organization of stimulus dimensions plays a crucial role in the allocation of attentional resources in these settings.

Previous work has focused on the phenomenon of *dimensional contrast*, a reliable finding from maintained generalization procedures (e.g., D. S. Blough, 1975; Hinson & Higa, 1989; Hinson & Malone, 1980; Reynolds, 1961). Dimensional contrast refers to an enhancement of discrimination performance for relatively similar positive (S+) and negative (S−) training stimuli, compared with more dissimilar stimuli. As one example, D. S. Blough (1975) reported two complementary effects—positive and negative dimensional contrast—when pigeons were trained on a maintained generalization procedure with wavelength stimuli. Positive dimensional contrast appeared as highest responding to S+ stimuli near S− on the wavelength continuum. Negative dimensional contrast appeared as lowest responding to S− stimuli near S+. In general, dimensional contrast occurs when discrimination performance is best in a region of the stimulus continuum where S− and S+ are relatively similar, rather than greatly dissimilar. This finding is interesting because it indicates that performance does not always improve monotonically as S− and S+ become more discriminable from one another.

Dimensional contrast is a common finding in the maintained generalization literature. These effects have been reported with many reinforcement contingencies and with a variety of stimulus continua, such as angular orientation, spatial position, wavelength of visible light, and visual flicker rate (e.g., D. S. Blough, 1975; Catania & Gill, 1964; Hinson, 1988; Hinson & Higa, 1989; Reynolds, 1961). In addition, dimensional contrast is typically a large effect that can easily represent a 50%–100% increase in response rate (e.g., Hinson & Tennison, 1997). In other words, an S+ quite similar to S− can maintain almost twice the response rate of another S+ that is very dissimilar from S−. This enhancement occurs despite the fact that all positive stimuli provide identical rates of scheduled and obtained reinforcement.

We have previously argued that dimensional contrast reflects the allocation of attentional resources during discrimination training (Hinson & Tennison, 1997). More specifically, the enhancement of discrimination between negative and positive stimuli that are relatively similar is presumed to be due to increased allocation of attention to these stimuli. While discriminability increases monotonically with differences between stimuli, actual performance obtained may be nonmonotonic because attentional resources are preferentially allocated in the region of the stimulus continuum where S− and S+ are most likely to be confused.

Our formal model of dimensional contrast treats attention as a gradient that extends over an internal representation of the stimuli being presented during the training task (see Hinson & Tennison, 1997). The model states that discrimination performance is based on the joint contribution of a function representing discriminability between stimuli and a function representing the allocation of attentional resources. The *discriminability function* is given by

$$d = 1 - e^{(-x * s)}, \tag{1}$$

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where $d$ is the potential level of discrimination between S− and S+, $s$ is the difference between S− and S+ along a physical dimension, $x$ is a growth parameter, and $e$ is the base of natural logarithms. The *attention function* is given by

$$a = e^{[-y * (1-d)]} * z, \qquad (2)$$

where $y$ is a decay parameter for the decline of attention, and $z$ is a parameter that reflects the asymptotic level of attention. Actual discrimination performance is described by the performance function, given by

$$p = a * d. \qquad (3)$$

Thus, measures of discrimination performance reflect the joint impact of discriminability and attention.

Predictions of the model are based on an assessment of Equation 3. Prior studies of the model (Hinson & Tennison, 1997) have tried to hold discriminability constant by using a fixed set of training stimuli. Experimental manipulations were then designed to alter the allocation of attentional resources. In general, the model provides a good quantitative fit to results using only two free parameters from Equation 2. Moreover, obvious predictions of the model concerning allocation of attentional resources have been confirmed. For example, a discrimination task that has two borders between S+ and S−, rather than one, results in a diminution of performance (e.g., Hinson & Tennison, 1997, Experiment 2). Also, a discrimination task that requires attention to an orthogonal stimulus dimension reduces attention to the primary discrimination task (e.g., Hinson & Tennison, 1997, Experiment 5).

The model described above is a spatial one, based on the properties of gradients of attention and the spatial distribution of stimuli in an internal representation of similarity. The model predicts that increased spacing between S− and S+ should produce an interaction between ease of discrimination and dispersal of attentional resources. That is, Equation 1 predicts that increased spacing between S− and S+ should improve performance. At the same time, Equation 2 indicates that attentional resources will be spread more thinly as stimuli are spaced more widely. This tradeoff in performance predicted by the interaction of Equation 1 and Equation 2 has been observed (e.g., Hinson & Tennison, 1997, Experiment 4). Thus, when the overall range of positive stimuli increases, the quality of overall discrimination performance declines. However, this decline in performance can be offset by increasing the spacing between S− and S+.

The present experiments examined how performance changes when training stimuli vary along an orthogonal stimulus dimension. In three experiments, a discrimination was trained between S− and S+ along a primary stimulus dimension. In some cases, S− also varied along a secondary dimension that was orthogonal to the primary dimension. The novelty of the present experiments was that variation in S− along the orthogonal dimension was actually irrelevant to the primary discrimination task.

In human perceptual studies, the type of orthogonal stimulus variation used here is employed in the *filtering*

paradigm (e.g., Lockhead, 1970; Maddox, 1992). A major issue addressed by the filtering paradigm is the selectivity of attention when an observer is faced with increased variation in the stimulus set. Two classes of outcomes are possible. First, if the orthogonal dimension can be completely ignored, attention can be exclusively applied to the primary stimulus dimension, and there should be no detrimental impact on performance. Alternatively, if variation in the orthogonal dimension cannot be ignored, then attention devoted to the orthogonal dimension can reduce the quality of discrimination for stimuli along the primary dimension.

The degree of attentional selectivity obtained in the filtering task should be based on the way that stimulus dimensions are organized for the observer. For example, one popular conception of dimensional organization is in terms of integrality and separability (e.g., Garner, 1974; Shepard, 1991). Stimuli composed of integral dimensions are stimuli organized in terms of overall similarity relations, whereas stimuli composed of separable dimensions are organized in terms of values of component dimensions.

Dimensional integrality and separability constrain the way attention can be employed in discrimination tasks. Dimensions of separable stimuli can be easily and independently analyzed. Different dimensions of an integral stimulus cannot be attended to easily, and, instead, they combine in a more holistic fashion to determine overall similarity. In the filtering task, orthogonal stimulus variation should be irrelevant for separable stimuli, while, depending on the condition, causing either interference or facilitation for integral stimuli (Grau & Kemler Nelson, 1988; Maddox, 1992).

We have studied visual forms that appear to have relatively integral or separable dimensions for the pigeon (see Hinson, Cannon, & Tennison, 1998). For example, in our work and work by others (e.g., D. S. Blough, 1988), rectangles appear to have integral dimensions. Rectangles also appear to have integral dimensions for human observers (Monahan & Lockhead, 1977). On the other hand, a modified rectangular form with an inverted U as its lower aspect appeared to have dimensions that could be selectively ignored. These stimuli, patterned after earlier forms developed by D. S. Blough (1988), showed strong evidence of dimensional separability.

The present experiments employed these stimuli in order to take advantage of the putative selectivity of attention to different dimensions of the stimuli. Experiment 1 examined orthogonal variation in S− using rectangles, whereas Experiment 2 used modified rectangles. Experiment 3 looked at the effect of orthogonal variation in S− using a presumptively separable, distinctive feature.

## EXPERIMENT 1

Experiment 1 examined discrimination performance by pigeons using rectangular forms. In one condition of Experiment 1, S− differs from S+ either along a primary stimulus dimension of width or along both the primary dimension of width and an orthogonal dimension of

height. If the dimensions of the rectangles are integral, then the pigeons should not be able to selectively attend to the independent dimensions. As a result, there should be an attentional cost to attending to the orthogonal dimension that will be reflected by a decline in performance along the primary dimension.

## Method

**Subjects.** Four homing pigeons with varied training histories served as subjects. The birds were maintained at 80% of their free-feeding weights.

**Apparatus.** The experiment was carried out in a Campden Instruments, three-key operant conditioning chamber with internal dimensions of 35 × 35 × 33 cm. The center key was located 27.5 cm above the floor and 16 cm from either side of the chamber. It was made of clear Plexiglas and provided a circular viewing region with a diameter of approximately 3 cm. Black tape covered the two side keys. A 6-W houselight provided diffuse illumination throughout the chamber during experimental sessions. A 5 × 6 cm aperture, located in the middle of the front panel 13.5 cm from the floor, directly below the center key, provided access to a food magazine. Mixed grain presented for 3 sec was used as a reinforcer. The experimental chamber was part of a larger sound-proofing box, which contained a fan for ventilation and for masking of extraneous noise.

An IBM XT-type computer, along with a dedicated single-board microcomputer, controlled real-time contingencies during the experiment and collected all data. Stimuli were displayed on an attached monochrome monitor. The 14-in. monitor had a dot pitch of 0.39 mm with a resolution of 640 × 480 pixels at a 60-Hz refresh rate. All stimuli were drawn from lines 1 pixel in width and appeared in a yellow phosphor. A double-lens assembly projected the screen image to the response key. Inspection of the stimuli by the experimenters indicated that the projected form appeared in a totally black background. To the human eye, the form looked to be slightly behind the response key, although there were no other strong indications of depth. Movement of viewing position several inches vertically and horizontally had no obvious impact on the quality of the stimulus as it appeared on the key. Size measurements of the stimuli were made on the front of the key.

**Procedure.** After preliminary autoshaping in the chamber to develop some responding to the key, training for Experiment 1 began.

Stimulus 1 was designated S−, and Stimuli 2–13 were designated S+. Responses during S− and S+ were reinforced according to a probabilistic fixed-interval (FI) 20-sec schedule. For S+, the first response after 20 sec always resulted in 3-sec access to mixed grain. During S−, the first response after 20 sec produced food reinforcement on 3% of the presentations. On the other 97% of stimulus presentations of S−, a 3-sec intertrial interval, with houselight off, was provided instead of food.

The 4 birds received training with rectangular forms in two conditions. In the *baseline* condition, Stimulus 1 (S−) was a rectangle 10 mm high and 12 mm wide. Stimuli 2–13 (S+) were rectangles 10 mm high, but each rectangle differed from S− in 2-mm increments in width. Thus, Stimulus 2 was 14 mm wide, and Stimulus 13 was 36 mm wide. In the *orthogonal* condition, S− differed from S+ in both width and height on some occasions. On half of the S− presentations, the rectangle signaling S− was 12 mm wide × 10 mm high. On the other half of the S− presentations, the rectangle was 12 mm wide × 26 mm high. The manipulations are schematically represented in Figure 1.

Pairs of birds received training on the two conditions in counterbalanced orders. Each condition lasted for 21 daily sessions, conducted 6 or 7 days a week. During each session, there were 120 stimulus presentations. The sequence of stimuli was determined by a pseudorandom process, with a .5 probability of selecting either S− or S+. Responding appeared stable after 7 sessions, as evidenced by a lack of trend in responding from session to session and by small changes in absolute responding from session to session (i.e., less than 5% change from one session to the next).

## Results and Discussion

Figure 2 shows the group mean response rate during each stimulus, for the last 10 sessions of each condition in Experiment 1. Responding during the orthogonal condition is divided into two components: primary S−, which reflects stimuli varying in width alone, and orthogonal S−, which reflects the orthogonal variation in height. The response rate functions show large positive dimensional contrast. Response rate during S+ peaked near S− and declined as S+ values became increasingly different from S−.
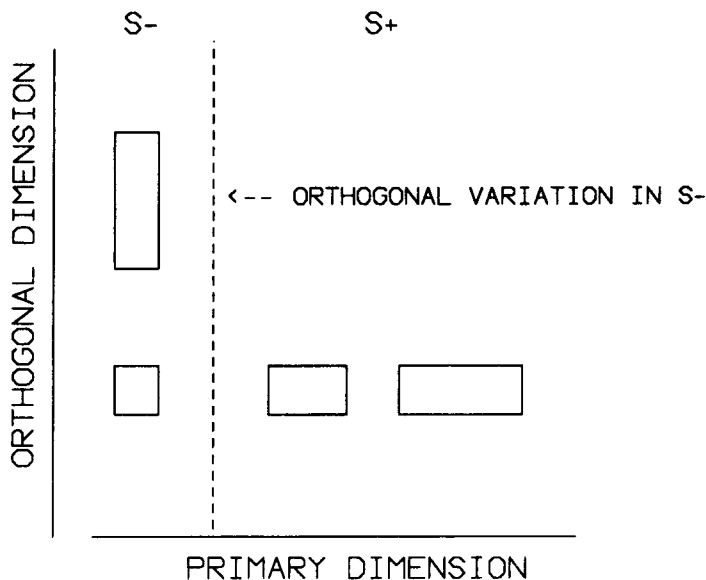


**Figure 1. Schematic representation of stimulus manipulations in Experiment 1.**

●●●●● PRIMARY DIMENSION
■■■■■ ORTHOGONAL DIMENSION
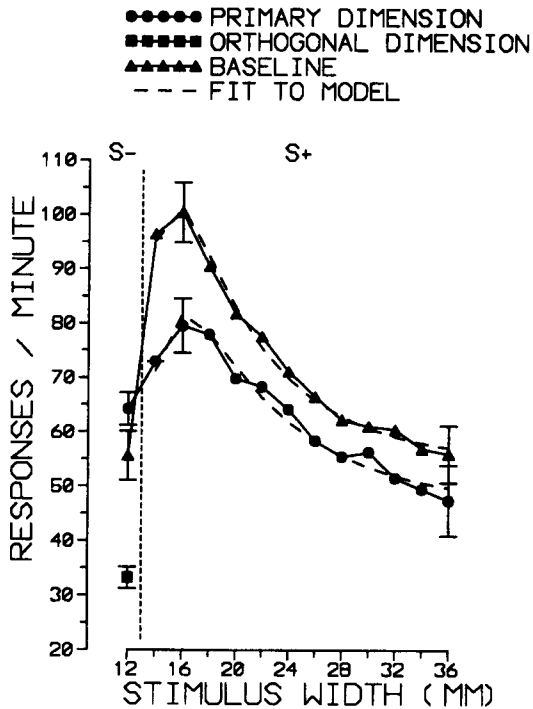▲▲▲▲▲ BASELINE
− − − FIT TO MODEL



Figure 2. Group mean response rates during each stimulus for the last 10 sessions of Experiment 1. Vertical bars show ±1 *SEM* for responding during S− and S+. Dashed lines indicate the best fit of the attentional model.

Responding during S− changed across conditions. Mean S− response rate during baseline was 55 responses/minute. During the orthogonal condition, primary S− response rate was 63 responses/minute, and orthogonal S− rate was 34 responses/minute. A repeated measures analysis of variance (ANOVA) showed the global change in response rate across conditions to be statistically reliable [$F(2,6) = 23.573, p < .001$]. Pairwise comparisons by means of a two-tailed $t$ test were used to assess the reliability of differences in S− responding. Orthogonal S− was lower than primary S− responding [$t(3) = 7.752, p < .004$] and lower than baseline S− responding [$t(3) = 3.776, p < .03$]. Baseline and primary S− responding did not differ significantly. Thus, the S− with orthogonal variation in height was easier to discriminate than was S− without orthogonal variation.

Responding during S+ also changed across conditions. Mean response rate during S+ declined from 74 responses/minute during baseline to 63 responses/minute during the orthogonal condition. The significance of this change was confirmed by a repeated measures ANOVA [$F(1,47) = 18.295, p < .0001$].

A more precise analysis of the discrimination profile for S+ can be made by fitting the attentional model to the response rate functions. Previously (e.g., Hinson & Tennison, 1997), we have fit the attentional model to relative discrimination functions, based on the relative dif-

ference between S− and S+ responding. In the present experiment, it was difficult to know how best to calculate relative discrimination given the fact that we had a primary S− and an orthogonal S−. As a result, we fitted the attentional model to absolute S+ response rates. Because the model works equally well with absolute or relative response rates, we were able to directly compare S+ responding across conditions without making an arbitrary decision about how to compute relative discrimination.

Equation 3 was fit to the mean S+ response functions appearing in Figure 2 by using the quasi-Newton, nonlinear estimation technique from SYSTAT (1990). The fits involved the three free parameters of Equations 1 and 2 that are combined in Equation 3, following the procedure described by Hinson and Tennison (1997). To assess statistical reliability of differences in parameters between conditions, we compared 95% confidence intervals. The nonlinear estimation procedure in SYSTAT provides asymptotic standard errors for each parameter. Confidence intervals were calculated from the obtained standard errors and the degrees of freedom—namely, one less than the number of stimuli in the S+ response function (e.g., Hays, 1988). For a difference in parameters to be considered reliable by this measure, there could be no overlap in the confidence intervals for each estimated parameter. The best estimated functions from the fitting procedure appear as dashed lines in Figure 2. Obtained parameter values and quality of fit appear in Table 1.

To begin, fits for the baseline and orthogonal conditions are quite good, indicating that the model accounts well for the data. Next, the discriminability parameter $x$ does not differ between conditions. This is consistent with our previous assumption (e.g., Hinson & Tennison, 1997) that parameter $x$ reflects limits on the ability to resolve differences between stimuli. Therefore, if training stimuli are the same across conditions, discriminability should not change even though task requirements may differ.

The only significant change between conditions is in one of the attentional parameters. Parameter $y$, which reflects how rapidly the gradient of attentional declines across the spatial representation, does not change reliably. But the value of $z$ is reliably lower in the orthogonal condition. Parameter $z$ acts as a general multiplier, so that the higher its value, the better performance will be. In Experiment 1, the overall decline in S+ performance when

**Table 1**
Estimates of Parameters for Equation 3 ($x$, $y$, and $z$) and Corrected Estimate of Fit ($r^2$) for Baseline and Orthogonal S+ Response Rate Functions From Experiment 1

| Conditions | Parameters | | | |
| --- | --- | --- | --- | --- |
| | $x$ | $y$ | $z$ | $r^2$ |
| Baseline | 0.31[a] (0.01) | −2.56[a] (0.03) | 55[a] (1.1) | .99 |
| Orthogonal | 0.26[a] (0.02) | −2.46[a] (0.07) | 47[b] (1.7) | .97 |

Note—Asymptotic standard errors appear in parentheses. Superscripts that differ indicate parameter values that differ from one another outside a 95% confidence interval.

S− varied in an orthogonal dimension is accounted for by the smaller value of parameter $z$. Thus, the *cost* of attention to the orthogonal dimension in S− was a lower level of attention to the primary dimension of S+.

## EXPERIMENT 2

Experiment 1 revealed that when pigeons discriminated rectangles, attention changed to accommodate the distribution of stimuli along two dimensions. Discrimination between S− and S+ improved when S− varied along an orthogonal dimension. But there was also an attentional cost to orthogonal variation in S−. That is, when there were interspersed trials of S− with and without orthogonal variation, discrimination of S+ along the primary dimension was poorer than baseline.

Experiment 2 examined the effects of orthogonal variation in S− using modified rectangular forms. All training conditions and contingencies in Experiment 2 were comparable to those in Experiment 1, except for the stimuli. On the basis of earlier work (e.g., Hinson et al., 1998), there is reason to expect that the dimensions of these modified forms will be more nearly separable. If the dimensions of these forms can be attended to independently, there may be little or no attentional cost associated with orthogonal variation in S−.

### Method

**Subjects**. Four homing pigeons with varied training histories served as subjects. The birds were maintained at 80% of their free-feeding weights.

**Apparatus**. The experiment was carried out in an apparatus with the same physical dimensions and features as the apparatus used in Experiment 1.

**Procedure**. Experiment 2 began with no preliminary training. Stimulus 1 was designated S−, and Stimuli 2–13 were designated S+. Responses during S− and S+ were reinforced according to the same probabilistic FI 20-sec schedule described in Experiment 1.

The birds were trained in two conditions. In the *baseline* condition, training was identical to that in Experiment 1, except that each stimulus appeared with an inverted U beneath the rectangle. The inverted U was 3 mm high and 12 mm wide. In the *orthogonal* condition, S− differed from S+ in the width of the upper rectangle and, on some occasions, the width of the inverted U. On half of the S− presentations, the inverted U was 12 mm wide. On the other half of S− presentations, the inverted U was 26 mm wide. The manipulations used are schematically represented in Figure 3.

Training conditions in Experiment 2 were comparable to those in Experiment 1. Pairs of birds received training on the two conditions in counterbalanced orders. Each condition lasted for 21 daily sessions, conducted 6 or 7 days a week. During each session, there were 120 stimulus presentations. The sequence of stimuli was determined by a pseudorandom process, with a .5 probability of selecting either S− or S+. Responding was considered stable by the criteria used in Experiment 1.

### Results and Discussion

Figure 4 shows the group mean response rate during each stimulus, for the last 10 sessions of each condition in Experiment 2. The best estimated functions from the fitting procedure appear as dashed lines in Figure 4. Again, responding during the orthogonal condition is divided into two components of primary S− and orthogonal S−, reflecting orthogonal variation in width of the lower inverted U. As in Experiment 1, response rate functions show large positive dimensional contrast. Also, during the orthogonal condition, the birds clearly discriminated the presence versus absence of variation in width of the lower inverted U for S−. But, unlike the results of Experiment 1, Figure 4 shows no difference in S+ responding between baseline and orthogonal conditions of Experiment 2.

The observations from Figure 4 can be confirmed statistically. Response rate for S− during baseline was 34
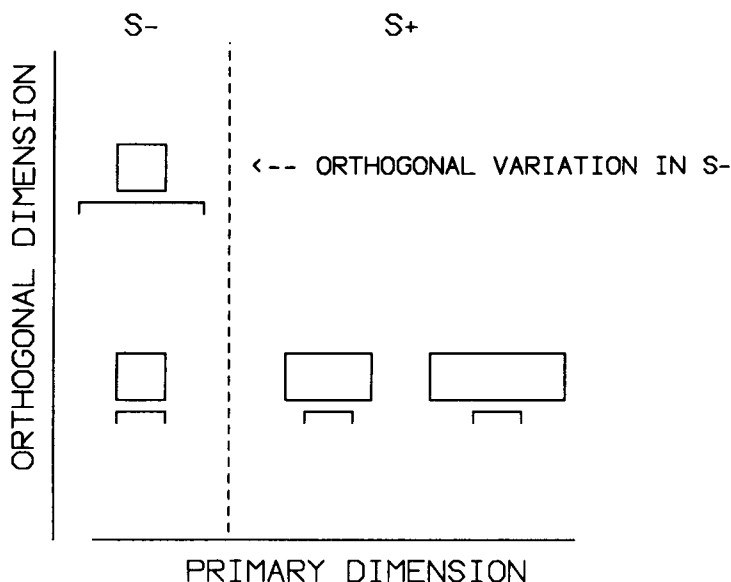


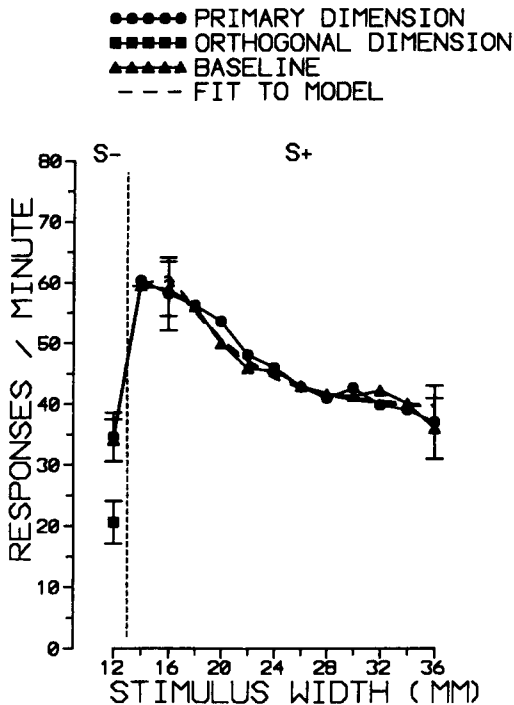Figure 3. Schematic representation of stimulus manipulations in Experiment 2.

•••• PRIMARY DIMENSION
■■■■ ORTHOGONAL DIMENSION
▲▲▲▲▲ BASELINE
- - - FIT TO MODEL

**Figure 4. Group mean response rates during each stimulus for the last 10 sessions of Experiment 2. Vertical bars show ±1 *SEM* for responding during S− and S+. Dashed lines indicate the best fit of the attentional model.**

responses/minute. During the orthogonal condition, primary S− response rate was 33 responses/minute, and orthogonal S− rate was 21 responses/minute. A repeated measures ANOVA showed the global change across conditions to be statistically reliable [$F(2,6) = 9.132, p < .015$]. Pairwise comparisons confirmed that orthogonal S− responding was lower than primary S− responding [$t(3) = 3.323, p < .045$] and lower than baseline S− responding [$t(3) = 10.574, p < .002$]. Baseline and primary S− responding did not differ significantly. Finally, mean response rate during S+ did not change reliably across conditions, as indicated by a repeated measures ANOVA [$F(1,47) = 0.257, p = .614$].

Table 2 provides the fits of the attentional model from Equation 3. The fit of the model is good for both conditions of Experiment 2. But, unlike Experiment 1, there were no reliable changes in parameters between baseline and orthogonal conditions. Thus, orthogonal variation in S− during Experiment 2 made it easier to discriminate that S− from S+. However, there was no impact of this improvement on responding to S+ along the primary dimension.

## EXPERIMENT 3

Experiment 2 showed that orthogonal variation in S− does not always impair performance along the primary S+ dimension, as it did in Experiment 1. If stimulus di-

mensions are organized so that an orthogonal dimension can be easily analyzed, there may be no measurable attentional costs. Experiment 3 examined another way in which stimuli could vary in an orthogonal dimension without incurring attentional costs. In this experiment, a distinctive feature was added to the rectangles used in Experiment 1. Studies of visual search in humans have found that distinctive features permit preattentive processing, thereby limiting the impact of the task on attentional resources (e.g., Treisman & Gormican, 1988). If orthogonal variation in S− occurs by means of a distinctive feature, this may prevent a significant allocation of resources away from the primary stimulus dimension.

### Method

**Subjects.** Four homing pigeons with varied training histories served as subjects. The birds were maintained at 80% of their free-feeding weights.

**Apparatus.** The experiment was carried out in the apparatus described in Experiment 1.

**Procedure.** Experiment 3 began with no preliminary training. Stimulus 1 was designated S−, and Stimuli 2–13 were designated S+. Responses during S− and S+ were reinforced according to the same probabilistic FI 20-sec schedule described in Experiment 1.

The birds were trained in two conditions. In the *baseline* condition, training was identical to that in Experiment 1. In the *orthogonal* condition, S− differed from S+ in width of the rectangle and, on some occasions, by the appearance of a distinctive feature. On half of the S− presentations, the rectangle signaling S− was 12 mm wide × 10 mm high. On the other half of the S− presentations, the rectangle was 12 mm wide × 10 mm high and was also transected vertically by a solid bar measuring 1 mm wide × 14 mm high. These conditions are schematically represented in Figure 5.

Training conditions in Experiment 3 were comparable to those in Experiment 1. Pairs of birds received training on the two conditions in counterbalanced orders. Each condition lasted for 21 daily sessions, conducted 6 or 7 days a week. During each session, there were 120 stimulus presentations. The sequence of stimuli was determined by a pseudorandom process, with a .5 probability of selecting either S− or S+. Responding was considered stable by the criteria used in Experiment 1.

### Results and Discussion

Figure 6 shows the group mean response rate during each stimulus, for the last 10 sessions of each condition in Experiment 3. The best estimated functions from the fitting procedure appear as dashed lines in Figure 6. As before, responding during the orthogonal condition is divided into two components of primary S− and orthogo-

**Table 2**
**Estimates of Parameters for Equation 3 ($x$, $y$, and $z$) and Corrected Estimate of Fit ($r^2$) for Baseline and Orthogonal S+ Response Rate Functions From Experiment 2**

| Conditions | Parameters | | | |
|---|---|---|---|---|
| | $x$ | $y$ | $z$ | $r^2$ |
| Baseline | 0.35[a] (0.03) | −2.33[a] (0.06) | 38[a] (2.8) | .96 |
| Orthogonal | 0.38[a] (0.03) | −2.29[a] (0.05) | 39[a] (0.9) | .97 |

Note—Asymptotic standard errors appear in parentheses. Superscripts that differ indicate parameter values that differ from one another outside a 95% confidence interval.
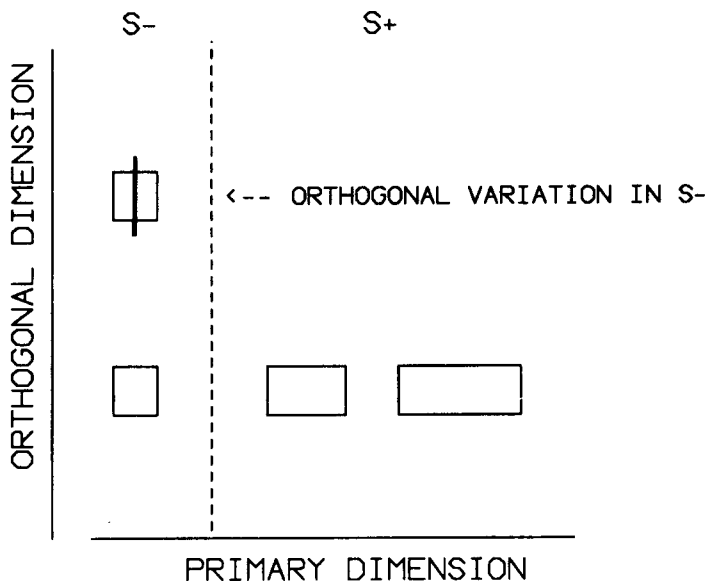
Figure 5. Schematic representation of stimulus manipulations in Experiment 3.

nal S−, reflecting orthogonal variation by means of the presence of the distinctive feature. The overall pattern of results in Experiment 3 was highly similar to that obtained in Experiment 2.

Baseline response rate for S− was 56 responses/minute. During the orthogonal condition, primary S− response



Figure 6. Group mean response rates during each stimulus for the last 10 sessions of Experiment 3. Vertical bars show ±1 *SEM* for responding during S− and S+. Dashed lines indicate the best fit of the attentional model.

rate was 58 responses/minute, and orthogonal S− rate was 35 responses/minute. A repeated measures ANOVA showed the global change across conditions to be statistically reliable [$F(2,6) = 32.015, p < .001$]. Pairwise comparisons revealed that orthogonal S− responding was lower than primary S− responding [$t(3) = 5.799, p < .01$] and lower than baseline S− responding [$t(3) = 8.736, p < .003$]. Baseline and primary S− responding did not differ significantly. There was no reliable difference in mean responding during S+ across conditions, as confirmed by a repeated measures ANOVA [$F(1,47) = 0.698, p = .408$].

Table 3 provides the fits of the attentional model from Equation 3. The fit of the model is good for both baseline and orthogonal conditions. Like Experiment 2, there were no reliable changes in parameters between baseline and orthogonal conditions. Again, orthogonal variation in S− improved discrimination of that S−, without measurable impact on responding to S+ along the primary stimulus dimension.

## GENERAL DISCUSSION

The results of these experiments support the attentional model of dimensional contrast (e.g., Hinson & Tennison, 1997). The model, which describes the allocation of limited attentional resources during discrimination training, provides a good quantitative fit to results from all the experiments reported here. In all cases, discrimination performance was adequately described as the interaction of a set of discriminability factors and a set of attentional factors postulated by the model.

The present work used a manipulation that is commonly employed to study attentional selectivity (see Lockhead, 1970; Maddox, 1992). By varying S− along a stimulus dimension orthogonal to the primary training
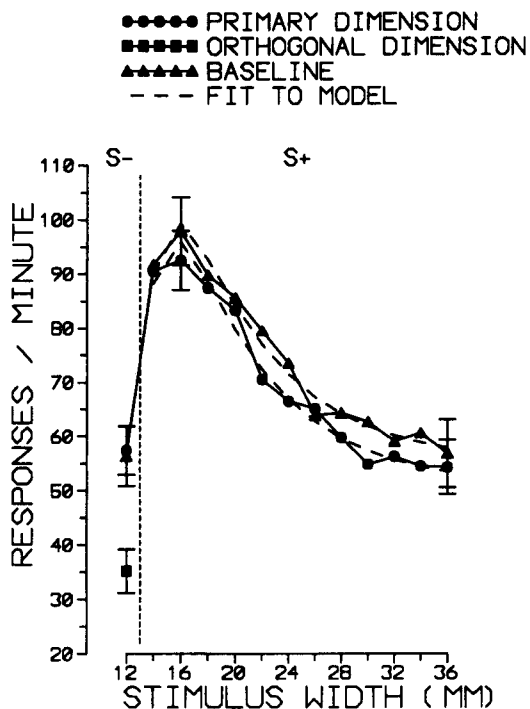
### Table 3
Estimates of Parameters for Equation 3 ($x, y$, and $z$) and
Corrected Estimate of Fit ($r^2$) for Baseline and Orthogonal
S+ Response Rate Functions From Experiment 3

| Conditions | Parameters | | | |
|---|---|---|---|---|
| | $x$ | $y$ | $z$ | $r^2$ |
| Baseline | 0.29[a] (0.02) | −2.51[a] (0.05) | 55[a] (1.6) | .98 |
| Orthogonal | 0.29[a] (0.02) | −2.58[a] (0.06) | 51[a] (1.6) | .98 |

Note—Asymptotic standard errors appear in parentheses. Superscripts
that differ indicate parameter values that differ from one another out-
side a 95% confidence interval.

dimension, we had the opportunity to examine whether
our subjects could selectively deploy attentional re-
sources. As assessed by our model, attentional resources
were, in fact, selectively applied. But this selectivity de-
pended on the type of visual forms used during training.

In Experiment 1, using simple rectangles, orthogonal
variation in S− had two effects. Variation in the orthog-
onal dimension made it easier to discriminate S− from
S+. However, this improvement came at a cost. Perfor-
mance during S+ actually declined, reflected by a de-
crease in overall response rate and a lower value of pa-
rameter $z$ in the model.

In Experiment 2, using modified rectangles, and in Ex-
periment 3, using rectangles with a distinctive feature,
there was also improvement in performance when S−
differed from S+ along the orthogonal dimension. But, in
these two experiments, there was no associated cost to
orthogonal variation in S−. Responding during S+ was
identical during baseline and orthogonal conditions.

Outcomes of these three experiments are readily in-
terpreted in terms of the organizational features of stim-
ulus dimensions. The rectangles used in Experiment 1
appear to have integral dimensions (cf. D. S. Blough,
1988; Shepard, 1991). Different dimensions of an inte-
gral stimulus cannot be attended to easily, and, instead,
they combine in a more holistic fashion to determine
overall similarity. The result in Experiment 1 is that or-
thogonal variation in S− could neither be ignored nor
easily analyzed as a separate dimension. In terms of the
attentional model, S− became more widely separated
from S+, contributing to improved performance when
the orthogonal dimension was varied. But, at the same
time, limited attentional resources were more widely dis-
tributed, leading to a relative decline in performance for
S+ along the primary stimulus dimension.

In contrast to Experiment 1, the component dimen-
sions for stimuli in Experiment 2 appeared to be separa-
ble. Dimensions of separable stimuli can be easily and
independently analyzed. As a result, in Experiment 2, or-
thogonal variation contributed to improved performance
without associated attentional cost. Similarly, the dis-
tinctive feature used in Experiment 3 was apparently an-
alyzed without significant attentional cost.

It is important to note that the apparent cost of or-
thogonal variation in Experiment 1 cannot be attributed
to greater difficulty of this task. Comparison of Figures

2 and 6 shows that the level of discrimination between
baseline and orthogonal S− conditions was comparable
in Experiments 1 and 3. The only important difference be-
tween these experiments was the relatively poorer level
of discrimination during S+ along the primary stimulus
dimension.

An interesting comparison can be made between the
present findings and results from a previous study that
manipulated attentional demands during visual discrim-
ination by presenting a primary stimulus continuum and
an orthogonal stimulus (Hinson & Tennison, 1997, Ex-
periment 5). In that study, the primary discrimination
task involved visual wavelength stimuli, whereas the or-
thogonal stimulus was a tone. Different conditions ex-
amined the impact of the tone when it was redundant
with the wavelength S− or when the presence of the tone
was a conditional cue necessary to distinguish S− from
S+. Simply put, the birds attended to the tone both as a
redundant cue and as a conditional cue. The impact of
attending to the tone was evidenced by a decline in per-
formance along the primary wavelength dimension, con-
sistent with predictions of the attentional model discussed
earlier.

It is not surprising that when limited attentional re-
sources are directed toward one set of signals, perfor-
mance for other available signals will suffer. This feature
is often exploited in manipulations of attention (e.g.,
P. M. Blough, 1989; Posner & Snyder, 1975) and is the
rationale for the present experiments. What is unusual in
our prior study is that the tone was attended to even in the
redundant case. Presumably, auditory and visual dimen-
sions are potentially separable for pigeons. For example,
D. S. Blough (1972) and Chase and Heinemann (1972)
provide evidence for the separability of auditory and vi-
sual dimensions under some circumstances. And yet, in
our study, in which pigeons could have ignored the or-
thogonal auditory stimulus without penalty, they did not,
and therefore, a cost in performance was incurred along
the primary visual dimension.

This curious result provides reason for caution in our
interpretation of stimulus organization. The absence of
performance indicating separability of stimulus dimen-
sions does not mean the stimulus dimensions are inte-
gral. A stimulus that is potentially analyzable may not be
analyzed or filtered out in a given task. Hence, it may be
difficult to arrange contingencies that simply and clearly
distinguish between integral and separable dimensions
for animals—a point noted by others (e.g., D. S. Blough,
1991; D. S. Blough & P. M. Blough, 1997). Furthermore,
stimulus organization that is potentially available may
not be used by pigeons the way in which it is used by hu-
mans. For example, reaction time functions for visual
search in humans show a striking asymmetry when a dis-
tinctive feature is present versus when it is absent. This
asymmetry is indicative of processing that makes negli-
gible demands on attentional resources (Treisman & Gor-
mican, 1988). Pigeons, on the other hand, do not show
this asymmetry in comparable tasks (e.g., Allan & D. S.

Blough, 1989), meaning either that pigeons *cannot* analyze features preattentively or that they *do not* show preattentive processing in some places we expect.

In conclusion, while the attentional model provides a good fit to the results from the present experiments, one refinement is needed. As it now stands, there is nothing in the model that explicitly distinguishes between integral and separable stimuli. As we have shown, these different forms of stimulus organization may have an impact on the allocation of attentional resources. Therefore, future development of the attentional model should include some way of accommodating the consequences of separable and integral stimulus dimensions.

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