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Influences of Categorization on Perceptual Discrimination

Robert Goldstone

Four experiments investigated the influence of categorization training on perceptual discrimination. Ss were trained according to 1 of 4 different categorization regimes. Subsequent to category learning, Ss performed a Same–Different judgment task. Ss' sensitivities (*d'*s) for discriminating between items that varied on category-(ir)relevant dimensions were measured. Evidence for acquired distinctiveness (increased perceptual sensitivity for items that are categorized differently) was obtained. One case of acquired equivalence (decreased perceptual sensitivity for items that are categorized together) was found for separable, but not integral, dimensions. Acquired equivalence within a categorization-relevant dimension was never found for either integral or separable dimensions. The relevance of the results for theories of perceptual learning, dimensional attention, categorical perception, and categorization are discussed.

Psychologists have long been intrigued by the possibility that the concepts that people learn influence their perceptual abilities. It may be that the way people organize their world into categories alters the actual appearance of their world. The purpose of the present research is to investigate influences of concept learning on perception.

The notion that experience and expectations can influence perception can be traced back to the "New Look" movement of the 1940s and 50s (J. A. Bruner & Postman, 1949). Evidence suggests that experts perceive structures in X rays (Norman, Brooks, Coblentz, & Babcook, 1992), beers (Peron & Allen, 1988), and infant chickens (Biederman & Shiffrar, 1987) that are missed by novices. As the experts in these fields learn to distinguish among the concepts in their domain (types of fractures, brands of beer, or genders of chickens), they seem to acquire new ways of perceptually structuring the objects to be categorized.

This suggestion—that categorization causes changes to perceptual abilities—is not implicated in most traditional accounts of concept learning. In J. S. Bruner, Goodnow, and Austin's (1956) classic studies of concept learning, subjects saw flash cards with shapes and were required to learn rules such as "If the flash card has a circle or something black, then it belongs in Category A" on the basis of feedback provided by the experimenter. Although work in concept learning has come a long way since J. S. Bruner et al.'s study (Estes, 1986; Kruschke, 1992; Medin & Schaffer, 1978; Nosofsky, 1986; Reed, 1972), vestiges of this earlier work are apparent in current research. Specifically, many researchers have investigated concept learning using stimuli that have clear-cut dimensions with clearly different values on these dimensions. Although such stimuli are mandatory in many cases for experimental control and precision, they do not require subjects to perceptually learn new dimensions or finer discriminations. In the present described concept learning tasks, subjects had to make fine discriminations along dimensions or isolate dimensions that normally are fused together. In both cases, the perceptual abilities required for the categorization task are not at a ceiling level before categorization training begins; consequently, experience with categorization may drive perceptual learning.

Evidence for an Influence of Learning on Perception

Perceptual Learning

Although most concept learning work has not dealt with the development of new perceptual abilities from experience (but see Norman, Brooks, & Allen, 1989; Wisniewski & Medin, in press), this topic has been addressed in other literature. Most influential, perhaps, has been E. J. Gibson's (1969) treatment of perceptual learning, the process by which there is "an increase in the ability to extract information from the environment, as a result of experience and practice with stimulation coming from it" (p. 3). Gibson demonstrated several times that people can increase their perceptual sensitivity by categorizing or identifying stimuli. One type of perceptual learning, called *predifferentiation* (E. J. Gibson, 1991) or *preexposure effect* (Hall, 1991), entails heightened perceptual sensitivity following exposure to the tested materials. Simply preexposing subjects to stimuli often facilitates their later discriminations among the stimuli. For example, E. J. Gibson and Walk (1956) placed cutout shapes in the cages of some rats but not others.

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Correspondence concerning this article should be addressed to Robert Goldstone, Psychology Department, Indiana University, Bloomington, Indiana 47405. Electronic mail may be sent to rgoldsto@ucs.indiana.edu.

Although no response to the shapes was required, animals that were raised with the shapes in their cages were better able to learn a subsequent discrimination task that used the shapes as relevant cues. Similar results have been found with human subjects (Goss, 1953; Vanderplas, Sanderson, & Vanderplas, 1964). Similarly, J. J. Gibson and Gibson (1955) showed that simple practice in identifying visual "scribbles" increased subjects' identification performance, even when no feedback was provided. The existence of predifferentiation effects indicates that differential rewards among cues to be discriminated are not required for facilitation of perceptual discrimination. Mere experience with the stimuli is sufficient.

However, there is also evidence that subjects become perceptually attuned to diagnostic physical features that facilitate discrimination among presented stimuli (e.g., J. J. Gibson & Gibson, 1955). For this class of experiments, the organization of the stimuli into categories has an influence on subsequent discrimination. Lawrence (1949) developed a theory of *acquired distinctiveness* of cues, according to which cues that are relevant for a task become generally distinctive. In one experiment, Lawrence trained rats on either a black–white or a rough–smooth discrimination. Rats received a reward for choosing one stimulus rather than another. The rats were subsequently transferred to a discrimination task in which, for example, when black shapes were presented, the rat was rewarded for a left response, and when white shapes were presented, the rat was rewarded for a right response. Rats learned this second discrimination better when they had been trained earlier to make a black–white discrimination. Stimuli also acquire nondistinctiveness (or equivalence); when cues are irrelevant for an earlier discrimination, there is a deleterious effect on subsequent discrimination learning with them (Waller, 1970). Both of these effects are common in human subjects (E. J. Gibson, 1969).

Cautions From Perceptual Learning Work

It is important to distinguish transfer between two types of discrimination experiments, associative and perceptual. Lawrence's (1949) experiment pertains to associative discrimination; the task is to learn to associate a particular cue with a particular response. Perceptual discrimination experiments involve simply distinguishing between two perceptual cues. For example, in a perceptual same–different judgment task, subjects are shown a pair of stimuli and must decide whether the stimuli are exactly the same. Perceptual sensitivity in a same–different judgment task can be measured by comparing, in accordance with signal detection theory (Swets, Tanner, & Birdsall, 1961), the probability of correctly calling a pair "different" with the probability of incorrectly calling a pair of identical stimuli "different." Although most of the work testing the theory of acquired distinctiveness has used associative discrimination tasks, if the goal is to find an influence of stimulus categorization on perception per se, it is important to use perceptual discrimination tasks. Findings of acquired distinctiveness that use associative discrimination do not necessarily require changes to perceptual abilities. In fact, Hall (1991) reviewed the evidence used to support perceptual learning using associative discrimination paradigms and concluded that there is little reason to postulate perceptual changes rather than the acquisition of associations among stimulus cues. For example, Lawrence's results can be accommodated if one assumes that stimulus cues that determine correct responses are more likely to be associated with other responses. However, simple associationist theories are less likely to be relevant in cases in which perceptual sensitivity is measured by same–different judgments. One of the purposes of the present experiments is to find evidence for perceptual, not simply associative, changes that are due to training.

Although same–different judgments are used as the measure of perceptual sensitivity, the claim is not made that they are strictly perceptual judgments, if *perceptual* is interpreted narrowly. Same–different judgments involve a memory component (Pisoni, 1973). Often, the two items that are compared are not presented simultaneously. Even if there is a only a short delay between items, a short-term memory encoding of the first presented item is required. One might even argue that if the items are simultaneously presented, there is still a need for an item to be encoded in memory before it can be compared with the other item if the items are spatially separated. Same–different judgments also involve attentional mechanisms. When viewing an item, subjects may attend to some aspects and ignore others. Contextual, instructional, and motivational variables may influence what stimulus aspects attract attention. Thus, although the same–different judgment task is used in these experiments as a measure of perceptual sensitivity, higher level cognitive functions such as memory and attention also have an influence on same–different judgments. In fact, one of the conclusions from the present research is that a clear distinction between sensory and cognitive processes is not tenable (Algom, 1992; Goldstone, 1993; Marks, 1992).

Categorical Perception

The largest bulk of evidence that is used to support the contention that concepts influence perception comes from the field of categorical perception (see Harnad, 1987, for reviews and recent research). According to the phenomenon of categorical perception, people are better able to distinguish between physically different stimuli when the stimuli come from different categories than when they come from the same category. The effect has been best documented with speech phoneme categories. For example, Liberman, Harris, Hoffman, and Griffith (1957) generated a set of vowel–consonant syllables going from */be/* to */de/* to */ge/* by varying the onset frequency of the second-formant transition of the initial consonant (the details are not important for the present purpose). The 14 speech sounds were created by making equal physical spacings between neighboring sounds. Observers listened to three sounds—A followed by B followed by X—and indicated

whether X was identical to A or B. Subjects performed this task more accurately when syllables A and B belonged to different phonemic categories than when they were physical variants of the same phoneme, even when the physical difference between A and B was equated. Liberman et al. concluded that the phonemic categories possessed by an adult speaker of English influence the perceptual discriminations that he or she can make.

The degree to which categorical perception phenomena are learned rather than innate is not clear (Pastore, 1987; Rosen & Howell, 1987). On the one hand, it appears that discriminability in some regions of acoustical continua is higher than in other regions, irrespective of category structure. Phoneme categories may naturally use regions with intrinsically higher discriminability as boundaries (Kuhl & Miller, 1978; Stevens, 1981). Consistent with an innatist perspective are Eimas's results (1974; Eimas, Siqueland, Jusczyk, & Vigorito, 1971) that show that infants of only 4 months show increased sensitivity to acoustical differences in the same region of a physical continuum as do adults. Thus, there is evidence that suggests that people's increased sensitivity to acoustical differences that straddle category boundaries may either be innate or a property of the acoustical signal, rather than learned.

However, there is also evidence that the categorical perception effect is subject to learning (Logan, Lively, & Pisoni, 1991). Lane (1965) found categorical perception effects for laboratory-created materials that were placed in different categories by their labels, even though the categories did not correspond to a naturally occurring distinction. E. M. Burns and Ward (1978) found that expert musicians, but not novices, showed a categorical perception effect for pitch differences, suggesting that training was instrumental in creating differential sensitization along semitone boundaries. Finally, cross-cultural evidence suggests that the learning of a particular language influences the pattern of discriminability among speech sounds. In general, a sound difference that crosses the boundary between phonemes in a language will be more discriminable to speakers of that language than to speakers of a language in which the sound difference does not cross phonemic boundaries (Repp, 1984; Strange & Jenkins, 1978).

Another issue in categorical perception research concerns whether categorical perception is a general perceptual effect or is found only for language-related stimuli. Liberman, Harris, Kinney, and Lane (1961) originally argued that categorical perception is found for speech-like stimuli but not for control stimuli that do not sound like speech (also see Miyawaki et al., 1975). Since then, however, other researchers (Cutting, 1982; Pisoni, 1977; also see Bornstein, 1987) have found categorical perception effects for nonspeech materials.

The categorical nature of categorical perception has been called into question. Researchers (Pastore, 1987; Pisoni, 1977) have argued that discrimination for physical differences within a category is not at chance, as would be expected by a theory that states that discrimination is based *entirely on category membership*. Massaro (1987; Masarro & Cohen, 1983) has developed a Fuzzy Logical Model of Perception (FLMP) that produces results that other researchers have taken to be indicative of categorical perception, even though the model assumes completely continuous perceptual information. Specifically, FLMP predicts sharp identification boundaries between categories. In FLMP, continuous perceptual information from different dimensions is integrated, and classification of an item depends on the relative similarity of the perceptual information to each of the candidate categories. Thus, the simple presence of sharp boundaries between categories is not sufficient to conclude that perceptual dimensions are perceived categorically or even nonlinearly.

Dimensional Attention

Research on attention to dimensions in categorization is also relevant to current research. Virtually all of the research on categorical perception concerns differential patterns of perceptual sensitization *within* a dimension (as an exception, Massaro, 1987, considered how two dimensions interact to obtain effects similar to categorical perception). Much of the work in category learning concerns situations in which multiple dimensions are relevant and varied.

One issue in the area of dimensional attention in categorization concerns whether entire dimensions are sensitized when they are relevant for a categorization (Kruschke, 1992; Nosofsky, 1986), or whether local regions of a dimension can be selectively sensitized. For example, consider applying Nosofsky's generalized context model (GCM) to objects that vary in size and hue. Suppose that objects that are 1 or 2 cm belong to Category 1, and objects that are 3 or 4 cm belong to Category 2. According to GCM, the attentional weight given to the size dimension will be greater than the attentional weight given to hue because of the relevance of size for the categorization. Attentional weights refer to the importance of a dimension in a categorization decision. No assumption is made that different attentional weights correspond to perceptual differences (Nosofsky, 1987). Because entire dimensions are weighted, the difference between 2 cm and 3 cm objects will become particularly salient, but so too will the difference between 1 cm and 2 cm objects. That is, the difference between objects that fall in the same category but differ along a categorization-relevant dimension will become more important for determining categorization.

Aha and Goldstone (1990) predicted that local regions of a dimension may become selectively attended. With their model, as applied to the example above, size categorization may selectively highlight the difference between 2 cm and 3 cm, without having much influence on the difference between 1 cm and 2 cm. Aha and Goldstone (1992) found empirical support for such a local selective attention effect. The design and partial results from one experiment are shown in Figure 1. Subjects categorized objects that varied on two dimensions: the size of a rectangle, and the position of a line within the rectangle. Six Category A and six Category B members were presented. After learning the

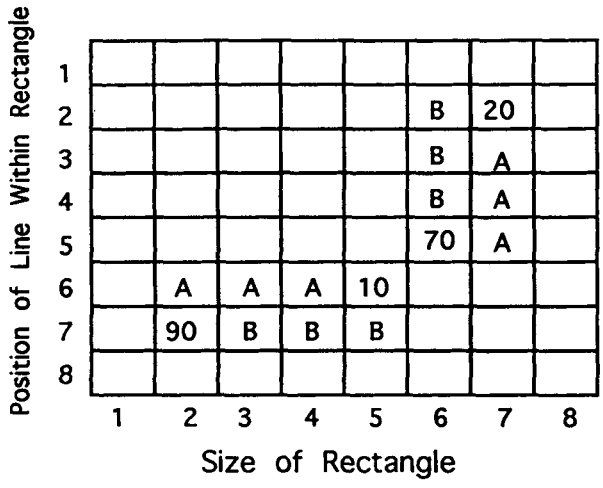

Figure 1. Categorization data from Aha and Goldstone (1992). Numbers indicate the percentage of Category B classifications for each specified stimulus. *A*s and *B*s represent the 12 original training stimuli. The results indicate that subjects tend to classify on the basis of line position for stimuli with small sizes but tend to classify on the basis of size for stimuli with larger sizes. From "Concept Learning and Flexible Weighting" by D. W. Aha and R. L. Goldstone, 1992, in Proceedings of the Fourteenth Annual Conference of the Cognitive Science Society, Hillsdale, NJ: Erlbaum. Copyright 1992 by Lawrence Erlbaum Associates. Adapted by permission.

categories, the subjects were shown new stimuli to categorize. The numbers in the grid in Figure 1 show the percentage of time that a particular object, defined by its value on the two dimensions, was placed into Category B. The results indicate that subjects learned to selectively weight size when an object has a high value on size and to selectively weight position of line when an object has a low value on size. Thus, people appear to be able to, at times, heighten the attention paid to only a local region of a dimension. Whether this attention is actually perceptual or is simply a change to the categorization strategy is not clear.

One aim of the present research is to determine whether the perceptual changes that occur from category learning, if they occur at all, are limited to the particular local region that is the boundary between categories, or whether the perceptual changes generalize to other values on the categorization-relevant dimension. The answer to this question, in addition to being relevant to the models of categorization described above, also bears on explanations of categorical perception. Typical explanations of categorical perception assume that local regions of a dimension can be selectively sensitized to a greater extent than other regions of the same dimension, in accordance with Aha and Goldstone's (1992) results. If entire dimensions must be attended without differential attention placed on select regions or values of a dimension, then a learning explanation of categorical perception is not possible.

An issue that arises with stimuli that vary on more than one dimension is whether dimensions compete for attention. On the one hand, in Nosofsky's (1986) GCM model of categorization, the sum of attentional weights is constrained to equal 1; thus, if more attention is placed on one dimension, it must be removed from another dimension. On the other hand, it is possible that as the attention paid to one dimension increases, that the perception of other dimensions does not suffer. Again, the assumption of GCM does not necessarily extend to perceptual attention. One of the purposes of the current experiments is to determine the circumstances under which dimensions compete for perceptual attention.

Some research has suggested that the degree to which dimensions compete for attention may depend on the nature of the dimensions tested. Garner (1974) distinguished between integral and separable dimensions. In general, with integral dimensions, attending to one dimension without attending to the other is relatively difficult; with separable dimensions, this is relatively easy. Integral dimensions, such as the saturation and brightness of a color (B. Burns & Shepp, 1988), have been argued to be psychologically "fused." Typically, variations along one integral dimension interfere with the processing of the other integral dimension (Garner, 1974). Categorization judgments of stimuli that vary on integral dimensions tend to be made on the basis of overall (B. Burns & Shepp, 1988; Smith, 1979) Euclidean distance (Shepard, 1964) similarity. Conversely, separable dimensions, such as the brightness and size of a shape (Gottwald & Garner, 1975), are perceptually independent. Variations along one separable dimension cause no interference in the processing of the other dimension. Categorization judgments with separable dimensions tend to focus on particular dimensions, and to use city-block similarity.

Given this characterization, we might expect integral and separable dimensions to have different patterns of perceptual competition. One could argue that if integral dimensions are used and Dimension X is relevant for a categorization, sensitization might spread over to Dimension Y. Integral dimensions are assumed to be similar or close to each other in an abstract space (Melara, 1992), and unless the focus of attention is very narrow, if it is placed on one dimension, it will cover the other dimension as well. Assuming that separable dimensions are further separated, this view predicts less spread of sensitization for separable dimensions. However, it is also possible to predict the opposite pattern of results. During category learning one could argue that subjects will learn to actively filter out or ignore irrelevant dimensions to the extent that they intrude on category decisions. Because integral dimensions intrude on each other more than do separable dimensions (Garner, 1974), one might think that subjects will become particularly *de*sensitized to irrelevant integral dimensions.

Current Experimental Issues

The present experiments address the issues discussed above in perception and perceptual attention. The broadest

question addressed is, Does categorization training alter perceptual judgments measured by a same–different task? If training does influence perceptual judgments, several more refined questions can be asked.

1. Do dimensions acquire equivalence or distinctiveness? A categorical perception effect, defined as elevated discriminability for items that straddle a category boundary relative to control items that fall into one category, could arise from acquired equivalence or distinctiveness. According to acquired equivalence, there is a decrease in perceptual sensitivity to differences that are not relevant for a categorization (Pearce & Hall, 1980). According to acquired distinctiveness, there is an increase in perceptual sensitivity to differences that are relevant for a categorization (E. J. Gibson, 1969; Miller & Dollard, 1941). Figure 2, from Pisoni (1991), distinguishes between these two theories. Panel 2A, which depicts acquired similarity (acquired equivalence), shows that at one time (the white circles), all stimuli are well discriminated. At a later time (the black circles), stimuli that are at the boundary between two categories (the boundary is assumed to fall at Stimulus 4) retain their high discriminability but the other stimuli lose their discriminability. Panel 2B, which depicts acquired distinctiveness, shows a final pattern of discriminability that is identical to Panel 2A but achieves this result by elevating the discriminability of the boundary stimuli rather than by depressing the discriminability of the nonboundary stimuli.

In the domain of speech perception, claims have been made that acquired equivalence may underlie the categorical perception effect (Pisoni, 1991). Infants are able to make discriminations between speech sounds that belong to the same phoneme category of their native language. (Eimas, Miller, & Jusczyk, 1987; Eimas et al., 1971). Other experiments have found that very young infants (2 months old) show sensitivity to differences between speech sounds that they lose by the age of 10 months (Werker & Tees, 1984).

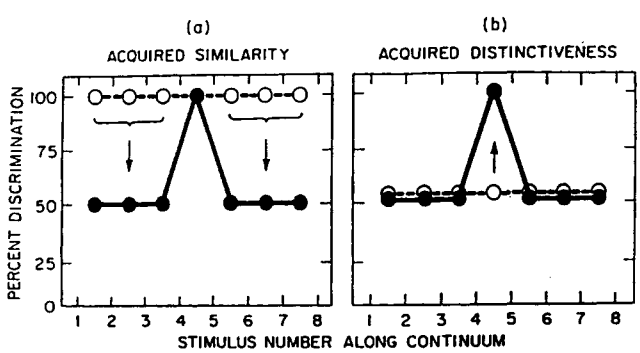

Figure 2. Demonstrations of acquired equivalence (acquired similarity) and acquired distictiveness. The category boundary is assumed to occur at stimulus number 4. The white circles show discrimination performance before training. The black circles show discrimination performance after training. From "Modes of Processing and Speech Signals" by D. B. Pisoni, 1991, in I. G. Mattingly and M. Studdert-Kennedy, *Modularity and the Motor Theory of Speech Perception,* Hillsdale, NJ: Erlbaum. Copyright 1991 by Lawrence Erlbaum Associates. Reprinted by permission.

However, one should be wary of the conclusion of these studies that acquired equivalence underlies categorical perception. First, the strategy of comparing adult to infant performance is far from perfect, because it is difficult to test adults and infants with similar methods. Adults and infants differ in many ways besides their experience with speech, and obtaining accurate measures of infants' perceptual abilities is subject to many potential obstacles. Although infants show above-chance ability to discriminate sounds within a phoneme category, so do adults (Pisoni, 1973). Thus, it would be important to quantitatively compare perceptual sensitivities between adults and infants, but this is pragmatically precluded because of difficulties in testing infants with standard discrimination paradigms. In the present experiments, a cleaner comparison is achieved by presenting different groups from a single population (undergraduate students at Indiana University) with the relevant categories.

Although many theories have proposed either acquired equivalence or distinctiveness, Hall (1991) noted that few if any experiments have had an appropriate design to tease these two processes apart. Figure 3 abstractly shows a set of stimuli that can distinguish between these processes. Subjects are given different categorization rules; for one group, size is relevant; for another group, brightness is relevant; another group receives no categorization training. For example, a subject assigned to the size categorization group would receive feedback indicating that any object with a size dimension value of 1 or 2 belongs to Category A, and any object with a size value of 3 or 4 belongs to Category B. After prolonged categorization training, subjects are presented with pairs of adjacent objects (or with the identical object repeated twice) and are asked to indicate whether the objects are exactly identical or not.

It is possible to obtain evidence for acquired equivalence along a categorization-relevant or -irrelevant dimension. Evidence for acquired equivalence of a categorization-irrelevant dimension exists, for example, if the size categorizers are worse at making brightness discriminations than are subjects who had no categorization training at all. Evidence for acquired distinctiveness of a categorization-irrelevant dimension exists if the size categorizers are better at making size discriminations than are the no categorization subjects.

Evidence for acquired equivalence of a categorization-relevant dimension exists if the size categorizers are *worse* at making size discriminations between objects with size values of 1 and 2 than are the no categorization control subjects. That is, acquired equivalence of a categorization-relevant dimension occurs if discrimination among values of Dimension X is impaired when categorization depends on Dimension X and the values being discriminated belong to the same category.

By comparing categorization groups to a control group that performs no categorization, acquired equivalence and distinctiveness can be teased apart. Thus, it is possible to gather evidence for either acquired equivalence or acquired distinctiveness, both, or neither.

2. Must entire dimensions be perceptually sensitized, or can regions within a dimension be sensitized? If entire

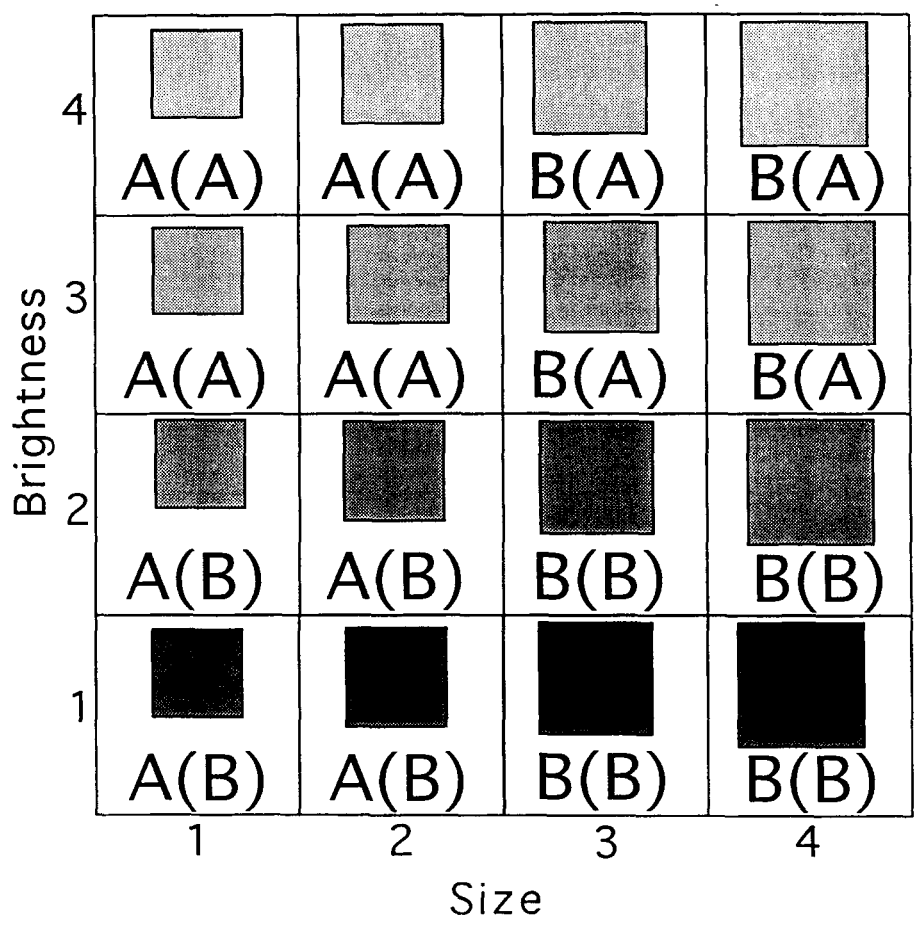

Figure 3. Stimuli used in Experiment 2. Sixteen squares are constructed by combining four values of brightness with four values of size factorially. A and B refer to categorization (Category A or B) of the stimuli. Letters in parentheses indicate the categories for brightness categorizations.

dimensions must be perceptually sensitized, then acquired equivalence in a categorization-relevant dimension should not be found. In fact, the opposite effect would be predicted. Size categorizers' ability to distinguish between size values of 1 and 2 (in Figure 3) should exceed that of subjects with no categorization training, even though size values of 1 and 2 both belong to Category A for size categorizers. If particular regions of a dimension can be sensitized, then size categorizers should be better able to discriminate between size values of 2 and 3 than they can distinguish between size values of 1 and 2. It is possible that evidence could be obtained in favor of both general sensitization of a dimension and specific sensitization of one region, because the former hypothesis involves comparison to the control group and the latter claim involves comparing sensitivities within a categorization condition.

3. Does the degree of competition between dimensions for perceptual attention vary with the integrality–separability of the dimensions? Competition between dimensions can be measured in two ways. First, the extent or presence of acquired equivalence along a dimension that is irrelevant for categorization may be related to the ability of subjects to attend to both the relevant and irrelevant dimensions. If acquired equivalence along the irrelevant dimension occurs, this can be taken as evidence that the requirement to attend a relevant dimension causes the other dimension to become desensitized.

Competition between dimensions can also be measured by including a fourth category training condition, in which subjects must use information from both dimensions in order to make the categorization. In this condition, four categories are learned, one for each quadrant of four stimuli in Figure 3. This condition can be compared to the other categorization conditions to determine whether attention, when divided across two dimensions, results in less perceptual sensitization than when it is focused on one dimension. Such competition would exist if, for example, size categorizers are better able to make size discriminations than are subjects who must use both size and brightness to categorize. If such competition exists, one can ask the refined question, Is this competition greater for integral or separable dimensions?

Experiment 1: Scaling Brightness and Size

The stimuli for Experiment 2 are shown in Figure 3. Sixteen squares were constructed by factorially combining four values on two dimensions (size and brightness). In Experiment 1, the psychological differences between adjacent stimuli in Figure 2 are roughly equated. This is not strictly necessary in order to test perceptual learning effects, because learning is assessed by comparing the perceptual sensitivities of a categorization group to the sensitivities of a control group. With this technique, discriminability differences between pairs of items should not affect the measure of learning as long as it influences both the experimental and control groups equally. However, it is pragmatically useful to scale the stimuli because that increases the sensitivity of the experiment.

Consequently, Experiment 1 is a preliminary "stimulus customization" experiment, conducted to determine the correct appearance for each of the 16 squares in Figure 3. On some of the trials, two identical squares are shown; on the other trials, two adjacent squares are shown. Subjects respond as to whether the two stimuli are exactly the same or different in their sizes or colors. When the squares are actually different but the subject responds "Same," the square with the larger value on the varying dimension increases its value on this dimension by a small amount. With this method, the next time that the same two squares are compared, distinguishing them will be somewhat easier. When the squares are different and the subject responds "Different," the square with the larger dimension value decreases its value on this dimension by the same small amount, making it somewhat more difficult to distinguish the squares on subsequent trials. After many adjustment trials, the set of squares will be scaled such that each pair of adjacent squares is approximately equally discriminable.

Method

Subjects. Forty-five undergraduate students from Indiana University served as subjects in order to fulfill a course requirement.

Materials. Sixteen squares that varied in their size and brightness were displayed on Macintosh IIsi screens. The 16 squares were obtained by factorially combining four values of size with four values of brightness. The exact values for size and brightness were varied during the procedure.

Procedure. Subjects were instructed that they would see a pair of squares on the screen that might or might not slightly differ on their size or the brightness of their color. Subjects were instructed to press the *S* key on the keyboard if they believed the two squares were physically identical, and to press the *D* key if they believed the two squares differed along either dimension. They were also told that the discriminations they would be required to make would become more difficult as the experiment continued.

The two squares were presented successively on the screen. The exact vertical and horizontal locations of the two squares was randomized, under the constraint that the first presented square occupied the left portion of the screen and the second presented square occupied the right portion of the screen. No square was shown within a 5-cm vertical column in the center of the screen. At the beginning of a trial, the first square was displayed for 1,000 ms. The square was then removed, and a blank screen was presented for 33 ms. The second square was then displayed for 1,000 ms. The second square was then replaced with a blank screen until the subject made an *S* or *D* response. The intervals between all trials were 1,500 ms. Subjects made 576 judgments.

The 576 judgments were divided into 18 blocks. Each block consisted of 8 same trials and 24 different trials, randomly ordered. For the same trials, one of the 16 squares abstractly shown in Figure 3 was shown to subjects, and was repeated as the second square. For the 24 different trials, two vertically or horizontally adjacent squares from Figure 3 were selected as the squares to be compared. There were 24 different pairs of immediately adjacent squares. Diagonally adjacent squares were not tested.

The distances between adjacent squares were customized for each subject by changing individual squares' appearances. No changes were made on same trials. On different trials, if a subject correctly responded different, the larger or brighter square was assigned a slightly smaller size or brightness value. If a subject incorrectly responded same when the squares were different, the larger or brighter square was assigned a slightly larger size or brightness value. In this manner, subjects will eventually have an accuracy of 50% on different trials. However, subjects' accuracy on same trials will be higher, yielding d' scores that are above zero. For brightness changes, the constant adjustment increment was 1,200 brightness units in Macintosh's hue–saturation–brightness representation for colors (the final standard Commission Internationale de L'Eclairage [CIE] color coordinates and lengths in centimeters are presented later in this article). For size changes, the constant adjustment increment was 0.07 cm.

In addition to changing the size or brightness of the larger or brighter square, it also was necessary to adjust the sizes of all of the squares that were brighter or larger than this square. If this had not been done, then making the square more similar to a smaller or darker square would also have made the square much less similar to larger or brighter squares. Consequently, the same absolute adjustment (in size or brightness units) that was made to the larger or brighter of the compared squares also was made to all squares that had still larger or brighter values on the dimension of variation between the compared squares. With this method, the absolute differences between other adjacent pairs of objects remained fixed. Initial dimension values for the 16 squares were set at plausible, fairly discriminable values.

Results

Subjects required about 55 min to complete the same–different judgments. The average values along the size and brightness dimension for each of the 16 squares are shown in Table 1. The values indicate a slight interaction between size and brightness. In particular, as the size of objects increases, increasingly similar brightness values yield the same discriminability.

For Experiment 2, it was necessary to calculate dimension values as though there were no dimension interactions. The height (and width) of the four size values in centimeters were 2.85, 3.12, 3.45, and 3.79. These values are roughly consistent with Weber's law; bigger absolute differences are required to produce equal psychological differences as the magnitude of the stimuli increases. The CIE (1976 model) color coordinates and luminance (in cd/m^2) as measured by a Spectra Scan 714 chromometer were X = .5463, Y = .3696, luminance = 21.62; X = .5405, Y = .3730, lumi-

Table 1
Averaged Stimulus Values Obtained From Experiment 1

Brightness value	Size value 1	2	3	4
4				
Size	2.85	3.19	3.59	4.02
Brightness	21.62	21.62	21.62	21.62
3				
Size	2.85	3.16	3.49	3.83
Brightness	19.61	19.95	20.36	20.43
2				
Size	2.85	3.08	3.38	3.65
Brightness	18.12	18.61	19.1	19.33
1				
Size	2.85	3.09	3.38	3.69
Brightness	13.60	15.67	17.21	18.16

Note. Size values are expressed in height and width centimeters. Brightness values are expressed in cd/m^2.

nance = 20.09; X = .53, Y = .3737, luminance = 18.79; and X = .5266, Y = .3764, luminance = 16.17.

Discussion

It is not a complete surprise that brightness and size values interacted such that finer discriminations in brightness were easier to make when the sizes of the compared objects were relatively large. Although size and brightness are separable dimensions in that there is no interference of one dimension on another in a speeded sorting task (Gottwald & Garner, 1975), they have failed other tests of separable dimensions. For example, Biederman and Checkovsky (1970) found that size and brightness produced a redundancy gain: Subjects were faster to make judgments about materials that varied in a correlated fashion on size and brightness than they were to make judgments about materials that varied only on size or brightness. These results support the notion that different types of stimulus integrality are experimentally dissociated. The discriminability of differences on one dimension is influenced by the value along another dimension, even though previous results have indicated that attention can be selectively focused on only one of the two dimensions. Perceptual interactions between dimensions do not necessarily entail a failure to selectively attend (see also Ashby & Townsend, 1986).

In Experiment 2, stimuli that were horizontally or vertically adjacent (in Figure 3) varied on only one dimension. Two squares that are horizontally adjacent must vary only on size and not brightness. If this condition were violated, it would be impossible to tell whether size or brightness differences were used to make a particular perceptual discrimination. Thus, the brightness and size values obtained from Experiment 1, averaging out the slight dimensional interaction, were used in Experiment 2.

Experiment 2

Experiment 2 addressed the three questions raised at the end of the introduction, using the stimuli scaled in Experiment 1. The first part of Experiment 2 involved training subjects to make a single- or a double-dimension categorization. The second part measured subjects' sensitivity in making perceptual same–different judgments.

Method

Subjects. Eighty-four undergraduate students from Indiana University served as subjects in order to fulfill a course requirement. The subjects were evenly divided among the four conditions.

Materials. The 16 squares scaled in Experiment 1 were used as stimuli. The stimuli formed a 4 × 4 matrix (see Figure 3) with every brightness level combined with every size level. The scaling results, after averaging across dimension values to eliminate dimension interactions, guaranteed that horizontally and vertically adjacent squares differed only on their size or brightness and that each pair of adjacent squares was approximately equally discriminable for control subjects.

Procedure. Subjects (except for the control group) were given an approximately 60-min categorization task, followed by a 40-min perceptual discrimination task for all subjects. Both tasks were completed in the same session.

There were four categorization conditions: size categorizers, brightness categorizers, size and brightness categorizers, and controls. The control subjects did not undergo any categorization training. For the size categorizers, the squares in the left two columns of Figure 3 were assigned to Category A and the squares in the right two columns were assigned to Category B. For the brightness categorizers, the squares in the upper two rows were assigned to Category A, and the squares in the lower two rows were assigned to Category B. For the size and brightness categorizers, four categories, corresponding to the four quadrants (upper left, upper right, lower left, and lower right), each included four squares.

Twenty repetitions of the 16 squares were shown in the categorization training. On an individual trial, a square was shown in a randomly generated location on the screen. The square remained on the screen until the subject pressed a key corresponding to his or her guess as to the square's category. Category responses were made by pressing the keys *1, 2, 3,* and *4*; only the first two responses were required for size categorizers and brightness categorizers. After a response was made, feedback was given as to the correctness of the response, and the correct category label was displayed. After 1.5 s, the screen was erased, and after another 1 s, the next trial began. Subjects were instructed that the squares would vary in brightness and size.

All four categorization training groups received the identical subsequent discrimination experiment. Subjects were shown pairs of adjacent squares (or the identical square repeated twice) and responded either "same" or "different." The procedure exactly followed the procedure used in Experiment 1, with two exceptions. First, the initial values for the dimensions were set to the values determined in Experiment 1, rather than to arbitrary initial values. Second, there was no modification of the squares' size and brightness values. The number and distribution of same and different trials were identical to those of Experiment 1.

Results

The most important results are related to the relative ability of each of the four categorization groups to discriminate between different pairs of squares in the same–different judgment portion of the experiment. The measure d' was computed as an indicator of perceptual sensitivity (Swets, Tanner, & Birdsall, 1961) that is based on subjects' ability to correctly discriminate between different stimuli (subjects' probability of responding "different" when different squares are presented), adjusted by subjects' false alarm rate (subjects' probability of responding "different" when identical squares are presented). By comparing the perceptual sensitivity (d') of subjects who underwent category learning with the d' of those subjects who did not, one can assess the nature of the influence that category training had on perceptual same–different judgments.

The results from all four categorization training conditions are shown in Table 2. Correct response percentages are shown. For example, when the square in the upper left corner of Figure 3 is displayed twice in the size categorization condition, that indicates that subjects correctly responded "same" 82% of the time. When these same subjects were shown the upper left square compared with the square immediately to its right, they correctly responded "different" on 44% of the trials, yielding an average d' of 0.78. Although a correct response rate of 44% might seem to be less accurate than would be predicted by chance, the 84% correct same response rate shows a tendency for subjects to respond "same" more than "different." In fact, the greatest tendency to respond "same" over "different" is found in the no categorization control condition, followed by the size categorizers and brightness categorizers, who did not significantly differ, followed by the size and brightness categorizers, $F(3, 20) = 7.4$, $p < .01$, Fisher's post hoc probabilistic least significant difference (PLSD) $p < .01$.

Many of the important questions involve the comparison of a categorization group's sensitivity (d') to the control group's sensitivity. Consequently, Figures 4, 5, and 6 show the difference between d' scores of subjects who were trained to make categorizations and d' scores of subjects who received no categorization training. There is a rectangle for each of the 24 pairwise comparisons of squares. A black rectangle indicates a greater d' for the categorization condition than for the control. A white rectangle indicates the opposite. The size of the rectangle indicates the absolute magnitude of the difference between the d's.

Acquired distinctiveness. Dimensions acquire distinctiveness if perceptual discriminations along a categorization-relevant dimension are better for the categorization condition than for the control condition. Separate tests were conducted for size categorizers and brightness categorizers. For size categorizers, there are four comparisons that would unambiguously become sensitized if relevant dimensions acquire distinctiveness—the four comparisons that involve a square with a size value of 2 and a square with a size value of 3. In Figure 4, these four comparisons occupy the center column of horizontally extended rectangles. These four comparisons were averaged together for each subject in the size categorization and the control conditions. Overall, the size categorizers' d's for these four comparisons were greater than the control subjects' d's for the same comparisons, unpaired $t(40) = 3.6$, $p < .05$. This difference can be clearly seen in Figure 4 from the fact that all four of the d' differences for the center size comparisons are large (wide) and positive (black).

The equivalent test for acquired distinctiveness for brightness categorizers compares brightness values of 2 and 3. These comparisons are found in the center row of vertically extended rectangles in Figure 5. The brightness categorizers' d's were greater than the control subjects' d's for these comparisons, $t(40) = 2.9$, $p < .05$. Again, this is evident in Figure 5 from the long black rectangles along the center row. Thus, for both categorization groups, there is evidence for acquired distinctiveness between values of the categorization-relevant dimension that belong to different categories.

Acquired equivalence of the irrelevant dimension. Acquired equivalence along a dimension that is irrelevant for a categorization occurs if discriminations along such a dimension are worse than they are for the control subjects. This occurs if, for example, size categorizers have a lower d' for trials that differ on brightness than do control subjects. Again, this hypothesis can be tested separately for the two single dimension categorization conditions. For size categorization subjects, there are 12 square comparisons that involve differences in brightness (the 12 vertically extended rectangles in Figure 4). Averaging over these comparisons, there is no significant difference between d' scores for the control and size categorization conditions, unpaired $t(40) = 0.85$, $p > 0.1$.

The analogous test of acquired equivalence in brightness categorizers involves the 12 horizontally extended rectangles in Figure 5. These data show a significant difference between the brightness categorizers and the control subjects, unpaired $t(40) = 2.3$, $p < .05$. The d's are significantly greater for control subjects than for brightness categorizers, as shown by the preponderance of white horizontally extended rectangles in Figure 5.

Acquired equivalence within a relevant dimension. Acquired equivalence within a categorization-relevant dimension can occur if squares that have different dimension values on this dimension but belong to the same category become less discriminable as a result of categorization training. Again, this can be tested separately for both categorization conditions. For the size categorization condition, eight relevant square comparisons are collapsed together—the left and right columns of horizontally extended rectangles in Figure 4. These rectangles span squares that differ on their sizes but belong to the same category. Overall, the d' associated with these eight squares is greater for the size categorization condition than it is for the control group, $t(40) = 2.6$, $p < .05$. This result is apparent in Figure 4 in that all but one of the rectangles in the first and third columns are black. This significant difference is in the *opposite* direction as hypothesized by acquired equivalence within a relevant dimension.

Table 2
Discrimination Performance for Four Training Conditions in Experiment 2

Brightness values	Size values 1 & 1 P(C)	1 & 2 P(C), *d'*	2 & 2 P(C)	2 & 3 P(C), *d'*	3 & 3 P(C)	3 & 4 P(C), *d'*	4 & 4 P(C)
4 & 4							
P(C)							
S	82	44, 0.78	84	52, 0.98	81	41, 0.71	82
B	86	33, 0.59	84	38, 0.67	83	34, 0.56	84
No	84	36, 0.64	85	40, 0.73	83	36, 0.65	82
S & B	74	49, 0.69	76	54, 0.81	77	43, 0.60	77
3 & 4							
P(C), *d'*							
S	47, 0.83		47, 0.87		55, 1.05		53, 1.00
B	44, 0.84		54, 0.94		51, 0.99		58, 1.11
No	40, 0.80		47, 0.92		52, 1.02		53, 1.07
S & B	54, 0.81		58, 0.93		64, 1.07		60, 0.97
3 & 3							
P(C)							
S	81	47, 0.86	82	55, 1.07	81	38, 0.63	83
B	82	33, 0.53	85	35, 0.59	81	33, 0.53	83
No	84	33, 0.56	86	35, 0.61	86	33, 0.56	87
S & B	79	45, 0.59	73	62, 1.0	73	45, 0.58	76
2 & 3							
P(C), *d'*							
S	46, 0.83		50, 0.94		52, 0.99		55, 1.06
B	50, 0.97		56, 1.12		59, 1.20		61, 1.25
No	45, 0.87		45, 0.87		48, 0.94		49, 0.97
S & B	63, 1.03		65, 1.09		64, 1.06		68, 1.19
2 & 2							
P(C)							
S	81	46, 0.83	80	51, 0.96	82	38, 0.64	81
B	83	34, 0.56	86	34, 0.56	85	29, 0.42	83
No	86	37, 0.67	84	32, 0.54	83	37, 0.67	85
S & B	75	50, 0.71	74	53, 0.79	75	45, 0.58	76
1 & 2							
P(C), *d'*							
S	46, 0.83		46, 0.83		49, 0.95		48, 0.91
B	45, 0.84		48, 0.92		54, 1.04		52, 0.95
No	45, 0.87		46, 0.90		50, 0.97		48, 0.93
S & B	57, 0.89		57, 0.88		61, 0.98		57, 0.90
1 & 1							
P(C)							
S	80	46, 0.83	83	54, 1.04	83	40, 0.68	82
B	82	34, 0.56	82	36, 0.61	85	33, 0.53	83
No	87	36, 0.64	85	40, 0.74	85	36, 0.64	86
S & B	76	56, 0.67	79	55, 0.83	78	48, 0.69	76

Note. Each of the two presented squares has a brightness and size value. The values for the two squares on a dimension are combined by an ampersand. P(C) = percentage of correct judgments. When the presented squares have identical values on both dimensions (e.g., values 1 & 1 on brightness and 4 & 4 on size), the correct response is *same*. When the squares differ on either brightness or size, the correct response is *different*. S = size categorization condition; B = brightness categorization condition; No = no categorization training; S & B = size-and-brightness categorization.

The analogous comparison for the brightness condition involves the eight vertically extended rectangles that form the top and bottom rows of Figure 5. The *d'*s associated with these comparisons are (marginally) significantly greater for the brightness condition than for the control group, $t(40) = 1.87$, $p = 0.07$. In Figure 5, six out of the eight *d'*s are greater for the brightness condition, as shown by the black rectangles.

Local sensitization of a dimension. Given that acquired equivalence was not found within the categorization-relevant dimension, all values on a categorization-relevant dimension may or may not be equally sensitized. To test this, discriminations between the squares that belong to different categories can be compared to discriminations between squares that belong to the same category but vary on the categorization-relevant dimension. However, even though

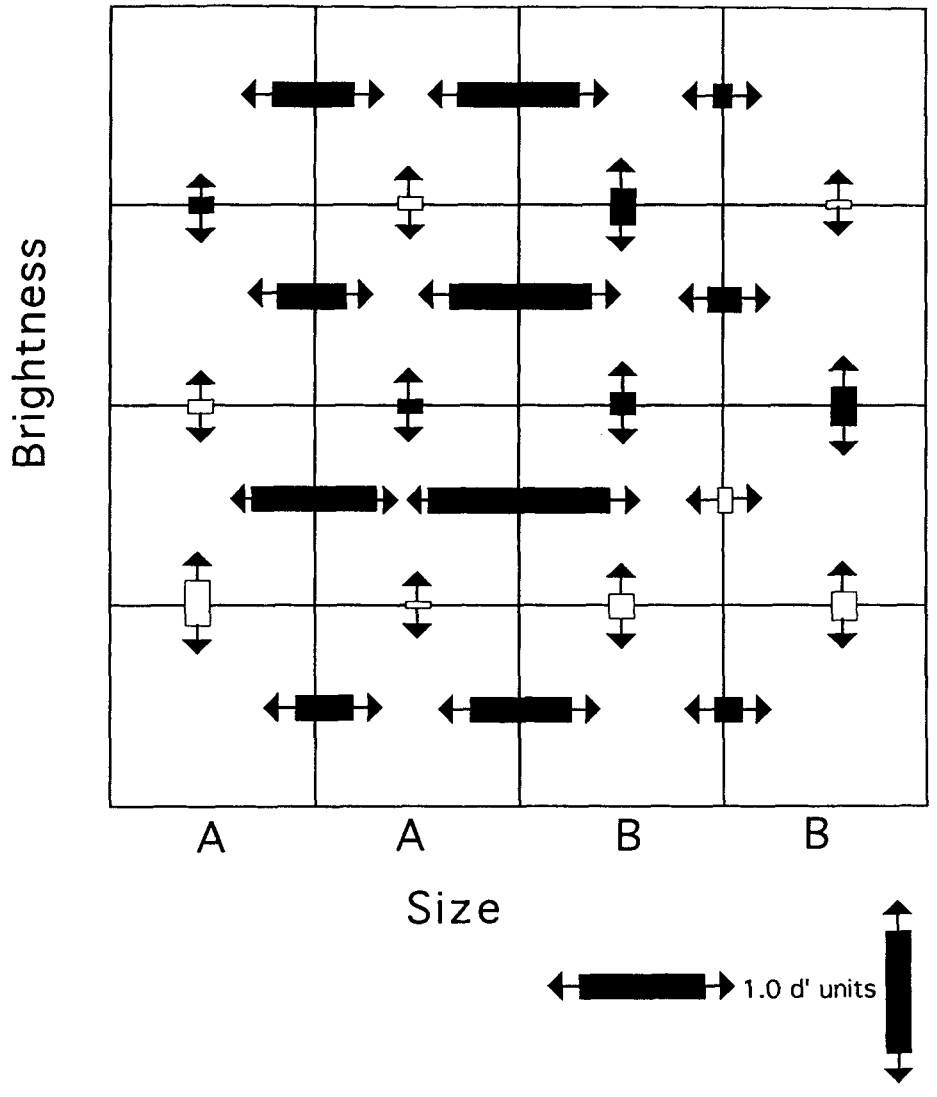

Figure 4. (Size categorizers' d') − (No categorizers' d'). This figure shows the gain in perceptual sensitivity that is due to size categorization training. A black rectangle indicates a positive difference. A white rectangle indicates a negative difference. The size of the rectangle indicates the absolute magnitude of the difference. Rectangles are placed between the two squares that are being discriminated. A and B refer to categorization (Category A or B) of the stimuli.

the psychological scaling conducted in Experiment 1 roughly equated the psychological differences between adjacent squares, the data in Table 2 for the control subjects indicate that the scaling was not perfect; for the control subjects, some pairs of squares are more discriminable than others. Thus, although the test for local versus dimension-wide sensitization is ideally a within-condition test, the results described here take into account the slightly different context-free discriminabilities of the pairs of squares. This is done by comparing two differences—the difference between control and categorization conditions on relevant dimension differences that straddle categories, and the difference between the two conditions on relevant dimension differences that remain in one category.

To test local sensitization for size categorizers, two sets of comparisons were formed. One set (the *critical value* set) contained the four comparisons that paired a square with a size value of 2 with a square with a size value of 3 (the middle column of horizontally extended rectangles in Figure 4). The other set (the *noncritical value* set) contained the other eight comparisons involving squares that differed in their sizes. The d' scores for the size categorizers for each set were adjusted by subtracting from these scores the respective d' scores from the control condition. The ad-

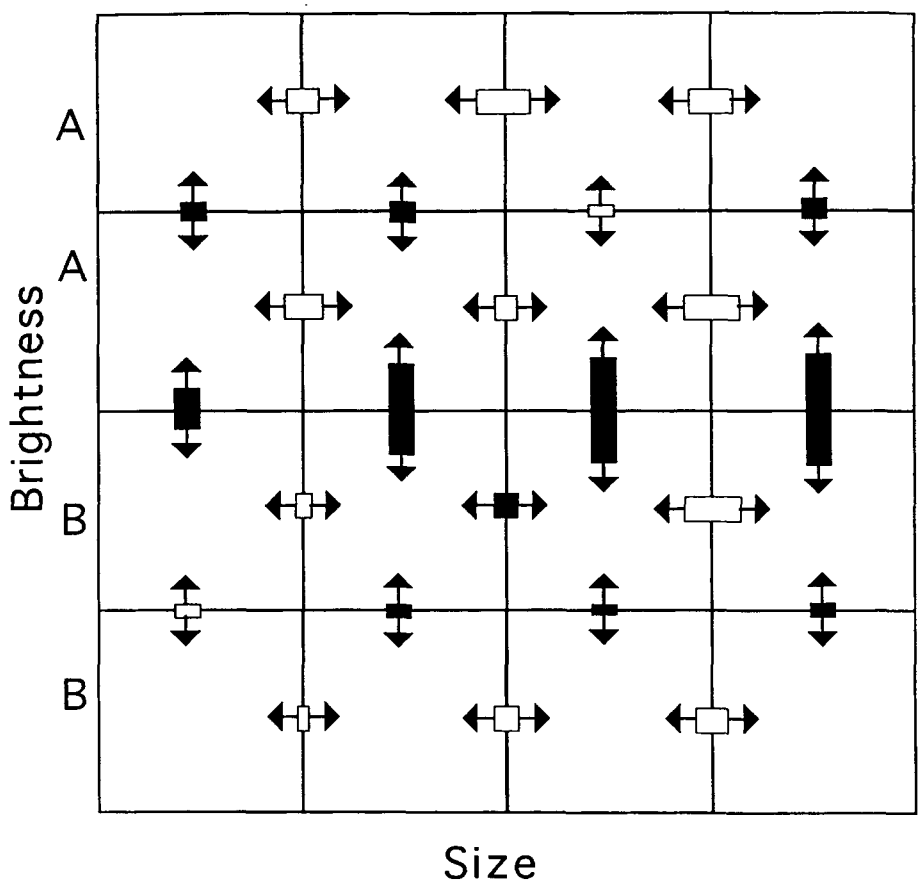

Figure 5. (Brightness categorizers' d') − (No categorizers' d'). This figure shows the gain in perceptual sensitivity that is due to brightness categorization training. A and B refer to categorization (Category A or B) of the stimuli.

justed d' scores for the critical set were significantly greater than the adjusted d' scores for the noncritical set, $t(40) = 2.6$, $p < .05$. In Figure 4, this is apparent in the relatively wider rectangles in the middle column than in the left and right columns.

The analogous sets of critical and noncritical comparisons were compared for the brightness categorizers. Again, the adjusted d' scores for the critical set were significantly greater than the adjusted d' scores for the noncritical set, $t(40) = 3.5$, $p < .05$. This strong effect is shown clearly in Figure 4. The middle column of vertically extended rectangles contains very tall, black rectangles. The upper and lower columns are much shorter and are not uniformly black.

Attentional competition. The final major question that the results of Experiment 2 addressed concerns the competition of dimensions for perceptual sensitization and attention. The specific question was: Does sensitization produced by categorization of Dimension X diminish if categorization by Dimension Y is also required? Once again, this question can be tested individually with size and brightness each occupying the Dimension X slot. For the size dimension, the ability of size categorizers to make size discriminations is compared with the ability of subjects who need to categorize on the basis of both size and brightness to make size discriminations. The overall d' for size discriminations by size categorizers is greater than the d' for the same items by the size and brightness categorizers, $t(40) = 3.0$, $p < .05$. This result can be seen by comparing the rectangles spanning horizontally adjacent squares in Figures 4 and 6. These rectangles are somewhat wider in Figure 4 than they are in Figure 6.

The analogous test of dimensional competition for brightness compares the 12 brightness discriminations for brightness categorizers to the same brightness discriminations for the size-and-brightness categorizers. Again, the overall d' is greater for the brightness condition, $t(40) = 2.4$, $p < .05$.

The size-and-brightness categorizers developed sensitivities to both size and brightness (as shown by the prevalence of black rectangles in Figure 6). The overall d' for this group is higher than the d' for the control subjects, $t(40) = 3.4$, $p < .05$. Still, the d's are not as high as they are for the single-dimension categorization conditions along the categorization-relevant dimension.

Other results. Although subjects did not receive feedback in the same–different judgment portion of the exper-

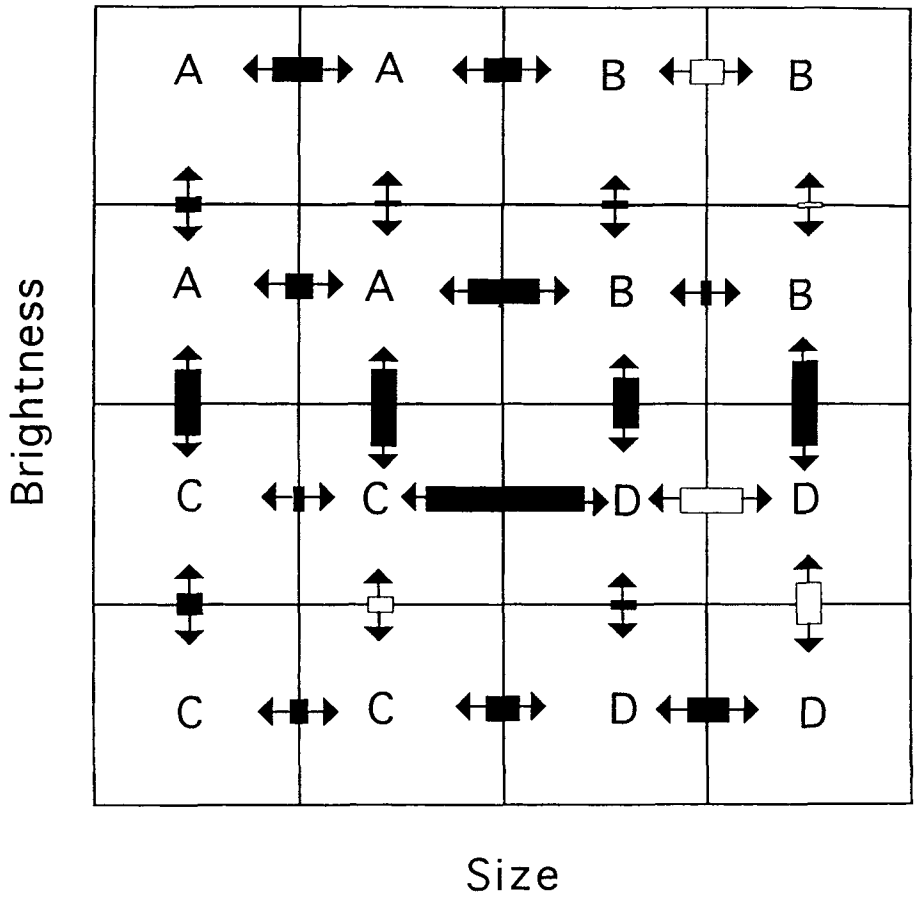

Figure 6. (Size & brightness categorizers' d') − (No categorizers' d'). This figure shows the gain in perceptual sensitivity that is due to categorization training that requires attention to both size and brightness. A, B, C, and D refer to categorization (Category A, B, C, or D) of the stimuli.

iment, their perceptual sensitivities improved over the course of testing. There was a positive correlation of $r = .05$, $p < .05$ between trial number and d' score. This is consistent with J. J. Gibson and Gibson's (1955) finding that false "old" judgments in an identification judgment decreased during practice without feedback, although the current result is somewhat more surprising in that the d' measure is an unbiased measure of perceptual sensitivity and thus cannot be attributed to changes in decisional strategies.

Subjects in the size-and-brightness condition took longer to train than the other two categorization conditions, $F(2, 20) = 5.2$, $p < .05$. To achieve a categorization accuracy of 90%, the size, brightness, and size-and-brightness groups required an average of 134, 113, and 217 trials, respectively.

Discussion

At the broadest level, the results confirm that experience in categorization influences later perceptual sensitivity, as measured by same–different judgments. The clearest support for this comes from the acquired distinctiveness that occurs along the critical values of a dimension that are relevant for categorization. Strong acquired distinctiveness was found for both size and brightness.

The evidence for acquired equivalence was somewhat more complex. There was evidence on one dimension, but not the other, for acquired equivalence when a dimension is irrelevant for categorization. When size is irrelevant for the categorization (for brightness categorizers), size discrimination become desensitized, relative to the control group. This provides a demonstration of a situation in which subjects would have done better in a perceptual task if they had never experienced the materials before in a categorization experiment, or if they had been able to ignore their previous exposure. Neither acquired equivalence nor distinctiveness was found along the brightness dimension for size categorizers. Clearly, there is a difference between how these dimensions are processed, even though scaling was done to make differences on the dimensions equally salient. Future work will be necessary to determine why the two dimensions do not equally acquire equivalence.

The two dimensions do, however, behave similarly as far as acquired equivalence along noncritical values of a rele-

vant dimension. In particular, the opposite of acquired equivalence is found for both dimensions. For example, although size values of 1 and 2 both belong to Category A for size categorizers, size categorization training produces sensitization to the difference between these values.

Although the opposite of an acquired equivalence effect within the categorization-relevant dimension is consistent with dimension-wide sensitization, there is other evidence for a more local, value-specific sensitization. For both size and brightness dimensions, sensitization that is due to categorization is most pronounced when dimension values are chosen that straddle two categories. This local, value-specific sensitization is more clear for brightness than it is for size.

The results from Experiment 2 also indicate a particular way that dimensions compete with each other for attention. For both size and brightness, less perceptual sensitization occurs when two dimensions must be attended for categorization than when only one must be attended. This result is important for two reasons. First, it suggests that the attentional competition between dimensions that has been hypothesized in models of categorization (e.g., Nosofsky, 1986) is not simply a strategic selective weighting of dimensions for categorization. Rather, it also has a nonvolitional component that emerges even when tested in a perceptual task with no logical relation to the categorization task (see General Discussion).

Second, the result opposes one possible nonperceptual explanation of the differences that have been found between categorization conditions. It might be argued that subjects are better at making size discriminations after size categorization because during categorization they learn that even a very small size difference counts as a difference. Thus, categorization training might increase only one's willingness to base a decision on a dimension if it is relevant for categorization but might not change one's ability to spot differences on the dimension. The comparison of the size-and-brightness condition with the size condition makes this approach less plausible. For both of these groups, size clearly is a relevant dimension for categorization. Thus, there is evidence for two groups having different perceptual sensitivities along a dimension even when both groups know that the dimension is relevant and are calibrated to the correct magnitude of value differences along the dimension.

Experiment 3

Experiments 3 and 4 were replications of Experiments 1 and 2, but used different dimensions. Testing new dimensions is desirable for two reasons. First, one of the results from Experiment 2 was that although most conclusions were similar for the two dimensions tested, there were also some differences. Additional dimensions must be tested to gain confidence in the external validity of the results from Experiment 2. Second, and more important, it is informative to compare dimensions that vary in their integrality. Although size and brightness are fairly separable dimensions, results may differ with integral dimensions. In particular, there are reasons (see the introduction) for predicting either more or less acquired equivalence and attentional competition between integral dimensions than was obtained with separable dimensions. Thus, in Experiments 3 and 4, stimuli varied in brightness and saturation, two color dimensions that substantial evidence has shown to be integral.

Experiment 3 is the analog of Experiment 1 in that it provided the scaling data for Experiment 4. Experiment 3 provided 16 stimuli that varied in saturation and brightness such that adjacent stimuli were approximately equally discriminable for the control subjects, who did not receive any categorization training.

Method

Subjects. Forty-two undergraduate students from Indiana University served as subjects in order to fulfill a course requirement.

Materials. Sixteen squares that varied in their saturation and brightness were displayed on Macintosh IIsi screens. The 16 squares were obtained by factorially combining four values of saturation with four values of brightness. All squares measured 6 cm^2.

Procedure. The same–different judgment procedure from Experiment 1 was used, with only the slight variations described here. Initial dimension values for the 16 squares were set to plausible, fairly discriminable values. For saturation, the constant increment or decrement to the more saturated square when incorrect or correct responses on different trials were made, was 527 Macintosh saturation units. For brightness, the increment or decrement was 1,462 Macintosh brightness units.

Results and Discussion

The average values along the saturation and brightness dimension for each of the 16 squares are shown in Table 3. The values indicate very little interaction between saturation and brightness. That is, the physical difference in saturation values required to make a discriminable difference was fairly constant across different values of brightness.

Table 3
Averaged Stimulus Values Obtained From Experiment 3

Brightness value		Saturation value 1	2	3	4
4					
	Luminance	19.57	23.85	29.08	36.66
	Purity	70.37	52.62	35.71	26.19
3					
	Luminance	17.7	21.89	25.82	31.94
	Purity	71.53	54.81	38.4	28.27
2					
	Luminance	16.74	18.09	22.05	26.84
	Purity	71.21	55.7	39.73	28.54
1					
	Luminance	15.26	15.27	19.89	23
	Purity	70.29	56.25	42.31	29.71

Note. Luminance values are expressed in cd/m^2; purity values are percentages.

For Experiment 3, it is necessary to calculate dimension values as if there were no dimension interactions. The CIE 1976 color coordinates were determined with a Spectra Scan 714 chromometer. The X and Y coordinates for all 16 squares are approximately 0.45 and 0.35, respectively. The actual luminance and purity values are shown in Table 3.

Experiment 4

Experiment 4 was a replication of Experiment 2 but used integral instead of separable dimensions. Three issues were explored by varying the integrality of the materials. First, the extent to which perceptual attention is naturally and nonstrategically placed on integral dimensions was explored. Previous researchers have shown that even with integral materials, categorization decisions can be made to selectively weight one dimension over another (Foard & Kemler Nelson, 1984; Nosofsky, 1987). For example, if saturation but not brightness is relevant for a categorization, subjects can learn this categorization rule, with sufficient practice. However, whether this categorization regime causes a change to subjects' actual perceptual processes remains an open question. Some researchers have speculated that during the course of experience or maturation, dimensions that were once originally fused become differentiated (C. Smith, Carey, & Wiser, 1985; L. B. Smith, 1979, 1989). It is conceivable that, if saturation but not brightness (or vice versa) is relevant for a categorization, saturation would become differentiated from brightness and selectively sensitized. If this occurs, then saturation but not brightness might show sensitization that is due to saturation categorization.

Second, integral dimensions are used to test whether acquired equivalence along a categorization-irrelevant dimension is more or less prominent with fused dimensions. As discussed in the introduction, the answer to this question has a bearing on whether subjects learn to actively filter out irrelevant dimensions that intrude on categorization (yielding greater acquired equivalence for integral dimensions), or whether irrelevant dimensions become less influential when attention shifts toward relevant dimensions that are far removed (yielding greater acquired equivalence for separable dimensions).

Third, integral dimensions also test predictions about competition between dimensions. In Experiment 2, there was evidence of competition from the comparison of two-dimension and one-dimension categorization conditions. However, if it is easier to attend to two dimensions simultaneously if they are integral (Garner, 1974; Melara, 1992), then there may be less evidence for competition with saturation and brightness.

Method

Subjects. Eighty undergraduate students from Indiana University served as subjects in order to fulfill a course requirement. The subjects were evenly divided among the four conditions.

Materials. The 16 squares scaled in Experiment 3 were used as stimuli. The stimuli formed a 4 × 4 matrix similar to that shown in Figure 3, with every brightness level combined with every saturation.

Procedure. The procedure was identical to that used in Experiment 2 except as noted here. There were four categorization conditions: saturation categorizers, brightness categorizers, saturation-and-brightness categorizers, and controls (no categorization training). Before the categorization training, subjects were instructed that the squares presented would have slightly different colors. After categorization training, all groups were given the same same–different judgment task. Subjects were told that they should respond "different" if the squares presented had even slightly different colors.

Results

The d' results from all four categorization training conditions are shown in Table 4. As in Experiment 2, there was a bias for subjects in the control condition to respond "same" more frequently than in the other conditions and a bias for subjects in the saturation-and-brightness categorization condition to respond "same" less frequently than in the other conditions, $F(3, 19) = 4.5$, $p < 0.05$, post hoc differences significant at $p < .05$ by Fisher's PLSD.

Acquired distinctiveness. Dimensions acquired distinctiveness if perceptual discriminations along a categorization-relevant dimension were better for the categorization condition than for the control condition. Separate tests were conducted for saturation categorizers and brightness categorizers. For saturation categorizers, there were four comparisons that would unambiguously become sensitized if relevant dimensions acquired distinctiveness—the four comparisons that involved a square with a saturation value of 2 and a square with a saturation value of 3. In Figure 7, these four comparisons occupy the center column of horizontally extended rectangles. These four comparisons were averaged together for each subject in the saturation categorization and the control conditions. Overall, the saturation categorizers' d' for these four comparisons was greater than the control subjects' d's for the same comparisons, unpaired $t(38) = 3.2$, $p < .05$. This difference can be clearly seen in Figure 7 from the fact that all four of the d' differences for the center size comparisons are large (wide) and positive (black).

The equivalent test for acquired distinctiveness for brightness categorizers compared brightness values of 2 and 3. These comparisons are found in the center row of vertically extended rectangles in Figure 8. The brightness categorizers' d' was greater than the control subjects' d's for these comparisons, $t(38) = 3{,}4$, $p < .05$. This is evident in Figure 8 from the long black rectangles along the center row. Thus, for both categorization groups, there is evidence of acquired distinctiveness between values of the categorization-relevant dimension that belong to different categories.

Acquired equivalence of the irrelevant dimension. Acquired equivalence along a dimension that is irrelevant for categorization occurred if discriminations along such a dimension were worse than they were for the control subjects. This occurred if, for example, saturation categorizers had a lower d' for trials that differed on brightness than did

Table 4
Discrimination Performance for Four Training Conditions in Experiment 4

Brightness values	Saturation values 1 & 1 P(C)	1 & 2 P(C), *d'*	2 & 2 P(C)	2 & 3 P(C), *d'*	3 & 3 P(C)	3 & 4 P(C), *d'*	4 & 4 P(C)
4 & 4							
P(C)							
S	82	61, 1.23	83	68, 1.35	80	64, 1.28	80
B	84	56, 1.08	83	55, 1.09	81	56, 1.10	82
No	83	54, 1.04	86	53, 1.06	85	53, 1.02	83
S & B	80	62, 1.19	81	66, 1.29	83	61, 1.16	82
3 & 4							
P(C), *d'*							
S	52, 0.97		56, 1.04		56, 1.06		55, 1.05
B	57, 1.12		54, 1.05		58, 1.16		55, 1.11
No	43, 0.78		48, 0.91		57, 1.14		46, 0.86
S & B	59, 1.11		61, 1.16		57, 1.08		49, 0.88
3 & 3							
P(C)							
S	83	58, 1.12	84	65, 1.26	84	62, 1.23	83
B	84	55, 1.07	85	56, 1.10	83	56, 1.10	82
No	85	49, 0.93	83	51, 0.99	84	51, 0.98	82
S & B	82	57, 1.06	82	63, 1.21	79	58, 1.08	81
2 & 3							
P(C), *d'*							
S	55, 1.08		54, 1.02		55, 1.09		52, 0.98
B	61, 1.23		62, 1.25		65, 1.33		66, 1.36
No	49, 0.93		51, 0.98		51, 1.03		53, .03
S & B	60, 1.13		63, 1.21		64, 1.24		63, 1.21
2 & 2							
P(C)							
S	82	58, 1.16	81	64, 1.35	82	61, 1.23	81
B	82	56, 1.10	82	55, 1.09	83	56, 1.08	84
No	86	48, 0.90	82	52, 1.00	83	53, 1.03	82
S & B	84	57, 1.05	80	64, 1.24	82	59, 1.11	83
1 & 2							
P(C), *d'*							
S	53, 1.03		54, 1.06		54, 1.03		57, 1.06
B	55, 1.10		56, 1.07		55, 1.10		57, 1.12
No	47, 0.88		47, 0.89		53, 0.96		51, 0.98
S & B	55, 1.00		56, 1.03		56, 1.03		55, 1.03
1 & 1							
P(C)							
S	83	59, 1.14	81	62, 1.18	82	59, 1.07	82
B	83	53, 1.10	84	54, 1.02	81	50, 0.90	83
No	85	53, 1.03	83	50, 0.95	82	49, 0.93	84
S & B	81	61, 1.16	80	60, 1.13	81	58, 1.08	79

Note. Each of the two presented squares has a brightness and saturation value. The values for the two squares on a dimension are combined by an ampersand. P(C) = percentage of correct judgments. When the presented squares have identical values on both dimensions (e.g., values 1 & 1 on brightness and 4 & 4 on saturation), the correct response is *same*. When the squares differ on either brightness or saturation, the correct response is *different*. S = saturation categorization condition; B = brightness categorization condition; No = no categorization training; S & B = saturation-and-brightness categorization.

control subjects. For saturation categorization subjects, there were 12 square comparisons that involved differences in brightness (the 12 vertically extended rectangles in Figure 7). Averaging over these comparisons, there is a significant difference between d' scores for the control and saturation categorization conditions, unpaired $t(38) = 2.7$, $p < .05$. This result is in the opposite direction as that predicted by acquired equivalence. As evidenced by the black vertically extended rectangles, subjects in the saturation group were more sensitive than the control group at detecting brightness differences.

For the analogous test (the 12 horizontal rectangles in Figure 8) of acquired equivalence in brightness categorizers, there is a significant difference between the brightness categorizers and the control subjects, unpaired $t(38) = 2.4$, $p < .05$, with the brightness categorizers producing higher

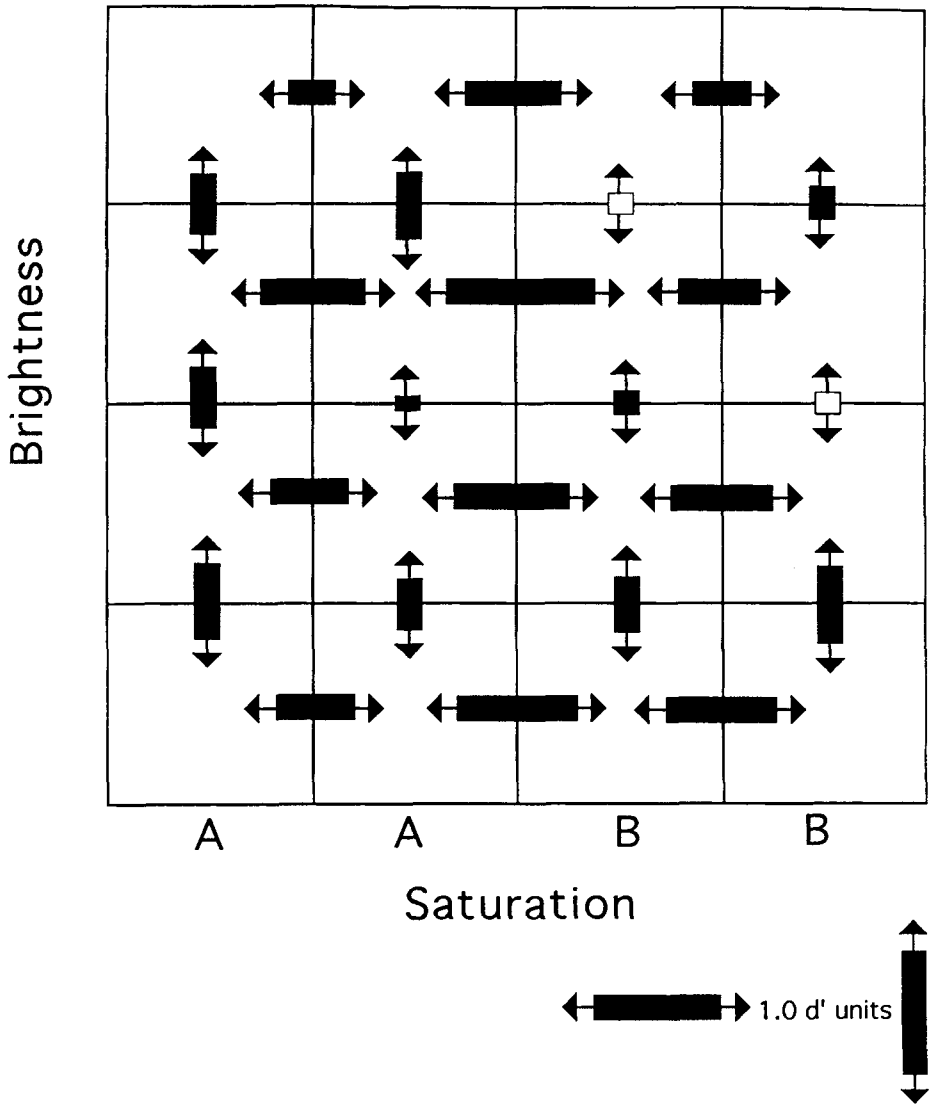

Figure 7. (Saturation categorizers' d') − (No categorizers' d'). This figure shows the gain in perceptual sensitivity that is due to saturation categorization training. A and B refer to categorization (Category A or B) of the stimuli.

d's. Again, this is the opposite of the pattern predicted by acquired equivalence. This is evident in Figure 8 from the preponderance of black horizontal rectangles spanning squares that differ in their saturations.

Acquired equivalence within a relevant dimension. Acquired equivalence within a categorization-relevant dimension occurred if squares that had different dimension values on a categorization-relevant dimension but belonged to the same category became less discriminable as a result of categorization training. For the saturation categorization condition, eight relevant square comparisons were collapsed together—the left and right columns of horizontal rectangles in Figure 7. These rectangles span squares that differ on their saturations but belong to the same category. Overall, the d' associated with these eight squares is greater for the saturation categorization condition than it is for the control group, $t(38) = 2.8$, $p < .05$. This significant difference is in the opposite direction as that hypothesized by acquired equivalence within a relevant dimension.

The analogous comparison for the brightness condition involves the eight vertically extended rectangles that form the top and bottom rows of Figure 8. The d's associated with these comparisons are greater for the brightness condition than for the control group, $t(38) = 2.1$, $p < .05$, in opposition to acquired equivalence with a relevant dimension.

Local sensitization of a dimension. Given that acquired equivalence was not found within the categorization-relevant dimension, all values on a categorization-relevant dimension may or may not be equally sensitized. To test this, discriminations between the squares that belong to different

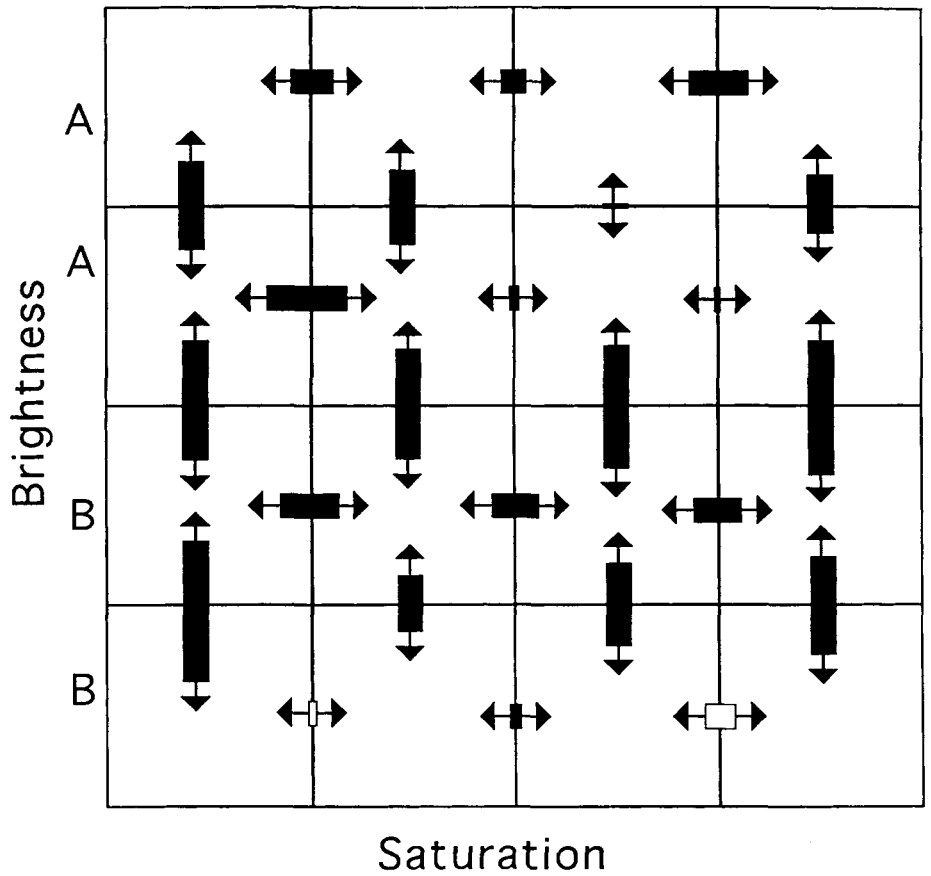

Figure 8. (Brightness categorizers' d') − (No categorizers' d'). This figure shows the gain in perceptual sensitivity that is due to brightness categorization training. A and B refer to categorization (Category A or B) of the stimuli.

categories can be compared to discriminations between squares that belong in the same category but that vary on the categorization-relevant dimension. This is done by comparing two differences—the difference between control and categorization conditions on relevant dimension differences that straddle categories, and the difference between the two conditions on relevant dimension differences that remain in one category.

To test local sensitization for saturation categorizers, the experimenter formed two sets of comparisons. One set (the *critical value* set) contained the four comparisons that paired a square with a saturation value of 2 with a square with a saturation value of 3 (the middle column of horizontally extended rectangles in Figure 7). The other set (the *noncritical value* set) contained the other eight comparisons involving squares that differed in their saturations. The d' scores of the saturation categorizers for each set were adjusted by subtracting the respective d' scores from the control condition. The adjusted d' scores for the critical set were (marginally) significantly greater than the adjusted d' scores for the noncritical set, $t(38) = 1.74$, $p = .083$. In Figure 7, this is apparent in the relatively wider rectangles in the middle column than in the left and right columns.

The analogous sets of critical and noncritical comparisons were compared for the brightness categorizers. The adjusted d' scores for the critical set were significantly greater than the adjusted d' scores for the noncritical set, $t(38) = 2.2$, $p < .05$. The middle column of vertically extended rectangles in Figure 8 contains relatively tall, black rectangles. The upper and lower columns are somewhat shorter.

Attentional competition. Does sensitization produced by categorization on Dimension X diminish if categorization by Dimension Y is also required? For the saturation dimension, the ability of saturation categorizers to make saturation discriminations is compared to the ability of subjects who need to categorize on the basis of both saturation and brightness to make saturation discriminations (shown in Figure 9). The overall d' for saturation discriminations by saturation categorizers was not significantly greater than the d' for the same items by the size and brightness categorizers, $t(38) = 1.4$, $p = 0.17$. The overall d' for brightness differences was marginally greater for the brightness condition, $t(40) = 2.0$, $p = .05$, than it was for the saturation-and-brightness condition.

Selective sensitization of a dimension. Thus far, the evidence has suggested sensitization of the irrelevant dimension, rather than acquired equivalence. Given this, one could

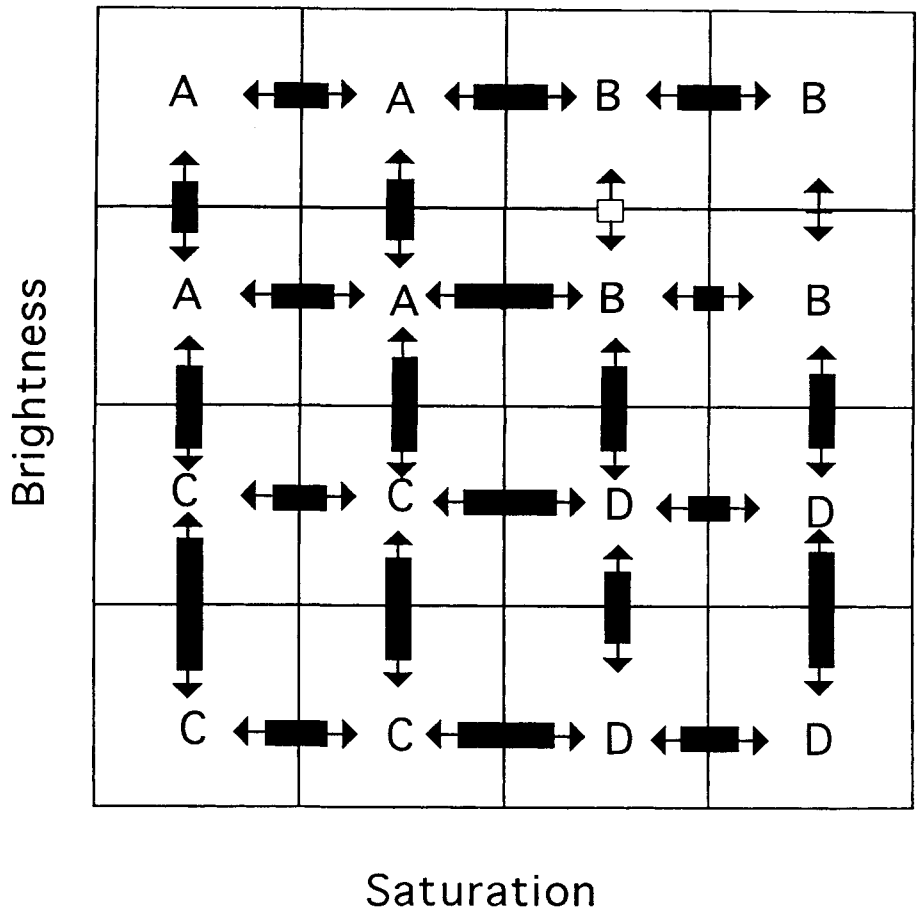

Figure 9. (Saturation & brightness categorizers' d') – (No categorizers' d'). This figure shows the gain in perceptual sensitivity that is due to categorization training that requires attention to both saturation and brightness. A, B, C, and D refer to categorization (Category A, B, C, or D) of the stimuli.

ask a second question: If Dimension X is relevant for categorization, is there equal sensitization of Dimensions X and Y? To answer this question, we can compare the d's along the saturation (or brightness) dimension for the two single-dimension categorization conditions. The d's for saturation differences were greater for saturation categorizers than for brightness categorizers, $t(38) = 3.4$, $p < .05$. The horizontally extended rectangles are longer in Figure 7 than Figure 8. Likewise, the d's for brightness differences were greater for brightness categorizers than for saturation categorizers, $t(38) = 3.1$, $p < .05$. Thus, although brightness is sensitized for saturation categorizers (and vice versa), there is still more sensitization of the dimension that is relevant for categorization.

Other results. As was found in Experiment 2, subjects' perceptual sensitivities improved over the course of testing. There was a positive correlation of $r = .07$, $p < .05$ between trial number in the same–different portion of the experiment and d' score.

The categorization portion of the experiment was harder than the categorization in Experiment 2. To achieve a categorization accuracy of 90%, the saturation, brightness, and saturation-and-brightness groups required averages of 167, 173, and 212 trials, respectively.

Discussion

The results from Experiment 4 share significant similarities and differences with the results from Experiment 2. The current results with integral dimensions replicate several of the results found with separable dimensions. First, acquired distinctiveness effects were always found. Categorization yielded selective sensitization along dimension values that determined the categories. Second, no evidence for acquired equivalence within a categorization-relevant dimension was found. In fact, the results indicate that dimension differences along a relevant dimension that did not cross category lines were still sensitized by categorization training. Third, there was evidence for local sensitization of particular dimension values. Although entire saturation and brightness dimensions were sensitized,

there was also selective sensitization of dimension values that fell on the boundaries between categories.

There were also two important differences in the results between Experiments 2 and 4. First, Experiment 4 showed the opposite of acquired equivalence along the categorization-irrelevant dimension, for both saturation and brightness. Second, far less competition between dimensions was found in Experiment 4 than in Experiment 2. Requiring subjects to use both saturation and brightness during the categorization portion of Experiment 4 did not attenuate sensitization on either dimension as much as it did in Experiment 2. This result is consistent with integral dimensions being easy to attend simultaneously. The claim is that perceptual sensitization occurs when subjects learn to perceptually attend to a dimension during categorization training.

General Discussion

At the broadest level, these experiments support the contention that experience in acquiring new categories can alter perceptual sensitivity. Training subjects on different simple categorization rules resulted in different abilities to make perceptual discriminations (subject to the earlier caveat that same–different judgments probably involve memory and attentional components in addition to purely sensory processes). In addition to this broad conclusion, the experiments also identify a number of specific details about the particular manner in which categorization exerts its influence.

Acquired Equivalence and Distinctiveness

In Experiments 2 and 4, there was consistent support for acquired distinctiveness. For all three dimensions tested (saturation, brightness, and size), dimension differences that crossed category boundaries became sensitized with training. This effect is predicted by several theories of associative and perceptual learning (E. J. Gibson, 1969; Lawrence, 1949; Miller & Dollard, 1941).

It is particularly informative that acquired distinctiveness was found for integral dimensions. Although saturation and brightness behave as psychologically fused dimensions by many measures, categorization training acted to separate and differentiate the dimensions. For example, although saturation is sensitized somewhat when categorization is based on brightness, brightness becomes more sensitized than saturation. Thus, Experiments 2 and 4 both provide evidence that categorization can change subjects' perceptual abilities. Experiment 4 goes further, suggesting that categorization training can cause previously undifferentiated or fused dimensions to become differentiated.

There was similarly consistent evidence against the variety of acquired equivalence that occurs within a categorization-relevant dimension. For all three dimensions, the evidence suggests that sensitization to stimuli differences occurs even if the stimuli belong in the same category, as long as the dimension that the stimuli vary on is generally relevant for categorization. This result is at odds with acquired equivalence explanations of categorical perception. If categorical perception occurs by a process of acquired equivalence, then dimension values that belong to a categorization-relevant dimension must become desensitized with time. However, the present experimental results, to the extent that they can be generalized to speech perception, argue that this process of learning to neglect differences along a categorization-relevant dimension does not occur. Instead, acquired distinctiveness seems to be the general method for establishing selectively heightened sensitivities within a dimension.

The results with regard to acquired equivalence along an *irrelevant* dimension were more complicated. With the separable dimensions of size and brightness, acquired equivalence was found for size, but not for brightness. That is, when brightness determined categorization, subjects actually decreased their sensitivity at spotting size differences relative to the control group. When size determined categorization, there was neither cost nor benefit for brightness discriminations relative to the no categorization control condition. This latter null effect may mask predifferentiation and acquired equivalence effects that cancel out one another. Because effects of predifferentiation would attenuate any effects of acquired equivalence, the present experiments may underestimate the prevalence of acquired equivalence.

Acquired equivalence along the irrelevant dimension was found for one dimension when separable dimensions were tested but was not found with integral dimensions. In fact, the opposite of acquired equivalence was found. Training with brightness facilitated saturation discriminations, and vice versa. Although this is consistent with predifferentiation, predifferentiation does not explain why this strong bidirectional facilitation is found with integral, but not separable, dimensions. An account that resorts to differences between individual dimensions is not satisfactory because one of the dimensions, brightness, was the same in the two situations. An explanation that takes into account the relation between the two dimensions seems necessary. Such an account is provided in a later section.

Local Sensitization of Dimensions

Although apparently contradictory, evidence in favor of both dimension-wide and more local sensitization were found. The evidence against acquired equivalence within a categorization-relevant dimension is evidence in favor of dimension-wide sensitization. For example, when size values 1 and 2 were assigned to Category A and size values 3 and 4 were assigned to Category B, there was sensitization to the difference between values 1 and 2 on size relative to the control group. Both saturation and brightness in Experiment 4 showed significant results in the same direction. These results suggest that subjects learn to attend not simply to particular values on a dimension, but also learn to attend to the dimension itself (Zeamon & House, 1963).

However, there also is evidence for local sensitization. Specifically, although the difference between values 1 and 2

were sensitized, the value difference that was critical for categorization—the difference between values 2 and 3—was sensitized even more. This was found for all three of the dimensions that were tested. This local sensitization indicates that the perception of particular parts of dimensions can be selectively enhanced when useful for categorization. If the basic result of acquired distinctiveness because of categorization training attests to the flexibility of the perceptual system, the additional result of selective acquired distinctiveness within a dimension attests to even greater flexibility.

Competition Between Dimensions and Integrality and Separability

The present experiments provide two sources of evidence for competition between dimensions. The first evidence comes from comparing perceptual sensitization produced by training with a one-dimension categorization rule with the sensitization produced by a two-dimension categorization rule. If Dimension X is more sensitized when categorization depends only on Dimension X than when it depends on Dimensions X and Y, then this is some evidence for competition between dimensions.

By this measure of dimensional competition, there is evidence for strong competition between dimensions in Experiment 2 and evidence for some competition in Experiment 4. The extent of the competition appears to be somewhat greater in Experiment 2 than in Experiment 4. In Experiment 2, the sensitization of either dimension suffered from a categorization rule that required attention to both dimensions. In Experiment 4, only brightness sensitization was marginally affected. A major difference between these experiments is that integral dimensions were used in Experiment 4 and separable dimensions were used in Experiment 2. Thus, by this measure, separable dimensions seem to compete with each other for dimensional attention more than do integral dimensions. These results fit with Garner's (1974) conception of integral dimensions as being easy to attend simultaneously relative to separable dimensions. The results augment previous support for Garner's distinction by showing that this competition for attention has an influence on a later task and that it has a relatively low-level perceptual influence.

The second measure of dimensional competition yields similar results. The second measure examines the degree of acquired equivalence or distinctiveness along the categorization-irrelevant dimension. The claim is that if two dimensions are naturally attended simultaneously, then requiring attention to be placed on one dimension should not necessarily cause another dimension to be processed less. However, if the dimensions cannot be simultaneously attended, then *desensitization* (acquired equivalence) of competing dimensions is expected when attention is required elsewhere. As earlier reviewed, the opposite of acquired equivalence was found for categorization-irrelevant integral dimensions. One case of acquired equivalence (and one null effect) was found for categorization-irrelevant separable dimensions. This is consistent with the view that integral dimensions are easily and naturally attended simultaneously.

There are at least two accounts for how the opposite of acquired equivalence can be obtained for irrelevant dimensions. According to predifferentiation (E. J. Gibson, 1969), distinctiveness is acquired simply by exposure to the stimuli that are later included in the same–different task. However, predifferentiation does not explain why acquired equivalence was found for separable dimensions. Another explanation can be given in terms of diffusion of attention. Sensitization of an irrelevant dimension is hypothesized if attention is focused on the categorization-relevant dimension but also spreads to cover similar dimensions (also see Melara, 1992). More diffusion would be expected to occur for integral than for separable dimensions because of the greater similarity of integral dimensions.

There are also two accounts for the occurrence of acquired equivalence within an irrelevant dimension. According to one account, acquired equivalence occurs when a person actively learns to filter out intrusive dimensions. According to the other account, acquired equivalence occurs when attention, which is usually distributed over many dimensions, becomes focused on one dimension and thereby displaces attention from irrelevant dimensions. The present results, with respect to integral and separable dimensions, are more consistent with the latter account. According to the latter account, separable dimensions are less similar and are farther removed from each other than are integral dimensions, and consequently, when attention is focused on one separable dimension, it must be removed from the other separable dimension. At least in this instance, irrelevant dimensions seem to be ignored because other dissimilar dimensions are relevant, rather than because they are actively filtered out (James, 1890/1950; Neisser, 1976).

Conclusion

Although there has been considerable speculation about the relation between conceptual structure and perception (J. A. Bruner & Postman, 1949; Goldstone, in press; Whorf, 1941), there have been few attempts to obtain rigorous experimental support for concept–percept interactions in controlled laboratory conditions. By training otherwise equivalent subjects on different categories, it was possible to single out category differences as the grounds for the perceptual differences that were observed. The particular results obtained generally indicate that categorization training does influence perceptual sensitivity on later tasks. In particular, acquired distinctiveness effects were found with all tested dimensions; no evidence for acquired equivalence for same-category values within a relevant dimension was found; evidence both for dimension-wide sensitization and for more local value-specific sensitization was found; and competition between dimensions for sensitization was found and was stronger for separable than for integral dimensions.

In sum, the results suggest that categorization training, in addition to requiring subjects to determine a categorization

rule, can also produce perceptual learning that lasts beyond the categorization task. One productive and influential approach to cognition maintains that categorization, and higher-level cognitive processes in general, operates on the output of lower-level perceptual processing. That is, our perceptual systems provide us with a set of fixed features. These features are the inputs to higher-level cognitive processes. However, the present experiments may illustrate a situation in which the higher-level cognitive process being executed has an influence on the lower-level features that are used. In addition to categorization being based on featural and dimensional descriptions of objects, it also appears that the categorization process partially forms the descriptions that are used.

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