

## Before You See It, You See Its Parts: Evidence for Feature Encoding and Integration in Preschool Children and Adults

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Preschool children and adults were compared in two experiments examining the basic issue of whether perceptual representations of objects are built-up from independent features along the dimensions of size and brightness. Experiment 1 was a visual search experiment. Subjects searched for targets which differed from distractors either by a single feature or by a conjunction of features. Results from preschoolers were comparable to those from adults, and were consistent with Treisman and Gelade's (1980, *Cognitive Psychology*, 12, 97-136) feature-integration theory of attention. Their theory states that independent features are encoded in parallel and are later combined with a spatial attention mechanism. However, children's significantly steeper conjunctive search slope indicated a slower speed of feature integration. In Experiment 2, four mathematical models of pattern recognition were tested against classification task data. The findings from both age groups were again consistent with a model assuming that size and brightness features are initially registered, and then integrated. Moreover, the data from Experiment 2 imply that perceptual growth entails small changes in the discriminability of featural representations; however, both experiments show that the operations performed on these representations are the same developmentally. © 1989 Academic Press, Inc.

Researchers concerned with visual perception in adults have advanced a number of theories concerning pattern recognition. Many of these theories have a similar theme, which can be simply put: People first encode features contained in the visual field before those features are recognized as patterns or objects (e.g., Biederman, 1987; Julesz, 1984; Marr, 1982; Massaro, 1985; McClelland & Rumelhart, 1981; Neisser, 1967; Treisman & Gelade, 1980; but see Navon, 1981, for an alternative view). The term

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"perceptual primitives" is used to refer to the features, aspects, or components of objects which, when combined, give rise to phenomenologically real perceptual forms. Several types of perceptual primitives have been proposed, including but not limited to, color, brightness, line ends or terminators, blobness or closure, tilt, and curvature (Treisman, 1986); simple geometric components such as blocks, cylinders, wedges, and cones (Biederman, 1987); spatial frequency components (e.g., DeValois & DeValois, 1975); and bars and edges of different widths and orientations (Hubel & Wiesel, 1968).

However, similar theories of pattern recognition are absent within the area of visual perceptual development. This is partly due to the dominance of the "direct perceptionists," a view opposed to structuralist accounts of perception which are, in Gibson's words, "... [theories about] static snapshots that must be integrated" (Gibson, 1983, p. 308). In addition, developmental researchers have relied heavily on the "restricted classification task" paradigm, which was originally used in exploring developmental changes in "perception" (e.g., Shepp, 1978; Smith & Kemler, 1977), but is now used to study developmental similarities and differences in "comparisons," "classifications," or "decisions" (Smith & Kemler Nelson, 1984; Smith, 1984, 1985; Ward, 1980, 1983; Ward, Foley, & Cole, 1986). In this task, people are shown three objects and are asked to choose the two objects that best go together. Older children and adults tend to group objects which share a value on one dimension, whereas young children group objects that are most similar overall. Using Garner's (1974) terminology, these differing groupings indicate that stimulus dimensions which are perceived separably (analytically) for older children and adults, seem to be perceived by young children in an integral (holistic) fashion. Developmental differences in classification responses have been found using a variety of visual dimensions of geometric forms, including size and brightness (Smith & Kemler, 1977; Ward, 1983), length and density (Ward, 1980, 1983), and color and form (Shepp & Swartz, 1976).

However, much recent research using the restricted classification task paradigm has brought into question the holistic-to-analytic developmental shift hypothesis. Under certain circumstances, preschool children can classify stimuli on the basis of a single dimension (Kemler, 1983; Odom, 1978; Smith, 1983, 1984, in press; Wilkening & Lange, in press). Moreover, adults will classify in a "child-like," holistic way when under pressure to perform quickly (Smith & Kemler Nelson, 1984; Ward, 1983) and when required to perform a concurrent task (Smith & Kemler Nelson, 1984). Adults also perform holistically when instructed to respond on the basis of their "first impressions" (Foard & Kemler Nelson, 1984; Smith & Kemler Nelson, 1984). As a result, researchers in this area are now careful not to imply that children and adults are restricted to either the holistic or the analytic mode of perceptual processing.

More relevant to the present study, the change in terminology from "perception" to "decision" acknowledges that there could be early stages of perceptual processing which are not tapped by the classification task. Some have proposed that percepts used to compare objects in this task "may be built from prior independent analyses of the dimensions" (Smith, 1985, p. 473, in press; see also Aslin & Smith, 1988; Smith & Kemler Nelson, 1984). Thus, a critical, although untested, assumption is that separate features are processed, analyzed, and formed into representations of whole objects in preschool children and adults. Consequently, it is important to address questions concerning developmental changes in visual pattern recognition as a process of building perceptual objects from their primitive components.

The focus of the present study was to explore the nature of perception in preschool children during the earliest moments of visual processing, by comparing their data to those of adults performing the same tasks. Since much previous research has shown developmental differences in processing size and brightness (Kemler, 1982; Smith & Kemler, 1977; Ward, 1983), these dimensions were used to optimize the chance of finding qualitative differences between young children and adults in *early* perceptual processing. The experiments test a general hypothesis common to two theories of adult perception (Massaro, 1985; Treisman & Gelade, 1980). That is, for preschool children as well as for adults, perceptual processing of complex visual stimuli involves an initial stage of featural analysis, followed by a stage involving integration of features derived from this analysis. Thus, one may think of feature registration as an "early" temporal stage of processing, and of feature integration as a later, but still early, stage. Finally, subsequent perceptual processing occurring later than either of these two stages includes making decisions and preparing responses.

In Experiment 1, a visual search paradigm is used to compare the performance of children and adults, and results are tested against Treisman and Gelade's (1980) feature-integration theory of attention. Experiment 2 provides experimental tests of models of information integration that make explicit assumptions about the nature of early perceptual processing (Massaro, 1987). In both experiments, the critical question is will preschool children's and adults' data match the general prediction that perceptual processing involves parallel and independently registered features, followed by feature integration? The data could provide converging evidence in favor of this hypothesis.

#### EXPERIMENT 1: VISUAL SEARCH FOR FEATURE AND CONJUNCTIVE TARGETS

Feature-integration theory assumes that "features are registered early, automatically, and in parallel across the visual field, while objects are

identified separately and only at a later stage, which requires focused attention'' (Treisman & Gelade, 1980, p. 98). In a visual search task, people are shown stimulus arrays, and are asked to find a target (e.g., red circle). Depending upon the target-to-distractor relationship, they will be performing either a feature search or a conjunctive search. In feature search, the target and distractors differ from each other on the basis of a feature along a single dimension. For example, the target might be a red object and the distractors might be blue objects of the same shape. Conjunctive search results from having to look for a target which is defined by a conjunction of features. For example, the search may be for a red circle among distractors which are blue circles and red squares.

When search times are plotted against the number of items in the display, the two search conditions produce two distinct patterns of results in adults. Feature search results in a positive search function which is flat or nearly flat (approximately 3-ms per item), while conjunctive search produces a much steeper positive search function of about 28-ms per item (Treisman & Gelade, 1980). The flat search functions imply parallel featural registration, while linearly increasing search functions imply serial processing of objects whose features have to be integrated with the focal attention mechanism. If preschool children process size and brightness features separately, and then integrate them with focal attention, then similar search functions should be obtained with children as with adults.

We can expect, however, that children will differ somewhat from adults, due to children's slower speed of processing. For example, significant age differences (with 9, 11, 13, and 15 year olds) were found in the visual scanning task used by Keating, Keniston, Manis, and Bobbit (1980). More specifically, the slope of the reaction time functions relating search speed to display size was steeper for younger subjects, and the y-intercept value decreased significantly with age. The slope indicates relative efficiency of visual search, whereas the y-intercept contains decision and response components. Given these results, children's reaction times should also be slower than adults' in all conditions. In both search conditions, the y-intercept values should be higher for children, because children are expected to be slower than adults in making decisions and initiating motor responses. Furthermore, the slope of the conjunctive search function for children should be significantly steeper than for adults because the children would be less efficient at visual search. If features are encoded in parallel for both children and adults, however, the reaction time function should be flat for participants in both age groups, provided that the entire display is within the limits of foveal acuity. A failure to support parallel encoding of features would be evident in a feature search function that departed significantly from the nearly flat functions obtained with adults in Treisman's search tasks (e.g., Thompson, 1987a; Treisman

& Schmidt, 1982, Experiments 1 and 3; Treisman & Gelade, 1980, Experiments 1 and 4; Treisman & Paterson, 1984, Experiment 2; Treisman, Sykes, Gelade, 1977, Experiment 1).

### *Method*

*Participants.* Two age groups were tested in Experiment 1. One group was composed of ten 4- and 5-year-old preschool children. Eight of them were female, and two were male. Their ages ranged from 4;7-6;0 (mean age = 5;6). Ten college students from the University of California, Santa Cruz, six males, and four females, made up the adult group (mean age = 26 years). Adults volunteered for the study, most of them to fulfill a course requirement, while children obtained a toy at the end of each experimental session for their participation. All adults had normal, or corrected-to-normal, visual acuity. The children were free of any known visual impairments.

*Stimuli and apparatus.* Feature and conjunctive search conditions are defined by different target/distractor relationships. In feature search, the target differed from the distractors by a single feature along either the size or brightness dimension. In conjunctive search, the values along both dimensions differed between the target and distractors. Targets were the same for both feature and conjunctive search conditions. However, the distractor backgrounds differed, depending upon the search condition.

The targets were a large, dim square and a small, bright square. One target appeared in the display on every trial. Rather than using two different sets of targets for feature and conjunctive search, we chose instead to use the cognitively less-demanding method of using the same targets, while varying distractors, across the feature and conjunctive search conditions. We did not want children's poorer performance to be attributed to difficulties holding the targets in memory. Given this constraint, the distractor backgrounds for feature search were of two types, either large, bright squares or small, dim squares. Each nontarget background was presented equally often with each target. In conjunctive search, the distractor backgrounds were always composed of a mixture of small, dim squares and large, bright squares. The brightness values (dim and bright) were made by lighting 40 and 90% of the pixels per line of each square. Size values were 1.1 and 1.7 cm for small and large, respectively.

The display area was divided into four imaginary quadrants, and the target appeared equally often in each quadrant. The distractor stimuli appeared in approximately equal numbers within the four quadrants. The distance between the centers of each display item was kept at a constant 3.8 cm (horizontal) and 3.0 cm (vertical) separation for every stimulus array. Therefore, the area of the array increased with increases in display size.

The stimuli were displayed on IBM 5153 color monitor controlled by an IBM personal computer. Reaction time responses were recorded by the computer to the nearest millisecond.

*Design.* Three factors were included in the experiment. Age was a between-subjects factor with two levels (preschoolers, adults). The other two factors were within-subject factors: search condition (feature, conjunctive) and display size (4, 9, 16, and 25 items).

The sessions were divided into blocks of 24 trials. Each block contained six replications of each display size for either feature or conjunctive search. There was a randomized order of trials within a single block. There were two blocks of practice trials, the first a feature search block, and the second, a conjunctive search block. Four experimental blocks of trials were given to each participant. Each person received a total of 96 test trials, 12 per condition. The order of presentation of search condition was counterbalanced. Half of the participants in each age group began with a feature block.

*Procedure.* All participants were tested in a quiet location, with the experimenter present.

They were seated in front of the computer monitor, and were instructed to find the target as quickly as they could. Children were tested in a research van parked outside of the daycare center (Mayer, 1982), and adults were tested in a laboratory.

Pilot testing revealed that children had great difficulty using a reaction time button. To use a reaction time button, children needed to look away from the screen, down at the keyboard, locate the appropriate button, and then press it. These steps increased the likelihood of becoming distracted before the reaction time button was actually depressed. This problem was avoided in the present study by having the child instead point to the target on the screen. Consequently, the response key was pressed by the experimenter as soon as the child's finger touched the computer screen. The experimenter sat at a 90° angle to the screen, focusing on the point of contact between the finger and the screen. From this position, the experimenter could not see the number nor the configuration of items in the display. The procedure was the same for the adults. Trials in which the child became distracted or began talking were recorded as errors, and were not included in the analysis.

Each trial began with the presentation of the target (which also served as a fixation point) in the middle of the screen, lasting for 3 s. A 500-ms tone was played simultaneously with the onset of the target to alert participants' attention to the screen. A 2-s blank screen (pause) then occurred and, finally, the presentation of the search array. The array remained on the screen until it was extinguished with the onset of the response key (the space bar on the computer keyboard). The intertrial interval was 4 s. The timing of the trial events was the same for both children and adults.

### *Results and Discussion*

Each individual's mean reaction time was calculated across responses in each condition. From this analysis, cut-off scores were computed separately for children and adults that were higher than two standard deviations from the mean in each cell of the design. This was done to adjust for extremely long reaction times. Reaction times above the cut-off scores were discarded from the original data; mean reaction times were recalculated for each condition, and were submitted to an ANOVA. Six percent of the adults' and 15% of the children's reaction times did not enter into the final analysis.

Age, Search Type, and Display Size were significant as main effects,  $F(1,18) = 449.12, p < .0001$ ;  $F(1,18) = 265.76, p < .0001$ ; and  $F(3,54) = 59.01, p < .0001$ , respectively. Children were slower than adults, feature search reaction times were faster than conjunctive search reaction times, and reaction times increased with larger display sizes.

All main effects were qualified by significant interactions. There were significant Age  $\times$  Display Size ( $F(3,54) = 14.42, p < .0001$ ) and Search Type  $\times$  Display Size ( $F(3,54) = 16.65, p < .0001$ ) effects. Children's reaction times increased more across display size than adults'. In addition, the pattern of reaction times across display size is different for feature, compared to conjunctive, search. Figure 1 shows the average reaction times in each condition for children, and Fig. 2 displays the results for adults. The interaction of age with search type was significant,  $F(1,18) = 129.15, p < .0001$ , revealing a larger difference in reaction

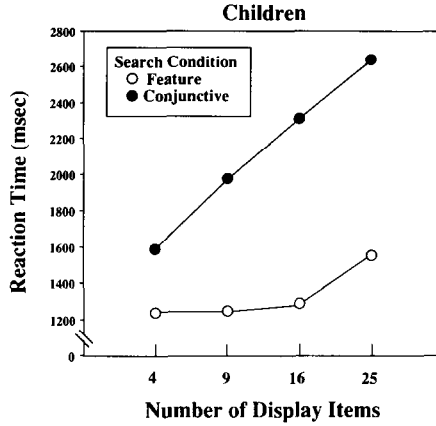


FIG. 1. Children's mean reaction times for feature and conjunctive search conditions in Experiment 1.

times between adults and children for conjunctive, compared to feature, search conditions.

As can be seen in Figs. 1 and 2, reaction times increased with display size in the conjunctive search condition for both age groups. A multivariate test on the conjunctive search data showed that the linear components, and not the residual trends, were significant at both age levels,  $F(1,18) = 14.41, p < .002$  for adults, and  $F(1,18) = 132.02, p < .0001$  for children. Planned comparisons showed that the slope of the line for conjunctive search was significantly steeper for children compared to adults,  $F(1,18) = 29.60, p < .0001$ . This difference in conjunctive search slopes

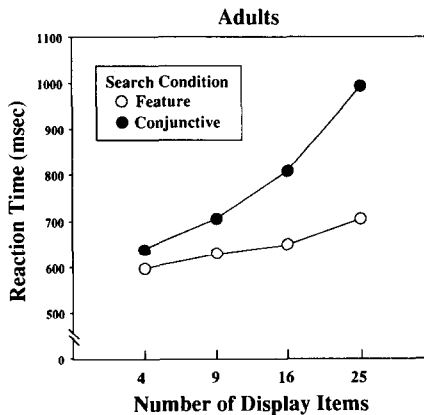


FIG. 2. Adults' mean reaction times for feature and conjunctive search conditions in Experiment 1.

demonstrates that focused scanning for conjunctions of separable features is significantly faster for adults than for preschoolers.

Other comparisons were carried out, all using the Bonferroni procedure, to determine if the pattern of reaction times for feature search was the same across age groups. For both adults and children, there was a simple main effect for display size ( $F(3,54) = 5.56, p < .005$  in the adult group and  $F(3,54) = 62.37, p < .0001$  in the children's group). These effects are primarily due to relatively long reaction times at the 25-item display. For children, the average reaction times across the first three display sizes was faster than the fourth display size ( $F(1,18) = 5.56, p < .0001$ ) and there was no significant difference in reaction times across the first three display sizes,  $p > .05$ .

Similarly, adults' reaction times were independent of display size for the 4-, 9-, and 16-item displays,  $p > .05$ , and the average of these display sizes was significantly shorter than the 25-item display ( $F(1,18) = 12.48, p < .005$ ). Two factors are probably responsible for the increase in the 25-item display. One factor is eye movements (Treisman and Gelade provide this account for their increase in feature search times), and the other is motor movements. It could take longer to point to targets appearing in positions away from center in larger displays.

The means and standard deviations for each of the parameters for both age groups are displayed in Table 1. Table 1 shows that the y-intercept value is longer in both feature and conjunctive search for children compared to adults. According to an explanation by Keating et al. (1980), this finding represents a developmental difference in time taken to execute task components other than active visual search. In addition, the age difference in slope values for conjunctive search revealed a slower speed of visual search in younger children than adults.

A similar search study was carried out by the senior author with eighteen 4- and 5-year-old children. The critical differences in methodology were (1) the child pressed the response key (space bar on the keyboard), (2) after display presentation, the children had to indicate which of two

TABLE 1  
Slopes and y-Intercepts (ms) for Visual Search Functions in Experiment 1

	Slope	Intercept
Children		
Feature search	15	1133
Conjunctive search	49	1468
Adults		
Feature search	5	578
Conjunctive search	17	561

possible targets they found in the previous display, and (3) no location judgment was required. The reaction time of this keypress was recorded by the computer. The error rate was extremely low (0.9%). After removing search times longer than two standard deviations above the mean for each of the six conditions, average feature search times were (for 4, 9, and 16 items) 1.23, 1.36, and 1.35 s. In conjunctive search, they increased across display size from 1.70, 1.81, to 2.64 s. Results revealed a significant interaction between search condition and display size ( $F(2,32) = 10.20, p < .001$ ). Using the Bonferroni procedure, there were no significant differences between feature search means ( $p > .10$ ).

Technically, the pointing feature search task paradigm requires a different type of conjunction, that of conjoining an object attribute with its spatial location. Related to this issue, Treisman and Gelade reported two experiments demonstrating that features can be correctly detected without being spatially localized (1980; Experiments 8 and 9). The question is whether the localization response used in this study, but not in Treisman and Gelade's search studies, compromises the interpretation of the feature search data as support for their theory. On both logical and empirical grounds, we argue that this cannot be so. As described in the previous paragraph, a flat feature search function was found in a task in which children did not point to the target, but rather pressed a key when they found the target. The statistically nonsignificant differences in RTs for 4, 9, and 16 items in the present study imply that the additional operation of "homing in" on the target containing the detected feature does not seem to modify parallel feature encoding. The same can be said of the adult data, by comparing the results from the present experiment with any of Treisman's adult feature search data. As also found by Nissen (1985), selection of a given feature such as color or form makes location information about that feature available. Therefore, similar results are found whether or not location information is required.

Thus, we conclude that the results from both age groups, but most importantly from the preschool children, support the notion that processing during visual search involves two stages: (1) feature registration and (2) feature integration. If children perceived holistically at a very early temporal stage of processing, then these results should not have been obtained.

## EXPERIMENT 2: MATHEMATICAL MODEL TESTS OF CLASSIFICATION DATA

The second experiment provides another test of the hypothesis of whether young children register size and brightness features independently prior to their integration. The experimental test is carried out within the paradigm of information integration and mathematical model

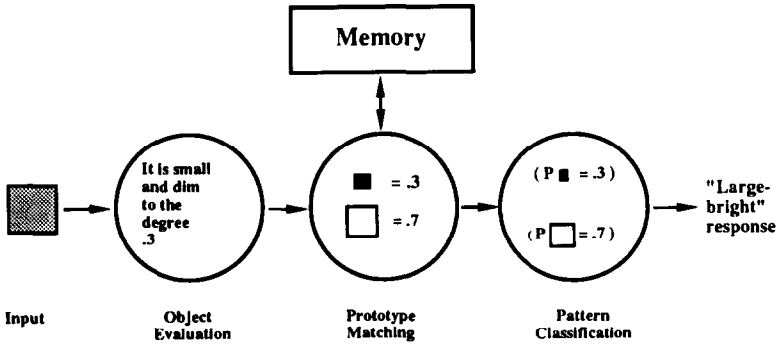
testing (Anderson, 1980; Massaro, 1987). The logic of the paradigm is to manipulate two sources of information independently of one another and to measure their joint influences on classification performance. A general model of the task is that evaluation, integration, and decision operations contribute to observed classification performance.

In this experiment, participants were shown single squares, one at a time, on a computer screen, and were asked to judge whether this square was "more like" the small-dim or the large-bright squares which they learned during training. The stimulus squares each contained one of five values for size, and likewise for brightness. Within the present framework, the question of interest is whether size is evaluated independently of brightness and whether brightness is evaluated independently of size before integration. Models of performance are formulated that either assume independent evaluation or do not. Figure 3 summarizes the major aspects of three of the four mathematical models tested against individual's classifications of size-brightness stimuli. (More complete explanations of the models appear in the appendices.)

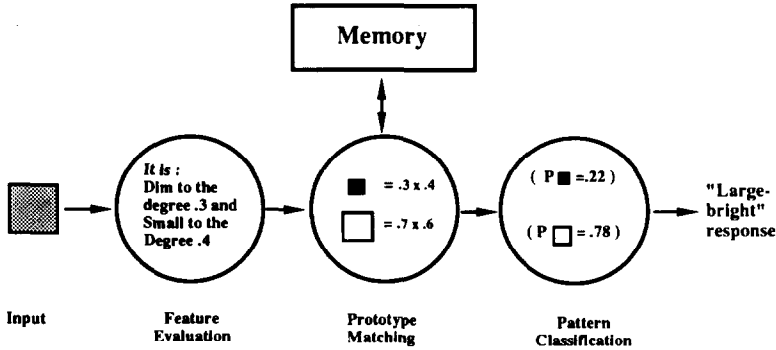
Holistic processing, nonindependence, implies that the value of one source of information, size, would modify the evaluation of the other source of information, brightness. A model to represent this assumption assumes a linear dependence between size and brightness features. This particular model was chosen in part because it represented the most parsimonious account of holistic processing we could think of, and also because it gave a credible account of nonindependent evaluation of two dimensions in a previous perception experiment (Massaro & Cohen, 1977).

The other three models assume that the evaluation of one source is not influenced by the other. That is, the features size and brightness are independently evaluated prior to their integration. Two models, the fuzzy logical model of perception (FLMP) (Oden & Massaro, 1978) and the additive model, differ only in terms of feature integration. The FLMP assumes a nonlinear (multiplicative) integration of size and brightness information, whereas the additive model assumes an additive integration. Both models assume that the decision process follows Luce's choice rule (Massaro, 1987). Furthermore, all models do not permit rescaling of the internal response scale into the observed probabilities.

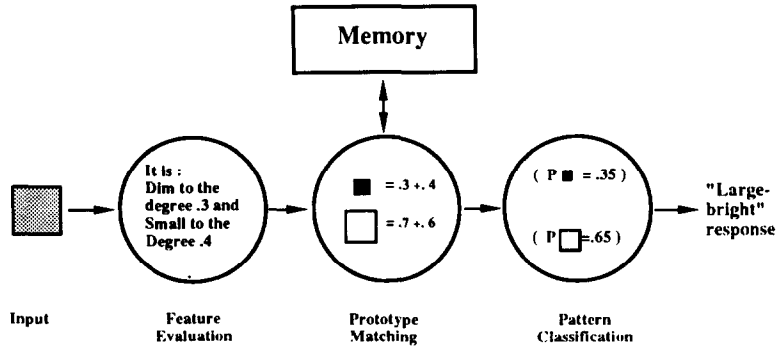
In previous developmental studies within the paradigm of information integration, there is no evidence for nonindependence at the evaluation operation. Performance is adequately described by the independent evaluation of the sources of information of interest. On the other hand, past developmental research has documented evidence for both types of integration processes. In the domain of speech perception, several experiments showed that both preschool children and adults integrate audible



Linear Dependence Model



Fuzzy Logical Model of Perception



Additive Model

FIG. 3. Three models of information processing tested against classification data from Experiment 2.

and visible speech in a multiplicative, as opposed to an additive, fashion (Massaro, 1984; Massaro, Thompson, Barron & Laren, 1986; Thompson & Massaro, 1986). In contrast, other researchers have found developmental differences in integration rules. For example, Anderson and Cuneo (1978) and Cuneo (1980) showed that preschoolers' judgments of the area of a rectangle were best described by the addition of height and width, whereas adults' responses were more in line with the correct mathematical (multiplicative) rule for judging area. Developmental differences in psychological integration rules have also been obtained in judgments of time, distance, and velocity information (Wilkening, 1981) and for judgments of motion mechanics (Anderson, 1983). The type of information integrated is quite varied in these studies; therefore, the integration of size and brightness could plausibly follow either the additive or multiplicative integration rules.

A fourth model is called a centration model, and is mathematically equivalent to the selective-attention model derived by Massaro (1985). Following the Piagetian concept of centration for young children, this model assumes that the perceiver selectively uses only size or brightness on a given trial. An observer is assumed to make a judgment based on the evaluation of size ( $s_i$ ) with some probability  $p$ , and based on brightness ( $b_j$ ), with probability  $1-p$ . Thus, the probability of making a "small-dim" response is

$$P(\text{small-dim}:S_iB_j) = ps_i + (1-p)b_j.$$

This model claims that only a single dimension influences the judgment on any given trial, but that the influential dimension can change from trial to trial. Although the spirit of this model conflicts with the spirit of the integration models, both classes of models assume independence at the evaluation stage of processing.

### *Method*

*Participants.* There were 10 children participants, three males and seven females, ranging in age from 4;8-6;6 years (mean age, 5;10). Another child was tested, but dropped out of the experiment after the second session. All children were attending daycare at the University of California, Santa Cruz at the time of testing. The 10 adults were students at UCSC, five males and five females (mean age, 21 years). Participants had normal visual acuity, with or without correction.

*Design and procedure.* There were two types of trials in the experiment, training trials and testing trials. The objective of training was to teach people the mapping of response keys to the response alternatives to be remembered for the two prototypes. During training, everyone learned that the left key corresponded to the small-dim square and that the right key corresponded to the large-bright square. After a "right" answer, for example (pressing the left key when shown a small-dim square), the computer flashed a happy face on the screen and made a pleasant sound. A "wrong" answer was followed by a sad face and an unpleasant sound.

For adults, training trials came prior to test blocks 1 and 3. Adults reached a criterion of 10 correct answers in a row before beginning a testing block. Children were given training trials at the beginning of each of the four test sessions. For children, trials-to-criterion were 20, 15, 10, and 10 on successive training blocks.

During testing trials, participants were told to decide whether each square was "more like one that went with this button, or the one that went with this button." A bell signalled the onset of the stimulus square, and the square remained in the middle of the screen until a response was made. Adults and children made their responses by pressing one of two marked buttons on the computer keyboard. Children had no difficulty in learning how to use the response keys. However, since the timing of the trial sequence was under their control, some needed to be prodded by the experimenter to make their decisions.

A single block of test trials consisted of the factorial combination of five levels of brightness information and five levels of size information. The order of trials within a block was randomized. Everyone received 12 test blocks, which resulted in 12 trials per cell in the design for each participant. Adults completed the experiment in a single one-hour session, while children were tested in four 20-min sessions. There was a short break midway through each session.

*Stimuli and apparatus.* The experiment was run using the same IBM personal computer and monitor as was used in Experiment 1. The stimuli representing the response alternatives were slightly different in both size and brightness from their closest test stimuli. The small-dim prototype square had 0.25% pixels lit per line of the square, and side lengths of 0.95 cm. The large-bright square had 100% lit pixels and 1.85-cm side lengths. Test squares had brightness values of 0.30, 0.44, 0.58, 0.72, and 0.86% pixels lit per line, and size values for side lengths of 1.10, 1.25, 1.40, 1.55, and 1.70 cm.

## *Results and Discussion*

*Proportion "small-dim" responses.* There were two possible classification responses to the 25 stimulus squares, either "small-dim" or "large-bright." For each individual, the average proportion of "small-dim" responses was calculated for the 25 stimuli. To determine if there were large individual or group differences in the classification data, a measure of the strength of each individual's effect for size and for brightness was calculated. That is, for a given individual, the average proportion of small-dim responses for the smallest sized square (averaged across all levels of brightness) was subtracted from the average proportion of small-dim responses for the largest sized square to obtain the "size effect" measure, and likewise the "brightness effect" measure. Somewhat unexpectedly, as Fig. 4 shows, the data for 18 of the 20 participants clearly split into two subgroups, those whose dominant dimension was brightness, and those for whom it was size.

Accordingly, each individual was categorized as "brightness-dominant" or "size-dominant" on the basis of their highest size- and brightness-effect values, since averaging data across these two subgroups would have yielded a characterization of responses in both age groups which was not an accurate picture of responding at the individual level. Thus, the data will not be reported which treat individuals in both age groups as a single class. Separate analyses of variance were performed on

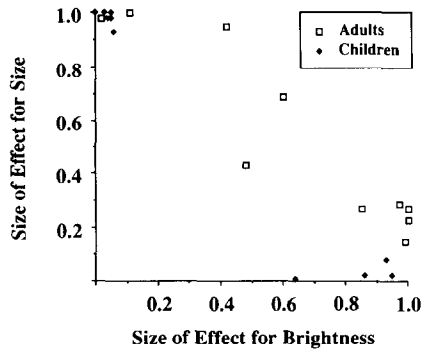


FIG. 4. A comparison of the strength of both variables in each individual's classification responses in Experiment 2.

the size-dominant and brightness-dominant groups' data for both age groups separately. Significant Size  $\times$  Brightness interactions were obtained in both adult groups ( $F(16,48) = 1.90, p < .05$ , for size-dominant, and  $F(16,80) = 3.76, p < .0001$ , for brightness-dominant adults). Figure 5 shows that there is a stronger effect of the nondominant dimension at the more ambiguous regions of the dominant dimension. In addition, there were significant main effects of both variables in both of these groups ( $p < .05$  in each case). Therefore, although the adults were primarily influenced by one dimension of the squares, their perceptual judgments were significantly affected by information about the other dimension. This re-

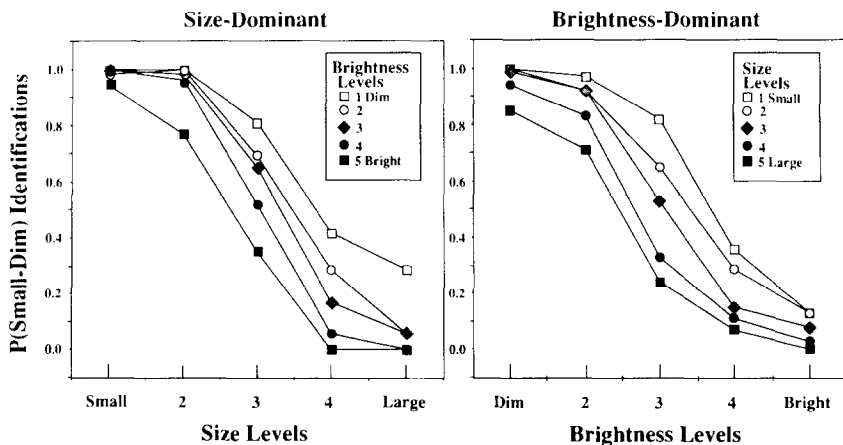


FIG. 5. Observed proportion of "small-dim" responses for adults whose dominant dimension was either size or brightness, Experiment 2.

sult was robust enough to achieve statistical significance even in the group with only four participants' data.

A somewhat different pattern of results was obtained when the same analyses were performed on the children's data. In the "size-dominant" group ( $n = 6$ ), reliable effects were found for brightness,  $F(4,20) = 6.49$ ,  $p < .002$ ; for size,  $F(4,20) = 65.08$ ,  $p < .0001$ ; and for the Brightness  $\times$  Size interaction,  $F(16,80) = 3.02$ ,  $p < .001$ . However, since the points were not regularly ordered on the dimension of brightness, the brightness effect and the interaction must be spurious (see Fig. 6). The analysis of variance for children considered "brightness-dominant" ( $n = 4$ ) revealed a significant effect for Brightness,  $F(4,12) = 29.64$ ,  $p < .0001$ , which was modified by a reliable interaction between size and brightness,  $F(16,48) = 2.27$ ,  $p < .05$ ; however, there was no significant effect for size on these children's judgments. Due to low power, conclusions based on the results concerning children's nondominant dimension must be treated with caution.

To summarize this section, adults use information about both size and brightness to make their judgments about the similarity of a particular stimulus to two prototypes in memory. The classification data for children are more in line with a Piagetian *centration* explanation (Piaget, 1970). That is, preschool children exhibit more of a tendency than adults to ignore information from their nondominant dimension. However, classification data cannot prove that *perceptual* centration has occurred, because it cannot be determined from an analysis of variance on classification responses which stage of processing is revealed by the lack of an

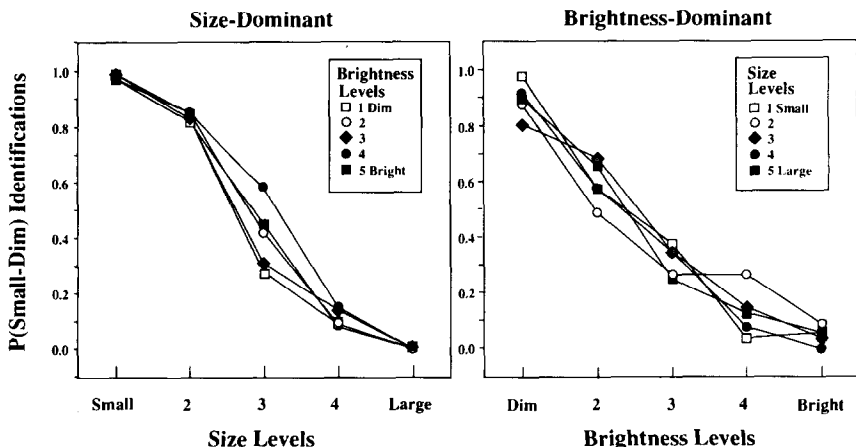


FIG. 6. Observed proportion of "small-dim" responses for children whose dominant dimension was either size or brightness, Experiment 2.

effect of the other factor. [A similar point was made by Wilkening and Lange (in press).] The model-testing results should offer some insight into this ambiguity.

### *Formal Models of the Pattern Recognition Processes*

The computer program STEPIT (Chandler, 1969) was used to fit each model to each subject's classification judgments. Each parameter value was initially set at .5. Then STEPIT iteratively adjusted the parameter values until these values, when set into the model's equation, provided the best fit between the 25 observed and the 25 predicted data points. The goodness-of-fit of the models is the root mean squared deviation (RMSD) between the observed and predicted points. The average parameter values from the individual models are shown in Table 2 for adults and in Table 3 for children.

Tables 2 and 3 also display the average RMSD scores for the adults and children, respectively. An analysis of variance was performed on the RMSD values from the individual fits to each model, for children and adult groups separately. There were significant effects for model type in both age groups ( $F(3,37) = 31.83, p < .0001$ , for adults, and  $F(3,37) = 46.28, p < .0001$ , for children). These results indicate significant differences in the adequacy of the separate models to represent the obtained

TABLE 2  
Best-Fitting Parameter Values and RMSDs for Models Tested against Adults' Data in Experiment 2

Model	Levels					RMSD <sup>a</sup>
	1	2	3	4	5	
FLMP						0.037
Size	0.878	0.791	0.545	0.228	0.090	
Brightness	0.873	0.821	0.562	0.296	0.132	
Linear dependence						0.116
Size	0.999	0.991	0.841	0.611	0.487	
Brightness	0.999	0.960	0.738	0.505	0.364	
Additive						0.191
Size	0.867	0.786	0.577	0.228	0.127	
Brightness	0.913	0.855	0.551	0.280	0.117	
Centration						0.105
Size	0.997	0.907	0.543	0.166	0.006	
Brightness	0.942	0.807	0.595	0.298	0.043	
Decision Parameter						
Size-dominant				0.191		
Brightness-dominant				0.799		

<sup>a</sup> RMSD refers to the root mean squared deviation between observed and predicted data points.

TABLE 3  
Best-Fitting Parameter Values and RMSDs for Models Tested against Children's Data in  
Experiment 2

Model	Levels					RMSD
	1	2	3	4	5	
FLMP						0.067
Size	0.802	0.706	0.451	0.258	0.204	
Brightness	0.591	0.542	0.384	0.384	0.316	
Linear dependence						0.082
Size	0.972	0.855	0.597	0.425	0.366	
Brightness	0.974	0.861	0.722	0.645	0.605	
Additive						0.184
Size	0.766	0.751	0.384	0.178	0.157	
Brightness	0.724	0.615	0.387	0.299	0.249	
Centration						0.081
Size	0.747	0.696	0.378	0.233	0.092	
Brightness	0.517	0.562	0.300	0.534	0.203	
Decision Parameter						
Size-dominant				0.045		
Brightness-dominant				0.842		

data. Planned comparisons showed that, in both age groups, the RMSDs for the FLMP were significantly lower than the RMSDs for each of the other three models ( $p < .01$ ). Given the relative dominance of one dimension over the other for most of the subjects, the fact that the centration model did not fit the children's data as well as the FLMP may appear surprising. However, two dimensions could be integrated on each trial even if one consistently contributes much more than the other. It must keep in mind that the model fits were performed separately for each individual, and therefore give a fairly precise characterization of processing at the individual level. (Please refer to Figs. 7 and 8 for examples of individual model fits.) Thus, the processing assumptions instantiated in the FLMP are well-supported by the findings in this experiment.

An analysis of variance was carried out on the parameter values for the FLMP, with age (5 year olds, adults), dimension (size, brightness), and feature level (one through five) as factors in the design. This analysis should uncover whether the informativeness of the feature values differed across the two age groups. If the levels of the parameter values for a dimension are widely separated, then one can argue that the perceiver can discriminate changes along that dimension quite well. The analysis of variances revealed significant main effects for age,  $F(1,18) = 4.23$ ,  $p < .05$ , and for feature level,  $F(4,72) = 153.77$ ,  $p < .0001$ . The latter shows that the dimensions were discriminated well by all individuals. Moreover, a significant Age  $\times$  Feature Level interaction was obtained,  $F(4,72) =$

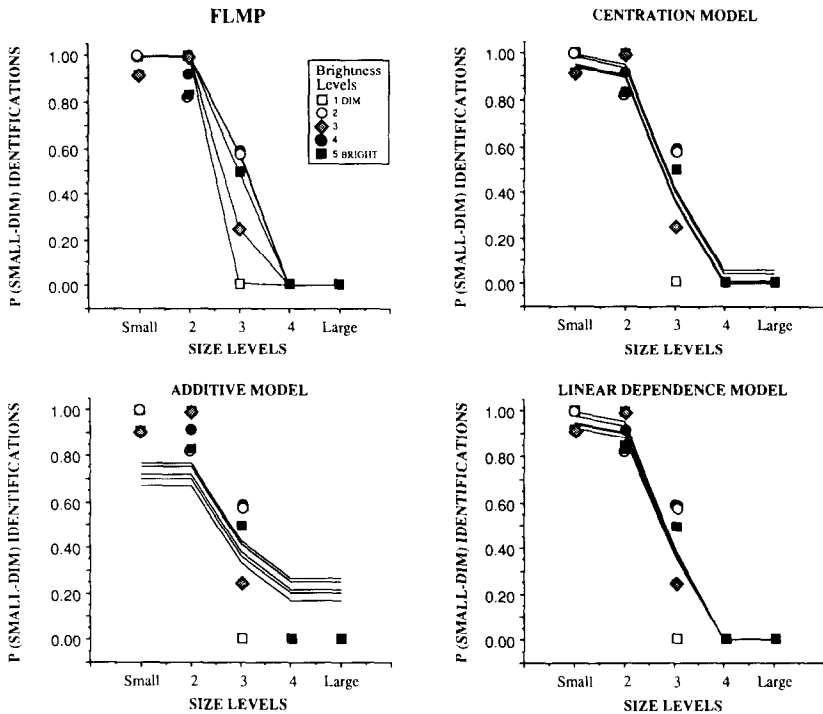


FIG. 7. Observed proportion of "small-dim" responses (points) for a single, typical child plotted against the predictions made by each model (lines) for this child's data.

13.20,  $p < .0001$ , indicating that the parameter values were not as widely separated for children as they were for adults.

According to the theory underlying the FLMP, parameter values serve as an index of the relationship between the stimulus as it is made available to the senses, and the perceived nature of the stimulus. The interaction between feature levels and age indicates a developmental increase in perceptual sensitivity. Perhaps the degree of discriminability of the feature values is greater for adults compared to children. Similar age differences in perceptual sensitivity have been found in the perception of speech and pointing gestures (Thompson & Massaro, 1986), and for speech and lip movements (Massaro, 1984; Massaro et al., 1986). Alternatively, other effects at a more central level cannot be ruled out by the data. For example, the representations of the test alternatives may be less accurate for children than for adults.

## GENERAL DISCUSSION

The visual search data from Experiment 1 and the model-testing results

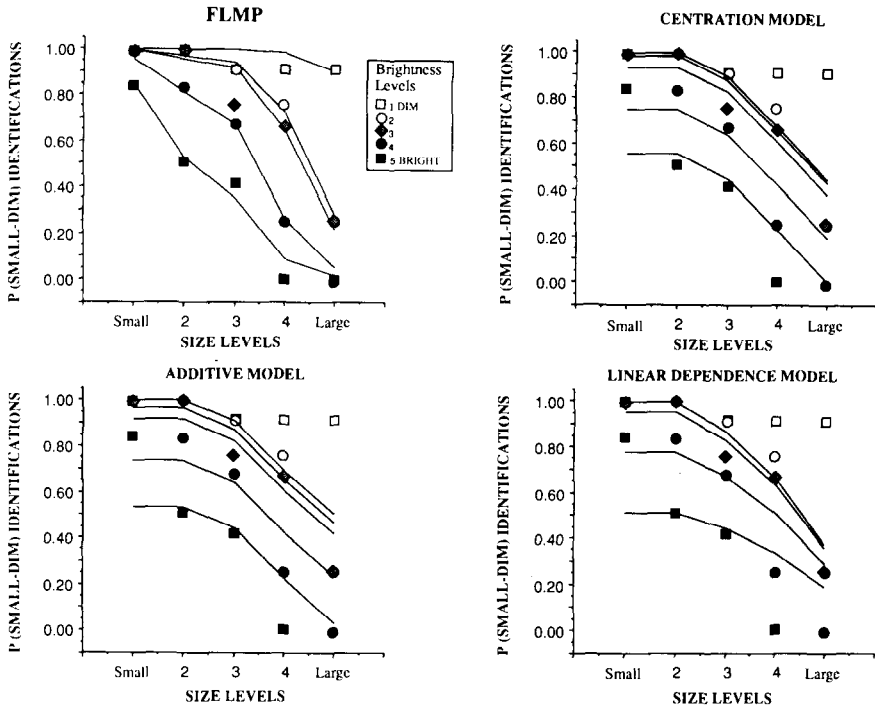


FIG. 8. Observed proportion of "small-dim" responses (points) for a single, typical adult plotted against the predictions made by each model (lines) for this adult's data.

from Experiment 2 provide converging evidence that both preschool children and adults initially evaluate information about an object's size independently from brightness. Evaluation is followed by an integration operation in which the features are combined. In Experiment 1, both the preschoolers' and the adults' reaction times in the visual search task coincided with predictions based on Treisman and Gelade's feature-integration theory of attention. More specifically, search functions for both age groups were relatively flat when searching for targets identified by a single feature, indicating that both groups could process these single features independently and in parallel. In addition, their linearly increasing conjunctive search functions supported the assumption that a spatial "spotlight" of attention serves to glue features into the percepts we are aware of seeing.

However, as Townsend (1971) has cogently argued, one cannot unambiguously interpret reaction time functions as evidence for serial or parallel processes. A flat reaction time function could be extremely fast serial processing in disguise. For this reason, it has become important to establish the existence of feature registration and feature integration stages

through converging operations. Experiment 2 provided a novel assessment of evaluation and integration processes within the context of the same test objects. The fit of several processing models to the classification results were clear. The processing model best suited to fit preschoolers' and adults' data was a model assuming that, during encoding, size and brightness features maintain their continuous nature, and are evaluated independently. Like feature-integration theory, this model, the FLMP (Oden & Massaro, 1978), also assumes that features are combined during a second operation. An equally important issue, made possible with mathematical model-testing, concerned the integration rule used by the preschoolers and adults in this study. The multiplicative algorithm described how children and adults integrate size and brightness better than the additive integration rule. Since it should not be assumed a priori that the integration mechanism works the same way for children and adults, the present results were important in indicating the lack of a developmental difference.

The conclusion that the FLMPs assumptions fit the observed data better than the other assumptions tested is based on two observations. First, there were significantly lower RMSDs for the FLMP than for each of the other models tested, for both preschoolers and adults. In addition, an equal number, or fewer, free parameters were needed by this model compared to the others. Although the model fits directly eliminate only one nonindependence model, the good description by the FLMP provides evidence against all nonindependence models. That is, the FLMP is as parsimonious as potential nonindependence models and, therefore, it is unlikely that any nonindependence model can be developed that will simultaneously be as parsimonious as the FLMP and give a significantly better description of the results. One logically plausible, but impractical, test of the holistic processing hypothesis would be to assume that individuals used 25 mental templates for each of the 25 stimulus squares they saw in the experiment. Although such a model would fit the overall data perfectly, it is not sufficiently parsimonious.

### *Room to Grow*

This study revealed a quantitative equivalence in preschooler's and adult's perceptual processing of size and brightness; however, four quantitative differences were found. In Experiment 1, the y-intercepts of the RT functions were longer for preschool children than for adults in both search conditions. Developmental differences in y-intercepts are difficult to interpret, because they represent a compound of several processing components, such as response selection and execution. It is not surprising that children differ quantitatively from adults with respect to these processes.

Second, there was a significant difference between age groups in the slopes of the conjunctive search functions. Slope parameters reflect search processing efficiency (see, for example, Keating et al, 1980). Age differences in the slopes of both memory functions (e.g., Keating et al., 1980; Naus & Ornstein, 1977) and visual search functions (e.g., Keating et al., 1980; Madden, 1986) have been reported before in the literature. It follows that the attained developmental difference in slope indicates a quantitative difference between age groups in the efficiency of the scanning mechanism during conjunctive search. Perhaps the most intriguing related finding using the Treisman visual search paradigm comes from a study comparing 9-year-old schizophrenic and normal boys (Sherman & Asarnow, 1987). Their results showed that the schizophrenic boys' conjunctive search functions were not significantly steeper in slope compared to the normal boys, indicating equally efficient scanning processes for these two groups. However, since their *y*-intercepts were much higher in this condition, this implies that schizophrenic boys need more time to "start up" a focal attention mechanism. Further research should address the issue of a potential developmental difference in initiating a conjunctive search process.

Third, in Experiment 2, children's, but not adults', classifications revealed a strong tendency to focus their attention on a single dimension throughout the test sessions. Using a different classification task paradigm, Wilkening and Lange (in press) also found that children and adults consistently focus on either size or brightness. They referred to this centration strategy as the "uni-dimensional approach," and claimed that it is the contrary of any form of holistic perception. While this argument concurs with our general belief, we feel that one does not have sufficient leverage to draw conclusions about perceptual independence or nonindependence solely on the basis of the presence or absence of main effects and interactions between the two dimensions. If one assumes that there exist stages of perceptual processing between initial viewing and the final response, there are several, potentially competing, interpretations for the same data set. For example, without model tests, one could reconcile the holistic perception notion to the data from Experiment 2 by making the assumption that perception is holistic, but that the stimulus is decomposed into its constituent elements at a later stage of processing. In Experiment 2, both centration and holistic perception assumptions were instantiated in separate quantitative models, but they provided poorer fits to the data than a model assuming independent evaluation of both size and brightness, followed by multiplicative integration.

The fourth quantitative age difference was the significant age effect in the parameter estimates for the FLMP. These values represent the five levels of size and the five levels of brightness comprising the stimulus

squares. The ranges of parameter values along both dimensions were more compressed for preschoolers than they were for adults. This phenomenon can be linked to an important concept in perceptual learning research, namely, differentiated perception (Gibson, 1969; Gibson, 1983; Gibson & Spelke, 1983). According to Gibson (1983), differentiated perception involves small changes with experience in perceiving embedded relations in the world. A visual array may at first look like a meaningless composite of lines and curves until, finally, the higher-order structure is discovered. However, the results from the present experiments suggest that perceptual growth entails differentiation of a different kind, namely, growth in the ability to differentiate slight differences in sizes and brightnesses of objects. Potentially, there is room for growth, even at the feature evaluation stage of perceptual processing.

### *Implications for Developmental Theory and Research*

There is a long-standing belief in perceptual development theory centered around the idea that the child progresses from holistic to analytic processing (Shepp, 1978; Smith & Kemler, 1978; Werner, 1957). Our results showed that *early* perceptual processing was not holistic, at least for the dimensions of size and brightness. The findings from the present study cannot be used to reject the holistic-to-analytic shift hypothesis, because the type of processing that occurs with other visual dimensions remains to be uncovered. It is also possible that the major developmental changes in early perceptual processing occur prior to the age of 5 years. Smith (in press) found considerably less ability in 2 year olds to make independent decisions about dimensions during perceptual classification than older children.

We question, however, whether the traditional restricted classification task paradigm can continue to be productively applied to the study of perceptual phenomena, for two reasons: (1) Small quantitative differences in discriminability of the stimuli could be masquerading as qualitative differences in perceptual groupings; and (2) averaging across individuals' data showing centration to one or the other dimension yields "holistic" responding and hides the fact of centration.

Related to the first point, the results of Experiment 2 show that children transmit less information about size and brightness relative to adults. Using the restricted classification task, Thompson (1987b) showed that by varying the discriminability of the levels of size and brightness in squares, adults produce more holistic responses in the condition with less, compared to more, discriminable triads. By analogy, young children could be using the same qualitative mode of processing as adults, although their relatively degraded stimulus information yields a different pattern of results. While some of the later perceptual classification studies (e.g.,

Smith, 1985, in press) pilot-tested the stimuli to make sure young children could discriminate the one-step differences along the dimensions, it is still possible that the degree of discriminability differed for adults and children.

With respect to the second point, the classification task paradigm employed in Experiment 2 yielded very strong dimensional biases. In fact, the preschoolers' responses showed that their judgments tended to be dominated by one dimension, more so than adults' responses. Even in the restricted classification task paradigm, Wilkening and Lange (in press) found that children had a strong bias to use just a single dimension to make their classification judgments. These findings are the reverse of the developmental trend predicted in a newly proposed model of perceptual classification (Smith, in press). Thus, one of our concerns with previously reported developmental differences in classification responses derives from an inattention to individual differences. In our Experiment 2, and in Wilkening and Lange's (in press) studies, dimensional biases were not evident from the group-averaged data.

One of the knottiest issues to handle for any theory of cognitive processing is how to disentangle true perceptual effects from judgmental effects. In the language of stage models, questions of perceptual independence require specific experimental paradigms designed to separate perceptual from decisional processes, such as the paradigms employed in the present experiment. As Ashby and Townshend (1986) state, "A critical attribute of a theory of perceptual independence is that it have a separate structure devoted to both perceptual and decisional processes. This feature has been missing from most preceding treatments" (pg. 155). They argue for converging tests, such as signal detection theory and dimensional orthogonality, in order to more precisely define and establish the existence of perceptual independence. A theory of perceptual development must be no less concerned with providing testable hypotheses related to the development of truly *perceptual* phenomenon.

The framework of the FLMP goes beyond distinguishing between perceptual and judgmental phenomena by providing a more detailed description of the processes intervening between stimulus presentation and response execution (Massaro, 1987). The pattern classification task is modeled in terms of three stages of processing: feature evaluation, feature integration, and decision. The model also makes an important distinction between information and information processing. Information refers to the quality of the evaluation of a stimulus presented on a given trial, while information processing simply refers to how that stimulus information is processed. The question of developmental differences must address both information and information processing. With respect to the information question, children appear to transmit less information about the sizes and

brightnesses of objects relative to adults. In signal detection terms, the discriminability of differences along these dimensions showed small changes between 5 years of age and adulthood. While developmental changes could theoretically exist at any of the three stages of processing, the results of the second experiment provide evidence for developmental differences only at evaluation: Differences in the evaluation process appear to be due to differences in the quality of the information transduced by the perceptual system. Moreover, this experiment showed that the integration of information from size and brightness appears to occur in the same manner for children and adults: For both populations, the two sources of information are integrated in such a way that the most informative source of information has the greatest impact on the outcome.

## APPENDIX A

### Formalization of the Fuzzy Logical Model of Perception (FLMP) Assuming Continuous and Independent Sources of Brightness and Size Information, Combined with a Multiplicative Rule

Perceptual classification is carried out in three operations. In the first operation, feature evaluation, the stimulus is transduced by the visual system and various perceptual features are derived. This operation is *not* simply a matching process to determine if particular features are "present" or "absent." Instead, the end-product of the featural evaluation operation is a continuous variable reflecting the degree to which each relevant feature is present. These continuous values are assumed to be analogous to the truth values in the theory of fuzzy sets (Zadeh, 1965).

In the second operation, prototype matching, featural information is combined following the algorithm given by prototype definitions in long-term memory. The FLMP assumes that this algorithm is a multiplicative one. The outcome of prototype matching determines to what degree each prototype is realized in the stimulus.

The third operation is pattern classification. In this operation, the merit of each potential prototype is evaluated relative to the summed merits of the other potential prototypes (Luce, 1959). This relative merit gives the proportion of times a prototype would be selected as a response. An important property of the model is that the most informative cue has the greatest impact on the final judgment.

In Experiment 2, the response alternatives are "small-dim" and "large-bright." The individual evaluates the information conveyed along the brightness dimension, for example, and assigns a truth value between zero and one to the sensory information. With just two alternatives, it is reasonable to assume that the truth value supporting the alternative "large" is one minus that for "small."

Defining the important brightness cue as the amount of light reflected by the stimulus and the important size cue as the area of the square, the prototypes are

"small-dim": low reflectance and small area

"large-bright": high reflectance and large area.

Since the prototype specifies *independent* brightness and size information, the value of one source cannot change the value of the other source at the prototype matching stage. In addition, the negation of a feature is defined as one minus the opposing feature. That is, high reflectance is represented as  $(1 - \text{low reflectance})$  and large area as  $(1 - \text{small area})$ .

“small-dim”: low reflectance and small area

“large-bright”:  $(1 - \text{low reflectance})$  and  $(1 - \text{small area})$ .

The integration of the features defining each prototype is evaluated according to the product of the feature values. If  $b_i$  represents the degree to which the brightness information  $B_i$  has low reflectance and  $S_j$  represents the degree to which the size information  $s_j$  has a small area the outcome of prototype matching would be

“small-dim”:  $b_i * s_j$

“large-bright”:  $(1 - b_i) * (1 - s_j)$ .

The pattern classification operation determines the relative merit of the two responses alternatives leading to the prediction that

$$P(\text{“small-dim”}: B_i S_j) = \frac{b_i s_j}{b_i s_j + (1 - b_i)(1 - s_j)}.$$

Given five levels of  $B_i$  and five levels of  $S_j$  in the present task, the predictions of the model require 10 parameters.

## APPENDIX B

### Formalization of a Nonindependence Model of Perception

As in Massaro (1984) and Massaro and Cohen (1977), the nonindependence formalization was a linear relationship between size and brightness [see Massaro and Cohen (1977) for an example of a good-fitting linear dependence model]. This model assumes that one single, multiplicatively combined (holistic) feature is available for prototype matching. Thus, the prototype descriptions are

“small-dim”:  $(\text{low reflectance} \times \text{small area}) = (b_{ij})$ ,

where  $b_{ij}$  is the product of the brightness and size sources, and

“large-bright”:  $1 - (\text{low reflectance} \times \text{small area}) = 1 - (b_{ij})$

is the mathematical description for the alternative prototype.

This pattern classification operation is assumed to follow Luce's choice rule, and can thus be described as

$$P(\text{“small-dim”}: B_i S_j) = \frac{b_{ij}}{b_{ij} + (1 - b_{ij})} = b_{ij}.$$

The linear dependence model requires 10 parameters, one for each level of the two dimensions.

## APPENDIX C

### Formalization of an Additive Integration Model, Assuming Continuous and Independent Size and Brightness Information

This model assumes, along with the FLMP, that size and brightness features are independently registered, and that these features have continuous values between 0 and 1. The only difference between the FLMP and the additive model is that in the second operation, feature integration, size and brightness features are matched to prototype descriptions assumed to contain an *additive* integration rule.

The prototype for the integrated representations are thus

$$\begin{aligned}\text{"small-dim"}: & b_i + s_j \\ \text{"large-bright"}: & (1 - b_i) + (1 - s_j).\end{aligned}$$

The pattern classification equation would be

$$\frac{b_i + s_j}{(b_i + s_j) + [(1 - b_i) + (1 - s_j)]}.$$

This equation reduces to  $\frac{b_i + s_j}{2}$ .

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