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Learning categories by touch: On the development of holistic and analytic processing

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The development of holistic and analytic processing often studied in the visual domain was investigated in haptics. Children 3 to 9 years of age and adults had to categorize haptic exemplars that varied systematically in four attributes (size, shape, surface texture, and weight). The subjects could learn the categories either analytically—that is, by focusing on a single attribute—or holistically—that is, in terms of overall similarity. The data show that even the youngest children learned the haptic categories far more often in an analytic mode than in a holistic mode. Nevertheless, an age trend was observed, referring to the attributes that the analytic learners used for their categorization. The children preferred substance-related attributes, especially surface texture, whereas the adults preferred structure-related attributes, especially shape. Thus, it appears that analytic and/or holistic processing in category learning develops in a similar manner in the visual and haptic domains.

During the past decades, many researchers have asked whether young children process multidimensional stimuli holistically or analytically and whether and how they use such information in forming categories (see Aslin & Smith, 1988, and Smith, 1989, for overviews). This issue has almost exclusively been investigated in the visual domain. Analogous studies on the other senses are rare, particularly for haptics. This seems surprising, especially in view of the fact that exploring and perceiving the world by touch is developmentally basic (Bushnell & Boudreau, 1991; Streri, 1987). A processing mode acquired in the haptic domain may influence the mode of processing in the other senses. Therefore, studying the development of learning haptic categories seems of particular interest.

A notable exception to the prevailing concentration on visual perception in this field is the recent series of experiments by Berger and Hatwell (1993, 1995, 1996). They were the first authors to extend the hypothesis of a holistic-to-analytic shift in perceptual development (Shepp & Swartz, 1976; Smith & Kemler, 1977) to the domain of haptics, using the paradigms developed in that research tradition. The prototypical task is that of "free classification": Three stimuli that vary along two dimensions (say, shape and surface texture) are presented, and the child is asked, "Which two most go together?" Two of the three stimuli are identical on one dimension but very different on the other. When the child chooses these two, this is taken as evidence of analytic processing. Two stimuli of the same triad have no identical value on either dimension but are most similar overall. When the child picks these two, this is taken as evidence for holistic processing. With such tasks, Berger and Hatwell found surprising amounts of analytic processing in young children, in contrast to what one might have expected from the old hypothesis of the holistic-to-analytic developmental trend. Children as young as 5 years of age were found to focus on one attribute of the multiattribute stimuli—typically, hardness or surface texture—especially when the task favored sequential processing. On the other hand, adults had a stronger tendency to process the stimuli holistically than did children. The authors assumed that adults' holistic responses result from processing the haptic stimuli on a higher level, only after having completely explored the whole stimulus. Adults' responses, according to Berger and Hatwell's argument, contain a cognitive component, whereas children's analytic responses are much more based on a readily accessible perceptual level. Note that, according to studies on visual free classification tasks, it was shown that holistic responses can be made for reasons other than the holistic apprehension of objects. In particular, analytic processing—the separation of single attributes—probably underlies holistic responses in many cases (e.g., Thompson, 1994; Wilkening & Lange, 1989).

Thus, which conclusions can be drawn from the studies by Berger and Hatwell for the processing modes involved in learning haptic categories? To answer this question, it is necessary to compare the different demands of a category learning task with the demands of the triad paradigm as used in Berger and Hatwell's studies. The triad paradigm requires nothing more than a simple perceptual classification. The subject is "free" in the sense that he or she does not have to find a correct answer, because there is none. Each of the two classifications, following either the one-dimensional identity or the two-dimensional overall similarity principle, is sensible. However, the situation is different when the child has to learn a category. Here, the child has to find the correct answer—that is, to detect the category grouping principle the experimenter has in mind. The situation of category learning appears

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to require an apprehension of the stimulus on a higher level than in the free classification task. In the typical category learning task, which is described in detail later, the subject has to generate, test, and revise hypotheses about the definition of the categories. The cognitive demands appear to be higher than in the situation in which the subject is free to choose whatever grouping he or she wishes. Thus, in following Berger and Hatwell's argument that the processing of haptic stimuli on a higher cognitive level seems to induce holistic processing and in accepting the reasoning that category learning requires such an elaborate processing, one should expect more holistic responses in haptic category learning, even in children.

However, this expectation stands in contrast to studies carried out by Ward and his associates (Ward, 1989; Ward & Scott, 1987; Ward, Vela, & Hass, 1990) on category learning in the visual domain. The authors provided strong evidence for analytic processing in category learning. Because their experimental paradigm set the stage for the present experiments, the logic of that task will now be described in more detail.

In an initial learning phase, children had to learn from feedback to categorize visual exemplars (cartoon faces) into the Categories A and B. The exemplars varied in four attributes. As shown in Table 1, Categories A and B possessed a family-resemblance structure. This means that the categories have no defining attributes but have a set of characteristic ones (Level 1 for Category A, and Level 3 for Category B) that are shared by most category members. Note that each exemplar takes on the characteristic value for three of the four attributes but that the specific bundle of the three characteristic attributes is different for each exemplar in a given category. In the process of determining the category membership, the family-resemblance structure allows for both a holistic and an analytic category learning strategy. If the stimuli are compared on the basis of their overall similarity (holistic category learning), then the characteristic attributes of the category are responsible for the result of the categorization (1111 for Category A, and 3333 for Category B, with Level 1 or Level 3 for the Attributes 1, 2, 3, and 4, in that order). If a single attribute is focused on (analytic category learning), then any one of the four attributes may be used for purposes of categorization. Category learning based on exclusive focusing on a single haptic attribute leads to a 75% rate of correct categorizations of the category exemplars (1 or 3 in the attribute focused on). To achieve perfect categorization through focusing, the remaining cases (2 in the attribute focused on) must be treated as exceptions.

Table 1
Categories With Family Resemblance Structure
(Learning Stimuli, Presented During Learning and Test)

Exemplar	Attribute 1	Attribute 2	Attribute 3	Attribute 4
		Category A		
1	1	1	1	2
2	1	1	2	1
3	1	2	1	1
4	2	1	1	1
		Category B		
5	3	3	3	2
6	3	3	2	3
7	3	2	3	3
8	2	3	3	3

Note—Each attribute could assume one of three ordered levels (1, 2, or 3).

In order to determine whether the category learning was based on a holistic or an analytic learning process, test stimuli were constructed (Table 2). The attribute structures presented in Table 2 enable us to differentiate between the holistic and analytic learning strategies based on each subject's categorizations of the test stimuli. For instance, if only Attribute 1 was considered for purposes of category learning (analytic category learning), then the Test Stimulus 3111 would be assigned to Category B and Stimulus 1333 to Category A. In contrast, the opposite categorization would result from a holistic learning strategy: 3111 would be assigned to Category A, and 1333 would be assigned to Category B. The same reasoning applies for each of the four attributes. So, on the basis of the categorizations of the test stimuli, it was possible to determine whether the subjects had used the analytic or the holistic category learning strategy.

As already mentioned, the finding in the studies by Ward and associates (Ward, 1989; Ward & Scott, 1987; Ward et al., 1990) was that an analytic processing mode predominated even in the youngest children investigated (5-year-olds), as well as in adults—contrary to the original claim that there is a developmental trend from holistic to analytic processing in this age range (Kemler Nelson, 1984). It seems, thus, that the category learning task encourages the child to engage in a more analytic mode of processing, in an effort to find the predictive relationships in the stimuli—an interpretation suggested by Ward (1993).

More recently, in Schwarzer's (1997) experiments on categorizing such complex stimuli as melodies, analogous results have been found in the acoustic domain. The category learning paradigm introduced by Ward and Scott (1987) for visual stimuli was adopted. One might expect that melodies, because of their gestalt-like character, are particularly prone to holistic processing. However, Schwarzer found that even preschool children categorized melodies that varied in several attributes in an analytic mode. What differed between the children and the adults was not the processing mode, holistic or analytic, but the very attribute that was chosen for categorization. Children preferred melody-unspecific information, such as loudness, whereas adults preferred more structure-related and melody-specific information, such as melodic contour. Nevertheless, both young children and adults based their categorizations on one single dimension, thus giving evidence of analytic processing.

The results from category learning studies are in line with findings from several studies on perceptual development (Melara, Marks, & Pott, 1993; Thompson, 1994; Wilkening & Lange, 1989), which suggest that young chil-

Table 2
Structure of Test Stimuli, Presented During Test Only

Test Stimulus	Attribute 1	Attribute 2	Attribute 3	Attribute 4
1	3	1	1	1
2	1	3	3	3
3	1	3	1	1
4	3	1	3	3
5	1	1	3	1
6	3	3	1	3
7	1	1	1	3
8	3	3	3	1
Prototype A	1	1	1	1
Prototype B	3	3	3	3

Note—Prototypes A and B are the prototypes of Categories A and B (see Table 1).

dren's access to single dimensions is the rule rather than the exception. The findings from the melody category learning studies, moreover, fit nicely into Cook and Odom's (1992) differential-sensitivity account of cognitive processing, which holds that separate relations in multidimensional stimuli are perceived throughout development. What changes across age, in this view, is not the processing mode—from holistic to analytic—but the salience hierarchy of the separate dimensions. For melodies, it was a shift from loudness to contour, from a melody-unspecific dimension to a melody-specific dimension. It is an interesting question whether a similar developmental shift occurs in haptic categorization and, if so, which dimensions change their relative importance. This question, of course, can only be answered if analytic processing is found in haptic categorization at all ages—that is, when children and adults have access to the separate stimulus dimensions. Although this seems likely particularly for a category learning situation, in view of the previous findings in the visual and acoustic domain, analytic processing in haptic category learning cannot be taken for granted. Relevant studies on this issue are nonexistent.

Because, in the haptic domain, the existing studies on the development of analytic and holistic processing have used only the free classification task and because category learning data on these processing modes are available only from studies in the visual and acoustic domain, the question of the development of analytic and holistic processing in learning haptic categories is still unanswered. We have two hypotheses that can be derived from the literature: One predicts that category learning encourages children (and adults) to engage in a more analytic mode of processing haptic information; the other predicts that the higher cognitive demands involved in category learning lead to more holistic responses, which possibly are built up from separate dimensions and which could be true for both children and adults. The present experiments were designed to test these hypotheses in a first attempt to study the development of the processing mode in haptic category learning.

EXPERIMENT 1

The major focus of the present experiments was to examine whether children and adults learn haptic categories analytically (by focusing on a single attribute) or holistically (by focusing on overall similarity) by using the category learning task developed by Ward and Scott (1987). Therefore, it was essential to show that the formal structure of the test stimuli (see Table 2) created with haptic material corresponds to the observers' perception of them. In other words, the haptic test stimuli should allow a valid diagnosis of an analytic and a holistic learning strategy. This requires that no single haptic attribute overpowers all of the other attributes. The test stimuli had to allow for a match on each of the separate haptic attributes against overall similarity. Any other result would reveal that the remaining attribute was salient enough to overpower the other in assessments of overall similarity. Therefore, in Experiment 1, a dissimilarity judgment study was conducted to show that, regardless of which attributes are considered, a haptic test stimulus will always be judged as being more similar to the category prototype that it matches on three attributes than to the contrasting category prototype that it matches on the remaining attribute. According to the stimuli of Table 2, it should be shown that the constructed haptic attributes fulfill this condition in that Stimuli 3111, 1311, 1131, and 1113 are perceived as being more similar in overall appearance to the prototype of Category A (1111) than they are to the prototype of Category B (3333) and that the reverse holds true for Stimuli 1333, 3133, 3313, and 3331.

Method

Subjects. Sixteen adults (median age = 29 years 6 months; age range = 20 years 3 months to 35 years 1 month) participated in the experiment. They were 10 female and 6 male undergraduates at the University of Tübingen.

Stimuli. The stimuli consisted of wooden blocks varying in the attributes of size, shape, surface texture, and weight; there were

Table 3
Haptic Attributes

Level	Attribute 1 (Size)	Attribute 2 (Shape)	Attribute 3 (Surface Texture)	Attribute 4 (Weight, in grams)
1	small (length, 2.8 cm)	cylinder	fine (density of grains, No. 360)	4
2	medium (length, 4.0 cm)	mixture of a cylinder and a rectangular solid (rectangular solid with rounded corners)	medium (density of grains, No. 80)	12
3	large (length, 5.2 cm)	rectangular solid	rough (density of grains, No. 40)	25

three levels (1, 2, and 3) for each attribute. The stimuli were cylinders (see Table 3, Shape Level 1) or rectangular solids (Shape Level 3) or a mixture of these shapes (rectangular solids with rounded corners, Shape Level 2) made from beech wood. Independent of the different shapes, all of the large, medium, and small blocks had an identical volume in that the sizes of the stimuli (lengths of 2.8, 4.0, and 5.2 cm) correlated perfectly with their volume. The sizes of the stimuli were chosen by reference to Lederman and Klatzky's (1987) description of the "enclosure" exploratory procedure: This procedure consists mainly of an apprehension of the whole stimulus at once. To facilitate haptic exploration in younger children, small-sized stimuli were chosen. Even the larger stimuli could be apprehended in a single grasp by the younger children. To create different surface textures of the blocks, they were covered with different sandpaper (grained 360, 80, and 40). The weights of the blocks were made such that they were either hollowed out or both hollowed out and filled with lead so that they reached the weights of 4, 12, and 25 g. For an overview, Table 3 depicts the variations of the haptic attributes.

A pretest carried out with fifteen 3- to 5-year-old children (median age = 4 years 11 months; age range = 3 years 11 months to 5 years 2 months) showed that the selected adjacent values of each attribute were correctly discriminated in more than 95% of the trials.

On the basis of the variations shown in Table 3, two haptic prototypes were constructed. One prototype (1111) consisted of a small, light cylinder with a fine surface texture; the contrasting prototype (3333) was a large, heavy rectangular solid with a rough surface texture. Test stimuli were created using the haptic attributes depicted in Table 3 and the corresponding stimulus structure represented in Table 2. As shown in Table 2, for each of the four attributes, there were two critical test stimuli. A critical test stimulus for a given attribute is identical to one prototype on a single attribute but different from that prototype on the remaining three attributes. This test stimulus would also be different from the other prototype on the critical attribute but identical to the second prototype on the remaining three attributes. As an example, by assigning Attribute 1 to the attribute of size, the two critical test stimuli were Test Stimuli 1 and 2 (see Table 2).

Procedure. The subjects were tested individually. On each trial, they were presented with pairs of haptic stimuli and were asked to rate overall dissimilarity on a 9-point scale. The scale was bipolar, with 1 being *almost identical* and 9 being *very dissimilar*. The stimulus pairs consisted of all 16 possible comparisons created by pairing each test stimulus with each prototype; this procedure was repeated with a different random order for a total of 32 judgments.

Results and Discussion

The dissimilarity rating given by each subject to a critical test stimulus and the prototype identical to that test stimulus on one attribute was compared with the dissimilarity rating for that test stimulus and the other prototype (identical to the test stimulus on the other three attributes). For example, for the comparisons relevant to the attribute of size, the dissimilarity rating given to Test Stimulus 1 (3111) and Prototype B (3333) was compared with that given to Test Stimulus 1 and Prototype A (1111). Likewise, the rating given to Test Stimulus 2 (1333) and Prototype A was compared with that given to Test Stimulus 2 and Prototype B. The mean numbers of such comparisons indicating greater dissimilarity for the test stimuli sharing only one attribute than three attributes with the prototypes were 1.9 for the attribute size, 1.8 for the attribute shape, 2 for the attribute surface texture, and 1.9 for the attribute weight. Thus, the values were all close to the maximum of 2, which means that the test items clearly pitted a match on the single haptic attributes against overall similarity. There is no indication that any one attribute was so salient that it disrupted the similarity structure believed to be present. This conclusion was also confirmed by the results of an analysis of variance (ANOVA) of the dissimilarity ratings, with item and attribute as within-subjects factors. The analysis showed that all three-match comparisons were significantly more similar (3.13 for size, 3.38 for surface texture, 2.69 for shape, and 2.13 for weight) than the one-match comparisons (7.4 for size, 6.72 for surface texture, 7.26 for shape, and 7.38 for weight) [$F(1,15) = 331.38, p < .01$]. There were no significant differences between the attributes [$F(3,13) = 1.92, p > .05$] and no interaction [$F(3,13) = 2.64, p > .05$]. Thus, the results showed that, regardless of which attributes are considered, each test stimulus was always judged as being more similar to the category prototype that it matched on three attributes than to the contrasting category prototype that it matched on the remaining attribute. According to these results, the test items are a valid means of diagnosing whether people learn haptic categories by focusing on a single attribute or by focusing on holistic overall similarity.

EXPERIMENT 2

Using the haptic stimuli tested in Experiment 1 and the category learning task developed by Ward and Scott (1987), the goal of Experiment 2 was to examine whether children and adults learn haptic categories analytically or holistically.

Method

Subjects. Three age groups, twenty-eight 3- to 5-year-old children (15 female and 13 male; median age = 4 years 7 months; age range = 3 years 6 months to 5 years 9 months), twenty-one 8- to 9-year-olds (11 female and 10 male; median age = 9 years 3 months; age range = 8 years 1 month to 9 years 10 months), and 20 adults (11 female and 9 male; median age = 26 years 1 month; age range = 18 years 3 months to 40 years 4 months) participated in this experiment. The children were from middle- to upper-middle class families and attended local kindergartens and elementary schools in Tübingen, Germany. The adults were female and male undergraduates at the University of Tübingen.

Stimuli. The stimuli consisted of the haptic prototypes and the haptic test stimuli described in Experiment 1. Beyond that, on the basis of the attributes depicted in Table 3 and on the basis of the family-resemblance structure shown in Table 1, Haptic Categories A and B were constructed.

Procedure. Children and adults inserted their hands into a "haptic cinema." They were instructed to enclose the stimulus. The experiment was divided into a learning phase and a test phase. In the learning phase, the eight learning stimuli of Categories A and B (excluding the prototypes; see Table 1) were presented in four random sequences. Children and adults were asked to imagine wooden blocks belonging only to a red or a blue fantasy puppet (Categories

A and B). As concrete reminders of the categories, children and adults saw a red and a blue puppet. After touching the stimulus, the children were asked—without any time restrictions—to point to the appropriate figure or to give the verbal label *blue* or *red*. Both the nonverbal reaction and the verbal reaction were allowed. The experimenter gave feedback about the correctness of the categorization after each trial. In the subsequent test phase, the learning stimuli, test stimuli, and prototypical stimuli were presented. These 18 stimuli were presented one at a time in random order; this procedure was repeated with a different random order for a total of 36 testing trials. Again, the subjects' task was to categorize the stimuli. However, there was no longer any feedback. Reaction times (RTs) were measured from the beginning of stimulus presentation to the subjects' reaction both in the learning phase and in the test phase using a handheld digital stop watch. The exploration procedures in the learning and test trials were filmed with a Camcorder situated in the haptic cinema. The subjects were not aware that a camera was filming their hand movements. For most children, the session took around 15–20 min.

Results and Discussion

Amount of learning. A learning criterion of 12 out of 16 correct categorizations of the learning stimuli presented during the test phase was used to classify a participant as a *learner*. This criterion served two purposes. First, it required more correct responses than could be expected by chance (binomial probability < .05). Second, analytic learners who might have acquired category information only about the characteristic value of the attended attribute but not about the exceptions to that rule could still have met the learning criterion. Twenty-one of the twenty-eight 3- to 5-year-olds, 20 of the twenty-one 9- to 10-year-olds, and all the adults met this criterion. Even in the youngest group, the majority distinguished the haptic categories. For all further analyses, only the subjects who were classified as learners will be considered.

Type of learning. The analyses for the type of learning referred exclusively to the categorizations of the test stimuli presented during the test phase. The general condition for the diagnosis of an analytic learning strategy was that at least 14 out of the 16 test stimuli should be processed by focusing on the same haptic attribute, thereby excluding the haptic prototypes. Analogously, for the diagnosis of a holistic learning strategy, at least 14 out of the 16 test stimuli had to be classified on the basis of overall similarity.

As depicted in Figure 1, an analytic learning strategy was found in 17 of the twenty-one 3- to 5-year-olds, 16 of the twenty 9- to 10-year-olds, and 15 of the 20 adults who were classified as learners. Only 1 child of the 3- to 5-year-olds, 1 of the 9- to 10-year-olds, and 4 adults were classified as holistic learners. The remaining subjects also focused on single attributes but did not use the same attribute consistently. This learning group was classified as *other*.

Assignment to the different learning strategies was independent of age [χ^2 (4, $N = 61$) = 4.27, $p > .05$]. The analytic strategy clearly dominated in the children. Holistic categorizations, if they appeared, were most frequent with the adults (20%). Hence, analytic processing of learning haptic categories was observed in the children and adults.

Further indications of analytic learning rules. RTs and classification errors during the learning phase and the test phase were further analyzed to find converging evidence for the use of analytic learning rules. With each analytic learner, the mean RT referring to the correct categorization of the ambiguous learning stimuli was compared with the corresponding mean RT for all other learning stimuli. Which learning stimuli were considered ambiguous depended on the specific attribute on which the learner had presumably focused. For example, Learning Stimuli 4 and 8 (see Table 1) were ambiguous for a subject who had focused on size (Attribute 1). An ANOVA was conducted on the RTs, using stimulus (ambiguous

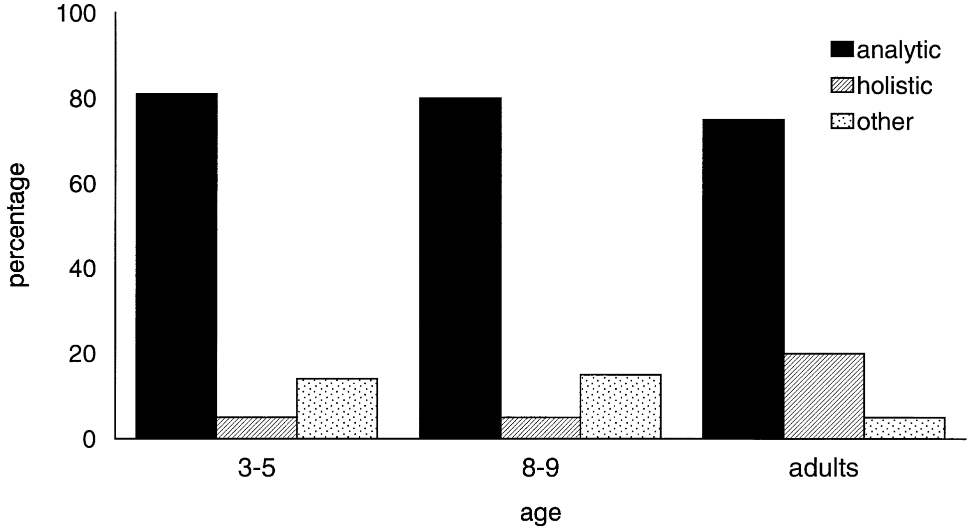

Figure 1. Percentage of learning strategies (analytic, holistic, other).

Table 4
Mean Correct Reaction Times (in Seconds) and Standard Deviations for the Ambiguous and Nonambiguous Learning Stimuli During Learning and Test, Analytic Processors Only

	Ambiguous		Nonambiguous	
Age Group	*M*	*SD*	*M*	*SD*
3- to 5-year-olds	2.61	1.0	2.17	0.75
8- to 9-year-olds	3.52	1.88	2.39	1.3
Adults	2.9	1.36	1.7	0.61

vs. nonambiguous) and age group as between-subjects factors. There was a significant effect of stimulus [$F(1,45) = 34.05, p < .01$], but there was no significant effect of age [$F(2,45) = 1.49, p > .05$] and no interaction between stimulus and age [$F(2,45) = 2.19, p > .05$]. As expected, the categorization of ambiguous learning stimuli took significantly longer than the categorization of the nonambiguous learning stimuli (see Table 4).

Errors regarding the learning stimuli during the learning and test phase also validated the diagnosis of analytic learning. Within each age group, the last categorization error made in the learning phase involved ambiguous stimuli more often than expected by chance (binomial probability < .01), which means that, for an analytic learner, the ambiguous learning stimuli were those that remained difficult to categorize. When categorization errors were found in the test phase, these also occurred more often with the ambiguous learning stimuli than would be expected by chance (binomial probability < .01).

Analytic learning and the influence of the remaining attributes. RTs for the test stimuli (presented during test only) were examined to determine whether the analytic learners were influenced by other attributes than the attribute primarily used for category learning. Of the 16 test items (2 × 8 test items, thereby excluding the prototypes; see Table 2), 4 (2 × 2) involved the critical test items in which the single haptic attribute of interest was pitted against the remaining three attributes. For example, for a "size attribute learner," Test Items 1 and 2 are critical items because they pit categorization based on size against categorization based on any or all of the other attributes. A learner who had category-relevant information about more than one attribute but who assigned the greatest weight to size might be slower in making categorization decisions for Test Stimuli 1 and 2 than for Test Stimuli 3–8, because the latter present no conflicting information about category membership from the other attributes. Using an ANOVA, mean RTs for critical test stimuli were compared with mean RTs for the categorization of noncritical test stimuli. If the attribute context of the focusing attribute influenced the RT, critical test stimuli should yield longer RTs than noncritical test stimuli. The results confirmed this expectation for the 8- to 9-year-old children and the adults. As displayed in Table 5, in these age groups, significantly longer RTs were associated with the categorization of critical test stimuli rather than with the categorization of noncritical test stimuli [8-to 9-year-olds, $F(1,15) = 5.99, p < .05$; adults, $F(1,14) = 14.41, p < .01$]. In the group of 3- to 5-year-olds, the analysis of RTs did not reveal an effect of critical versus noncritical test stimuli [$F(1,16) = 1.65, p > .05$].

These results indicate that, within the age groups of the 8- to 9-year-olds and adults, analytic learners' category knowledge was not exclusively based on a single attribute but included at least one of the remaining attributes as well. In determining the category decisions, however, the focusing attribute was weighed more heavily than the other attributes.

Effectiveness of different types of learning. The effectiveness of the different learning strategies was measured in terms of the number of correct categorizations of the learning stimuli presented during the test phase. Within each age group, learning strategy groups (analytic, holistic, other) were compared on the basis of correct categorizations (15–16 correct categorizations vs. 12–14 correct categorizations). A chi-square test indicated that assignment to learning strategy group was independent of the number of correct categorizations at test [3- to 5-year-olds, $\chi^2(2, N = 21) = 3.04, p > .05$; 8- to 9-year-olds, $\chi^2(2, N = 20) = 2.14, p > .05$; adults, $\chi^2(2, N = 20) = 0.35, p > .05$]. Thus, there was no difference between analytic, holistic, and other learning rules in terms of accuracy in categorizing the original learning stimuli during the test phase.

Haptic attributes selected for analytic learning. The numbers of analytic learners identified as using the attributes of size, shape, surface texture, and weight were 0, 1, 16, and 0 for the 3- to 5-year-olds, 0, 3, 12, and 1 for the 8- to 9-year-olds, and 0, 7, 8, and 0 for the adults, in that order (see Figure 2).

The haptic attributes were used with various frequencies by the analytic learners of the three age groups [$\chi^2(4, N = 48) = 9.73, p < .05$]. While focusing on surface texture clearly decreased with age, focusing on shape increased with age. Surprisingly, almost none of the analytic learners made use of the attributes of size and weight.

Exploratory procedures. The videos of the haptic exploration were analyzed by an unbiased observer according to Lederman and Klatzky's (1987) taxonomy. Of special interest was whether the subjects diagnosed as "analytical categorizers" had explored other haptic features in addition to the attribute focused on. In order to make a comparison between the children and the adults

Table 5
Mean Reaction Times (in Seconds) and Standard Deviations for the Critical and Noncritical Test Stimuli, Analytic Processors Only

	Critical		Noncritical	
Age Group	*M*	*SD*	*M*	*SD*
3- to 5-year-olds	2.39	1.35	2.1	0.88
8- to 9-year-olds	2.7	1.33	2.38	1.18
Adults	3.48	2.03	1.88	0.86

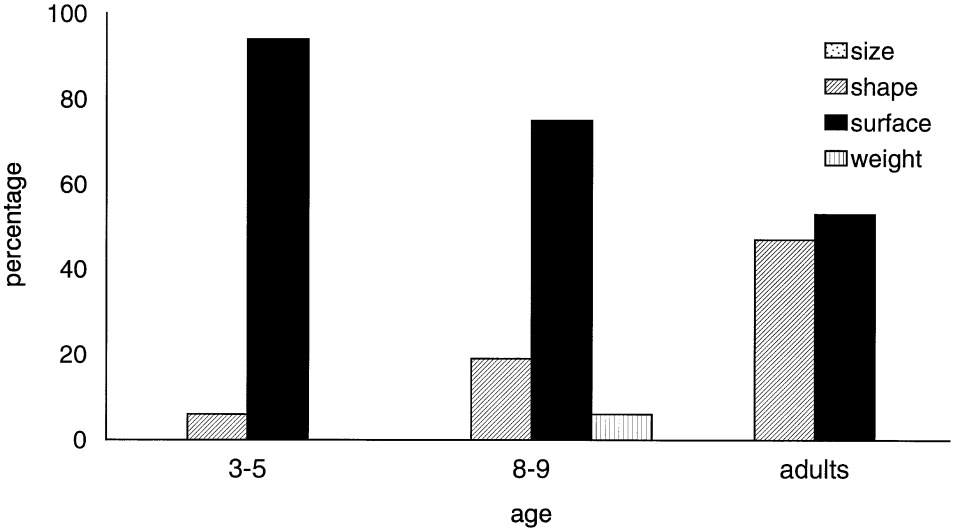

Figure 2. Percentage of haptic attributes (size, shape, surface texture, weight).

in this particular case, the exploratory procedures of the 3- to 5-year-olds who focused on surface texture were compared with the procedures of the adults who also focused on surface texture. For this purpose, the exploration procedures were analyzed according to the following six types:

Enclosure. With the enclosure exploratory procedure, the hand maintains simultaneous contact with as much of the envelope of the object as possible. Enclosure is mainly used to ascertain the general shape and volume of an object.

Lateral motion. The lateral motion manifests sideways movement between skin and object texture (i.e., rubbing; Lederman, 1982). With the help of this finger movement, the texture of the object can be explored.

Contour following. Contour following is a dynamic exploratory procedure in which the hand maintains contact with the contour of the object. Typically, the movement is smooth and nonrepetitive within a segment of object contour, stopping or shifting direction when a contour segment ends. The exact shape and volume can be measured with this exploration procedure.

Turning. The object is rotated between the thumb and the fingers to discover its shape.

Gripping. This exploration procedure describes gripping the object between the fingers in order to assess its size.

Unsupported holding. The object is lifted away from any supporting texture and maintained in the hand without any effort. This procedure gives a feeling for the weight of an object.

Each subject's use of the various procedures was noted as it occurred in the learning phase or in the test phase. Regardless of the length of time that the subject used a particular type of exploratory procedure, only its presence was registered. Figures 3A and 3B show the distribution of the exploration procedures for the children and the adults.

The distributions emphasize the fact that, despite the original classification as texture analyzers, both the children and the adults did not explore only the surface texture—they also explored the other attributes, such as shape (contour following, turning), size (gripping), and weight (unsupported holding). The assumption made by Berger and Hatwell (1993)—that, in comparison with adults, children show incomplete exploration procedures—is not supported by the results of this study.

GENERAL DISCUSSION

The findings clearly demonstrate that children and adults form haptic categories analytically in focusing on single haptic attributes. Developmental differences were observed referring to the attributes that were used in learning haptic categories. Whereas children preferred substance-related attributes, especially surface texture, adults preferred structure-related attributes, especially shape.

Thus, the present results did not confirm Berger and Hatwell's hypothesis that higher cognitive demands induce holistic processing in haptics. Rather, the results support the contrasting hypothesis in that category learning, even in haptics, encourages children and adults to process analytically. Consequently, the results of the present experiments agree with the results of the category learning experiments of Ward and Scott (1987). Using visual stimuli, these authors too found a marked dominance of analytic categorization in both children and adults. Ward et al. (1990) state that "there are no results from the present studies that suggest that holistic modes of learning

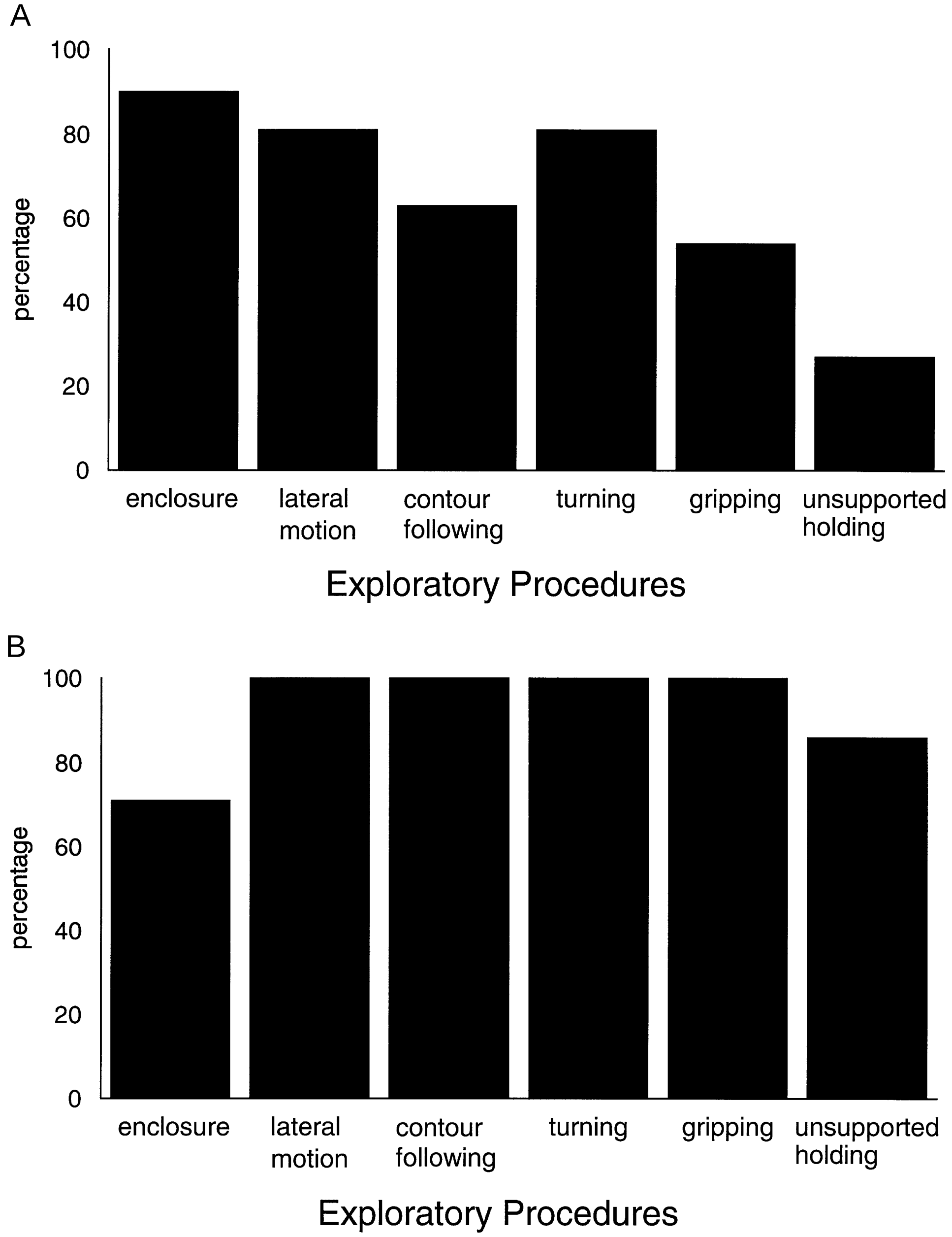

Figure 3. (A) Percentage of exploration procedures used by 3- to 5-year-olds, focusing on surface texture only. (B) Percentage of exploration procedures used by adults, focusing on surface texture only.

by young children are likely to be observed" (p. 603). Furthermore, the results are also in agreement with those that have been found in the acoustic domain, in that even melodies were processed analytically in children and in adults (Schwarzer, 1997). These parallels between visual, acoustic, and haptic category learning point out (1) that the processes of category learning in children are mainly analytical and (2) that the processing modes are similar for visual, acoustic, and haptic information.

The finding that children and adults mostly focused on one single haptic attribute does not mean that only the haptic system is involved in the entire processing of forming a haptic category. The observed performance could also be mediated through visual imagery or some other means. Nevertheless, in future studies, it would be important to figure out whether people will also respond analytically if only the haptic system takes part of the processing. A study with congenitally blind individuals could give an answer to this question.

The results of the present study confirm the results by Berger and Hatwell on haptic perception referring to the free classification task (Berger & Hatwell, 1993; Berger

& Hatwell, 1995, Experiment 1; Berger & Hatwell, 1996, Experiment 1). Their results also demonstrate, predominantly, the use of analytic processing with haptic two-dimensional stimuli by children and adults. On the basis of the results of the present study, it can be said that the results of those earlier studies on perceptual processing procedures can also be applied to haptic category learning.

Even though there was a general preference for the analytic learning strategy, the type of attribute chosen for analytic learning changed with age. Note that, as shown in Experiment 1, the haptic stimuli were constructed such that no single haptic attribute overpowered all of the other attributes. Therefore, the observed age-specific preferences for different haptic attributes cannot be due to differences in their salience. Mostly, the youngest children selected attributes that were substance related, especially surface texture, whereas adults focused on structure-related properties as well, particularly shape. These results can be interpreted in light of Cook and Odom's (1992) differential-sensitivity approach. What changes across age, also in haptics, is not the processing made but the importance of separated haptic attributes. Although, as mentioned above, the stimuli contained no single overpowering attribute, the different age groups clearly show differential sensitivity to the different attributes.

The finding that children prefer surface texture and adults additionally use shape as a focus attribute also agrees with the results of earlier studies on haptic perception. With two-dimensional haptic stimuli, surface texture was found to be more important than shape in younger children (5–7 years), whereas shape was more important than surface texture in older ones (e.g., Abravanel, 1970; Gliner, Pick, Pick, & Hale, 1969; Siegel & Barber, 1973). Berger and Hatwell (1993) also found a clear preference for surface texture as an analytic attribute in the children. The authors explain this result with the observation that the children focusing on the surface texture showed incomplete exploration procedures. However, in the present study, focusing on the surface texture was not associated with incomplete exploration procedures. The children who mainly focused on surface texture also explored the other attributes of size, shape, and weight. In addition, 90% of these children used enclosure as an exploration procedure, thus allowing them to gain a very good sense for all of the haptic attributes of the object (Lederman & Klatzky, 1987). A possible explanation for these results, which differ from those obtained by Berger and Hatwell on exploration procedures in children, could lie in the different haptic stimuli that they used and in their presentation of the stimuli. The stimuli used by Berger and Hatwell were varied only on two dimensions and were fixed on a board, whereas the stimuli used in the present study were varied on four dimensions and were presented in a nonfixed form, thereby encouraging the children to use dynamic exploration techniques.

The age-specific distribution of the haptic focus attributes is also related to the preference observed in younger children to spontaneously extract simpler and less informative attributes when given complex acoustic or visual stimuli. For example, given the comparable task of categorizing complex auditory stimuli, such as melodies, the children tend to concentrate on the less informative attributes, such as loudness, whereas adults use the informative attribute about the melodic contour as their key attribute (Schwarzer, 1993, 1997). Taking these results into account, again, interesting parallels emerge between haptic and acoustic information processing modes.

Finally, the question arises as to the type of category learning model that can be appropriate for the results obtained in the present haptic category learning task. According to Ward (1989), the present results seem to support an attentional weighting exemplar model rather than a purely holistic, unweighted exemplar model, as well as a simple single-attribute rule-based model. The unweighted exemplar model is inadequate because most subjects of all ages focused heavily on single haptic attributes. Although direct evidence for the preferred attentional weighting model against a single-attribute rule-based model can be given only by mathematical model tests, one argument for the attentional weighting model comes from the significantly differing RTs between the critical and the noncritical test stimuli (see Table 5) in the 8- to 9-year-olds and in the adult group. If the subjects were operating from a single-attribute rule-based representation for categorizing the haptic stimuli, then there would be no reason to obtain this kind of difference in RT for critical test stimuli as opposed to other test stimuli. The rule would be equally well satisfied in all cases. However, the attentional weighting exemplar model would allow for a prediction of RT differences. This model might represent a continuum of category learning performance from a nonanalytic exemplar mode, with equal weighting of all features to an analytic rule-based mode in which a single feature is weighted to the exclusion of all others. In this way, the attentional weighting exemplar model is consistent with the finding of the difference in RT in the older children and adults, which indicates that their selective attention to one single haptic attribute was not complete. This model is also consistent with the finding of a nonsignificant difference in RTs in the 3- to 5-year-olds, which indicates a complete selective attention to one of the haptic attributes. Generally, on exactly which point of the continuum a categorization takes place depends on further variables of person, task, and stimulus and on their interaction (Ward, 1989). Examining this relationship more closely in the area of haptics and further investigating the developmental course remain tasks for future studies.

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