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Developmental change in young children's use of haptic information in a visual task: The role of hand movements

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Abstract

Preschoolers who explore objects haptically often fail to recognize those objects in subsequent visual tests. This suggests that children may represent qualitatively different information in vision and haptics, and/or that children's haptic perception may be poor. Seventy-two children from 2 ½ to 5 years and 20 adults explored unfamiliar objects either haptically or visually, then chose a visual match from among three test objects, each matching the exemplar on one perceptual dimension. All age groups chose shape-based matches after visual exploration. Five-year-olds and adults also chose shape-based matches after haptic exploration, but younger children did not match consistently in this condition. Certain hand movements performed by children during haptic exploration reliably predicted shape-based matches but occurred at very low frequencies. Thus, younger children's difficulties with haptics-to-vision information transfer appeared to stem from their failure to use their hands to obtain reliable haptic information about objects.

The use of perceptual information obtained in one modality (e.g., haptics) to perform a task in another modality (e.g., vision) involves inter-modal information transfer. Inter-modal transfer allows for inter-sensory predictions - for example, anticipating what an object will look like given that you have touched but not yet seen it. Perceptual features that can be apprehended only in one modality – color, odor, and temperature – will clearly not be useful in tasks requiring inter-modal transfer. However, information about object properties like shape, texture, and rhythm can be obtained in more than one modality (Lewkowicz, 1994). Such information can also be obtained in one modality and then used for a task in a different modality. The fact that inter-modal transfer of perceptual information is possible implies that representations built from input in one sensory modality are accessible to multiple perceptual modalities (E. J. Gibson, 1969; J. Gibson, 1966).

Adults appear to have no difficulty accessing novel information gathered in one perceptual modality for use in a second (e.g., Abravanel, 1971, 1973; Easton, Srinivas, & Greene, 1997; Reales & Ballesteros, 1999). In contrast, children up to 5 or 6 years of age have difficulty in tasks involving inter-modal transfer (e.g., Goodnow, 1971; Milner & Bryant, 1970; Rose, Blank, & Bridger, 1972), especially the transfer of information from haptics to vision. Two explanations for these findings have been proposed. The first proposal is that the representations that children form from visual and haptic experience may contain different kinds of perceptual information (Abravanel, 1968; Birch & Belmont, 1965; Blank,

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Altman, & Bridger, 1968; Bryant & Raz, 1975; Bushnell & Baxt, 1999). Thus, visually based representations might highlight information about object shape, whereas haptically-based representations might highlight information about object texture or mass. The result would be at least partial incompatibility between representations in the two modalities that could hamper translation between them.

The second proposal is that young children might have poor haptic perception (e.g., Milner & Bryant, 1970; Rose, et al., 1972; Scofield, Hernandez-Reif, & Keith, 2009). Two different potential deficits in haptic perception can be distinguished. It might be that young children cannot efficiently or accurately form percepts from haptic sensory input; or it might be that the haptic input itself is deficient – perhaps because young children have poor manual exploratory abilities.

The three proposed explanations are not mutually exclusive: for example, it is possible that children form generally impoverished mental representations in haptics because they are capable of only limited manual exploration; or that young children's hand movements just happen to provide ample textural information but only limited shape information about the objects they touch. The present study is designed to gain insight into the reasons for children's poor haptic-to-visual information transfer abilities by examining both their performance in a haptic-to-visual object-matching task and the exploratory hand movements associated with the different object matches they make.

Do children form separate and qualitatively different representations from haptic and visual exploration?

A number of researchers have reported evidence that young children may represent qualitatively different information following their exploration of objects in different modalities (e.g., Abravanel, 1968; Birch & Belmont, 1965; Blank, et al., 1968; Bushnell & Baxt, 1999). In Blank et al. (1968), 3- and 4-year-old children studied novel objects either visually or haptically, then were tested for recognition in the opposite modality. Children were good at recognizing previously seen objects by touch, but not good at visually recognizing objects they had previously explored with their hands. The authors proposed that representations of information obtained haptically might not be easily used in visual tasks. More recently, Bushnell and Baxt (1999) used real-world familiar and unfamiliar objects to test 5-year-olds in intra- and inter-modal object recognition tasks – vision to vision, haptic to haptic, vision to haptic, and haptic to vision. The children did well in object recognition in intra-modal tasks with both familiar and unfamiliar objects, and in inter-modal tasks with familiar objects. The authors concluded that 5-year-old children's haptic abilities are actually quite good. However, children's inter-modal performance was much poorer with unfamiliar objects, especially when information obtained haptically was tested visually. Bushnell and Baxt (1999) suggested that “hand-mages” – representations formed from haptic exploration – differ in important ways from visual images, and might not be sufficient for visual recognition. They proposed that attention during haptic exploration might be focused on material-based properties (texture, mass, rigidity), and that such information might not transfer well to vision, or might be outweighed in visual object identification by shape and color information (Klatzky, Lederman, & Metzger, 1985).

None of the studies cited above measured children's hand movements during haptic exploration. It is possible that they did not use their hands effectively to gather information about the objects, so that they obtained less useable information in haptics than in vision. Thus, the information that children obtained in haptics and in vision may have differed in kind (i.e., may have been shape information in vision and texture information in haptics), in quantity, or both. If information in the two modalities differed in kind, then as Bushnell and Baxt (1999) suggest, the representations built from those inputs would be likely to also

differ in kind. Improved inter-modal transfer beyond the preschool period might then reflect the late development of some mechanism for translating perceptual information of one kind into another for use in another modality. If the information from haptics and vision just differed in quantity, however, then the representations built from haptic information when it *was* obtained might be similar enough to representations from visual input to support inter-modal transfer. Improved inter-modal transfer beyond the preschool period then might reflect changes in children's use of hand movements to obtain haptic information.

Are children's haptic exploratory behaviors inadequate for haptic perception?

How the hands are moved determines what sensory information is obtained through manual touch; and the sensory information obtained directly constrains what can be perceived. If children do not display mature haptic exploratory behavior, they may not be able to apprehend the kind of information – in particular, shape and texture information – needed to recognize unfamiliar objects either in haptics or in vision.

What, then, is mature haptic exploratory behavior? Lederman and Klatzky (1987) studied the hand and finger movements of adults who were attempting to extract perceptual information about specific object properties using haptics alone. The researchers identified eight stereotyped hand movements or “exploratory procedures” (EPs), each associated with a specific task goal (e.g., the goal of discovering object shape). The relations between particular hand movements and particular goals suggested that observing how participants moved their hands during haptic tasks could reveal the goals behind their exploratory behavior. For example, adults grouping objects by texture generally produced “lateral motion” – sideways back-and-forth movements of the fingers. In contrast, adults grouping objects by shape produced “contour following” – tracing the object's contours with their fingertips. Lederman and Klatzky (1987) proposed that the most common EPs used by their subjects to find specific kinds of object information were also the optimal EPs for those tasks.

Relatively little is known about how young children move their hands when exploring an object in haptics. A number of past studies have analyzed how children handle objects during *visual* exploration (e.g., Ruff, 1984, 1986, 1989; Ruff & Kohler, 1978), but the set of movements that serve and are controlled by vision may not overlap with the set of movements that serve haptic perception. Bushnell and Boudreau (1991, 1993, 1998) discussed which of the EPs in Lederman and Klatzky's (1987) taxonomy might become available to infants and young children as they achieve certain age-typical advances in motor behavior and attention. For example, infants should not be able to produce the contour-following EP until 9 or 10 months of age, when they acquire the ability to move their hands independently. Thus, infants might not perceive object shape through touch until they are this age or older. Bushnell and Boudreau's (1991, 1993, 1998) hypothesized connections between specific motor competencies and specific EPs suggest that preschool-aged children might have the capacity to display mature haptic abilities. However, there are few data on whether preschool-aged children actually employ adult-like EPs. An exception is a report by Schwartz, Kufer, and Wilkening (1999) that children 4 ½ years old on average as well as adults produced the EPs in Lederman and Klatzky's (1987) taxonomy to apprehend surface texture information. The task involved haptic exploration followed by haptic categorization of novel objects varying in shape, texture, size, and weight. Almost all of the participants categorized the objects by a single feature. The children reportedly produced the same EPs as the older participants at high frequencies. In particular, the children used each of four EPs – enclosure, lateral motion, and contour following – in 60% or more of their trials. However, despite their use of contour following – the EPs linked to shape perception in adults – the children did not make shape-based categorizations. Instead, 16 of 17 children categorized the objects by texture. It is possible that the children obtained shape information from

contour following and did not use it. It is also possible that the children did something like contour following, but not the specific behavior that adults use to obtain shape information.

Other researchers have suggested that children's haptic exploratory abilities are poor without presenting data on the children's actual hand movements. Rose et al. (1972) asked whether 3-year-olds could briefly retain visual and haptic information about object shape and texture in both intra- and inter-modal conditions with unfamiliar objects. Children were introduced to an exemplar object either visually or haptically, and then asked to indicate which of two comparison objects, presented either in the same or in the alternative modality, was the same as the exemplar. Children performed well when the two comparison objects were presented simultaneously. However, performance in all conditions involving haptics was hampered when the test objects were presented in succession, or after a 15-second delay. Rose et al. (1972) concluded that the children's poor performance was not a result of weakness in their ability to retain haptic information, since their performance was equally poor in haptic-to-visual transfer as in visual-to-haptic transfer tasks. Instead, the authors believed that the deficit in children's performance in delayed comparisons involving haptic information was due to poor haptic abilities.

Milner and Bryant (1970) offered a similar explanation for their finding that children's ability to make same/different judgments about object shape within and across haptics and vision increased significantly between 5 and 7 years of age. Because children's performance improved equally in both the haptic intra-modal condition and the two inter-modal conditions, the authors attributed the developmental change to gains in children's haptic abilities, not in their intermodal transfer abilities.

One striking, repeated finding is that young children are well able to recognize objects through haptics alone when those objects are familiar (e.g., Bigelow, 1981; Bushnell & Baxt, 1999; Morrongiello, Humphrey, Timney, Choi, & Rocca, 1994). It may be that partial perceptual information is sufficient for object recognition in haptics, as it is in vision, when the mental representation of that object is already richly elaborated. Bigelow (1981) asked 2 ½ and 5-year-olds to name familiar objects after haptic exploration of the objects, or after visual inspection. There were three categories – miniaturized large objects (e.g., a doll-sized bed), miniaturized small objects (e.g., a doll-sized spoon), and non-miniaturized small objects (e.g., keys). All of the objects were visually recognized by children in both age groups. The 5-year-olds also recognized most objects from touch alone, and recognized more objects from touch than 2 ½ - year-olds in all three conditions. The 2 ½-year-olds' poorest performance was in their haptic recognition of the miniaturized large objects. Bigelow (1981) suggested that the younger children had particular difficulty with small versions of objects like beds because their representations of haptic information about these large objects were incomplete and so were not evoked by haptic information gained in the moment from the miniature version. It is also possible that the haptic input from the 2 ½ - year-olds' hand movements on miniaturized large objects, as well as or instead of the mental representations of those objects, was lacking.

Summary

Preschool-aged children show a marked deficit in haptic-to-visual inter-modal identification of unfamiliar objects (e.g., Bushnell & Baxt, 1999; Milner & Bryant, 1970). Three possible reasons for this deficit have been suggested. First, object representations built from visual and haptic input may not translate well because they are qualitatively different: haptic representations may emphasize material features like texture or mass, whereas representations of objects explored in vision may emphasize structural features such as shape (e.g., Bushnell & Baxt, 1999). Second, children's haptic perception may be wanting: they may not be able to form useful object representations from haptic sensory input. Third,

children may have good haptic representational abilities, but may not obtain the required sensory input from their attempts at haptic exploration because they do not perform the kinds of hand movements that would yield information about specific properties (e.g., Milner & Bryant, 1970). None of these explanations are mutually exclusive: any or all might obtain.

In the present study, we investigated the source of children's deficits in haptic-to-visual inter-modal transfer using a modified version of the task developed by Bushnell and Baxt (1999). In our version of the task, participants visually or haptically explored unfamiliar objects that had textures and shapes designed to be distinctive in either modality, and that were also visually distinctive in color. Participants were then asked to visually identify one of three test objects as the object they had previously examined. Our study differed from Bushnell and Baxt's (1999) study in three major respects: first, we named the novel objects. A large body of research has shown that giving names to unfamiliar objects serves to organize young children's visual attention and direct it to object shape (e.g., Imai, Gentner, & Uchida, 1994; Landau, Smith, & Jones, 1988). We named the unfamiliar objects in the present study in case naming might similarly organize children's attention to focus on a particular perceptual dimension – shape or texture – in our tasks. The second difference is that we recorded and analyzed children's hand movements during exemplar exploration in both modalities, to compare visual and haptic exploratory behaviors, and especially to learn more about young children's haptic exploratory movements. Finally, we included children in a wider age range – from 2 ½ to 5 years of age -- to establish developmental trends both in haptic-to-visual intermodal object recognition and in haptic exploratory behavior.

Method

Participants

Seventy-two children and 20 adults participated in this study. The children spanned six age groups – 2 ½, 3, 3 ½, 4, 4 ½, and 5 years of age – with 12 children (5–7 males) in each group. Participants reflected the local community in social class, ethnicity and racial identity: almost all participants were from white, middle class families. Adults were university students (n=20) participating for partial fulfillment of a course requirement.

Stimuli

The stimulus set consisted of 16 novel category exemplars, three test objects for each exemplar, and nine familiar objects (e.g., cup, spoon, comb). Exemplars were 3-dimensional, nonsense objects constructed from a variety of materials including wood, clay, and cloth. Sizes ranged from 7 to 17 cm. Colors, textures, and shapes were widely varied. Each of the test objects shared a different attribute – its shape, texture, or color – with its exemplar, and differed from the exemplar and the other two test objects on the other two dimensions (see Figure 1 for a sample stimulus set). Of course, only shape and texture could be perceived through both vision and haptics. We wanted to provide children with more than two choices in order to better distinguish a pattern of perceptually- based object matches from chance responding. However, a third perceptual feature readily identifiable in both modalities does not appear to exist. We chose to include a same color object as the third choice, as is common in studies of a shape bias in visual matching (e.g., Smith, Jones, Landau, Gershkoff-Stowe, & Samuelson, 2002), acknowledging that color matches in a visual task might be meaningful, whereas color matches in a haptic task would clearly be random choices.

Procedure

All participants completed two blocks of trials, each consisting of three training trials and eight test trials. In one block of trials, children held and visually explored exemplar objects (“Visual Exploration” condition). In the other block of trials, children explored the category exemplars by touch alone (“Haptic Exploration” condition). In the testing phase of both conditions, children were visually presented with the test objects. The order in which the conditions were presented was counterbalanced across participants. In addition, the 16 stimulus sets were divided into two groups of eight sets and the order of presentation of the groups of stimulus sets was counterbalanced within blocks. Thus, in the Visual Exploration condition, half of the participants saw Stimulus Group 1, and the other half saw Stimulus Group 2.

Each participant was seated at a table (children were seated next to their parent) across from the experimenter, who explained that they were going to play a “matching game”. The procedure began with three training trials to ensure that participants understood the task. Training trials differed between the two experimental conditions. In each training trial in the Visual Exploration condition, participants were simply handed a familiar object and told its name (e.g., “Look, here is a spoon”). After five seconds, the experimenter retrieved the object. In each training trial in the Haptic Exploration condition, participants placed their hands and forearms inside a box; a piece of cloth was pulled over their arms to prevent participants from seeing inside the box. The experimenter put a familiar object into the hands of the participant within the box, identified it by name, and asked the participant whether he or she could feel it (e.g., “This is a spoon. Can you feel the spoon?”). In each trial in both conditions, the exemplar object was removed after five seconds and participants were then visually presented with three test objects (e.g., a cup, a comb, and a spoon) and asked to indicate the test object with the same name as the exemplar (e.g., “Can you show me the spoon?”). In the Haptic Exploration condition, participants removed their hands from the box and used them like children in the Visual Exploration condition to indicate their choice of a matching test object by pointing to or handing over one of the three choices. Note that color match choices in the Haptic Exploration condition could not reflect the perception of color during exploration, so were interpreted as random choices.

Test trials followed immediately and were structured just like the training trials: participants were handed the exemplar from one object set at a time either inside or outside of the box according to condition, and told its name (e.g., “This is a teeka”). Participants were given five seconds to explore the exemplar, after which the exemplar was removed. The three test items were then laid out in random order within reach of the child. The object category name was again used as the experimenter asked for a match (e.g., “Can you show me another teeka?”). The first test item touched, handed over, or pointed to was scored as the child's choice of match. No child failed to indicate a choice by one of these behaviors on any trial. Children were given a sticker after each trial regardless of which choice they made. The experiment was digitally recorded, and the records were later scored for the test objects – shape match, texture match, or color match – chosen on each trial.

The recordings were also coded for the children's hand movements while exploring category exemplars in both the Visual and Haptic Exploration conditions. Coders were blind to the hypotheses of the experiment. Initially, we attempted to code hand movements using the taxonomy of exploratory procedures developed by Lederman and Klatzky (1987) and reported by Schwartz et al. (1999). However, children in the present study did not produce these patterns of movements. Therefore, new categories were developed. The first author and two assistants initially coded five digital records randomly chosen from each condition. Hand movements observed in each record were time marked and described in sequence. The three coders reviewed their codings together, and agreed on category labels that captured

virtually every repeated type of hand movement in each condition. There was no overlap in the kinds of hand movements observed in the visual and haptic exploration conditions, and thus no overlap in the category labels applied by the coders to the movements identified in each condition in the remainder of the experimental recordings.

Results

Object matching

Figure 2 shows the mean frequencies with which children chose shape (white bars) texture (grey bars) and color (black bars) matches for exemplars at each age level, following haptic (Panel A) and visual (Panel B) exemplar exploration. The dashed lines show the chance level of performance (2.67) given three choices on each of eight trials.

Because our measures of children's choices of shape, texture, and color matches for the exemplar were not independent, the analyses compared only the frequencies of shape matches made by different age groups in the different conditions. A mixed analysis of variance - 6 (Age) $\times$ 2 (Exploratory Modality: Haptic/Visual) $\times$ 2 (Gender) $\times$ 2 (Order: Haptic Exploration first or second) on children's numbers of shape-based matches in each condition confirmed the two main trends illustrated in Figure 2. There was a main effect of Age ($F(5,48) = 3.41, p < .01$), reflecting the fact that older children made more shape-based matches than younger children, and a main effect of Exploratory Modality ($F(1, 48) = 28.78, p < .0001$), reflecting the fact that more shape-based matches were made after visual exemplar exploration than after haptic exemplar exploration. There were no other main effects and no interactions.

Table 1 shows the results of one-sample t -tests comparing children's numbers of shape-based matches at each age level in each condition to chance (2.67). The results confirm the impressions from Figure 2: in the Visual Exploration condition, children at all age levels, like the adults, showed the previously well-documented bias to preferentially attend to shape in object matching (e.g., Smith, et al., 2002). However, in the Haptic Exploration condition, only 5-year-olds resembled the adults in matching the exemplar systematically by shape. Because the 5-year-olds matched both haptically- and visually-apprehended exemplar objects on shape, not on texture, there was no evidence that these children formed qualitatively different kinds of representations from haptic versus from visual sensory input.

Children younger than 5 appeared to be choosing among the three test objects at random in the haptic exploration condition, but there are also two alternative possibilities. The first is that younger children in that condition were divided across stimulus sets as to whether the appropriate choice was a shape match or a texture match. This alternative cannot be ruled out, but is made less likely by the substantial numbers of non-matching (color match) object selections made in the haptic exploration condition. The second alternative is that the group results mask the fact that some children showed a shape bias in matching after haptic exploration, whereas other children showed a texture bias in that condition. We addressed this possibility by counting the numbers of children in each condition at each age level that made five or more matches on the same perceptual dimension – that is, on shape, texture, or color. We chose the criterion of five matches because a mean of five matches on one dimension would be significantly above chance for the group as a whole. The results are shown in Table 2. Consistent shape matching by our criterion was shown by almost half of even the youngest children following visual exploration of the exemplar. However, following haptic exploration, no children from age 3 until age 5 matched consistently on either shape or texture. Intriguingly, 1 in 3 of the 2½-year-olds consistently matched on shape following haptic exploration. However, only one of these also matched on shape in the visual exploration condition. Thus, it is not clear how this finding should be interpreted.

In general, however, it is apparent that the group finding of no consistent pattern of matching after haptic exploration accurately represents the performances of individual children in this condition.

We next examined children's hand movements during visual and haptic exploration, both to document the kinds of exploratory hand movements produced by children in each condition at each age level, and also to determine whether, despite children's lack of a clear preference for shape-based matches in the Haptic Exploration condition, specific hand movements on the objects while they were out of sight were nevertheless associated with subsequent choices of visual shape matches.

Children's hand movements during visual and haptic exploration of exemplar objects

Hand movements were clearly visible for coding in a total of 568 trials (98%) across all age levels in the Visual Exploration condition. In the Haptic Exploration condition, a total of 383 trials (66%) were visible for coding across all ages. Some trials could not be coded because children removed their hands (holding the object) from the box. In other trials, the children's hands remained inside the box but were too far back from the camera's angle to be clearly seen. The frequencies of each kind of uncoded trial at each age level are shown in Table 3. Not surprisingly, both kinds of trials were most common among the younger children. Because only small numbers of trials at even the youngest ages were uncoded due removal of the hands, there is no reason to believe that hand movements during the uncoded trials differed significantly from hand movements during the coded trials. Nevertheless, the smaller proportions of trials coded for the younger age levels should be kept in mind during the discussion of the hand movement data.

Visual Exploration

Only three different kinds of manual actions on the exemplar objects were each observed during at least 15% of trials in the Visual Exploration condition: (1) "major axis rotation" (rotating an object along the major axis of elongation: 77% inter-coder agreement on specific behaviors observed during individual trials); (2) "grasp both hands" (grasping with both hands: 86% inter-coder agreement); and (3) "moving object on table" (91% inter-coder agreement). Thus, children who had the opportunity to visually explore objects appeared to use their hands only to hold and occasionally turn the objects in the service of vision.

We also coded instances when children looked at but did not touch the object ("looked at, did not touch:" 98% inter-coder agreement). The frequencies of the four behaviors at each age level are shown in Table 4 Panel A. The data suggest that younger and older children differed in the frequencies with which they produced two of the three exploratory behaviors during visual exploration. We grouped younger children together to compare with older children on the number of trials in which they performed Major Axis Rotation and Looked, Did Not Touch. The 2 ½ - and 3-year-old children most often (81/192 trials), and significantly more often than older children (75/384 trials: $\chi^2(2, N = 576) = 33.04, p < .001$), held the objects and rotated them on their major axes while looking at them. The 4- to 5-year-old children most often (140/384 trials), and significantly more often than younger children (17/192 trials: $\chi^2(2, N = 576) = 50.34, p < .001$), visually examined the objects without touching them. Three-year-olds were more likely to grasp objects with both hands than any other age group, a finding with no clear significance. Children at the different age levels were equally likely to move objects around on the table top. Because the vast majority of children at all age levels in the Visual Exploration condition chose shape matches for the exemplar, their exploratory behaviors did not differentially predict different kinds of matches.

Haptic Exploration

Five manual actions quite different from the three that predominated during visual exploration were each observed during at least 15% of the trials in the Haptic Exploration condition. Those categories (and their inter-coder reliabilities) were (1) “sequential finger movements” (rotating the object around only with fingertips: 74% inter-coder agreement on specific behaviors observed during individual trials), (2) “fingers palpating” (fingers palpating/squeezing the object: 71% inter-coder agreement), (3) “static fingers” (fingers placed on object but not moving: 68% inter-coder agreement), (4) “hand grasping” (grasping the object with one hand: 82% inter-coder agreement), and (5) “hand press” (pressing the object between both hands with fingers outstretched: 76% inter-coder agreement). The proportions of coded trials in which the primary coder recorded that children at each age level produced each of these behaviors are shown in Table 4 Panel B.

It was possible to see and code hand movements during at least one trial and during an average of 5.79 trials ($SD = 2.31$) for 66 of the 72 children (98%). (The six children for whom no haptic exploratory hand movements could be coded were evenly divided among the age groups.) Proportions of shape choices and of each of the hand movements were calculated for each of the 66 children. Table 5 Panel A shows the simple correlations among children's ages, their proportions of shape matches, and the proportions of trials in which they produced each of the five hand movements. As is evident in the table, both the proportions of shape matches and the proportions of different hand movements were positively correlated with Age, as well as with one another. Thus, as children's age increased, so too did their tendency following haptic exploration of exemplars to visually choose test objects that matched the exemplar in shape; and so too did children's production of Sequential Finger Movements, Fingers Palpating, Static Fingers, and Hand Grasp increase with age.

In order to test for relations between specific hand movements and subsequent shape match choices, it was necessary to recalculate the correlations in Table 5 Panel A with the effect of Age partialled out. Table 5 Panel B shows those partial correlations. Two hand movements – Sequential Finger Movements and Hand Grasp – were each correlated with subsequent shape matches regardless of age. Static Fingers, perhaps not surprisingly, were negatively related to systematic shape matching. Occurrences of both Static Fingers and Fingers Palpating were negatively correlated with the Sequential Finger Movements that predicted shape matches. Together, these partial correlations indicate that active exploration of the objects through Sequential Finger Movements and Hand Grasp was associated with shape matching, but when children were not active in haptic exploration – when they laid unmoving fingers on the objects or aimlessly pressed the objects with their fingers – their subsequent matches were likely to be random.

The partial correlations indicate that the same children who produced more Sequential Finger Movements and/or Hand Grasps chose more shape matches for the exemplar object. However, simple correlations cannot tell us whether particular hand actions were directly related to the choice of a shape match within individual trials. To address this question, we used binary logistic regression analysis.

Binary logistic regression analysis is appropriate for the analysis and prediction of a dichotomous outcome (Peng, Lee, & Ingersoll, 2002). A logistic regression model was fitted to the data described above to test the relations between the dichotomous shape choice outcome (shape choice or non-shape choice) and the independent predictor variables – age, and the presence/absence of each hand movement pattern. Including age as one of the predictor variables in this analysis had a similar effect to partialling out the effect of age in a

linear regression analysis: it controlled for the possibility that age might co-vary with the other predictor variables and with the dependent measure.

In logistic regression analyses, a likelihood ratio chi-square test is analogous to an F test in analysis of variance, in that it indicates whether there are significant effects somewhere in the data. The follow-up analysis for the effect of each independent variable is Wald's Chi-square test¹. For the Visual Exploration condition, the likelihood ratio chi-square test indicated that the regression coefficient(s) of at least one of the predictor variables was not equal to zero, ($\chi^2 (5, N = 568) = 14.05, p < .05$). Table 6 summarizes the results of the logistic regression for all of the independent predictor variables in the Visual Exploration condition.

As can be seen from the table, a single variable, Age, accounted for the test statistic. The significant regression coefficient associated with Age indicated simply that with each increase in age level, the likelihood that children would make a visual shape match following visual exploration of the exemplar also increased. The analysis found no relation between specific hand movements during visual exploration of exemplar objects and subsequent shape-match choices within individual trials in the experiment.

In the Haptic Exploration condition, a significant likelihood ratio chi-square test again indicated that at least one variable's coefficient was not equal to zero, $\chi^2 (6, N = 383) = 125.62, p < .0001$. Table 7 summarizes the results of the logistic regression of "shape choice/non-shape choice" on Age and specific hand movements in the Haptic Exploration condition.

As shown in the table, the presence of Sequential Finger Movements and/or Hand Grasps during individual trials predicted that children would make shape choices in those same trials. The absence of Hand Press was also marginally negatively associated with shape choices. The odds that a child would make a shape choice rather than a non-shape choice on any trial given that she had produced Sequential Finger Movements during that trial was 7.48:1 (which is equal to $e^{2.01}$). Similarly, when Hand Grasp was produced during a given trial, a shape choice was 3.41 ($e^{1.22}$) times more likely than a non-shape choice.

In sum, the results of the logistic regression analysis indicate that the relations between the production of specific hand movements and subsequent shape-match choices revealed by simple correlations held true on a trial-by-trial basis. The fact that children's production of two specific hand movements (i.e., Sequential Finger Movements, and Hand Grasp) during haptic exploration predicted their subsequent choice of a same-shape match in the visual mode suggests first, that children were able to obtain shape information from those hand movements, and secondly, that they were able to use information obtained in haptics to complete a visual task.

However, children produced these potentially informative movements in only a small proportion of haptic exploration trials (see Table 4B). Thus, the children's inconsistent visual object matching following haptic exploration of exemplar objects appeared to result more from a failure to seek specific kinds of information through haptics than from either an

¹The logistic regression test estimates the effects of independent variables on the choice of a shape match over a non-shape-based match on a trial-by-trial basis. In logistic regression, the value of the regression coefficient (β) determines the direction of the relationship between shape choices and the independent predictor variables. The null hypothesis states that β equals zero (there is no relation), the test (i.e., the Wald chi-square) of statistical significance for individual predictors determines if values of β are statistically greater than/less than zero. Additionally, the regression provides odds ratios which can be used to infer how much more likely a shape choice would be on a trial given that a predictor variable was present (or absent) over a non-shape choice. Specifically, the odds are equal to e (the natural logarithm base) raised to the exponent of the slope β (e^β).

inability to obtain those kinds of information through hand movements, or an inability to transfer that information from one perceptual modality to the other.

Discussion

In this study, we asked why young children in previous experiments did not use perceptual information obtained from haptic exploration of objects to recognize those objects in the visual mode. Previous researchers had suggested that the representations built by children from haptic and visual input might be qualitatively different, either in containing information about different object features (e.g., Bushnell & Baxt, 1999), or in containing different amounts of information because of good visual perception and poor haptic perception (e.g., Milner & Bryant, 1970). Poor haptic perception would result in poor quality object representations regardless of whether the object features represented were the same as or different from those obtained from visual input.

Children in the present study did in general appear to have poor haptic perception, and the reason appeared to be that children younger than about 5 years of age did not systematically use their hands to explore objects that they could not see. In the rare instances in which young children did use their hands to actively explore out-of-sight objects, they seemed able to explore effectively. More specifically, the children produced two kinds of hand movements on out-of-sight objects (Sequential Finger Movements and Hand Grasps) that systematically led to successful visual identification of the objects based on those objects' shapes. Thus, even quite young children were able to obtain object shape information using their hands, and to use that information inter-modally in a visual object recognition task. They just did not do so very often. This failure to spontaneously use hand movements to gather perceptual information might well account for children's failures in inter-modal perceptual transfer tasks in previous research as well, but hand movement data from those studies are not available, so we cannot be sure.

Given that the children in our study did have haptic exploratory behaviors in their repertoires, movements that could have provided them with useable information for visual object recognition, why did the children not use those movements to succeed in our task? A possible answer is suggested by Lederman and Klatzky's (1987) original emphasis on the links between specific goals and particular haptic exploratory procedures. Lederman and Klatzky's (1987) taxonomy of "exploratory procedures" was based on their observations of hand movements performed by subjects who were explicitly instructed to use touch to gather information about particular object properties. Perhaps it is because the children in our task were given no clear goal that they failed to exercise their haptic exploratory abilities. Indirect support for this explanation comes from the experiment by Schwartz et al. (1999), in which preschool-aged children reportedly did produce adult-like EPs. In that study, the children were given an easily comprehended goal – to choose objects with the specific features that two different puppets liked. Perhaps this goal both motivated and guided children to use adult-like hand movements to gather perceptual information by touch, and to use that information to categorize objects on the basis of their texture or shape. Children in our study were not supplied with a comparable objective, and importantly, did not appear to spontaneously generate an objective for themselves.

We should note that the children in our study differed from those in Schwartz et al. (1999) in a second way: our participants showed no evidence of having adult-like EPs in their repertoires. The two hand actions linked to object recognition by shape in our study were produced by several children and thus were not idiosyncratic, but they did not resemble any of the movements described by Lederman and Klatzky (1987) or reported by Schwartz et al. (1999). We will need additional data to determine whether the movements we observed

are precursors to more adult-like EPs, or co-exist with adult-like EPs in the young child's repertoire. If the latter is true, the present data will be more evidence that EPs are strongly associated with specific exploratory goals.

Our results suggest that children's failures in haptics-to-vision intermodal transfer occur because the haptic input is not obtained in the first place. Thus, our findings do not bear directly on the issue of whether the object representations built from visual and haptic input are the same. However, developmental data are likely to be essential to resolving this issue, and the present results contain hints worth pursuing.

First: in many prior studies, correct inter-modal identification of objects has meant identification of the objects' shapes (e.g., Abravanel, 1970, 1972; Blank, et al., 1968; Milner & Bryant, 1970). In our experiment, the haptically-explored objects could have been represented and visually recognized by shape or texture or both. However, the only consistent feature used by children for inter-modal object recognition proved to be shape. There is already abundant evidence that shape similarity is the primary basis for object identification in purely visual tasks - at least when the objects have names (Imai, et al., 1994; Landau, et al., 1988). Children also recognize objects quite well when they first examine them in vision and then identify them by touch (Blank, et al., 1968; Bushnell & Baxt, 1999). Such findings suggest that visual exploration may highlight object shape, and may thus prepare children to seek shape information in a subsequent haptic test of object recognition.

Why is visual object exploration focused on shape? Multiple studies have established that children's early object name learning experience teaches them to visually attend to object shape more than to other object features when performing lexical categorization (e.g., Landau et al., 1988; Smith et al., 2002). This 'shape bias' in naming is usually measurable by the time children are about 2 years of age, and have about 50 nouns in their vocabularies (Gershkoff-Stowe & Smith, 2004). Such young children do not show a shape bias in categorizing objects with no names. The fact that naming directs children's visual attention to shape may eventually help to explain why children are so much better at identifying familiar than unfamiliar objects in haptics-to-vision transfer tests (e.g., Bushnell & Baxt, 1999). The familiar objects have familiar names, and those names may provide a link between identification of the familiar objects in the two modalities even if the perceptual information leading to object recognition is different in haptics and vision. For example, if a child identified a familiar object in haptics because the child recognized its texture, that identification would almost surely involve naming. The memory of the name could then facilitate identification of the same object in the visual task, even if in this modality the key perceptual property was shape. Obviously, nameless, unfamiliar objects could not be identified in this way.

It is theoretically possible that the shape bias in naming might generalize from visual to haptics, pushing children's attention to shape during manual exploration. It is also possible that early object name learning experience might bias children to attend to a different dimension - in particular, to texture - in haptic exploration. Such considerations led to our decision to name the unfamiliar objects in the present study. However, our results contain no indications that naming these unfamiliar objects systematically pushed the younger children's attention either to shape or to texture information in haptics, or served to link different object representations in the two modalities. Instead, the shape bias proved to be confined to the visual recognition of objects in children younger than 5, and we found no evidence that children up to this age had acquired any other perceptual bias in haptics.

Our findings suggest that one way to approach the question of whether the object representations children build from haptic and visual input are the same is to find a way to ensure that children obtain enough haptic perceptual input to build representations in the first place. To do this, it may be sufficient to provide young children with clear goals, like the goals that Lederman and Klatzky (1987) gave to adults. If clear goals fail to elicit exploratory hand movements, it might be possible to train young children to perform the hand movements that characterize adult searches for specific kinds of haptic information. If neither explicit goals nor trained hand movements lead to improved inter-modal object recognition, then we will be able to infer that the problem is not in the input but in the perceptual processing of the haptic information. The outcome of studies using either goals or training is not obvious: recall that 3–5- year- old children (most aged closer to 5) in Schwartz et al. (1999) produced the hand actions that adults use to search for shape information, then classified objects by texture. It remains to be seen whether this finding reflected the characteristics of a particular set of stimuli or more generally a point in the developmental trend for haptic object exploration and representation. Our results, in contrast to those of Schwartz et al., indicated that when younger children did do something systematic with their hands, they matched on – and therefore apparently attended to and represented – object shape. If shape turns out to dominate children's object representations in haptics as it seems to do in vision, this will suggest that the two kinds of representations are one.

Such an outcome would fit well with findings from neuroscientific studies of the cortical systems that subserve visual and haptic perceptual processing in adults. Imaging studies of adults indicate that visual and haptic sensory input is processed in separate neural pathways (Dijkerman & de Haan, 2007; Goodale & Milner, 1992; Milner & Goodale, 1993). Importantly, however, those pathways converge on the same neurons (James, Kim, & Fisher, 2007; James & Kim, 2010). This evidence suggests that mental representations of haptic and visual perceptual information may be multisensory representations available to both modalities. Our results hint that this convergence of the two kinds of inputs may begin with the convergence of object shape information in infancy or early childhood. The developmental trend will become clearer in the future with further research on the emergence of young children's haptic exploratory abilities.

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Figure 1.
Sample stimulus set: one exemplar object, and three test objects, each matching the exemplar on one dimension – shape, texture, or color – and differing from the exemplar and each other on the other two dimensions.

Figure 2.

Mean numbers of shape and texture matches (max = 8; chance = 2.67) made by children at each of 6 age levels and adults A) in the Haptic Exploration condition; and B) in the Visual Exploration condition.

Table 1

Results of one-sample t –tests comparing children’s numbers of shape-based matches at each age level in each condition to chance (2.67).

Age (years)	Visual Exploration condition			Haptic Exploration condition		
	t	df	p-value	t	df	p-value
2 1/2	3.69	11	0.004	1.65	11	0.126
3	4.05	11	0.002	−0.61	11	0.556
3 1/2	5.53	11	0.001	0.89	11	0.391
4	3.13	11	0.01	−0.01	11	0.994
4 1/2	4.69	11	0.001	1.34	11	0.207
5	6.71	11	0.001	3.14	11	0.009
Adults	15.33	19	0.001	10.01	19	0.001

Table 2

The number of children in each condition at each age level that made 5 or more matches on the same perceptual dimension, on shape, texture, or color.

Age (years)	Haptic Exploration			Visual Exploration		
	shape	texture	color	shape	texture	color
2 1/2	4	1	0	5	1	0
3	0	2	0	5	0	0
3 1/2	1	0	1	9	0	0
4	1	2	0	8	0	0
4 1/2	2	2	0	8	0	1
5	6	2	0	10	0	0
Adults	20	0	0	20	0	0

Numbers of trials in the Haptic Exploration condition at each age level that were coded for hand movement; could not be coded for hand movements because the child removed hands and object from the box (hands removed) or held hands and object within the box where they were not fully visible (hands not visible); or were not completed due to experimenter error. Total for each age level = 96 trials.

Table 3

	Age (years)				
	2 ½	3	3 ½	4	5
Hand Movements coded	44(46%)	53(55%)	58(60%)	71(74%)	82(85%)
Hands Removed	3	5	0	3	4
Hands not Visible	46	36	38	22	17
Experimenter Error	3	0	0	0	0

Table 4

A. Proportions of all trials visible for coding of hand movements in the Visual Exploration condition in which children performed each of 3 hand movements on the exemplar object, or looked at but did not touch that object. B. Proportions of all trials visible for coding of hand movements in the Haptic Exploration condition in which children performed each of 5 hand movements on the exemplar object. (Total trials in the Haptic Exploration condition visible for coding at each age level are shown in Table 1.)

A. Visual Exploration Condition:						
Age (years)	Major Axis Rotation	Grasp Both Hands	Moving Object on Table	Looked, did not touch		
2 ½	0.46	0.18	0.23	0.14		
3	0.39	0.35	0.19	0.03		
3 ½	0.25	0.14	0.24	0.29		
4	0.18	0.10	0.13	0.42		
4 ½	0.18	0.20	0.18	0.45		
5	0.27	0.08	0.16	0.30		

B. Haptic Exploration Condition:						
Age (years)	Sequential Finger Movements	Fingers Palpating	Static Fingers	Hand Grasping	Hand Press	
2 ½	0.05	0.80	0.15	0.45	0.28	
3	0.20	0.60	0.20	0.58	0.22	
3 ½	0.36	0.48	0.14	0.45	0.12	
4	0.31	0.68	0.05	0.40	0.22	
4 ½	0.49	0.27	0.07	0.4	0.11	
5	0.42	0.22	0.05	0.12	0.31	

Table 5

A. The simple correlations among children's ages, their proportions of shape matches, and the proportions of trials in which they produced each of the five hand movements. B. The simple correlations among children's proportions of shape matches, and the proportions of trials in which they produced each of the five movements with the effect of Age partialled out.

A.	Age	Proportion of Shape	Sequential Finger Movements	Fingers Palpating	Static Fingers	Hand Grasp	Hand Press
	1	.291*	.327**	(-.511)****	(-.258)*	(-.422)****	(-.064)
	Proportion of Shape	1	.423****	(-.29)*	(-.314)**	0.151	(-.141)
	Sequential Finger Movements		1	(-.691)****	(-.338)**	(-.025)	(-.208)
	Fingers Palpating			1	(-.227)	0.237	0.193
	Static Fingers				1	(-.133)	(-.265)*
	Hand Grasp					1	(-.174)
	Hand Press						1

B.	Proportion of Shape	Sequential Finger Movements	Fingers Palpating	Static Fingers	Hand Grasp	Hand Press
	1	0.362**	(-.172)	(-.257)*	.315**	(-.129)
	Proportion of Shape	1	(-.557)****	(-.278)*	0.131	(-.198)
	Sequential Finger Movements		1	(-.431)****	0.027	0.187
	Fingers Palpating			1	(-.275)*	(-.292)*
	Static Fingers				1	(-.222)*
	Hand Grasp					1
	Hand Press					

Note.

* p<.05

** p<.01

*** p<.001

**** p<.0001

Table 6

Results of the logistic regression for all of the independent predictor variables in the Visual Exploration condition.

Predictor	β	S.E. β	Wald's χ^2	df	p - value	odds ratio
constant	(-1.063)	0.44	5.833	1	0.016	0.345
Age	0.032	0.009	12.696	1	0.000	1.032
Major Axis Rotation	0.207	0.232	0.793	1	0.373	1.23
Both Hands Grasping	0.313	0.268	1.361	1	0.243	1.368
Moving on Table	(-0.174)	0.24	0.528	1	0.468	0.84
Only Looked	(-0.065)	0.244	0.07	1	0.791	0.937

Table 7

Results of the logistic regression for all the independent predictor variables in the Haptic Exploration condition.

Predictor	β	S.E. β	Wald's χ^2	df	p - value	odds ratio
constant	(-2.01)	0.92	4.73	1	0.03	1.35
Age	0.025	0.015	2.73	1	0.098	1.026
Sequential Finger Movements	2.01	0.363	30.73	1	0.000	7.48
Fingers Palpating	(-2.92)	0.345	0.715	1	0.398	0.747
Static Fingers	(-1.01)	0.562	3.22	1	0.073	0.365
Hand Grasp	1.22	0.293	17.49	1	0.000	3.41
Hand Press	(-658)	0.338	3.79	1	0.052	0.518