ACADEMIC PRESS
J. Experimental Child Psychology 82 (2002) 341–366
Journal of Experimental Child Psychology
www.academicpress.com

Knowledge is not everything: Analysis of children's performance on a haptic comparison task☆

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Received 16 August 2001; revised 9 May 2002

Abstract

The relative effects of developmental level and domain-specific knowledge on children's ability to identify and make similarity decisions about object concepts based only on haptic (touch) information were investigated. Children aged 4–9 years with varying levels of dinosaur knowledge completed a cross-comparison task in which they haptically explored pairs of familiar (dinosaur) and unfamiliar (sea creature) models that varied in terms of their degree of differentiability. Older children explored models more exhaustively, found more differentiating features and consequently made fewer errors than younger children did. High knowledge enabled children to identify models correctly, but was also associated with the use of a hypothesis testing strategy, which led children to make greater numbers of "miss" errors on the cross-comparison task. Performance in the control domain illustrated that the hypothesis testing strategy was specific to the high knowledge domain. Potential explanations for the role of knowledge and development in haptic exploration are considered. © 2002 Elsevier Science (USA). All rights reserved.

☆ We wish to thank the children and parents who participated in this study, Richard Foran for his constructive prowess, and Mudge Morris for her expertise on dinosaurs. Shannon Lazar and Rhonda Meyer assisted with home visits and data collection.

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PII: S0022-0965(02)00100-5

Most children and adults recognize and identify objects based on what they look like. Yet for some children (and for all children in particular situations), objects are explored through other sensory modalities. Stripping away visual information from familiar stimuli can force human categorizers to rely extensively on previously acquired knowledge when asked to make identifications based on sound or touch. Indeed, Lederman and Klatzky (1987, 1990) have argued that haptic (i.e., manual) exploratory procedures can serve as a window into our representations in memory. Because most everyday instances of object identification occur through visual recognition of features, it is not surprising that researchers have focused almost exclusively on processes related to categorization of two-dimensional picture stimuli (Deák & Bauer, 1996; Kintsch, 1970). Although objects can be recognized through manual exploration based exclusively on detection of features such as shape, weight, and texture, we know relatively little about processes related to object categorization within nonvisual modalities, particularly at the subordinate level. The present study uses the haptic modality to explore how domain-specific knowledge and developmental level interact to affect children's manual comparisons of three-dimensional objects.

Between the ages of 5 and 9 years, both haptic and visual processing speed seem to increase (Enns & Girgus, 1985; Hatwell, Orliaguet, & Brouty, 1990). Changes in the haptic modality can be partially explained by increases in the quality of exploratory strategies (Hatwell et al., 1990). Between 7 and 9 years, children tend to concentrate their exploratory actions on haptic information that is relevant to the task of identification while ignoring irrelevant features (e.g., contacting only aspects of objects that are required to make a judgment). In fact, even 5-year-olds' haptic recognition of highly familiar items is remarkably good (Bushnell & Baxt, 1999). However, children younger than 7 years tend to be less focused in their manual search strategies, exploring irrelevant haptic stimuli more than older children and adults do. Young children (5-year-olds) also are less good at part-similarity tasks in which they are asked to determine whether two aspects of two distinct haptic arrays are similar or not, when the arrays are either the same or different along one dimension (Berger & Hatwell, 1995). For example, Berger and Hatwell gave children an array of blocks that differed in density. Children explored the first "target" block and then were asked to choose the member of the array that "goes better with it." In the present study, we used a similar type of comparison task but we limited the comparative judgments to pairs of three-dimensional models. Children were simply asked to judge whether the two models were identical or not. Based on Berger and Hatwell's results, we would expect younger children to have difficulties focusing on specific parts of the models when drawing comparisons. We also were interested in whether high levels of knowledge might mitigate these developmental patterns. Below, we first review research related to the effects of domain-specific knowledge on categorization.

We then discuss the impact of knowledge on strategic aspects of object exploration.

Effects of knowledge on categorization

Domain-specific knowledge clearly exerts powerful effects on children's memory, problem solving, and categorization performance (Bjorklund, 2000; Chi, 1978; Ornstein, Baker-Ward, & Naus, 1988). It has been shown repeatedly that when children possess large amounts of knowledge about a domain, they process information from that domain very rapidly (e.g., Gaultney, Bjorklund, & Schneider, 1992). Less research has been directed at the effects of high levels of knowledge on object categorization, particularly in object domains such as dinosaurs.

Categorization of objects at the subordinate level is generally more difficult than at the basic level due to the high degree of similarity among coordinate subordinate category exemplars (Mervis & Crisafi, 1982; Rosch, 1978). For example, all dogs share sets of physical features and behave similarly relative to basic level contrasts among dogs, cats, and birds. However, research has shown that high levels of knowledge lead individuals to detect and selectively attend to previously unnoticed features associated with subordinate level categories and their correlated functions (Johnson & Eilers, 1998; Johnson & Mervis, 1997, 1998; Tanaka & Taylor, 1991). Thus individuals with high levels of knowledge are superior at object identification due to their advantage at selectively attending to subtle perceptual features that gain salience through experience.

Lederman and Klatzky (1990), in a haptic exploration task, found that object identification at the basic and subordinate levels was related to knowledge of naturally co-occurring properties in a domain. Adults freely explored objects (like frying pans or watches) through general "grasp and lift" routines followed by knowledge-driven movements of the hand that were more precise and fine-tuned. Lederman and Klatzky maintained that subordinate category identifications were based on most diagnostic attributes (MDAs)—those attributes of objects that provided the highest amount of diagnostic information. They found participants' knowledge of MDAs helped to guide specialized haptic exploration of subordinate exemplars. For example, when participants were asked to differentiate between two kinds of frying pan (one cast iron, the other not), participants generally attended to weight. In this case, weight was considered the MDA for subordinate category membership determination and makes apparent the category knowledge necessary to differentiate two subordinate members.

In the present study, we selected the domain of dinosaurs to investigate the effects of heightened knowledge on children's haptic explorations during a comparison task. Previous research on other biological object domains has indicated that modified part features such as beak shape and toe configuration are weighted heavily by experts making visually based categorizations at both the subordinate and sub-subordinate levels (Biederman & Schiffrar, 1987; Johnson & Mervis, 1997, 1998; Tanaka & Taylor, 1991). We suspected that high levels of dinosaur knowledge would prompt children to explore the modified part features that co-vary with membership in a particular dinosaurs species. That is, modified part features (such as shape of mouth and number of claws) should be recruited by children with high knowledge as MDAs for subordinate identification within the domain of dinosaurs.

Impact of knowledge on strategy use

Previous studies have demonstrated that children both learn and use strategies more effectively within a more familiar domain (Bjorklund & Buchanan, 1989). Age-related changes in domain knowledge have been found to be related to children's tendency to use strategies, the likelihood that children will benefit from strategies, the degree to which strategy training is successful, and the likelihood that such strategy use will transfer outside of the domain within which it has been trained (Bjorklund, Muir-Broaddus, & Schneider, 1990; Corsale & Ornstein, 1980; Rabinowitz, 1984, 1988). Given this background, Alexander and Judy (1988) argue that "a foundation of domain-specific knowledge seems requisite to the efficient and effective utilization of strategic knowledge" (p. 384). They then proceed to build a case that domain-specific knowledge, as it is proceduralized, gives rise to strategies that recruit domain knowledge (Anderson, Greeno, Kline, & Neves, 1981; Chi, 1981). Successful performance on a given task requires knowledge about the domain, availability of general strategies, and typically some higher-level planning or metacognitive-type strategies for monitoring task completion (i.e., McCutchen, 1986). Children who possess low levels of knowledge may lack prerequisite skills that would otherwise enable them to benefit from general strategy use (Alexander, Pate, Kulikowich, Farrell, & Wright, 1989). In sum, being an effective strategy user depends on a child possessing a requisite amount of domain knowledge.

As noted above, knowledge likely affects the types of planning and monitoring children execute when performing a particular task, including the development of leading hypotheses and investigation plans. During this planning and monitoring, children's performance often is influenced by their misconceptions concerning the domain (e.g., Hatano & Inagaki, 1996; Massey & Gelman, 1988; Vosniadou, 1991). Furthermore, many children (especially those in the elementary grades) fail to separate and control variables when testing their hypotheses. Children look for evidence to confirm their initial hypotheses and ignore evidence (or fail to seek out evidence) that would disconfirm their hypotheses, leading to a confirmation bias (Kuhn, Garcia-Mila, Zohar, & Andersen, 1995; Schauble, 1990).

High levels of knowledge theoretically should improve children's hypothesis testing skills by providing a broader corpus of data from which to generate predictions. Alternatively, the availability of domain-specific knowledge may exacerbate children's tendency to seek only confirmatory evidence, leading young experts to make decisions too rapidly on the basis of incomplete data. According to this scenario, children with less domain knowledge may actually be at an advantage in terms of being forced to rely exclusively on "bottom-up" (i.e., perceptually driven) processing.

Goals of the present study

Previous research on haptic exploration has focused on the means by which individuals identify specific objects through particular types of touch patterns (i.e., Hatwell et al., 1990; Lederman & Klatzky, 1987, 1990). The present study is the first investigation to quasi-experimentally compare how different levels of domain-relevant knowledge impact older and younger children's haptic comparison strategies. We used a task in which multiple levels of haptic exploration could occur. Children were asked to identify specific dinosaurs. However, this identification task was embedded within the more general context of determining whether pairs of dinosaur models were identical or not (hereafter referred to as the *cross-comparison task*). Identification of the first dinosaur within the pair would depend heavily on detecting modified part features that predicted subordinate category membership. Cross-dinosaur comparisons, however, would depend on the child's ability either to focus explorations on MDAs when making comparisons across models, or to exhaustively search both models to detect subtle differences, detecting both MDAs and features not pertinent to decision making with the domain.

Two alternative influences of knowledge on haptic exploration strategies seem possible. First, high levels of domain knowledge may enhance performance on the cross-comparison task by enabling children to hone in on features that potentially would be relevant to the differentiation of subordinate kinds. Alternatively, this heightened knowledge of differentiating features could actually impede children's performance by enhancing the likelihood that they demonstrate a confirmatory bias when making comparisons (e.g., Schauble, 1990). For example, a child with relatively high levels of dinosaur knowledge may briefly explore the first member of the pair and hypothesize (based on feeling a crest on the head) that the dinosaur's identity is a parasaurolophus. This hypothesis could lead the child to immediately search for a head crest on the second dinosaur and perhaps prematurely decide that the dinosaurs are the same, when indeed the latter was a Lambeosaurus (which has a similar crest). A child who lacked knowledge of crested heads would potentially execute a more data-driven search that might actually be more exhaustive and accurate than that of a child whose search is guided by domain-relevant schemata. To verify that differential response patterns across groups were attributable to differences in relative levels of dinosaur knowledge (rather than to domain-general strategies), all children in the present study completed equal numbers of trials involving a less familiar control domain (sea creatures).

Method

Participants

Participants included 36 children (mean age 6;9, range 4;9–9;8) who expressed an interest in dinosaurs. Parents of children responded to an advertisement in an area newspaper or were referred by respondents. There were 32 boys and 4 girls. [1] One boy was later dropped due to an equipment problem. Children were assigned to two age groups (based on a median split 6;8) with the expectation that performance would improve with age as children's exploration strategies became more effective (Berger & Hatwell, 1995). Assignment of children to knowledge groups was based on both parental ratings of the child's knowledge and the child's actual performance on a test of dinosaur knowledge, as described in the Results section. In addition, 10 adults from an introductory psychology course participated in a similarity-rating task.

Materials

Materials included 12 realistic three-dimensional dinosaur models and 12 comparable models of whales and sharks mounted onto 2-in. (5.08 cm) dowels and attached to individual plywood shelves. Models from both domains were purchased from the same commercially available museum series and size was presented to scale to the extent possible. Lines were painted on the models to demarcate body part sections (e.g., head, neck, tail, and legs) to facilitate later coding. Shelves fit interchangeably into slots within a larger wooden frame positioned 4 ft (1.2 m) above the floor with twelve 8 × 11 in. (20.32 × 27.94 cm) openings arranged into two rows of six, as illustrated in

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[1] Although we intended to test comparable proportions of boys and girls across low and high knowledge groups, more boys than girls were interested in dinosaurs and responded to our advertisements. This is similar to other cross-sectional analyses (e.g., Johnson & Eilers, 1998). In an ongoing prospective analysis of factors that influence the development of expertise (Johnson, Alexander, Spencer, & Kohler, 2001; Johnson, Alexander, Spencer, & Neitzel, 2002), we have found that boys are four to five times more likely than girls to manifest this pattern of focused interests on domains characterized by declarative conceptual knowledge (e.g., trucks, bugs, horses, and dinosaurs).

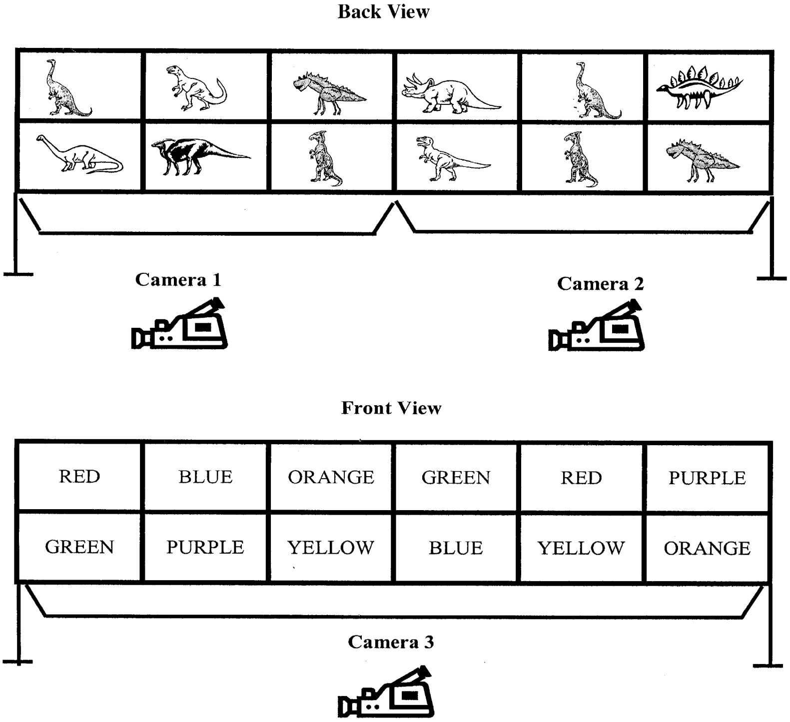

Fig. 1. Schematic diagram of cross-comparison task apparatus.

Fig. 1. Each shelf was hidden from view by black vinyl through which a 6 in. (15.24 cm) vertical slit had been cut to facilitate passage of the child's dominant hand. The windows were covered by 9 × 12 in. (22.86 × 30.48 cm) colored felt squares (two each of six different colors). Each matching pair of felt squares marked a pair of category exemplars that the child was to judge either as "the same" or "not the same." Felt squares were affixed with Velcro to enable the creation of two random configurations of the six pairs. A smaller version of the haptic exploration apparatus (with only 4 windows) was used to train children to perform the cross-comparison task. Finally, 20 realistic color pictures of dinosaurs were individually depicted on laminated 4 × 6 in. (10.16 × 15.24 cm) cards for use in the assessment of children's dinosaur knowledge. This set included all species included in a similar assessment developed by Gobbo and Chi (1986).

Procedure

Adults were asked to complete a similarity-rating task with nine dinosaur and sea creature models to create three *same pairs* and three *different pairs* within each domain that varied in terms of the relative distinctiveness of their features. Adults were asked to rate each of the 36 possible pairs of exemplars within each of the two domains on a 7-point scale (1 = very different; 7 = very similar). Pairs were presented in a random order, blocked by domain, with domain order counterbalanced across raters. Ratings for each pair were then averaged across participants and the pair with the highest mean similarity rating was used as the low differentiability (LD) *different pair*. The pair with the lowest mean similarity rating was used as the high differentiability (HD) *different pair*. The pair whose mean rating most closely approximated the median of the averaged ratings was selected as the moderate differentiability (MD) *different pair*. The three remaining exemplars (one possessing highly salient features, one possessing moderately salient features, and one possessing minimally salient features, again based on adult ratings) were used for the three *same pairs*. Each of these pairs featured two identical models representing the same species. Table 1 presents the three identical pairs and three non-identical pairs used across the two domains.

Data collection was divided into two sessions to maximize children's levels of motivation and attention, and to minimize attrition due to the lengthy assessments necessary to assign children to knowledge groups. All testing for Session 1 took place in a laboratory located on a major university campus. All but three children were tested in their homes during the follow-up session; the remaining children were tested in the laboratory. Each session took approximately 30 min. An average of 14.8 days (range 10–24 days) separated the two sessions. Both sessions were audiotaped and haptic explorations during Session 1 were videotaped. While children were participating, a parent was asked to complete a brief questionnaire on which the child's relative levels of interest in and knowledge about dinosaurs and the control domain of sea creatures were rated along an 8-point scale (1 = knows nothing; 3 = average level of knowledge compared to children this age; 5 = a good deal more knowledge than average; 8 = knows just about all there is to know).

Table 1
Stimulus exemplars represented across same and different pairs

Domain	Pair type	High differentiability (HD)	Moderate differentiability (MD)	Low differentiability (LD)
Dinosaur	Same	Spinosaurus–Spinosaurus	Euoplocephalus–Euoplocephalus	Iguanodon–Iguanodon
	Different	Stegosaurus–Parasaurolophus	Triceratops–Apatosaurus	Tyrannosaurus–Allosaurus
Sea creature	Same	Hammerhead–Hammerhead	Beluga–Beluga	Sperm Whale–Sperm Whale
	Different	Sawfish–Gray Whale	Whale Shark–Great White Shark	Dolphin–Orca

Session 1. Children first completed a training trial involving familiar mammals. A smaller version of the test apparatus with four windows enabled children to explore two pairs of mammals: One identical (two dogs), and one non-identical (gorilla–tiger). Mammal models were concealed by black vinyl through which the child's hand could pass. Same-colored felt squares hung over the vinyl to denote the windows that constituted a pair (green squares were hung over the members of one pair and blue squares were hung over the members of the other pair). The experimenter introduced the game by saying, "In this game, I'd like you to see if you can figure out whether the things behind these two green windows are exactly the same, or whether they are different." The child was then told that behind the green windows were models of animals and they were encouraged to insert their hand into the slot and to feel the animals. After both green windows had been checked, the child was asked, "Were those two animals exactly the same or were they different?" Children recorded their response by placing a sticker on a record sheet. The child was then asked to try to identify what animals had been felt and then the vinyl was removed to provide feedback on his or her response. The second pair of windows was presented in a similar manner. The order in which the identical and non-identical training pairs were presented was counterbalanced across children.

Following the practice trials, children were randomly assigned to receive the familiar (dinosaurs) or less familiar (sea creatures) domain first and instructions for the test trials were given. Children were told that all 12 windows of the apparatus concealed dinosaur or sea creature models, and that some of the pairs were exactly the same and some of the pairs were different. Children were reminded that they were to judge whether the two animals behind the same color windows were the same or not the same. The experimenter explained that if the animals were exactly the same, they would be just like the dogs during the practice trial—identical models facing in the exact same direction. Children were instructed to use only their dominant hand to explore the models, and to explore each of the models separately. However, children were permitted to go back and "recheck" previously explored models prior to giving a judgment of "same" or "not the same." If the child chose two windows that were not the same color they were asked to begin again and reminded of the directions. No time limits were imposed. After the child had made a final decision for each pair they were invited to place a sticker on their record sheet and then were asked to identify each pair member. Feedback was not provided on children's responses, but they were allowed to view the rear side of the apparatus after all trials within a domain were completed. Children were videotaped from both sides of the apparatus throughout the duration of the task. One camera was placed so that it recorded the child's explorations from the side of the apparatus displaying the colored felt squares. The second and third cameras were placed on the other side of the apparatus so that they each recorded the child's haptic exploration of the models within 6 of the 12 windows, as depicted in Fig. 1. Two different position orders were created for both the placement of the model shelves and placement of the colored felt squares and these were counterbalanced both within and across domains.

Session 2. Knowledge of dinosaur names and attributes were assessed separately. Both assessments involved the 20 dinosaur stimulus pictures; name and attribute knowledge were assessed using different (randomly ordered) stacks of stimulus cards. During the name assessment, children were told that they would be shown a series of dinosaurs and that they should state the names of those dinosaurs that they knew. Children were told that some of the names of the dinosaurs were quite tricky and assured that it was fine to say, “I don’t know.” During the attribute assessment, children were provided with the correct names of the 20 dinosaurs. In reference to each, children were asked to state everything that they knew about that dinosaur. Again, children were reminded to say “I don’t know” if they did not know anything about a particular dinosaur. Children’s responses were audiotaped and subsequently transcribed. Finally, the Kaufman Brief Intelligence Test (K-BIT; Kaufman & Kaufman, 1990) was administered to determine whether domain-specific knowledge covaried with intelligence. This test provides both verbal and nonverbal subscale IQ scores, as well as a composite score. Correlations between .58 and .80 with the WISC-R indicate that the K-BIT composite score is a reasonably valid measure of general intelligence.

Results

The results are divided into three sections. We first discuss the procedure used to quantify children’s levels of domain-specific knowledge. We then present results concerning children’s overall performance on both the cross-comparison task and the identification task for each of the two domains. Finally, we consider interrelations between the types of haptic exploration strategies recruited and children’s levels of knowledge, age, and overall performance on the cross-comparison and identification tasks. Preliminary analyses indicated that there were no significant main effects or interaction effects involving position order or domain order for any of the dependent variable measures. Therefore, we collapsed across orders throughout all subsequent analyses.

Quantification of dinosaur knowledge levels

Each child’s relative level of knowledge about dinosaurs was determined based on both parental ratings of the child’s knowledge level, and the child’s performance on the name and attribute production task involving the standard set of 20 dinosaur pictures. In the name production task, children received one point for generating a correct species name (apatosaurus), family/suborder name (sauropod), or appropriate nickname ("long-neck" for apatosaurus), for each of the 20 dinosaurs. All name productions were coded by two independent raters with 98.9% reliability. The few discrepancies were resolved through discussion. In the attribute production task, children were given one point for each correct proposition produced. Attributes were not counted if they described an ambiguous or transitory feature (e.g., "It's red.") or if all dinosaurs possessed the feature (e.g., "It has a tail."). Attribute productions were scored by the first author. A second coder scored a randomly drawn 15% of the transcripts with 93% agreement. Again, disagreements were resolved through discussion. Both the name and attribute scores were then standardized and combined with the parent's rating of dinosaur knowledge to yield a domain knowledge score using a formula adopted by Johnson and Eilers (1998, NAME + ATTRIBUTE + (PARENTAL RATING/2)). The resulting domain knowledge scores ranged from −2.99 to 3.86 and were used in some analyses to divide children into high and low knowledge groups based on a median split. [2] However, it is important to reiterate that even children with "low" knowledge were recruited into the study based on their high level of interest in dinosaurs and they were reasonably familiar with the dimensions along which features within the domain could vary. Characteristics of children assigned to the high and low knowledge groups are presented in Table 2. As expected, children could name significantly fewer sea creatures than dinosaurs (related sample $t(34) = 2.81$, $p < .01$) and their parents rated them as significantly less knowledgeable (related $t(34) = 4.22$, $p < .001$) and less interested (related $t(34) = 5.3$, $p < .001$) about sea creatures than about dinosaurs.

Although there was a significant correlation between knowledge scores and K-BIT (IQ) scores, IQ did not meet the criteria for a good covariate in any analysis because it was not significantly correlated with any dependent variable (Kirk, 1995). In contrast, knowledge was significantly related to dependent measures pertaining to ability to name dinosaurs and strategy choice, as elaborated below. Thus, our analytic strategy was to test our

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[2] We have generally collected parents' (or peers') subjective ratings of knowledge levels along with direct tests of knowledge in all of our studies of expertise, based on the notion that expertise itself is a relative state. Although a "pure" measure of knowledge without the dimension of social comparison might be more appropriate in situations where parents have few opportunities to draw comparisons across children, we have found that parents generally are quite sensitive to their child's relative levels of knowledge and interest. In this study, the Spearman rank order correlation between children's knowledge scores calculated with and without parental ratings was .97. If parent ratings are left out of the knowledge index, two children currently in the low knowledge group move to the high knowledge group, and two children currently in the high knowledge group move to the low knowledge group (all four children were clustered close to the median knowledge score). Given the similarities in the rankings, we chose to retain parental ratings in our domain knowledge score to preserve the sociorelational aspect of expertise.

Table 2
Participant characteristics across knowledge groups

Characteristic	Low knowledge	High knowledge	$t(33)$
Age (in months)			
M	78.64	84.11	.94
SD	17.46	16.78	
IQ			
M	110.17	120.89	3.23*
SD	10.32	9.27	
Dinosaur names known (out of 20)			
M	5.29	12.06	6.28**
SD	2.87	3.45	
Dinosaur attributes produced (across set of 20 dinosaurs)			
M	7.06	26.33	5.20**
SD	6.25	14.02	
Parent rating of dinosaur knowledge (out of 8)			
M	3.68	5.65	5.39**
SD	1.19	0.98	

* $p < .05$.
** $p < .01$.

predictions through factorial analysis of variance and bivariate correlations, rather than analysis of covariance and partial correlations, due to the lack of a relationship between children's task performance and K-BIT (IQ) scores.

Overall performance on the cross-comparison and identification tasks

Correct trials on the cross-comparison task. The knowledge and age factors were crossed to produce four groups; young high knowledge (young HK; $N = 8$), young low knowledge (young LK; $N = 9$), older HK ($N = 10$), and older LK ($N = 8$). The number of trials for which correct (same vs. different) judgments were made was noted for each child and compared across groups and domains in a mixed 2 (age) × 2 (knowledge) × 2 (domain: Dinosaurs vs. control) × 3 (level of differentiability: LD, MD, and HD) ANOVA with both domain and level of differentiability as within-subject factors. Significant main effects of age $F(1,31) = 15.50$, $p < .001$, level of differentiability $F(2,62) = 19.30$, $p < .001$, and domain $F(1,31) = 7.34$, $p < .01$ emerged. There were no significant interactions. Overall, children performed better in the dinosaur than the control domain (dinosaur $M = 1.60$, $SD = .06$; sea creature $M = 1.42$, $SD = .06$; out of two cross-comparisons at each level of differentiability). Older children solved a greater number of cross-comparison trials correctly than younger children did ($M = 1.70$, $SD = .07$ for older children and $M = 1.32$, $SD = .07$ for younger children). Bonferroni post-hoc tests revealed that LD trials

($M = 1.21$, $SD = .07$) were more difficult than MD trials ($M = 1.55$, $SD = .08$), which were in turn more difficult than HD trials ($M = 1.76$, $SD = .06$; all $ps < .05$). Although children did find the dinosaur domain cross-comparisons easier, surprisingly, dinosaur knowledge level did not affect children's overall performance on the cross-comparison task. Regardless of children's specific level of knowledge about dinosaurs, older children tended to be at an advantage. Dinosaur knowledge exerted more subtle effects on the types of explorations that children made and even impeded overall performance in certain contexts, as described below.

Identification of models based on haptic exploration. Following their determination of whether a particular pair contained models that were the same or not the same, children were asked, "What kind of [dinosaur/sea creature] is it?" The names children generated in response to this question were coded for accuracy and level of specificity. Children were given credit for a correct identification if they named the model with the appropriate species or genus-level name, or with a nickname that uniquely identified the model at the same level (e.g., "bonehead" for the pachycephalosaurus, a dinosaur with bony skull plates presumably used for head-butting). Incorrect identifications were divided into reasonable versus unreasonable names. Reasonable names included nicknames referring to the taxonomic family to which the exemplar depicted by the model belonged (e.g., meat-eater), as well as names or nicknames referring to a species or genus included within the same taxonomic family as the modeled exemplar (e.g., "diplodocus" for the apatosaurus; both are included within the family of sauropods). Names referring to exemplars with very similar morphological characteristics also were considered reasonable (e.g., "iguanodon" for tyrannosaurus rex; both exemplars are bipedal with relatively short "arms," although they come from different taxonomic families). All other incorrect names were considered unreasonable. There were a total of nine possible names in each domain a child could generate (one for each unique model used). A second author coded 20% of the names with 91% agreement.

A 2 (age) × 2 (knowledge) × 2 (domain) mixed model ANOVA conducted on the number of correct names produced revealed a significant main effect of age, $F(1,31) = 7.30$, $p < .05$. The significant main effects of knowledge, $F(1,31) = 13.40$, $p < .01$ and domain, $F(1,31) = 15.46$, $p < .01$ were tempered by a significant knowledge by domain interaction, $F(1,31) = 8.01$, $p < .01$. As Fig. 2 illustrates, children with high knowledge generated significantly more correct names for dinosaurs than for sea creatures. However, children with low knowledge generated comparable numbers of correct identifications across the two domains. Table 3 presents an item analysis for the names produced by knowledge level in both domains. It is clear that domain-specific knowledge was recruited by children with high knowledge and used to make significantly greater numbers of correct identifications, even in the absence of visual perceptual information. In addition, incorrect

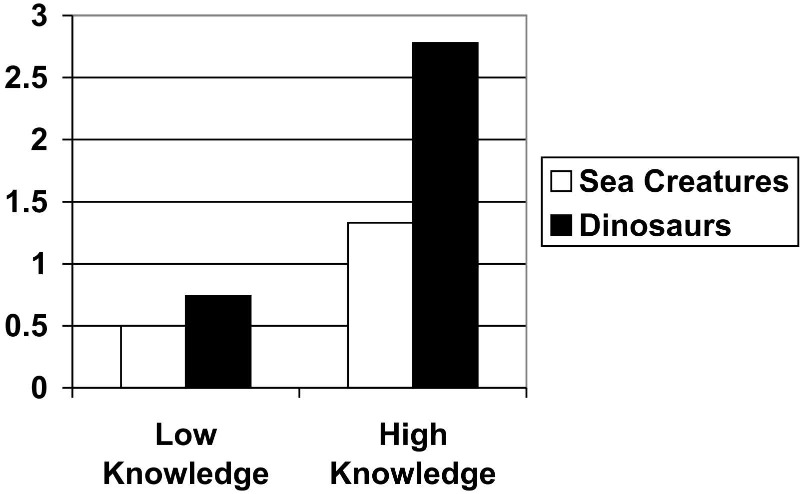

Fig. 2. Number of models identified correctly (out of 9) across domains.

reasonable names were generally at a more specific level of identification for the dinosaur than sea creature domain.

It is important to note that the generation of a reasonable name for the first dinosaur does not mean that it will be useful to aid identification of the second dinosaur in this task. Names that are too general (e.g., “meat-eater”) or names that are specific (e.g., “t-rex”), but that do not represent a full understanding of how tyrannosaurus rex differs from other meat-eating dinosaurs will be an inadequate guide in the present cross-comparison task and may contribute to confirmatory bias.

Interrelations among child characteristics, haptic exploration strategies, and performance on the cross-comparison and identification tasks

Our objective was to determine the relative contributions of children’s developmental level and level of domain-specific knowledge to strategic aspects of performance on the cross-comparison task. We first consider the degree to which children focused their explorations on MDAs (Lederman & Klatzky, 1990) when examining the first member of each pair. We then consider children’s overall pattern of exploration across both members of each pair, and the degree to which those patterns of exploration were related to knowledge, developmental level, and to overall performance in the two domains.

Exploration of most diagnostic attributes. We predicted that knowledge would impact the degree to which children concentrated their explorations on MDAs only when exploring the first member of each pair. We reasoned that the features detected on the first model would potentially serve as a

Table 3
Mean number of correct and incorrect-reasonable names generated across domains by model

Domain	Exemplar	No. of names generated	Proportion of correct identifications		Proportion of incorrect-reasonable		Most frequent incorrect-reasonable name
			HK	LK	HK	LK	
Dinosaur	Spinosaurus–Spinosaurus	8	25	0	63	12	Dimetrodon
	Euoplocephalus–Euoplocephalus	16	81	19	0	0	
	Iguanadon–Iguanadon	6	33	0	50	12	Duckbill
	Stegosaurus–Parasaurolophus	20	65	35	0	0	
		4	75	0	25	0	Duckbill
	Triceratops–Apatosaurus	11	73	17	0	0	
		9	33	0	66	0	Brachiosaurus
	Tyrannosaurus–Allosaurus	10	70	10	10	10	Meat-eater
		4	50	0	25	25	Meat-eater
Sea Creature	Hammerhead–Hammerhead	11	73	18	9	0	Shark
	Beluga–Beluga	9	22	0	56	22	Whale
	Sperm Whale–Sperm Whale	10	10	0	60	30	Whale
	Sawfish–Gray Whale	12	50	8	33	17	Sawshark
		2	50	0	50	0	Whale
	Whale Shark–Great White Shark	3	66	0	33	0	
		10	40	10	30	20	Shark
	Dolphin–Orca	14	36	23	31	15	Whale
		12	17	0	42	42	Dolphin

schematic guide for exploration of the second member of each pair, particularly for "different" judgment pairs. Analyses of MDA exploration were therefore based only on the first model explored within each pair. A parallel analysis of MDAs was not conducted for the domain of sea creatures because of concerns that the MDAs across the sea creature and dinosaur domains were not equivalent. In particular, whales and sharks tend to share the same overall body shape and vary only in terms of extremely subtle facets of fin shape and orientation (or in terms of visual properties such as color). Dinosaurs differed on more dimensions than sea creatures did, and features tended to vary considerably within those dimensions. Thus, analyses of MDA detection were constrained to the domain of dinosaurs.

We operationalized MDAs based on an a priori analysis of 10 recently published children's books that together contained descriptions of 34 different types of dinosaurs. We tabulated the frequency of occurrence of specific modified parts (e.g., long neck) or conjunctions of modified parts (e.g., sharp teeth + three claws) across the set of 34 types. Modified parts or conjunctions of modified parts that occurred only in relation to taxonomic families of dinosaurs were considered distinctive and were identified as MDAs. [3] These features were sufficient for enabling family-level (and in some cases species level) identifications if they were detected during haptic exploration (a list of MDAs specific to the nine models in the task is included in the Appendix).

Explorations of the models that comprised each pair were coded from videotapes using frame-by-frame analysis. Each part of the model touched (determined by lines painted directly on the models) was considered a separate haptic event. During coding, the total time spent exploring each model was calculated using a digital timer. The 35 children generated a total of 2224 discrete haptic events in the dinosaur domain. There were 17 instances of mistaken haptic events in which the wrong model was explored, and these were excluded from later analyses. There were 168 dinosaur "re-explorations" in which the child went back and explored again a model that had already been examined. These were included in the analyses of strategy use (described below), but not MDA identification, as MDA exploration was only considered in reference to the first model explored within each pair.

Coding was completed using a 4-step process aimed at ensuring acceptable reliability. Twenty percent of all eligible haptic events were coded together by the first and third authors. After discussions, each rater then independently rated another 20% of the haptic events with 79% reliability. Disagreements were discussed and resolved through consensus among the three authors. Each rater next coded an additional 20% of the haptic events

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[3] Lederman and Klatzky (1990) used a separate group of adults to determine the MDAs for the objects in their study. Because most adults know less about dinosaurs than the children participating, we decided to operationally define MDAs based on published books about dinosaurs that were likely to have been familiar to participants.

independently with 90% reliability; discrepancies were again discussed and resolved through consensus. Finally, the first author coded the remaining 40% of the haptic events.

Because nearly all children performed at ceiling on the cross-comparison task when exploring HD pairs, only data from the LD and MD pairs from both domains are included in the remainder of the analyses. Children were assigned one point for each instance where contact was made with a dinosaur MDA (or *both* conjunctive MDAs) during exploration of the first member of each of the four pairs, yielding a total of four possible points across the two LD and MD trials. These scores were compared in a 2 (age) × 2 (knowledge) between-groups ANOVA. Only a significant main effect of age emerged, $F(1,31) = 3.88$, $p = .05$. Older children ($M = 2.18$ out of 4) detected more MDAs than younger children did ($M = 1.37$). As anticipated, thorough exploration of the first dinosaur led to many children inadvertently discovering MDAs. Thus, level of dinosaur knowledge was not related to the detection of diagnostic features during analysis of the first member of each pair. However, there was a significant positive correlation between children's MDA score and the number of correct identifications made based on touch ($r = .64$, $p < .001$). It thus seems plausible that the detection of MDAs enabled models to be differentiated and correctly named.

Sea creature explorations were coded at the same time and through the same process described above. There were 2326 haptic events in the sea creature domain, 24 instances of mistaken touches, and 158 retouches. All percentage agreements reported above were calculated with the sea creature domain included. Although an MDA analysis was not conducted for the sea creature domain, the data are included in the analysis of exploration strategies below.

Exploration strategies. Our primary question revolved around the degree to which developmental level and/or domain-specific knowledge influenced the patterns of exploration and correct performance for dinosaur pairs. We also were interested, however, in using the exploration strategy data from the control domain to rule out the possibility that we could be finding simple variations among children in terms of their personal exploration styles, rather than differences attributable to variations in knowledge.

We first classified each child's pattern of haptic events across the two members of each pair in terms of its fit with one of three strategy profiles: *hypothesis testing*, *full comparison*, or *inefficient*. Initial agreement between two independent raters (the first and third authors) on the determination of strategy profiles was 83%; discrepancies were again resolved through discussion. Explorations classified as Inefficient were those for which the child did not acquire sufficient information to make a judgment (e.g., the child's fingers brushed rapidly over different parts of the two models). Descriptions and findings associated with the other two strategy profiles are presented below.

First, the hypothesis testing strategy involved a relatively thorough exploration of the first member of a pair and the identification of salient feature(s). The exploration of the second pair member was then focused on a subset of these features. The absence of the feature(s) yielded a decision that the models were different. Hypothesis testing was efficient to the extent that salient features were identified during exploration of the first model. However, it had the potential to yield "miss" errors in which the child announced that the members of a pair were the same when they actually were different. Such errors are characteristic of confirmatory biases in general, where individuals formulate a single hypothesis and attempt to seek only evidence that confirms that hypothesis (and to disregard or weight as less salient information that does not confirm the hypothesis; Schauble, 1990).

The full comparison strategy also involved a comprehensive exploration of the first model and an identification of salient feature(s). However, exploration of the second model extended beyond the simple checking of a subset of features detected on the first model. The exploration of both models was comparably thorough and exhaustive, with additional parts of the second model often explored. The full comparison strategy had the potential to consistently yield a correct decision. However, the potential cost of its execution was inefficiency, particularly when the child persisted in searching beyond the point at which sufficient information for a correct decision had been acquired. Children using full comparison were likely to take more time (in seconds) to explore each model ($r = .64$, $p < .001$). A 2 (age) × 2 (knowledge) ANOVA also revealed that average time was moderately related to age $F(1,30) = 3.63$, $p = .06$, confirming that older children spent more time exploring each of the models. There were no systematic differences in exploration time across high and low knowledge groups.

For trials involving dinosaurs, the numbers of instances of each strategy type across the four LD and MD trials were summed for each child and then entered into a correlation matrix together with age, knowledge scores, and the dependent variables related to overall performance. Means and standard deviations of individual variables across the four groups created by the intersection of the age and knowledge variables are presented in Table 4. The intercorrelations among these variables are presented in Table 5. Since correlations involving knowledge scores remained significant even with the effects of IQ partialed out, raw correlations (rather than partial correlations) are presented.

Optimal performance on the dinosaur cross-comparison task was positively associated with age, the degree to which MDAs were detected during exploration of the first model within each pair, and the use of the more conservative full comparison strategy. Interestingly, knowledge was positively correlated with use of the hypothesis testing strategy, although hypothesis testing did not lead to better performance on the cross-comparison task. Inefficient strategy use was negatively associated with all measures of task

Table 4
Descriptive statistics for variables related to exploration and strategy use across age × knowledge groups in the dinosaur domain

Variable	Younger		Older	
	Low knowledge	High knowledge	Low knowledge	High knowledge
Number of MDAs identified				
M	1.11	1.63	2.25	2.10
SD	1.05	1.06	1.04	1.52
Inefficient strategy use				
M	1.89	0.63	0.50	0.70
SD	1.90	1.41	0.93	1.16
Hypothesis testing strategy use				
M	0.56	2.38	1.13	1.80
SD	1.33	1.19	0.83	1.14
Full comparison strategy use				
M	1.56	1.00	2.38	1.50
SD	1.74	0.76	1.19	1.35
Time (in s)				
M	4.63	4.26	6.53	5.99
SD	3.26	2.21	3.31	2.01

Table 5
Intercorrelations among variables for the dinosaur domain (LD and MD trials only)

Variable	1	2	3	4	5	6	7	8
1. Knowledge	—	.21	.19	.53**	.17	.46**	−.17	−.25
2. Age		—	.55**	.46**	.48**	.06	.29	−.32
3. Correct judgments			–	.45**	.59**	.07	.46**	−.49**
4. Correct identifications				—	.64**	.31	.15	−.42**
5. MDA detection					—	.14	.68**	−.76**
6. Hypothesis testing strategy						—	−.40*	−.52**
7. Full comparison strategy							—	−.58**
8. Inefficient strategy								—

$^{*}p < .05$.
$^{**}p < .01$.

performance. Older children appeared to take more time to explore the models, they found more differentiating features, and they tended to do better on the task, regardless of their level of domain specific knowledge. Children with higher levels of dinosaur knowledge were more adept at identification, and were more prone to rely on hypothesis testing as an exploration strategy.

A thorough analysis of Table 5 presents an interpretation dilemma. In particular, correct specific identification of dinosaurs is significantly related to children's level of dinosaur knowledge. Furthermore, correct cross-comparison judgments are related to correct specific identifications. However, it was surprising that overall, correct cross-comparison judgments were not related to children's level of dinosaur knowledge. To examine this further, we analyzed trials separately based on whether they contained identical species or different species, partialing out age because of its significant relation to correct performance and strategy use noted earlier. Although our variance on the dependent variable is reduced, we found that correct identifications were related to correct judgments only for pairs containing the same type of dinosaurs ($r(32) = .31, p = .06$). For pairs containing different exemplars (for which more exhaustive searching is necessary to prevent "miss" errors), there was no relation between identification and correct judgment ($r = -.10$). Rather, only use of the full comparison strategy predicted correct judgments when pairs contained different dinosaurs ($r = .32$, $p < .07$). This pattern of results helps bolster our argument concerning the relation between knowledge and hypothesis testing. In particular, knowledge about dinosaurs seems to lead some children to use the hypothesis testing strategy to selectively search features of the dinosaurs, causing more miss errors on "different" judgment pairs.

To test the degree to which strategy use was domain-specific, correlations were computed between exploration strategy use in the control domain and relevant variables from the dinosaur domain (see Table 6). Dinosaur knowledge had no relation to the use of any of the exploration strategies in the control domain, or to correct cross comparison judgments ($r = -.11$, ns). Importantly, the use of hypothesis testing in the control domain was not significantly related to the use of hypothesis testing in the dinosaur domain ($r = .17$, ns). Because children with high knowledge restricted their use of the hypothesis testing strategy to the dinosaur domain, we can be reasonably sure that hypothesis testing was related to higher levels of

Table 6
Intercorrelations among strategy use variables for the control and dinosaur domains

Variable	Control domain hypothesis testing	Control domain full comparison	Control domain inefficient strategy
Dinosaur hypothesis testing	.17	.19	−.30
Dinosaur full comparison	.18	.38*	−.48**
Dinosaur inefficient strategy	−.32	−.53**	.72**
Dinosaur knowledge	.11	−.04	−.04
Age	.07	.33*	−.36*
Cross-comparison judgments (control)	−.11	.52**	−.42*

* $p < .05$.

** $p < .01$.

domain-specific knowledge, rather than to a more global cognitive style that influenced performance across both domains. Within the control domain, superior performance on the cross-comparison task was associated with utilization of the full comparison strategy, in keeping with the pattern for children with lower knowledge on dinosaurs.

Discussion

Research involving child experts has demonstrated fairly consistently that high knowledge can eradicate developmental differences on particular tasks (Chi, 1978; Johnson & Eilers, 1998). Possession of high knowledge also enables children to execute strategies more efficiently and consequently benefit more from their use (Alexander & Schwanenflugel, 1994; Bjorklund et al., 1990). In the present study, we found no such advantage of expertise when the effects of knowledge were pitted against the effects of developmental level. Surprisingly, children with high knowledge did not perform optimally when asked to judge whether two dinosaur models were identical or not based only on touch. On the other hand, high knowledge was associated with superior identification of dinosaurs, even in the absence of visual features. Developmental level exerted a strong effect on performance, with older children tending to detect more differentiating features and spending more time on task than younger children.

In the cross-comparison task there were two alternate paths to success—one based on a schema-driven search and one based on the data-driven detection of subtle perceptual feature differences. We speculate, based on the superior identification skills of children with high knowledge, that such children solved the task by identifying the first member of each pair and then proceeding to seek confirmatory evidence when exploring the second model. Knowledge provided a corpus of data that subsequently may have enabled confirmatory biases to emerge during execution of the hypothesis testing strategy. This confirmatory bias may have led children with high knowledge to prematurely stop searching the second model in pairs that contained different dinosaurs. In the present study, the more methodical (but less efficient) data-driven strategy yielded superior performance.

Our findings fit well with the data from the developmental literature on haptically-based information processing (e.g., Hatwell et al., 1990). Younger children did have more difficulties with the cross-comparison judgment than older children did. It is important, however, to consider carefully the underlying mechanism through which developmental level provided an advantage on the cross-comparison task. It is unlikely that older children were simply more motivated to complete the task, as all children seemed to find the task enjoyable and engaging and all participants were recruited based on their expressed interest in dinosaurs. It seems plausible that older children may have benefited from superior working memory capacity when exploring the first model in each pair and then attempting to determine whether or not the second model was identical. It could be that full search strategies simply overwhelmed working memory for the younger group, and the less effective hypothesis testing strategy protected against such overstimulation (Bjorklund, 1997). An alternative explanation involves cognitive style.

Previous research has shown that cognitive style predicts performance on visual tasks related to subordinate categorization (Mervis, Johnson, & Mervis, 1994; Johnson & Eilers, 1998). Reflective children tend to be more analytic and more apt to attend to subtle features of pictures (e.g., Kagan & Kogan, 1970). Since impulsivity tends to decrease with age, it seems likely that part of the older children's advantage in the cross-comparison task stemmed from a more reflective, analytic approach to exploring and comparing features. Indeed, children who are impulsive in haptic exploration have been shown to be impulsive in the visual domain (Butter, 1979). Future research in which children are provided with a fixed (rather than an open) time interval for haptic exploration of each model would be useful for addressing this issue further. If older children still performed better than younger children when the time for exploration was held constant, we could conclude that working memory provides the principal advantage on the cross-comparison task. If knowledge exerts a stronger effect on performance than developmental level with fixed time intervals, we could conclude that impulsivity was the basis for the younger children's disadvantage in the present study.

It seems possible that children with higher levels of knowledge may have possessed higher levels of self-efficacy related to the haptic exploration task. A child who knows that he or she possesses a relatively high quantity of knowledge related to dinosaurs (and whose parents probably mentioned this fact in explaining why the child was going to visit our laboratory) may have been fairly cavalier in approaching the task and perhaps overly confident in their decision making. That is, higher knowledge may have been associated with a tendency to engage in more risky (and faster) decision making. However, based on some of our past work (Johnson & Eilers, 1998; Mervis et al., 1994), we would anticipate that children with higher knowledge would be more analytic and reflective than children with lower knowledge. Finding that children with low knowledge search more systematically and exhaustively conflicts with this pattern and strengthens our argument that children with higher knowledge are hindered by a confirmatory bias.

Our findings support the idea that content knowledge and strategy use are closely interrelated (Alexander & Judy, 1988; Gaultney et al., 1992). Children with less content knowledge were more likely to use a full comparison strategy, while children with more knowledge were more likely to use a hypothesis testing strategy. It is important to reiterate that children with lower knowledge scores were highly interested in the domain and generally familiar with the dimensions along which dinosaurs could differ. They may not have, however, been able to generate a name when asked to identify specific models. Thus, they relied predominantly on "bottom up" processing when examining the models and consequently were more likely to be correct on difficult trials. Goldstein (1996; Goldstein & Gigerenzer, 1999) has argued that an intermediate amount of knowledge in a domain can yield the highest proportion of correct answers. Adelson (1984) has reported a similar finding from the domain of computer programming. In particular, adults who were expert programmers performed worse than adult novices did on particular tasks that were conducive to reliance on more concrete representations.

Hypothesis testing may also be adaptive because it is highly efficient. When one searches for and has gathered enough information to make a decision, why continue looking for cues? Gigerenzer and Goldstein (1999) have called this "one-reason decision making," in which individuals satisfice by basing a decision upon the first viable cue encountered. Todd (2000) reports that decision making based on such "fast" heuristics is equal to or better than decision making based on more thorough "tallying" of cues or based on processes analogous to multiple regression. If the children in our task utilized their knowledge to identify the first member of the pair explored, and then used one-reason decision making to determine whether the second member of the pair was identical or not, the connection to confirmatory bias is transparent. Todd argues that simple heuristics are "noncompensatory, meaning that once they have used a single cue to make a decision, no further cues in any combination can undo or compensate for that one cue's effect" (p. 946). Unfortunately, children with high knowledge may have inadvertently overlooked cues that would have allowed them to disconfirm their hypothesis in the cross comparison task.

Finally, it is important to consider that the continuum of performance on a given procedural task and the continuum of domain-specific knowledge may interact in complex ways. In the present study, it was almost certainly the case that being asked to identify models based on touch and to make decisions concerning the similarity of those models was an extremely novel task for all participants. Because all children were extreme novices on this task, it seems possible that knowledge did not exert much influence on performance because of the low level of task familiarity. It would be interesting to test whether knowledge exerts stronger effects on performance once moderate levels of practice on haptic exploration (with feedback on whether similarity decisions were correct or not) had been attained. It seems reasonable to hypothesize that with high levels of practice (or among children who are visually impaired), haptic exploration would be similarly influenced by knowledge effects and perceptual learning as is the case for visually based categorization. Future longitudinal or microgenetic studies would be very helpful in delineating the relative impact of domain knowledge on strategy use throughout the continuum of task expertise.

Appendix

Most diagnostic attributes (MDAs) identified for dinosaur models

Model	Most diagnostic attributes
Allosaurus	Sharp teeth + 3 claws on forearms[a]
Apatosaurus	Long neck
Euoplocephalus	Armored spikes on back + clubbed tail[a]
Iguanadon	Duckbilled mouth + thumb spike[a]
Parasaurolophus	Duckbilled mouth + crest on back of head[a]
Spinosaurus	Fin on back
Stegosaurus	Plates on back
Triceratops	Three horns in middle of head
Tyrannosaurus rex	Sharp teeth + 2 claws on forearms[a]

[a] Conjunctive attribute.

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