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Infant Behavior & Development 28 (2005) 240–249

Infant Behavior & Development

Visual and haptic exploratory procedures in children's judgments about tool function

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Abstract

Preschool children (*M* age = 4 years, 7 months) verbally judged whether a spoon would function to transport a target object (small versus large candy) and whether a stick would function to stir a target substance (sugar versus gravel). The spoons varied in bowl size, and sticks varied in rigidity. Children's judgments were sensitive to task goals (transport versus mixing), to tool properties (size and rigidity), and to target properties (size to be transported; resistance to mixing). Moreover, children used appropriate perceptual exploration to determine tool function. Judgments about transport were made after visual inspection of the spoon, and judgments about rigidity were made after haptic exploration of the stick. Children did not directly perform the task in order to judge whether the tool would be adequate. Differential visual and haptic object exploration during a perceptual-comparison task additionally confirmed the role of perceptual exploration in determining tool function.

Keywords: Haptic exploratory procedures; Perceptual-comparison task; Tool function

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Early in life, children seek to learn about the properties of objects in order to determine their function. Infants' interactions with objects progress from predominantly active mouthing at about 5 months (Ruff, 1989; Ruff & Dubiner, 1986) to combinations of vision and manipulation (Ruff, Saltarelli, Capozzoli, & Dubiner, 1992; Stack & Tsonis, 1999).

Infants show sophisticated coupling between manual activities and the properties of objects: They bang hard objects more than compliant ones (Lockman & Wright, 1988; Palmer, 1989), jitter their fingers

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0163-6383/$ – see front matter © 2005 Elsevier Inc. All rights reserved.
doi:10.1016/j.infbeh.2005.05.002

on rough objects more than smooth ones (Lockman & McHale, 1989; Ruff, 1984), and explore the contours of geometrically novel or complex objects by rotation and hand-to-hand transfer (Ruff, 1984). Preverbal infants use visual and haptic information to make judgments about whether an object can be reached and grasped and whether a surface will support locomotion (e.g., Adolph, 1995; Gibson et al., 1987; von Hoftsten & Fazel-Zandy, 1984). Walking infants, for example (Gibson et al., 1987), tested the traversability of a surface by manual exploration more when it was a waterbed than when it was made of rigid plywood. They decreased the duration of manual exploration and simply looked at the waterbed when it was made to jiggle, which provided an obvious visual cue to its precariousness. In short, the ability to judge the utility of objects for basic functions such as grasping and locomotor support appears to be present early in development. In the present research, we ask whether older children use perceptually available properties to make more complex judgments about how one object can operate on another, specifically, to judge whether an object can function as a tool.

Previous research with preverbal infants and animals implicates perceptual activity in the spontaneous discovery of how objects function as tools. Perceptually salient cues increase the chance that a tool's function will be discovered. Köhler's (1921) seminal work with apes showed that the likelihood of using a stick to reach a remote object increased when the tool and target were close together, a phenomenon that was subsequently confirmed with human children (Bates, Carlson-Luden, & Bretherton, 1980; Richardson, 1932). As the complexity of the chain of events needed to apply a tool increases, and perceptual cueing gives way to the need for more elaborate means-end analysis, younger children have more difficulty in discovering that a tool is functional. Thus, for example, Koslowski and Bruner (1972) reported that few 12- to 14-month-olds discovered how to reach a toy by rotating a lever arm on which it was placed, but more 16- to 24-month-olds succeeded. Van Leeuwen et al. (1984) found that when children 1–2 years of age were provided with a hook to pull in a remote target, they were more likely to use it when success could be achieved by simply pulling than they were when it was necessary to rotate or translate the hook. Older children, however, succeeded even with the more complex transformation.

Brown (1990) showed that children as young as 17 months were sensitive to the attributes needed in order for a tool to pull in a remote target. Once children had learned to use a tool for this purpose, she examined their selections of new objects in a transfer task. The transfer objects were similar to the original in prominent properties, only some of which were relevant to the objects' function as tools. Relevant properties were rigidity, length, and head width of the tool; irrelevant properties included color and pattern. Children clearly did not select tools in the transfer phase based on irrelevant dimensions, but rather based their choices on relevant ones. Although there were age differences in initial learning, all children who had achieved unguided tool use in the learning stage showed this selection of transfer tools based on task-relevant properties.

More recently, Chen and Siegler (2000) used a task similar to Brown's (1990), combined with microgenetic methods and detailed assessments of strategy, to track 1.5 and 2.5-year-old's progress in understanding the utility. After three trials where attempts were unguided, some children received hints or a model. Older children tended to immediately benefit from these guides, whereas younger children's performance changed more gradually. Both age groups, however, showed the ability to base their tool choices on structural features (e.g., shape of head) rather than superficial ones (e.g., color).

Children can learn about the functional potential of an object as a tool in various ways. They can follow a model or hint, recognize a tool as familiar, or relate a new object to familiar tools by analogy. They may "learn by doing," that is, discover that an object can function as a tool by actually trying it out. Another important alternative is that children may undertake a perceptual analysis to determine whether the object has features that predict its functionality. In most previous work on tool discovery, one cannot assess the degree to which children use perceptual analysis to determine an unfamiliar object's potential as a tool, because the use of the tool is taken as the evidence of judging it to be functional. Typically, children are not asked to make prior judgments about functionality based on perceptually accessible properties, nor is their initial exploration formally evaluated. In the current experiment, we asked children to make a formal judgment about whether a tool would perform a function. We then determined whether they exhibited perceptual exploration prior to making the judgment or used the tool before judging. We further assessed the appropriateness of their perceptual activities, by considering which modality they used for exploration (vision versus touch) and their specific haptic exploratory patterns.

The distinction between learning about objects by perceptual exploration and directly performing with them has been explored formally in the field of robotics by Bogoni and Bajcsy (1992), who discussed two types of robot operations for testing tool function. In a perceptual test, properties of the object that are relevant to its function are assessed using robotic perceptual systems. For example, geometric properties may be analyzed to determine whether the object can be grasped (Connell & Brady, 1987) or sat on (Stark & Bowyer, 1990). In a performative test, the action of the tool on the target is tested directly, for example, by executing piercing or cutting algorithms and assessing the consequences (Bogoni & Bajcsy, 1992).

In contrast to much of the literature on children's tool use, our tasks were complex relative to that of reaching for a remote target, and our subjects were at preschool age. We asked children to make formal judgments about tools with a specific goal in mind, rather than to discover a function serendipitously. We were interested in the extent to which children use perceptual operations to assess tool function prior to performance. Particularly important was whether children tuned those operations to the critical, function-limiting properties of the object. Across two tasks, we constrained tool function by properties that are haptically and visually accessible to different degrees. Children judged in one task whether a spoon could be used to transport a piece of candy. Here the critical property was the size of the bowl of the spoon. In a second task, the children judged whether a stick could be used to stir a target substance. Here the critical property was the rigidity of the stick.

Adults exhibit very specific coupling of environmental exploration to perceptual goals, using what Lederman and Klatzky (1987) have called haptic *exploratory procedures* (EPs), specialized patterns of movement that are typical (and generally optimal) for extracting information about objects and surfaces. To assess the rigidity of an object, even when vision is available (Klatzky Lederman, & Matula, 1993), they use the EP called *pressure*—pushing against its surface or twisting it, for example. Children's perceptual tests of the rigidity of a mixing stick should optimally take this form. Recent work by Baxter (2002) supports this prediction. She showed that children aged 3–5 years chose to execute adult-like exploratory procedures that were optimal for making perceptual discriminations pertaining to hardness (as well as to texture and weight) of multi-attribute objects. In contrast, adults use vision alone, when available, to judge the size of objects (Klatzky et al., 1993). If children behave similarly, their tests of spoon size should involve simply looking at it. Contact is neither necessary nor optimal for size perception, but the relevant haptic EPs (those likely to be used in the absence of vision) would be enclosing the bowl of the spoon and following its contours with the fingers.

The present experiment incorporated two testing procedures, performed in sequence: function judgments and perceptual comparisons. The function judgments were made about tools for mixing and transport. The perceptual comparisons requested children to indicate which of two objects was greater on each of several dimensions. Patterns of exploration during directed, perception-based comparison and function testing could then be compared.

1. Method

1.1. Participants

Ten children (five boys, five girls) enrolled in a University Children's Center participated in both tasks. Children's age ranged from 3 years, 11 months to 4 years, 11 months ($M = 4$ years, 7 months).

1.2. Function task tools and targets

The target objects for transport were a round candy of approximately 2.5 cm diameter and a stick candy approximately 5.0 cm long, wrapped in cellophane. Thus, the stick candy required a larger spoon for transport than the round candy. The transport tools were five spoons with circular bowls in sizes 1/8 tsp (U.S. teaspoon measure), 1/4 tsp, 1/2 tsp, 1 tsp, 3 tsp. Each was painted black.

Targets for mixing included a bowl containing approximately 3/4-cup sugar and another containing an equal quantity of coarse gravel. Thus, the gravel required a more rigid mixing stick than the sugar. The mixing tools were five sticks approximately 15.0 cm × 1.2 cm × 1.2 cm. Each was painted black. In order of increasing rigidity, sticks were constructed of: cotton-stuffed felt, compliant polyfoam, stiff polyfoam, cardboard, and balsa wood.

1.3. Perceptual-comparison stimuli

Pairs of stimuli were used that contrasted on five dimensions: weight (two 35-mm film canisters, one empty and one filled with pebbles), size (a marble and a dried pea), roughness (2.5 cm × 5.0 cm × 1.2 cm pieces of polyfoam, one covered with sandpaper and one with cellophane), hardness (2.5 cm × 7.5 cm × 1.2 cm pieces of wood and compliant polyfoam), and shape (a styrofoam sphere of 6.2 cm diameter and a cone with a 5.6 cm base and 10 cm height).

1.4. Procedure

First the child made function judgments of tools for the mixing and transport tasks. Each child encountered each combination of target (2) and tool (5) once for each task (2), for a total of 10 mixing-task trials and 10 transport-task trials. Experimental conditions were blocked by task and targets within tasks, so that each child performed one task with both targets before doing the second task. All tools were evaluated with one target before the second target was introduced. Across children, order of tasks and targets within tasks was counterbalanced, and order of tools within tasks was varied.

Each task was preceded by a scenario. For the transport task, the child was told that the experimenter's friend was having a party and wanted her children to fill the candy bowls with candy like the round or stick target. Her children were not to touch the candy. The experimenter placed each spoon in front of the child and asked, "Can Stephanie's kids use this to put the candy in the bowl?" For the mixing task, the child was told that the experimenter's friend wanted to make a cake (sugar target) or a mud pie (gravel target) and needed something to stir with. For each of the tools, the experimenter placed it in front of the child and asked, "Can Bill use this to mix up the sugar/stones"?

The perceptual comparisons immediately followed the second function task. The five pairs of items were given in random order; in each case the child was asked which item was greater along the given dimension (harder, rougher, etc.), or for the shape pair, which item was more like a ball. The child was told that he or she could look at and touch the objects in any way but touching was not obligatory.

The child's vocal and manual activities were recorded on videotape for analysis. A mirror placed behind the objects allowed the backs of the hands to be seen.

2. Results

To summarize the results, our preschool participants used sophisticated, differential, and task-appropriate perceptual exploration to make judgments about how well objects would function as tools. Children's judgments and their patterns of perceptual exploration were sensitive to the task goal (transport versus mixing), to the properties of tools relevant to the task (size or rigidity), and to the constraints imposed by the target (small/large candy, sugar/gravel). Children judged mixing sticks based on appropriate manual exploration of stick rigidity, and they judged transport spoons based on visual inspection of spoon size. These same exploratory patterns emerged when they made directed perceptual comparisons.

2.1. Judgments of tool function

Judgments of tool function, shown in Fig. 1, indicate that children were more likely to say that the tool was functional, the more it satisfied constraints imposed by the task and the target. The figure shows percentage of "yes" responses, indicating that the tool was adequate for the task, as a function of tool size (transport task) or rigidity (mixing task). (Only one response could not be scored, the response to tool 3 in the transport task.) Children's "yes" responses increased by 70 percentage points or greater as the tools became larger or more rigid. The effect of the target can be seen by comparing the two functions in each panel. In the transport task, the percentage of "yes" responses, computed over the set of tools, was significantly greater for the smaller ball candy than for the larger stick candy, $t(9) = 3.17$, $p < .01$. There was a similar trend toward more "yes" responses when mixing sugar than gravel, but it did not reach significance, $t(9) = .94$, $p > .15$.

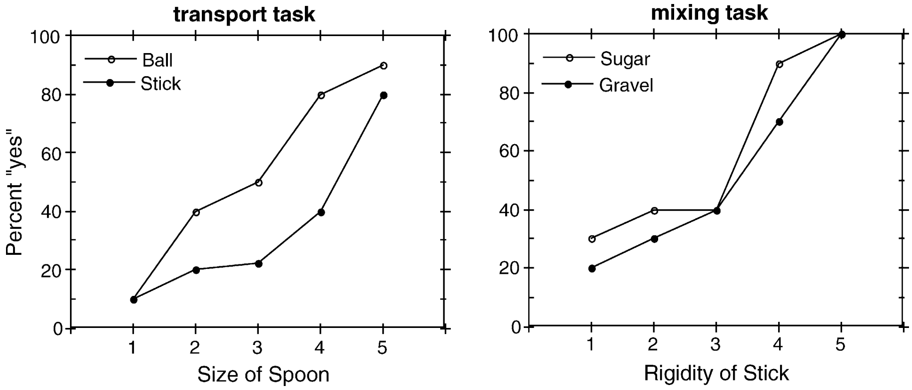

Fig. 1. Percentage of responses indicating the tool would be functional, for each task and target object. The x-axis represents five tools ordered by increasing size (transport task) or rigidity (mixing task).

2.2. Exploration when judging function

To assess exploration, coders scored the videotaped record. Analyses initially subdivided the record into the interval prior to and subsequent to the verbal judgment. If no contact was made with the object over the entire duration of an interval, it was scored as vision only. An interval in which contact occurred was coded as a sequence of (i) haptic EPs, (b) performative responses, in which the tool function was acted out, and (c) task maintenance, consisting of translation or reorientation of the tool. Haptic EPs were initially scored as appropriate or inappropriate, but only EPs appropriate to the particular task were ultimately considered[1]. In the mixing task, the appropriate EP was pressure on the mixing tool. In the transport task, the appropriate haptic EPs were contour following or enclosure on the bowl of the spoon. Performatives could involve the tool and the target object, performative with tool only (miming), or performative with the hand but without using the tool.

Reliability was computed by having a second coder evaluate 25% of the trials and determining the percentage of response categories recorded by either coder that were recorded in common by both. The intervals before and after the verbal judgment were evaluated separately—agreement was 87% in the pre-judgment interval and 88% in the post-judgment interval.

Data analysis was directed at the occurrence of appropriate EPs and performatives within the pre- and post-judgment intervals. On each trial, a 1 or 0 was scored within each interval for three exploratory categories—vision only, appropriate haptic EP, or performative, according to whether or not that category was observed during the scored interval, regardless of frequency of occurrence within the interval. The category of vision only was mutually exclusive with the other two exploratory categories, which could co-occur. (Visual analysis could also occur in conjunction with the performative and haptic-EP categories, of course, but in this case would not be vision only.) These scores were then summed over the five tools within each task and target, for a score of 0–5 within each condition, per subject.

The sums for each subject were entered into a three-factor analysis of variance (ANOVA), where the factors were task, target and a third temporal variable that was defined by separating the intervals before and after the verbal judgment, as explained for each ANOVA below. For the target factor, the levels represented the constraint the target imposed on the tool, which was greater for gravel than sugar and greater for the stick candy than the ball. A separate ANOVA was done for each exploratory category: vision only, appropriate haptic EP, and performative. Table 1 shows the mean number of tools with which each exploratory category occurred, for each cell of this design.

The first ANOVA considered the number of tools with which vision only (i.e., absence of contact) was used for exploration. There was an effect of task, $F(1, 9) = 9.33$, $p < .025$, indicating more reliance on vision only in the transport task than the mixing task. The temporal variable (i.e., separation of the pre- and post-judgment interval) was used to code the *persistence of vision only*: Separate tallies were made for exclusive use of vision during the pre-judgment interval (regardless of whether or not contact occurred subsequently) and for its use across both the pre- and post-judgment intervals. A significant effect of this variable reflected a decrease in the exclusive use of vision when counted within the pre-judgment interval

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[1] Most contact was clearly functional, and most exploration was appropriate: When we excluded contact that initiated a performative or that occurred when the tool was grasped and lifted, only 10 inappropriate haptic exploratory procedures were scored. We do not consider the grasp-and-lift sequence inappropriate, because it provides coarse information about multiple properties of objects—see Klatzky and Lederman (1993) and Lederman and Klatzky (1990). Given its generality, however, it also was not scored as appropriate exploration.

Table 1
Mean number of tools eliciting a particular category of exploration (vision only, haptic EP, performative) during each of two intervals, by task and target (S.D. is in parentheses)[a]

Interval(s) of vision-only	Mixing task			Transport task		
	Sugar target	Gravel target	Task mean	Ball target	Stick target	Task mean
Vision only						
Pre-judgment interval	1.1 (1.52)	.7 (1.25)	.90	1.7 (1.64)	2.2 (1.75)	1.95
Pre- and post-judgment	.6 (1.58)	.5 (1.08)	.55	1.3 (1.83)	1.4 (2.01)	1.35
Interval of first occurrence	Mixing task			Transport task		
	Sugar target	Gravel target	Task mean	Ball target	Stick target	Task mean
Haptic exploratory procedure						
Pre-judgment interval	2.0 (1.94)	2.1 (1.73)	2.05	.4 (0.70)	.9 (1.73)	.65
Post-judgment interval	.7 (1.25)	.4 (0.70)	.55	.1 (0.32)	.5 (0.85)	.30
Interval of first occurrence	Mixing task			Transport task		
	Sugar target	Gravel target	Task mean	Ball target	Stick target	Task mean
Performative						
Pre-judgment interval	.6 (1.35)	.9 (1.37)	.75	1.2 (1.55)	.9 (1.60)	1.05
Post-judgment interval	.9 (1.73)	1.0 (1.49)	.95	.8 (1.32)	.8 (1.03)	.80

[a] As vision-only required absence of contact throughout the interval, the maximum score is 5 (the number of stimuli) for each interval. For haptic exploration and performatives, the interval (relative to the judgment) in which contact first occurred was scored, and as the two intervals are mutually exclusive, the maximum total score adding both intervals together is 5.

only versus across the whole trial, $F(1, 9) = 15.55$, $p < .01$. This decrease reflects a tendency for subjects to touch the tool after the response, when they did not touch it previously. The effect of target was not significant, nor was any interaction.

The next ANOVA considered cases where contact occurred; specifically, contact in the form of appropriate haptic EPs. There was a significant effect of task, $F(1, 9) = 5.16$, $p < .05$. The mixing task elicited appropriate haptic exploration more frequently than the transport task. The temporal variable coded the *point of first occurrence* of the EP: in the pre-judgment interval or post-judgment interval (i.e., a post-judgment EP was not counted if one had already been observed before the judgment). The effect of this factor was significant, $F(1, 9) = 5.86$, $p < .05$, indicating that the appropriate EPs first occurred prior to the verbal judgment more often than after it. The effect of target was again not significant, nor was any interaction.

The third ANOVA included the same set of variables as the second, except that tallies of performatives replaced those of appropriate haptic EPs. There were no significant effects. Both the mixing and transport tasks elicited approximately one performative over the five tools, which emerged about equally often during the pre- and post-judgment interval.

2.3. *Exploration during perceptual-comparison task*

Performance in the perceptual-comparison task was virtually error free—the only errors were on two roughness comparisons, produced by children who failed to use the appropriate haptic EP, lateral motion.

Table 2
Number of subjects out of 10 exhibiting each observed exploratory category[a] during perceptual comparison, by judged property

Exploratory procedure	Lateral motion	Pressure	Unsupported holding	Enclosure	Vision only
Judged property					
Roughness	3[b]	4	4	9	1
Hardness	2	5[b]	8	8	0
Weight	0	1	10[b]	5	0
Size	0	0	2	5	4[b]
Shape	0	0	1	7	3[b]

[a] The haptic exploratory procedures of Contour Following and Static Contact are not shown, as they were not observed.
[b] Predicted exploratory procedure.

The videotape record was coded as a sequence of EPs. In general, children tended to explore as adults would (Klatzky et al., 1993). They looked at the objects rather than touched them when comparing size and shape. The haptic EPs they used for other perceptual judgments were appropriate ones: Children lifted the objects to judge weight, pressed or pinched them to compare hardness, and so on. Table 2 shows the number of children exhibiting each procedure at least once, by type of comparison. As can be seen, the maximum occurrence of an EP (i.e., greatest value within a column) tended to occur in the anticipated condition. (The strong visual cues to roughness in the comparison stimuli may underlie the relatively sparse use of lateral motion.)

3. Discussion

The data presented in Fig. 1 indicate that children's judgments about tool function were highly sensitive to the characteristics of the tool and to the constraints on its function. More children said that a spoon would function for transport, the larger its bowl, and more said that a stick would function for mixing, the greater its rigidity. Children appropriately tended to be more conservative about a tool's adequacy for transporting a large candy than a small one, and for mixing gravel than mixing sugar.

These judgments were achieved through focused perceptual analysis. Children executed specialized exploratory procedures that allowed them to extract relevant properties of the tool. When the task was constrained by the size of a tool, they used vision, and when it was constrained by the rigidity of a tool, they used touch. Further, in the case of touch, children used the appropriate haptic EP. Children pushed, squeezed, bent, or otherwise put pressure on the mixing stick, rather than using another specialized or arbitrary form of contact. Interaction with the object was highly purposive, directed toward extracting task-relevant properties.

Consistently with other research (see Baxter, 2002; Bushnell & Boudreau, 1991), the perceptual-comparison task confirms that children had an appropriate repertoire of EPs. Across each of the properties tested—roughness, hardness, weight, size, shape—they used adult-like patterns of exploration. Moreover, the procedures that the children used when they were directed to compare size and hardness were the same as those they used when making function judgments constrained by size (transport task) and hardness (mixing task). This parallel in exploration between a directed perceptual-comparison task and a function-judgment task further supports the conclusion that children were perceptually extracting information related to task constraints, in order to assess the tools' function.

By asking children capable of verbalization to make formal judgments of function, we could separate the judgment from use of the tool. Therefore, we could ask whether they exhibited learning by doing—making the judgment after performing with the tool—or used perceptual analysis (but not outright performance) before judging. Our results not only demonstrate that a focused perceptual analysis occurred before the judgment, but they also show little evidence of learning by doing. To the extent that they acted out the object's function at all, children were as likely to do so after the judgment as before it.

A substantial body of previous work (see reviews in Klatzky & Lederman, 1993, 2000; Lederman & Klatzky, 1993) points out the importance of active haptic exploration in acquiring knowledge about objects, whether or not vision is present. We have also suggested that haptic exploration can play a role in motor planning, serving to direct manipulation of familiar objects in the absence of vision (Klatzky & Lederman, 1999; Lederman & Klatzky, 1997). We contrast this manipulatory role of active exploration with that of low-level cutaneous processing, used to sense and correct for an object's slipping from one's grasp and to determine appropriate grip forces (see, e.g., Johannson & Westling, 1984). The data from the present experiment indicate yet another function of haptic exploratory procedures, namely, to provide inputs to processes that determine the utility of objects for desired functions.

Acknowledgements

This project grew out of discussions with Ruzena Bajcsy about robotic testing of functionality, in which the distinction between perceptual and performative tests was initially developed. We thank her for her perceptive insights. We also thank Karen Adolph for extensive and valuable comments on the manuscript.

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