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Infant Behavior & Development 27 (2004) 246–265
Infant Behavior & Development

Intermodal perception and physical reasoning in young infants

Amy Schweinle [a,*], Teresa Wilcox [b]

[a] *Department of Counseling and Psychology of Education, University of South Dakota, 414 E. Clark St., Vermillion, SD 57069, USA*
[b] *Texas A&M University, College Station, TX, USA*

Received 6 June 2003; received in revised form 28 October 2003; accepted 2 November 2003

Abstract

The present research investigated 5.5-month-olds' ability to (a) coordinate information from the tactile and visual modalities and (b) use their intermodal object representations to interpret physical events. Infants were tactilely presented with a ball that was either rigid or compressible. Following the tactile exploration trials, infants viewed a test event in which the ball moved back and forth through a tunnel. (Infants were given no information about the balls' substance in the test event.) The circumference of the ball was either larger or smaller than the tunnel opening. The main results were that (a) when the ball was much larger than the tunnel opening, the infants correctly judged that the compressible, but not the rigid, ball could pass through the tunnel and (b) when the ball was much smaller than the tunnel opening, the infants correctly judged that both the compressible and the rigid ball could fit through the tunnel. Together, these results suggest that young infants are capable of using information about object substance encoded tactilely to interpret a passing-through event presented visually and were discussed, more generally, within the context of how intermodal object representations are formed and used to interpret physical events.

Keywords: Infants; Cognitive development; Infant cognition; Intermodal perception; Physical reasoning

The field of infant cognition has experienced tremendous growth during the past 15–20 years. Two areas of study within this field that have generated a great deal of interest are intermodal perception and physical reasoning. The study of intermodal perception focuses on how and when infants perceive information from different modalities as belonging to a single unified object representation. Physical reasoning is the study of infants' expectations for the way that objects should move and interact and how this changes with time and experience. Although these two areas of research have developed relatively independently

* Corresponding author. Tel.: +1-605-677-5848; fax: +1-605-755-5438.
E-mail address: aschwein@usd.edu (A. Schweinle).

0163-6383/$ – see front matter
doi:10.1016/j.infbeh.2003.11.001

of each other, it is clear that they share an interest in similar theoretical issues. For example, both areas are concerned with how to best conceptualize the nature and development of the object representation system. Perhaps, if these two areas of research were brought together, new insight would be gained. One approach would be to explore how infants' experience with objects in one modality can influence their expectations for how those objects should behave in an event presented in a different modality. The outcome of studies like this would shed light on what kind of multimodal information infants include in their object representations and how infants bring this knowledge to bear within the context of physical events.

Before such studies can be proposed, however, we must be clear about (a) what kind of physical knowledge young infants possess and (b) the type of intermodal processing in which young infants are capable of engaging. The next two sections examine physical knowledge and intermodal perception in infants.

1. Physical knowledge in infancy

Studies of physical knowledge typically focus on what kind of knowledge infants possess about the physical world and how this knowledge is acquired. Often these studies use a violation-of-expectation method. In a violation-of-expectation task, infants are shown an event that is either consistent or inconsistent with the belief being tested. The rationale is that if infants possess the belief, they should find the inconsistent event unexpected. Since infants typically look longer at unexpected, or surprising, events, the prediction is that infants will look longer looking at the inconsistent than consistent event.

Findings obtained using this method suggest that from a very early age infants possess some fundamental or core knowledge about objects (e.g., Spelke, 1994; Spelke, Breinlinger, Macomber, & Jacobson, 1992; Spelke, Katz, Purcell, Ehrlich, & Breinlinger, 1994). For example, there is evidence that by 2.5–3 months of age, infants (a) understand that objects continue to exist even when out of view; (b) recognize that two objects cannot occupy the same space at the same time, just as one object cannot be in two places at the same time; and (c) expect objects to move on spatiotemporally connected paths (e.g., Aguiar & Baillargeon, 1999, 2002; Baillargeon, 1987a, 1987b, 1991; Baillargeon & DeVos, 1991; Baillargeon, Graber, DeVos, & Black, 1990; Hespos & Baillargeon, 2001; Hespos & Rochat, 1997; Simon, Hespos, & Rochat, 1995; Spelke et al., 1992; Spelke, Kestenbaum, Simons, & Wein, 1995; Wilcox & Baillargeon, 1998a, 1998b; Wilcox, Nadel, & Rosser, 1996; Wilcox & Schweinle, 2003; Wynn, 1992). Regardless of whether one believes that this knowledge is innate or learned and, if learned, how this knowledge is acquired, it seems that infants possess expectations that influence how they interpret the physical world as it plays out before them.

The knowledge that objects are solid, bounded entities that maintain their physical properties through space and time leads infants to attend to certain types of information when viewing physical events (Wilcox, 1999; Wilcox, Schweinle, & Chapa, 2003). Two types of information to which infants seem particularly sensitive are object size and object substance (e.g., rigid or compressible). These two types of information will be considered in turn.

There is evidence that infants attend to the *size* of objects when interpreting occlusion events. For example, infants 3–5.5 months respond as if they are surprised to see a tall object occluded by a short screen (Aguiar & Baillargeon, 2002; Baillargeon & DeVos, 1991; Baillargeon & Graber, 1987) and infants 4.5–11.5 months respond as if they find it unexpected to see two objects occluded by a screen that is narrower than the width of the two objects combined (Wilcox, 1999; Wilcox & Baillargeon, 1998a, 1998b; Wilcox & Chapa, in press). Similar results have been obtained in experiments investigating infants' perception of passing-through and containment events (e.g., Aguiar & Baillargeon, 1998, in press; Sitskoorn & Smitsman, 1995; Spelke et al., 1992). For example, Spelke et al. (1992) reported that 4-month-olds demonstrate surprise when a large ball, but not a small ball, passes through a narrow opening. Other researchers (Aguiar & Baillargeon, 1998, in press; Sitskoorn & Smitsman, 1995) have found that infants 6 months and older look longer when large balls or rectangular blocks are placed into smaller containers than when they are placed into larger containers, suggesting that the infants can correctly assess whether objects can fit into containers of different sizes. Most striking about this research is not that infants attend to and encode form features, as one would expect based on previous research (e.g., Fantz, 1961; Hayne, Rovee-Collier, & Perris, 1987; Quinn, 1987), but that infants draw on this information to make sense of physical events as they play out before them.

In addition to size features, infants also demonstrate sensitivity to object *substance* (i.e., whether an object is rigid or compressible) during the first year of life. For example, 12-month-olds engage in different kinds of behaviors when manually exploring objects composed of different substances (Gibson & Walker, 1984). Similarly, Walker, Owsley, Megaw-Nyce, Gibson, and Bahrick (1980) demonstrated that infants as young as 3 months respond differentially when a rigid object deforms (i.e., twists) than when a compressible object deforms, as if they consider substance, like shape, an invariant property of an object (Gibson, Owsley, & Johnston, 1978; Gibson, Owsley, Walker, & Megaw-Nyce, 1979; Gibson & Walker, 1984; Walker-Andrews & Gibson, 1986; Walker et al., 1980). Even more important to our discussion, however, is if infants can bring their knowledge about size and substance to bear when interpreting physical events (Aguiar & Baillargeon, 1998, in press; Baillargeon, 1987a, 1987b). For example, in one experiment Aguiar and Baillargeon (1998) presented 8.5-month-olds with a test event in which a large ball was inserted into a container whose diameter was either larger (large-container event) or smaller (small-container event) than the circumference of the ball. Prior to the test event, infants were allowed to see and touch the ball, demonstrating that the ball was rigid. The infants looked reliably longer at the small-container than at the large-container test event, suggesting that the infants (a) expected the ball to maintain its rigidity; (b) correctly judged that the ball fit into the large but not the small container and; hence, (c) found the insertion of the ball into the small container unexpected or surprising.

A second experiment assessed, more directly, infants' attention to substance information. In this experiment, 8.5-month-olds were tested using the same procedure except that the ball the infants saw and touched prior to the test events was compressible. The infants now looked about equally at the small- and large-container test events, suggesting that they (a) recognized that the ball's ability to compress afforded squeezing into a smaller container and hence, (b) assumed that the ball could fit into either the small or the large container. Together, the results of these experiments suggest two conclusions regarding the cognitive processes underlying the differences in looking time. First, infants expect objects to maintain their property of substance across encounters and situations, and recognize when they fail to do so. Second, infants draw on information about object substance to make inferences about how objects can be used, and the actions they afford, within the context of physical events.

At the same time, these results raise interesting questions about the nature of infants' capacity to use size and substance information to interpret physical events. In the studies conducted by Aguiar and Baillargeon (1998) infants only needed to determine substance within a single modality—visual. One might wonder whether infants would evidence the same measure of success if they were required to coordinate substance information from different modalities. Infants' everyday experiences are multimodal—infants touch, mouth, smell, look at, and listen to the objects they encounter. Can, and how do, infants make use of these multimodal experiences? This question is the impetus for the present research.

Before we can address this question, however, we must answer the more fundamental question of whether infants are capable of intermodal perception of such information.

2. Intermodal perception in infancy

There is now increasing evidence that even young infants possess the capacity for intermodal perception. This capacity has been demonstrated with oral–visual (e.g., Gibson & Walker, 1984; Meltzoff & Borton, 1979), auditory–visual (e.g., Bahrick, 1987; Lewkowicz, 1996; Spelke, 1979; Walker-Andrews & Lennon, 1991), and tactile–visual (e.g., Rose, Gottfried, & Bridger, 1981a, 1981b; Streri, 1987; Streri & Pêcheux, 1986) information. In addition, infants' sensitivity to many different object properties, both amodal and modality-specific, have been explored.

One of the first demonstrations of young infants' capacity for intermodal perception of object form was reported by Meltzoff and Borton (1979). These authors presented 1-month-olds with either a nubby or a smooth pacifier to suck. The pacifier was then removed and the infants were shown two pacifiers: one that was nubby and one that was smooth. The infants looked reliably longer at the pacifier that they had orally explored, suggesting that they discriminated between the familiar and the novel form. These findings have been replicated in both human (Kaye & Bower, 1994; Pêcheux, Lepecq, & Salzarulo, 1988; but see also Maurer, Stager, & Mondloch, 1999) and non-human primate (Gunderson, 1983) infants.

Other studies have investigated infants' intermodal perception of object form using the tactile and visual modalities. There is evidence that infants 2–12 months of age demonstrate visual recognition of an object that was previously encoded tactilely (Gottfried, Rose, & Bridger, 1977; Rose et al., 1981a, 1981b; Ruff & Kohler, 1978; Streri, 1987; but also see Streri & Pêcheux, 1986), although younger infants need longer to encode the object in order to demonstrate success (e.g., Rose et al., 1981a, 1981b).

There has been considerably less experimentation on infants' intermodal perception of substance information. This is unfortunate because the tactile system is especially suited to the encoding of substance information, just like the visual system is especially suited to the processing of shape information (Klatzky, Lederman, & Reed, 1987). Identification of the conditions under which infants demonstrate intermodal coordination of object substance would have important implications for theoretical accounts of intermodal perception in infancy.

The research that has been conducted can be summarized in the following way. First, there is evidence that young infants can coordinate *oral*–visual information about object substance. Using a procedure similar to Meltzoff and Borton (1979), Gibson and Walker (1984) found that 1-month-olds detected whether information about object substance presented orally (e.g., infants sucked a rigid or a compressible object) was consistent with that presented visually, later (e.g., an object was seen deforming or remaining rigid). Second, there is some evidence that infants 4–12 months can coordinate *tactile*–visual information about object substance (Gibson & Walker, 1984; Streri & Spelke, 1988). For example, Streri and Spelke (1988) allowed 4- and 5-month-olds to manually explore an object that was either rigid or elastic (i.e., two rings connected with either a rigid bar or an elastic band). The rings were then removed and infants saw, on alternate trials, the object undergoing either a rigid or an elastic motion. The infants looked longer at the object that underwent the novel motion, suggesting that they detected the inconsistency in object substance.

Together, the research presented here suggests two general conclusions about infants' intermodal perception of object form and substance. First, young infants are capable of tactile-to-visual coordination of object form, but are more likely to succeed when simple geometric shapes are used and when they are given sufficient time to encode the object. Second, young infants are capable of tactile-to-visual coordination of object substance, although the conditions under which this occurs are not fully understood.

3. Present research

Clearly, size and substance are particularly important properties for interpreting events in which objects travel into containers or through openings. Research suggests that even young infants are sensitive to violations of these characteristics when presented with visual physical events (e.g., Aguiar & Baillargeon, 1998). It has yet to be determined, however, whether infants can display the same ability if information concerning size and substance is presented in different modalities.

The present research builds on and integrates previous research in physical reasoning and intermodal perception by examining infants' ability to use multimodal object representations to interpret physical events. We used a procedure similar to that of Aguiar and Baillargeon (1998) with two main differences: (1) infants saw a passing-through rather than a containment test event[1] and (2) infants were allowed to tactilely explore, but not see, the ball prior to the test event. Additionally, in light of recent evidence that by at least 6 month, infants can correctly assess whether objects can fit into containers of different sizes (Aguiar & Baillargeon, 1998, in press; Sitskoorn & Smitsman, 1995), and that by 4–5 months infants demonstrate tactile to visual coordination of substance information (Streri & Spelke, 1988), younger infants (5.5 months) than those examined by Aguiar and Baillargeon were tested. By this age, infants are able to sit upright so their hands are free to manipulate objects and the functional capacity of the tactile system (i.e., both transportation and identification of objects) is firmly established (Streri, 1987, 1991/1993).

Two experiments were conducted using the violation-of-expectation method. The first experiment assessed 5- and 6-month-olds' ability to judge whether a ball could pass through a tunnel whose opening was either smaller or larger than the circumference of the ball. The purpose of this experiment was to establish that 5.5-month-olds could detect the size violation used in the present experimental context and extend the results of Aguiar and Baillargeon (1998, in press) to passing-through events.

The second experiment examined whether giving infants tactile information about the substance of the ball, through the tactile modality alone, would influence their interpretation of the passing-through event. Prior to the test trials, infants were allowed to manually explore, but not see, the ball. For half of the infants, the ball was rigid; for the other half, the ball was compressible. The results of these experiments provide insight into how intermodal object representations are formed and used during the first year of life.

[1] We have opted to use two different terms to distinguish between containment events and passing-through events. While size and substance information is important for evaluating both containment and passing-through events, the two offer different affordances—containers for holding items and tunnels for traveling through. They also present different causal relations—objects can pass completely through a tunnel, but not a container. We do not test infants' differential understanding of these two types of events, but use different terms to maintain clarity.

4. Experiment 1

Experiment 1 examined 5.5-month-olds' ability to accurately judge whether a ball could fit through a tunnel in a passing-through event. In one condition (experimental condition), infants saw a test event in which a ball passed through a tunnel that was smaller than the circumference of the ball (Fig. 1). If infants (a) compare the size of the ball to the size of the tunnel and (b) correctly judge that the ball is too large to fit through the tunnel, then they should find this event unexpected. The looking times of the infants in the experimental condition were compared to those of infants tested in two additional control conditions. In one control condition, the tunnel was made larger (larger tunnel control condition), so that the tunnel's dimensions were greater than the circumference of the ball (Fig. 1).

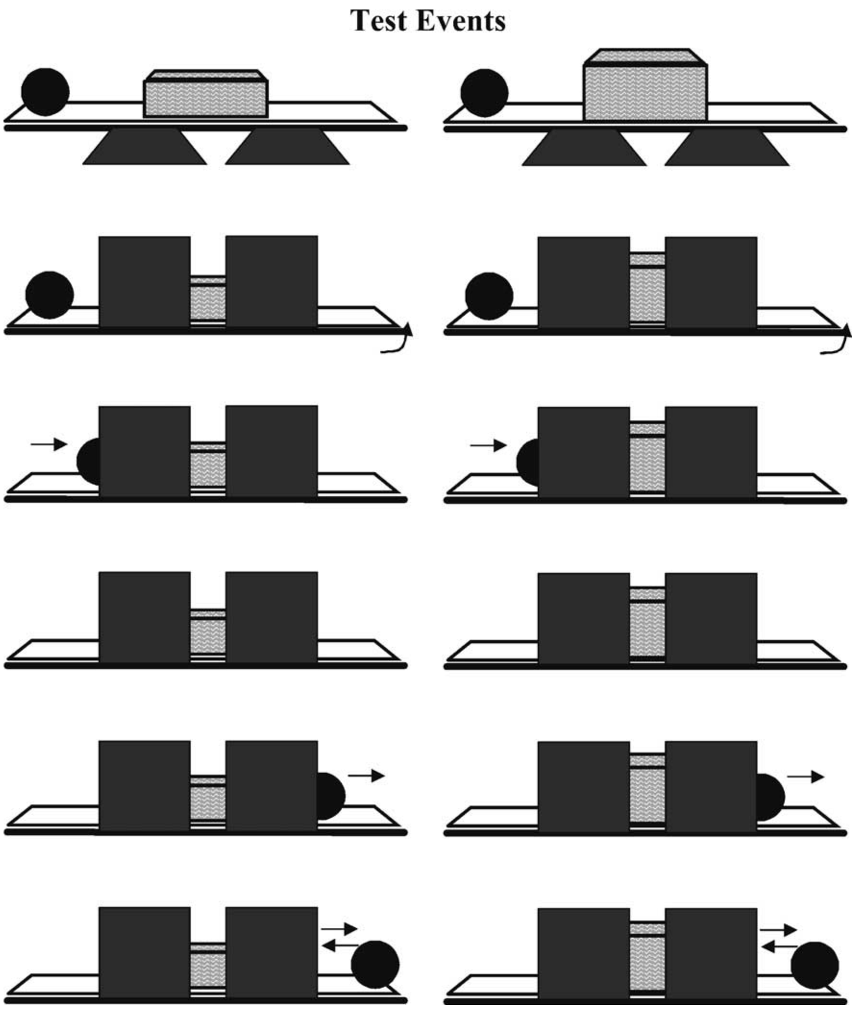

Fig. 1. Schematic drawing of the test events seen by the infants in the experimental condition (panel on the left) and the larger tunnel control condition (panel on the right) of Experiment 1.These are also the test events seen by infants in the small-tunnel and large-tunnel conditions of Experiment 2, respectively.

In the other condition, the size of the ball was reduced (smaller ball control condition) so that the ball's circumference was now less than the dimensions of the tunnel. If infants can correctly judge that the tunnel is sufficiently large to accommodate the ball, then they should find the control events consistent with their expectations. Hence, it is predicted that the infants in the experimental condition should look longer at the test event than the infants in the smaller ball and larger tunnel control conditions, and the looking times of the infants in the two control conditions should not differ from each other.

4.1. Method

4.1.1. Participants

Participants were 21 (10 male, 11 female) healthy, full-term infants ($M = 6$ months, 1 day; range $= 5$ months, 3 days to 6 months, 21 days). Eight additional infants were eliminated from the analyses because they failed to complete two valid test trials: two because of procedural error; two because they were distracted by a parent or sibling; one because the primary observer had difficulty following the direction of the infants' gaze; one because the infant was preoccupied with hiccups; and two because of fussiness. An equal number of infants were randomly assigned to the experimental, larger tunnel control, and smaller ball control conditions.

A between-subjects design was selected for each experiment because we were concerned that seeing one event (either experimental or control) would influence infants' perceptions of future events, especially since the events only varied by one characteristic (either size of the ball or size of the tunnel). Additionally, pilot research with a procedure similar to Experiment 2 suggested that infants grew tired after participation in one condition and failed to participate in a second condition.

In this and subsequent experiments the infants' names were obtained from birth announcements published in a local newspaper. Parents were contacted by letter and follow-up phone calls. They were offered reimbursement for their travel expenses but were not compensated for their participation.

4.1.2. Apparatus

The infants sat in a reclining infant seat mounted on a wooden table and faced a large, wooden, puppet-stage apparatus (213 cm high, 105 cm wide, and 43.5 cm deep) that had a front opening (51 cm high, 93 cm wide, and 31 cm deep) at eye level. The interior of the stage was cream-colored. The back wall was made of foam core board. To facilitate the insertion and removal of balls and tunnel pieces during test trials (see Section 4.1.4 below), two doors (12 cm^2) were located at the bottom of the back wall of the apparatus, 30.75 cm from both sides and 16 cm apart. They were hinged at the top so both doors could be opened from behind the apparatus. The dowel-handles of the large balls extended out of the back of the apparatus through two slits, each 1.5 cm high and extending 18 cm from each door, that were cut in the back wall 5 cm up from the stage floor. The slits were partially concealed with cream-colored fringe. A cream-colored platform (91 cm long, 19 cm wide, and 0.5 cm high) was placed lengthwise in the center of the stage floor, flush with the back wall. So that the objects moved smoothly and silently, a slip of blue flannel was glued down the center of the platform.

A muslin-covered frame 61 cm high and 100 cm wide was lowered to cover the opening in the front wall of the apparatus at the end of each pretest and test trial. Two wooden frames, each 213 cm high and 68 cm wide and covered with muslin, stood at an angle on either side of the apparatus. These frames isolated the infants from the experimental room and hid the observers from the infant's view. In addition to the room lighting, four fluorescent lights were attached inside each of the four walls of the apparatus above the stage.

4.1.3. Materials

The tunnel used in the pretest event of the experimental condition and the smaller ball control condition was made of cardboard, covered in wood grain contact paper, 28 cm long, 6.5 cm high, and 6.5 cm wide.

The tunnel used in the pretest event of the larger tunnel control condition was identical except that it measured 28 cm long, 11.67 cm high, and 11.67 cm wide.

The tunnels used in the test events were identical to those used in the pretest events, except that each tunnel was composed of two sections that broke apart to enable the experimental manipulation (see Section 4.1.4 below). The left section was 10 cm long and the right section was 18 cm long. There was a small handle on the back of the left section so that the experimenter could surreptitiously remove it after the screens were raised. When placed end-to-end, the two-section tunnel seen in the test trials appeared exactly like the one-section tunnel seen in the pretest trials.

Two balls per condition were required to produce each test event. The two balls used in the experimental condition and the larger tunnel control condition were 10.25 cm in diameter, made of Styrofoam, and covered in blue rayon. Each ball was glued to a small Plexiglas base that enabled it to move quietly and smoothly. The experimenter moved the balls by the use of a 19 cm long dowel rod that extended from the backs of the balls and through the slit in the stage back. The balls used in the smaller ball control condition were 5.08 cm in diameter and were also made of Styrofoam and covered in blue rayon. These balls were glued to a Plexiglas base (6 cm wide, 0.25 cm tall, 23 cm long) that extended out the back of the apparatus through a narrow gap between the back wall and the floor of the apparatus. The experimenter could grasp the extended part of the base to move the balls back and forth across the stage.

The two test screens, 20 cm^2, were made of yellow cardboard, and were connected by a 22.5 cm long dowel rod (1.2 cm diameter) at their bottom so that they were 8 cm apart. The screen set was attached to a long dowel rod that extended across the stage and through a small hole in the left wall of the apparatus; the experimenter could raise and lower the screens by turning the dowel. When the screens were raised, the two doors in the back wall of the apparatus and the ends of the tunnel were occluded from view.

4.1.4. Events

Three experimenters, who had undergone extensive training, worked together to produce the pretest and test events. The first experimenter wore white elbow-length gloves and moved the balls. The second raised and lowered the screens. The third surreptitiously inserted the second ball into the apparatus. The numbers in parentheses indicate the time taken to produce the actions described. A metronome ticked softly once per second to help the experimenters adhere to the events' scripts.

Events were identical in each condition with the exception of the sizes of the ball and the tunnel. Infants first saw a *pretest event* designed to acquaint them with the tunnel and the testing situation. Most importantly, we demonstrated that the tunnel was open at both ends, unobstructed, and made of a rigid material (because it maintained its shape when lifted). At the start of each pretest trial the tunnel sat on the platform with its left edge 27.5 cm from the platform's left edge. The screens were lowered to lay flat against the floor of the apparatus floor; the ball was not present. The first experimenter, whose arm entered the apparatus through a small door in the left wall, lifted the tunnel from the platform and turned it so that the right-hand opening faced the infant (1 s), then turned the tunnel approximately 30° to the left (1 s) and then 30° to the right (1 s) before returning the tunnel lengthwise on the platform (1 s). The experimenter then removed her hand (1 s) and the stage area remained empty until the end of the trial.

Next, infants saw a *test event* in which the ball appeared to move back and forth through the tunnel. At the start of each test trial, infants saw the tunnel on the platform and the ball sitting with its center 20 cm from the left edge of the tunnel. The two screens were lowered to the floor of the apparatus. After the infants looked at the display for 2 s, the screens were raised. After a pause (3 s), the ball moved to the right and disappeared behind the left screen (1.9 s). After the appropriate time given the object's rate of motion (2.2 s), the ball reappeared from behind the right screen, as if had traveled through the tunnel, and moved to the end of the platform (1.9 s). After a pause (1 s), the ball reversed direction and the actions of the previous 6 s were seen in reverse. The ball continued to travel back and forth in this fashion until the end of the trial. When in view, the ball moved at a rate of approximately 12 cm/s.

The illusion of passing through was accomplished in the following way. After the screens were raised, the first experimenter surreptitiously removed the left-most section of the tunnel through one of the doors in the back wall of the apparatus, so that the ball could sit to the left of the tunnel and still be hidden from view, and the third experimenter placed the second, identical ball to the right of the tunnel, behind the right screen, through the other door in the back wall. Hence, although from the infants' point of view it appeared as though one ball moved back and forth through the tunnel (whose ends were occluded by the screens), two separate balls were used to produce the event.

4.1.5. Procedure

The infant sat in the infant seat centered in front of the apparatus. The infant's head was approximately 68 cm from the front wall of the apparatus. The parent stood behind his or her infant during experimental session and was asked to refrain from interacting with the infant.

During the *pretest* phase of the experiment, infants saw the pretest event appropriate for their condition on two successive trials. Each trial ended when the infant looked at the display for a maximum of 60 s or looked away for one consecutive second after looking for a minimum of 5 s. During the *test* phase, the infants saw the test event appropriate for their condition on two successive trials. Test trials ended when the infant looked for a maximum of 60 s or looked away for one consecutive second after looking a minimum of 9 s (the time required for the ball to complete one trajectory, from when the screens were raised).

Infants' looking behavior during the pretest and test trials was monitored by two trained observers who watched the infants through peepholes in the cloth-covered panels on either side of the apparatus. Each observer held a game pad connected to a computer and depressed a button when the infant attended to the events. The looking times recorded by the primary observer (who was typically more experienced) determined when a trial ended and were used in the data analyses. Each trial was divided into 100-ms intervals, and the computer determined in each interval whether the two observers agreed as to whether the infant was looking or not. Interobserver agreement for the pretest and test trials was measured for 18 of the infants (for 3 of the infants only one observer was present) and was calculated for each trial on the basis of the number of intervals in which the computer registered agreement out of the total number of intervals in the trial. Agreement averaged 89.11 and 91.39% per trial per infant for the pretest and test trials, respectively.

4.2. Results

4.2.1. Pretest trials

The infants' looking times during the two pretest trials were averaged and analyzed by a one-way ANOVA with condition (experimental, larger tunnel control, or smaller ball control) as the independent variable. The effect of condition was significant, $F(2, 18) = 3.91$, M.S.E. $= 9.36$, $P < 0.05$. Post hoc analyses using Fisher's LSD tests revealed a significant pairwise difference between the two control conditions (larger tunnel, $M = 12.19$, S.D. $= 4.04$; smaller ball, $M = 7.67$, S.D. $= 1.71$; $t(18) = 2.77$, $P < 0.05$), but neither control condition differed significantly from the experimental condition ($M = 10.54$, S.D. $= 2.97$; larger tunnel, $t(18) = 1.01$, $P > 0.05$; smaller ball, $t(18) = 1.75$, $P > 0.05$). The pretest events seen by the infants in the two control conditions differed only in the size of the tunnel: a hand moved the large (larger tunnel condition) or the small (smaller ball condition) tunnel so that the infants could see inside of it. The tunnel seen by the infants in the experimental and larger tunnel control condition also differed in the size, yet those differences were not reliable. Hence, these results most likely reflect random sampling variation.

4.2.2. Test trials

The infants' looking times during the two test trials were averaged (Fig. 2). It was predicted that the infants in the experimental condition would look reliably longer at the test event than the infants in the two control conditions, but that the looking times of the infants in the two control conditions would not differ reliably from each other. To test these predictions, two planned contrasts were conducted. The results indicated that the infants in the experimental condition ($M = 36.28$, S.D. $= 17.52$) looked reliably longer at the test event than the infants in the two control conditions combined ($M = 22.44$, S.D. $= 11.83$), $F(1, 18) = 4.54$, M.S.E. $= 196.94$, $P < 0.05$; Cohen's f (effect size) $= 0.58$, a large effect (see Cohen, 1977). In contrast, the looking times of the infants in the smaller ball ($M = 19.44$, S.D. $= 11.04$) and larger tunnel ($M = 25.44$, S.D. $= 12.73$) control conditions did not differ reliably from each other, $F(1, 18) < 1.00$.

Due to small sample size, one might be concerned about parameter estimation. To compensate, the data were subjected to a rank-sum test, which is not dependent upon the underlying population distribution. Results confirmed the ANOVA in that scores in the experimental condition were higher than those in the other two conditions, $z = 2.09$, $P < 0.05$.

Finally, looking times in the pretest trials were not significantly correlated with looking times in the test trials, $r(19) = 0.34$, $P = 0.13$.

4.3. Discussion

The infants in the experimental condition looked reliably longer during the test trials than the infants in the smaller ball and larger tunnel control conditions, suggesting that the infants were surprised to see the large ball pass through the small tunnel (experimental condition), but recognized that if the ball was made smaller (smaller ball control condition) or the tunnel was made larger (larger tunnel control condition) the ball could be accommodated. Together, these results extend the positive results obtained by Aguiar and Baillargeon (1998, in press) and Sitskoorn and Smitsman (1995) to a different category of inclusion events—tunnel events—and provide converging evidence for the conclusion that young infants are sensitive to object size when interpreting physical events (Baillargeon, 1987b; Baillargeon & DeVos,

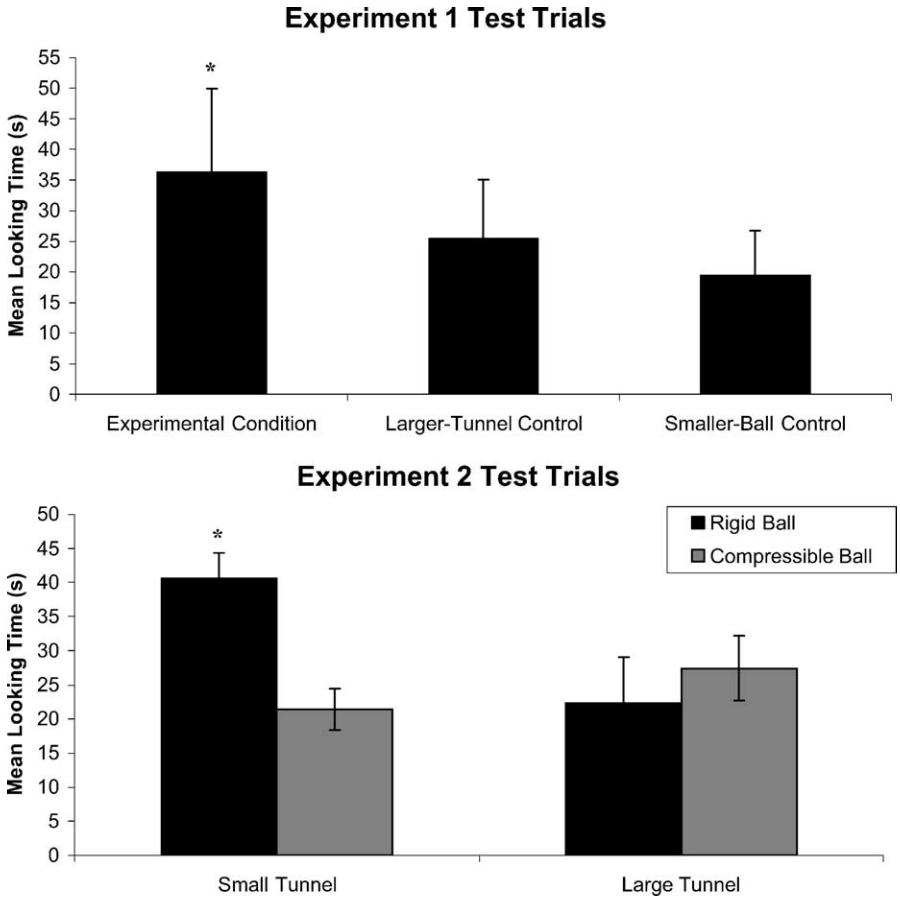

Fig. 2. Mean looking times and standard errors for the test trials Experiment 1 and Experiment 2.

1991; Baillargeon & Graber, 1987; Spelke et al., 1992; Wilcox, 1999; Wilcox & Baillargeon, 1998a, 1998b).

The next experiment examined whether infants' interpretation of the passing-through event would be altered if the infants were given tactile information about the objects' substance. More specifically, Experiment 2 assessed whether infants would respond differently to the experimental test event if it were revealed to the infants, through tactile exploration alone, that the ball was compressible.

5. Experiment 2

Experiment 2 examined infants' ability to draw on information about the substance of the ball (i.e., its rigidity or compressibility) acquired tactilely to inform their judgments about how the ball should behave in the passing-through event. As in Experiment 1, infants viewed passing-through events in which the tunnel was either smaller than (small-tunnel event) or larger than (large-tunnel event) the circumference of the ball (Fig. 1.) However, prior to viewing the test events, the infants in Experiment 2 received tactile exploration trials in which they were given tactile, but not visual, information about the ball's substance. During the tactile exploration trials the infants felt a ball that was either rigid or compressible. It is important to note that substance could not be determined visually; pressure was never applied to the balls during the test trials. In order for infants to consider substance information in their interpretation of the test event, they had to draw on their experience with the balls during the tactile exploration trials.

We reasoned that if the infants (a) perceive, based on the similarity in shape and size, that the object in the test events is the same as the one in the tactile trials, possessing the same substance; and (b) recognize that the compressible, but not the rigid, ball can fit through the small tunnel, then the infants in the small-tunnel rigid-ball condition should look longer at the test event than the infants in the small-tunnel compressible-ball condition. In addition, if the infants who see the large-tunnel event recognize that the large tunnel is sufficiently large for the ball to pass through unobstructed, regardless of whether it is rigid or compressible, then the infants in the large-tunnel rigid- and compressible-ball conditions should look about equally at the test event.

5.1. Method

5.1.1. Participants

Participants were 28 (14 male, 14 female) healthy, full-term infants ($M = 5$ months, 20 days; range $= 5$ months, 1 day to 6 months, 13 days). An additional 24 infants were eliminated from the analyses because they failed to complete two valid test trials: 8 because they saw the ball during tactile trials; 5 because of interference from a parent or sibling; 5 because of procedural error, 2 because the primary observer had difficulty following the direction of the infants' gaze; 2 because of fussiness; and 2 due to exceptionally long breaks before test trial began.[2] Infants were randomly assigned to one of four conditions formed by crossing tunnel (small or large) and substance (rigid or compressible).

5.1.2. Apparatus and materials

The apparatus and materials were identical to those of Experiment 1 with the following additions. During the tactile exploration trials, infants' hands were obscured from view with a large bib (90 cm long), made of white terrycloth. The bib was tied around the infants' necks and was large enough to cover the shoulders. At the bottom end, the bib was 126 cm wide and attached to the front wall of the apparatus so that it would not impede the observers' view of the infants' hands. Three lengths of boning added stability to the bib so it would not sag in the middle.

Two balls, one rigid and one compressible, were used during tactile exploration trials. The balls were matched in size (10.25 cm in diameter), weight (18.14 g) and surface texture (both covered with rayon) to each other and to the ball seen in the test trials. The rigid ball was made of Styrofoam and the compressible ball was composed of polyester fiber. The compressible ball was made in such a way that it took very little pressure to compress it. Simply, the weight of an infants' hand would deliver information about substance.

[2] This is a difficult procedure involving participation from several experimenters and the parent. It is not unusual for many infants to fail to complete the experiment or for parents to misunderstand the directions.

5.1.3. Events and procedure

The pretest and test events seen by the infants in the *small-tunnel* and *large-tunnel* conditions of Experiment 2 were identical to those seen by the infants in the experimental and larger tunnel control conditions of Experiment 1. Prior to the test events, however, the infants were allowed to freely manipulate, but not see, the ball appropriate for their substance condition (rigid or compressible). To maintain consistency, all test events involved the same balls (i.e., the rigid balls on the Plexiglas base) regardless of the substance condition to which infants were assigned.

During the tactile exploration trials, the infants sat in the infant seat centered in front of the apparatus (the same position they assumed during the pretest and test trials). The bib was placed around the infants' neck and attached to the front of the apparatus. The parents sat next to their infant and handed the infant the ball; they were asked to refrain from interacting with their infant. Pilot studies suggested that infants were less fussy when a parent stood nearby and handed the ball to the infant. Before beginning the experimental session, parents were carefully instructed on how to assist during the tactile exploration trials (e.g., how to surreptitiously remove the ball from under the infant seat, how to hand the ball to their infant, what to do if the ball dropped, etc.).

At the beginning of each tactile exploration trial, the parent handed the ball to the infant under the bib. If the infant refused to touch the ball, the parent was instructed to place the infant's hand on the ball, but to allow the infant to freely manipulate the ball once it was grasped. At the end of each trial, the parent removed the ball from the infant's grasp. Trials ended when the infant touched the ball for a maximum of 60 s or failed to touch the ball for two consecutive seconds after touching it for a minimum of 10 s. Infants received four successive tactile exploration trials. When the tactile exploration phase was completed, the parent returned the ball to its hiding place under the infant seat and the bib was removed.

The tactile exploration trials were videotaped through the use of a camera mounted beneath the stage. The camera allowed for an unobstructed view of the infants' hands through a hole, 7.5 cm in diameter, cut in the front of the apparatus, centered horizontally (63 cm from the floor), and observers could view the infant's hands via a video screen. A door could be shut to cover the hole during pretest and test trials to hide it from the infants' view.

Two trained observers, who watched the infants on the video screen, monitored infants' touching behavior during the tactile exploration trials in the same way that they monitored looking time during the pretest and test trials. The infant was considered to be touching the ball when any part of at least one of the infant's hands was in contact with the ball. Because the observers who watched the infant during the tactile exploration trials knew whether the infant had manipulated a rigid or a compressible ball, a different primary observer was used for the tactile exploration trials. The primary observer for the pretest and test trials was blind to which condition (both tunnel and substance) each infant was assigned.

For the tactile trials, interobserver agreement was measured for 20 of the infants (for 8 of the infants only one observer was present) and averaged 89.88% per trial per infant. For the pretest and test trials interobserver agreement was calculated for 24 infants and averaged 86.33 and 92.65%, respectively.

5.2. Results

5.2.1. Tactile exploration trials

The infants' touching times during the four tactile exploration trials were averaged and compared using a 2×2 ANOVA with tunnel (small or large) and substance (rigid or compressible) as between-subjects factors (Fig. 2). The main effects of tunnel, $F(1, 24) = 10.05$, M.S.E. $= 35.76$, $P < 0.01$, and substance, $F(1, 24) = 5.82$, $P < 0.05$, were significant. The infants in the large-tunnel condition ($M = 25.26$, S.D. $= 7.54$) touched the ball longer than the infants in the small-tunnel condition ($M = 18.09$, S.D. $= 5.16$). In addition, the infants touched the rigid ball ($M = 24.40$, S.D. $= 8.51$) longer than the compressible ball ($M = 18.95$, S.D. $= 4.76$). Importantly, the interaction between size and substance was not significant, $F(1, 24) < 1.00$; (small tunnel, rigid ball, $M = 20.03$, S.D. $= 6.48$; small tunnel, compressible ball, $M = 16.15$, S.D. $= 2.62$; large tunnel, rigid ball, $M = 28.77$, S.D. $= 8.38$; large tunnel, compressible ball, $M = 21.74$, S.D. $= 4.90$).

5.2.2. Pretest trials

The infants' looking times during the two pretest trials were averaged and analyzed in the same way as the tactile exploration trials. No effects were significant, for all $F(1, 24) < 1.00$, M.S.E. $= 47.17$, indicating that the infants in the four conditions did not differ reliably in their mean looking times during the pretest trials (small tunnel, rigid ball, $M = 12.47$, S.D. $= 3.48$; small tunnel, compressible ball, $M = 10.61$, S.D. $= 7.48$; large tunnel, rigid ball, $M = 11.90$, S.D. $= 5.20$; large tunnel, compressible ball, $M = 14.59$, S.D. $= 9.67$).

5.2.3. Test trials

The infants' looking times during the two test trials were averaged (Fig. 2) and analyzed in the same way as the tactile exploration and pretest trials. The main effects of tunnel size, $F(1, 24) = 1.67$, M.S.E. $= 157.57$; Cohen's $f = 0.22$, a small to medium effect, and substance, $F(1, 24) = 2.20$; Cohen's $f = 0.29$, a medium effect, were not significant, $P > 0.05$. The interaction between tunnel size and substance was significant,[3] $F(1, 24) = 6.53$, $P < 0.05$; Cohen's $f = 0.63$, a large effect. Planned comparisons indicated that the infants in the small-tunnel condition looked reliably longer at the test event after having felt the rigid ($M = 40.59$, S.D. $= 10.01$) as compared to the compressible ball ($M = 21.43$, S.D. $= 8.05$), $F(1, 24) = 8.15$, $P < 0.025$; Cohen's $f = 0.75$, a large effect. In contrast, in the large-tunnel condition, the infants who felt the rigid ($M = 22.34$, S.D. $= 17.55$) and compressible balls ($M = 27.43$, S.D. $= 12.54$) looked about equally at the test event, $F(1, 24) < 1$; Cohen's f is not computable as the variance accounted for by substance is less than that accounted for by error. Substance in the large-tunnel conditions accounts for only 1.67% of the total variance; whereas substance in the small-tunnel conditions accounts for 23.72% of the total variance. Given the small effect in the large-tunnel condition and the difference in amount of variance accounted for as compared to the small-tunnel condition, it is not likely that the failure to reject the null hypothesis is due solely to a small sample size.

Nonparametric tests confirmed these results. Overall, the ranks for the four groups were not identical, Kruskall–Wallis $H = 94.33$. In the small-tunnel condition, the scores were higher in the rigid condition

[3] Recall, however, that the infants demonstrated preferences in the tactile trials. To statistically control for the effects of touch time, the test data were also subjected to ANCOVA; the factors were the same as in the ANOVA, and the covariate was the infants' mean touch time during the tactile exploration trials. The main effects of tunnel, $F(1, 23) = 3.48$, M.S.E. $= 151.51$, $P > 0.05$, and substance, $F(1, 23) < 1$, were not significant. The interaction between tunnel and substance was significant, $F(1, 23) = 7.72$, $P < 0.05$. Planned comparisons, using adjusted means (i.e., means adjusted for touch time), confirmed that the infants in the small tunnel condition looked reliably longer at the test event after having touched the rigid ($M = 41.56$, S.D. $= 12.44$) as compared to the compressible ball ($M = 24.68$, S.D. $= 13.75$), $F(1, 23) = 6.58$, $P < 0.05$, whereas the infants in the large-tunnel conditions looked about equally at the test event (rigid, $M = 18.17$, S.D. $= 14.62$; compressible, $M = 27.39$, S.D. $= 12.31$), $F(1, 23) = 1.96$, $P > 0.05$.

than in the compressible condition, $z = 2.75$, $P < 0.01$. In the large-tunnel condition, the scores were not significantly different, $z = 1.09$, $P > 0.05$.

Finally, touch time in the tactile exploration trials was not significantly correlated with looking time in test trials, $r(26) = 0.12$, $P > 0.05$. Similarly, looking times in the pretest trials was not significantly correlated with looking times in the test trials, $r(26) = 0.12$, $P > 0.05$.

5.3. Discussion

When the tunnel was smaller than the circumference of the ball (small-tunnel event), the infants in the rigid-ball condition looked reliably longer at the passing-through test event than the infants in the compressible-ball condition. In contrast, when the tunnel opening was larger than the circumference of the ball (large-tunnel event), the infants in the rigid- and compressible-ball conditions looked about equally at the passing-through test event. These results suggest that the infants who saw the small-tunnel event (a) drew on information about the ball's substance acquired during the tactile exploration trials to interpret the test event; (b) recognized that the compressible ball could fit through the tunnel but that the rigid ball could not; and, hence (c) were surprised, in the rigid-ball condition, when the ball appeared to move unobstructed through the tunnel. Furthermore, the infants in the large-tunnel condition responded as if it did not matter whether the ball was rigid or compressible: either ball could fit through the tunnel.

It is important to point out that the test event seen by the infants in the small-tunnel conditions of Experiment 2 was identical, in every way, to the test event seen by the infants in the experimental condition of Experiment 1. The only difference in procedure between the two experiments was that in the former the infants were allowed to tactilely explore the ball prior to the test event. When the infants physically manipulated the rigid ball, they responded like the infants in the Experiment 1, but when the infants physically manipulated the compressible ball, they responded very differently. The finding that the infants' interpretation of the passing-through event changed markedly when the ball was compressible indicates that infants' tactile experiences with objects have a profound influence on how infants interpret physical events, even when the process requires intermodal integration of information.

6. General discussion

The present research examined, first, 5.5-month-olds' capacity to judge whether a large ball could fit through a small tunnel (Experiment 1) and, second, whether infants' interpretation of the passing-through event would be altered if they were presented, tactilely, with information about the ball's substance (Experiment 2). The results of both experiments were positive. Most importantly, the infants' pattern of looking suggested that they recognized that a ball whose circumference was larger than the tunnel opening could pass from one end of the tunnel to the other unobstructed if the ball was composed of a deforming substance, but not if the ball was composed of a substance resistant to pressure.

The present research is novel because it links together, and builds on, current research in intermodal perception (e.g., Gibson & Walker, 1984; Streri & Spelke, 1988) and physical reasoning (e.g., Aguiar & Baillargeon, 1998; Sitskoorn & Smitsman, 1995). The infants demonstrated the ability to draw upon previous tactile experience with the ball to interpret a passing-through test event that was presented visually. Several conclusions can be drawn about underlying processes responsible for these results. First, when viewing the test event, the infants had to determine whether the object they saw on the platform was the same object they had felt earlier. Presumably, the infants used the equivalence in shape to conclude that the two perceptual encounters—first tactile and then visual—involved the same object (similar to conclusions drawn by Gibson & Walker, 1984; Meltzoff & Borton, 1979). Second, once the two presentations were deemed equivalent, the infants had to retrieve information about the object that was not immediately apparent in the visual display, but that was necessary for interpretation of the passing-through event. The infants' response to the test events suggests that they successfully retrieved information about whether the object was composed of a rigid or a compressible substance. It is not likely that these results were due solely to perceptual preferences. We saw no evidence of a preference to view a passing-through event following exposure to a rigid, as opposed to compressible, ball, or to view events with different-sized tunnels or balls. Further, in Experiment 2, the visual events were identical across substance conditions.

There are probably a number of factors that contributed to the infants' success at coordinating the intermodal information. First, the infants were presented with an object that's shape was relatively easy to encode and identify, both tactilely and visually. We suspect that if the shape of the object were made more complex, it would be difficult for infants to determine whether the object they tactilely explored was equivalent to the object they saw on the platform (see Streri, 1991/1993 for a discussion; see also Klatzky et al., 1987 for a study of the salience of shape in the tactile modality). Second, the present experiments tested infants' capacity to form intermodal object representations using amodal information (i.e., information that can be detected by multiple modalities, e.g., shape and substance). A number of researchers have reported that infants are more likely to succeed at coordinating amodal than arbitrary, or modality-specific (e.g., color, weight, temperature) properties of objects (for reviews see Bahrick & Pickens, 1994; Walker-Andrews, 1994). We suspect that if the infants in the present experiments were required to draw on modality-specific information to interpret the test event (e.g., the color of the ball predicted whether it was rigid or compressible), rather than amodal information, they would experience much greater difficulty.

Perhaps of equal significance is that the current findings highlight the importance of substance information to infants' perception of how objects will behave or can be used. There is evidence that infants perceive object substance as stable over time and perceive that rigid objects move in ways that distinguish them from non-rigid objects (Gibson et al., 1978, 1979; Gibson & Walker, 1984; Walker-Andrews & Gibson, 1986; Walker et al., 1980). The experiments presented here join those of Aguiar and Baillargeon (1998) and Baillargeon (1987b) in demonstrating that young infants recognize that the substance of an object places constraints on what kinds of interactions it can have with other objects.

6.1. The underlying basis for infants' early sensitivity to substance information

What remains open to speculation is why young infants demonstrate sensitivity to substance information in tactile–visual tasks. One possibility is that these findings reflect early information processing biases. Following Leslie (1995), a number of investigators (Baillargeon & Wang, 2002; Kotovsky & Baillargeon, 1998; Wilcox, 1999) have argued that when building representations of objects, young infants focus on the spatial, temporal, and mechanical properties of objects; of most interest here is infants' attention to mechanical information. (Broadly speaking, mechanical properties refer to how force operates on objects and how objects interact through force.) Most relevant to the present discussion is that mechanical energy, or force, produces different outcomes on rigid as compared to compressible objects. The bias to attend to mechanical properties leads infants to be sensitive to how deforming and non-deforming surfaces might behave differently within the context of inclusion events.

Another possibility is that infants demonstrate sensitivity to substance information because resistance, or lack of resistance, of surfaces to deformation has implications for infants' behavior on objects. Put in different words, the property of substance affords different actions on objects. From an ecological perspective, Gibson and her colleagues (Adolph, Eppler, & Gibson, 1993; Gibson, 1969, 1988) argue that affordances, the match between what the environment has to offer and infants' behavioral capacities, is a driving force in infant perception and cognition. On this view, physical reasoning is the perception of object properties and what these properties mean in terms of how objects can be acted upon or used. Clearly, substance information plays an important role in this process.

Of course, it is possible that infants' early sensitivity to object substance reflects both the organization of physical knowledge and the importance of object properties to behavior. For example, a bias to attend to the mechanical properties of objects would lead infants to consider substance information in a variety of physical situations. In addition, physical situations that are of interest to the infant, especially those that involve infants' actions, provide a meaningful context in which to learn about the effect of mechanical energy on rigid and compressible surfaces.

7. Final comments

The world is composed of objects and events that provide multimodal stimulation. The present research adds to a growing body of evidence that young infants coordinate information from the sensory modalities to form intermodal object representations. More importantly, the present research sets the stage for new research that investigates how this information gets used as infants attempt to make sense of the physical world in which they live. It has become increasingly clear that infants view objects, and the actions that objects engage in, not as isolated incidents independent of other encounters, but instead as part of a continuous and ongoing series of connected events. It is the linking together of situations that allows infants to learn about their world. As we continue to explore intermodal perception and physical reasoning in infants, it will be important to identify the specific mechanisms that support the linking together of multimodal physical situations and the conditions under which these mechanisms operate.

Acknowledgements

This research was supported by a grant from the National Institute of Child Health and Human Development (HD-36741) to the second author. We would like to thank Catherine Chapa, Gevel Bruner, Roman Napoli, Carmen Nephew, Lisa Tuggy, Amy Waldrip, Rebecca Woods, and the undergraduate assistants of the infant cognition laboratories at Texas A&M University and The University of Texas at Arlington for their help with data collection. We would also like to thank the parents who kindly agreed to have their infants participate in the research.

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