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Development of Object Control in the First Year: Emerging Category Discrimination and Generalization in Infants' Adaptive Selection of Action

Clay Mash,

Child and Family Research, *Eunice Kennedy Shriver* National Institute of Child Health and Human Development

Marc H. Bornstein, and

Child and Family Research, *Eunice Kennedy Shriver* National Institute of Child Health and Human Development

Abhilasha Banerjee

Georgetown University

Abstract

This research examined the development of adaptive generalization in infants' object-directed actions. Infants of 9 and 12 months participated in an object manipulation task with stimulus objects comprising two categories that differed in shape and weight and that bore a consistent shape/weight correspondence. Weight differences between categories affected infants' actions required to handle objects effectively. Infants manually explored objects from both categories and then were tested for their selection of different actions between categories and their generalization to novel exemplars within categories. Nine-month-olds provided no evidence of category differentiation and generalization, however 12-month-olds adapted their actions selectively for objects of each category and generalized those actions to novel objects within categories. A second sample of 9-month-olds who were examined in a simplified task using just one object per weight level successfully adapted their actions by weight. Together, the findings provide evidence for the development of selection and generalization in manipulative action across the second half of the first year of life.

Keywords

action selection; categorization; infancy; motor control; generalization

Object control is a core aspect of human adaptation (Rosenbaum, Chapman, Weigelt, Weiss, & van der Wel, 2012), and descriptions of adult behavior estimate the frequency of object-directed actions on the order of several hundred each day for most people (e.g., Zheng, De La Rosa, & Dollar, 2011). Although taken for granted by healthy adults, every individual action, such as lifting a glass to drink, requires the precise selection and coordination of a

large number of parameters. Additionally, the specific sizes, spatial positions, and orientations of reach targets are rarely identical on any two occasions. This state of constant flux in the relation between individual and environment requires continuous online control of action.

When considering adaptive behavior beyond discrete individual actions, it is clear that effective actions also depend on systematic generalizations over dramatic variations in input (e.g., Poggio & Bizzi, 2007). Absent this ability, every act would require the exploration of infinite possibilities, the compilation of all relevant parameters, and the assembly of actions from scratch. The robust categorical organization of a typical adult's action indicates easy transcendence of this requirement: When visiting a new restaurant for the first time, most adults will ease into whatever chair is offered without first needing to explore what it might be used for. "Categorical" in this context refers to discriminable in appearance and identity yet equivalent in treatment and function. The categorical organization of knowledge and action is widely held as the core of intelligent behavior, and decades of research have detailed the characteristics of category learning and use in many contexts (see Bornstein, 1984; Murphy, 2002; Smith & Medin, 1981).

Origins and Early Development of Object Control

The computational complexity of visually guided object-directed action is even more striking when considered in relation to the strict motoric limitations of infants. The arm movements of newborns consist of little more than reflexive flapping, and the first signs of successful reaches that result in contact with target objects typically do not emerge until around 4 months of age (e.g., Thelen, Corbetta, Kamm, Spencer, Schneider, & Zernicke, 1993; von Hofsten, 1979). A critical and vitally adaptive change occurs subsequently with the emergence of infants' online control of object-directed action later in the first year (Lockman, Ashmead, & Bushnell, 1984; McCarty, Clifton, Ashmead, Lee, & Goubet, 2001). The generalization of action selection, however, has rarely been the focus of research on infants or young children.

One of the few studies to examine generalization of action selection in infants was reported by Hayne, Rovee-Collier, and Perris (1987), who used a conjugate reinforcement task to investigate category guidance of object-directed actions in 3-month-olds. In this work, infants demonstrated category discrimination and generalization through leg kicks when responses were systematically conditioned (see also Greco, Hayne, & Rovee-Collier, 1990). The reliance on behavioral conditioning in these studies, though, leaves open many remaining questions about learning and performance under more natural, untutored circumstances.

Other investigators have examined action generalization through infants' imitation of object-directed actions. In that work, experimenters modeled schematic manual actions on objects for infants ranging from 9 to 16 months of age and then examined which objects infants selected to imitate the actions (Baldwin, Markman, & Melartin, 1993; Mandler & McDonough, 1996; McDonough & Mandler, 1998). Although this selection for imitation reveals categorical organization of action early in life, it does so only for the actions

modeled and also leaves uncertain any extension to spontaneous behavior in natural contexts.

Present Concern

Within their first year, infants appear capable of adaptively generalizing actions under the highly structured and supportive conditions such as those provided in past research. As infants gain independence with maturity and mobility, the demands for adaptation rapidly exceed such structured conditions. With the developmental course of both motor control and cognition being protracted over many years, when might adaptive generalization of action emerge? In the present work, we used a conservative approach to address this question by testing infants' ability to detect, learn, and use a nonobvious affordance for action: object weight.

Effective object handling depends critically on the accurate scaling of actions for the weight of objects handled. Inadequate adaptation to weight yields erratic control (see Jenmalm, Schmitz, Forssberg, & Ehrsson, 2006). This circumstance is further complicated by the following fact: Unlike visually specified affordances for handling, such as size and shape, an object's weight is at best only partially specified by visual cues. Thus, reliance on experience and knowledge, in addition to online visual cues, is often necessary to guide the control of actions on objects whose weight normally varies over instances (e.g., glasses, boxes, suitcases).

In one early study, Mounoud and Bower (1974) examined the development of experience-driven weight adaptation in infants' object control. Stimulus objects consisted of solid brass rods varying in length, with longer ones weighing more than shorter ones. Infants 6 to 18 months old were presented each rod while their grasping and lifting were recorded. After infants were familiar with the objects, they were presented with a test object the same length as one of the heavier familiar ones, but which was hollow and so weighed substantially less. By 9 months of age, infants' lifts of the lighter test items were characterized by overshoots, revealing they had used greater force to lift objects appearing exactly like those that had been heavier before. In the present work, we examined weight adaptation under similar circumstances to investigate infants' developing ability to adaptively select actions for unfamiliar objects and to do so in a categorically organized manner without the support of the highly structured task contexts used in categorization studies noted above. In Experiment 1, infants of two ages were provided experiences with two contrasting categories of novel objects. We used wholly novel objects to examine the organization and use of information as it is acquired in real time. The objects differed between categories in shape and in weight, and they differed within categories in color and texture pattern. On test trials involving yet-unseen novel exemplars, the familiar shape/weight correspondence was reversed. If infants adaptively generalize their actions for a specific weight level on seeing a novel exemplar of a familiar shape category, then an unexpected shape/weight correspondence reversal would result in erratic transport due to the inadequate or excessive force used for lifting.

Experiment 1

Method

Participants—Twenty-six infants participated at 9 months of age ($M=39.02$ weeks, $SD=2.29$; 15 males, 11 females), and 26 participated at 12 months ($M=51.75$ weeks, $SD=1.17$; 14 males, 12 females). The families' SES was predominantly middle to upper-middle class; they were primarily of non-Hispanic ethnicity, and were distributed racially as 6% African American, 10% Asian American, and 84% European American. An additional 9 infants participated, but were not included due to fussiness and/or inattention (6) or technical problems (3).

Stimuli—Stimuli consisted of 10 simple, novel objects comprising 2 distinct shape categories. Five of the objects (henceforth referred to as “cones”) were composed of transparent plastic shaped as a frustum of a cone and measured 5.0 cm in height, 6.0 cm in diameter at the bottom, and 4.5 cm in diameter at the top (see Figure 1A). The cones were stuffed with tissue paper of a single color. Stimuli differed in color and texture pattern across exemplars. The other 5 objects (henceforth referred to as “bricks”) were shaped as a rectangular prism, measuring $4.5 \times 4.5 \times 6.0$ cm, and also made from transparent plastic and stuffed with paper differing in color and texture across exemplars (Figure 1B).

Six of the objects – 3 from each category – served as familiarization stimuli and varied consistently between categories in weight. The light objects weighed 10 g (the weight of 2 nickels), and the heavy objects weighed 185 g (nearly the weight of a roll of 40 nickels). The weight of the heavy objects was increased relative to the light ones with the addition of hidden lead weights which were wrapped inside the tightly stuffed paper and hidden from view.

Four additional objects differing in color from familiarization stimuli served as test stimuli. There were two types of test stimuli at each weight level: consistent and inconsistent. Consistent test objects (1 from each category) had the same shape/weight correspondence as the familiarization stimuli. Inconsistent test objects had the opposite category/weight correspondence as the familiarization set.

Apparatus—An electromagnetic motion analysis system (Ascension Technologies, Inc., Burlington, VT) was used to measure infants' exploratory actions during the task. The system consisted of an electronics unit that was connected to an electromagnetic transmitter, two small sensors (MiniBirds™), and a computer running MotionMonitor™ (Innovative Sports Training, Inc., Chicago, IL) experiment control software. The movement sensors were connected to the electronics unit by slender cables. A Sony digital video camera was used to record infants' reaches and object transports during the task. The camera's field of view was zoomed in on the stimulus presentation zone enabling clear judgments about object transfer for subsequent coding. The motion data stream was synchronized to the video record by calculating the recording offset and aligning the two data series using purpose-designed software settings.

Procedure—Infants were seated in an infant seat facing the experimenter. After securely attaching a sensor to the underside of each wrist using 3M Vetrap™ tape, a long-sleeve shirt was put on the infant to restrain and hide the sensor cables. The experimenter then handed the infant the stimulus objects in seriatim to explore for 10 s each over a series of 14 trials. Objects were presented on the experimenter's palm at infants' midline to enable free movement both above and below the level of the infant's grasp. The experimenter's hand position at stimulus presentation was standardized over trials and sessions using landmarks on the presentation table.

The task was composed of two blocks of trials. The first block consisted of 6 familiarization trials in which infants were presented with a different familiarization object for 10 s on each trial, 3 from each category (see Figure 2A). Objects were presented in a pseudorandom order that included no more than 2 consecutively from the same category. Immediately after the 6th familiarization trial, 2 test trials were presented, one involving a consistent test stimulus and the other involving an inconsistent test stimulus of the same weight level (e.g., light). Trials were timed with a digital timer, and at the end of 10 s the experimenter retrieved the object from the infant and removed it from view before presenting the next object.

The second block began immediately after with a reinstatement of the familiarization standards (Figure 2B). Over 4 trials, 2 familiarization standards from each category were reintroduced to reinstate the familiar category/weight correspondence. The 2nd pair of test trials was then presented and was structured like the 1st pair, but differed from the 1st pair in weight level (e.g., if the 1st pair was light, the 2nd pair was heavy).

Over the course of each trial, the 3D coordinate position of infants' wrists was recorded at 100 Hz. All objects except for the one in use on any given trial remained in a box and hidden from view throughout the rest of the session. The category/weight correspondence and weight levels for the 1st and 2nd test pairs were counterbalanced, and the objects serving as test items were randomly assigned for each session.

Data reduction—Position data were digitally filtered with a fourth-order, zero-lag Butterworth filter using a 10 Hz cutoff frequency (see Robertson, Caldwell, Hamill, Kamen, & Whittlesey, 2004). The transport interval of each trial was a 0.50-s window beginning when the object was first lifted. To identify the beginning of each transport interval, videorecords were coded frame-by-frame to identify the first frame in which the object was no longer in contact with the surface of the experimenter's hand as the infant lifted it.

This interval was selected for analysis because it reflects infants' anticipatory actions that precede their detection of the actual weight of the objects once lifted. Coders were blind to study hypotheses and were not the experimenters who collected the data. The reliability of the phase coding was assessed in relation to a second coder who coded 25% of the sessions. Ninety-six percent of the object transports coded twice differed between coders by no more than 0.15 s in onset time. A digital event marker was used to insert the temporal boundaries of each coded transport phase into the motion data stream. Although many reaches were bimanual, only data from the hand reaching the object first (or first on most trials in cases of simultaneous contact) were analyzed for each trial.

Design rationale—In the context of the present task, we operationalize categorization as the selection – for adapting action – of features that are invariant within, and different between, internally varying categories. Because the stimuli are similar in size and material between categories, their visually specified affordances for action are essentially equivalent. However, because members of one category weigh considerably more than those of the other, the heavier ones require different actions for effective transport. Scaling actions discriminatively for the objects' discrepant affordances requires that infants learn and internally represent the category/weight correspondence that they experience during the familiarization phase. The present design enables a test of this learning and transfer by comparing outcomes of actions associated with different weight expectations while actual weight is held constant (i.e., by comparing transport of “light consistent” to “light inconsistent” objects, and “heavy consistent” to “heavy inconsistent” objects).

Specifically, if infants can selectively scale and generalize their actions categorically, then seeing objects that resemble heavy ones they handled before may cue preparation of force for lifting a heavy object. Such actions would result in erratic transport when applied to an object that instead is light. Likewise, if infants categorically generalize specific action plans for the lighter weight of the light familiarization stimuli based on their experience with them, inadequate force may be used to lift the heavy inconsistent objects resulting in erratic transport. These outcomes would provide clear evidence for category generalization because the objects presented on test trials are completely novel, not having been seen or handled during the familiarization phase.

Transport measures—Efficient and effective movements are smooth through space and time (e.g., Berthier, Rosenstein, & Barto, 2005; Hogan & Flash, 1987; Wolpert & Gahrahani, 2000), while erratic ones are not. Transport smoothness was examined using two measures of performance. First, the linear smoothness of each transport was measured by calculating a least-squares linear function through the spatial coordinates of each trajectory. The goodness of fit of the linear function to the actual trajectory of transport was indexed by the norm of residuals, calculated as the square root of the sum of squared residuals of the linear fit. Greater values reflect more and larger deflections from a linear path in the transport of an object and are interpreted to reveal more erratic control of the object.

In addition to their spatial trajectories, object transports were also examined as a function of time. Toward this end we calculated and examined movement jerk, the 3rd derivative of position change over time, reflecting the rate of change in movement acceleration. Minimal jerk is a defining attribute of efficient manual actions (e.g., Hogan and Flash, 1987), and jerk has been used in studies of the early development of reaching and grasping (Berthier & Carrico, 2010; Lee, Ranganathan, & Newell, 2011). Notably, movement jerk diminishes with increasing development of motor control (Berthier & Keen, 2006) and increases with neurological compromise of the motor system (Smith, Brandt, & Shadmehr, 2000). Presently, jerk was derived from position change over each axis of the 3D measurement space, and a resultant vector was calculated by combining the axis vectors. Resultant jerk was then averaged over the entire transport providing a single value for each trial. Larger magnitudes of jerk in object transport are taken to reveal more erratic control of the object.

With both measures, evidence for categorical organization of action preparation is provided by a difference between consistent and inconsistent test trials.

Data analysis—Because test-trial performance is compared between categories within weight levels, baseline comparisons were conducted first to ensure there were no preexisting differences between categories in infants' handling of the objects. If objects of one category are in any way more difficult to handle effectively, transport at baseline should be more erratic. Baseline performance was compared between the first exemplars encountered from each category. If infants use very similar object-directed actions between the two categories, any differences observed in test-trial comparisons can be interpreted to depend on experience acquired during the familiarization phase of the task. Performance across the familiarization phase was then compared between successive trials at each weight level.

Category discrimination and generalization are examined in test-trial comparisons. If infants are able to differentiate their actions for objects of different shape/weight categories and generalize from experienced objects to novel ones, they should scale actions discriminatively for the previously unseen test objects of different categories, and doing so will lead to different outcomes between test conditions. Because we wanted to examine performance age specifically, and our samples were relatively large at each test age, we conducted analyses separately for each age group. Because the distributions of data for both measures were positively skewed, all values were log transformed for statistical analysis.

Results

Figure 3 presents examples of transport trajectories by trial condition and weight level, and the measure values associated with them.

Nine-month-olds

Baseline and familiarization: There was no baseline difference in transport linearity between cones ($M=2.67$, $SD=1.09$) and bricks ($M=1.82$, $SD=1.25$), $F(1,25)=0.29$, *ns*, and no baseline difference in transport jerk (cones, $M=3.21$, $SD=0.79$; bricks, $M=3.36$, $SD=0.61$), $F(1,25)=0.70$, *ns*. Infants' performance across the six familiarization trials was examined with ANOVAs that included planned contrasts of successive trial sequence positions (1st, 2nd, 3rd) within weight level (light, heavy) as within-subjects factors. The analysis of linearity revealed no significant effects (see Table 1). The analysis of jerk revealed greater jerk on the 2nd than on the 1st familiarization trial across weight levels, $F(1,24)=5.25$, $p=.03$, $\eta^2_p=.18$. No other effects were significant.

Test trials: Category discrimination and generalization were examined by comparing transports between test trial conditions (consistent, inconsistent) and weight levels (light test pair, heavy test pair). Mean norm linear residuals for the test trials are presented in Figure 4A, and mean jerk values are presented in Figure 5A. The analysis of transport linearity revealed no difference between consistent and inconsistent trials, $F(1,25)=0.78$, *ns*. Likewise, the analysis of transport jerk revealed no difference between test conditions, $F(1,25)=1.73$, *ns*, providing no evidence in either analysis for category generalization at 9 months of age.

Twelve-month-olds

Baseline and familiarization: Infants at 12 months also handled objects similarly between categories at baseline; there was no baseline difference in transport linearity between cones ($M=2.30$, $SD=1.26$) and bricks ($M=2.38$, $SD=1.04$), $F(1,25)=0.34$, *ns*, and no baseline difference in transport jerk (cones, $M=3.70$, $SD=0.75$; bricks, $M=3.88$, $SD=0.89$), $F(1,25)=0.91$, *ns*. Across the familiarization phase, there were no differences between weight levels or trials either in transport linearity, $F(1,25)=2.97$, *ns*, or in jerk, $F(1,25)=2.16$, *ns*.

Test trials: Mean norm linear residuals for the test trials are presented in Figure 4B, and mean jerk values are presented in Figure 5B. The analysis of transport linearity on test trials revealed larger norm residuals on inconsistent trials than on consistent ones, $F(1,25)=6.21$, $p=.02$, $\eta^2_p=.20$. Likewise, movement jerk was greater in infants' transport of inconsistent test objects, $F(1,25)=5.90$, $p=.02$, $\eta^2_p=.19$. Unlike infants at 9 months, infants at 12 months provided evidence of organizing experience with contrasting categories and generalizing to novel exemplars in their selection of actions on them.

Age differences—To directly test the age difference in category generalization implied by the pattern of results in the age-group analyses, the percentages of increase in infants' erratic transport from consistent to inconsistent trials were compared between age groups, weight levels, and measures. There was a main effect of age group with 12-month-olds demonstrating greater increase on inconsistent trials than 9-month-olds across measures and weights, $F(1,50)=5.43$, $p=.02$, $\eta^2_p=.10$. There was also a significant interaction between age group and measure, with 12-month-olds outperforming 9-month-olds more with respect to transport linearity than transport jerk, $F(1,50)=5.62$, $p=.01$, $\eta^2_p=.12$.

Discussion

Infants 9 months of age provided no evidence of category discrimination and generalization in the task used presently; infants at 12 months did. Twelve-month-olds' handling of objects similar to others they had previously experienced at one weight level was erratic when the objects weighed different amounts. Specifically, 12-month-olds' transport trajectories deflected further and more often from linear paths in lifts of inconsistent objects, and acceleration changed less smoothly in time. Infants' uniform handling of objects between categories at baseline indicates they learned handling affordances by category during familiarization, and they generalized actions accordingly to novel instances at test. Because the stimuli were novel prior to the task, infants appeared to learn the shape/weight correspondence during familiarization. The adaptation observed in test trials was not explicitly predicted by measurable adaptation during the familiarization trials, as no significant effects were observed at 12 months. This relative stability suggests that learning the objects' affordances for handling occurred gradually over the familiarization phase rather than instantaneously. By 12 months, infants appear to be capable of learning nonobvious object affordances, and generalizing their selection of appropriate actions for novel objects in a categorically organized manner.

When compared to 12-month-olds, 9-month-olds demonstrated significantly less adaptation of their actions during the test phase. This age difference leads to the question of what exactly is developing. We addressed this question in a second experiment.

Experiment 2

In very general terms, the demands of the task used in Experiment 1 tap skills in at least 2 different domains: category detection and representation on the one hand, and sensorimotor weight adaptation on the other. Limitations at 9 months in either domain could account for the different categorization outcomes observed between 9 and 12 months in the task used.

With respect to category detection and representation, previous findings suggest the possibility that infants at 9 months may not yet be able to construct the categories that were necessary for guiding action in the present task. Research has revealed several important advances in infants' categorization abilities over the second half of the first year (e.g., McDonough & Mandler, 1998; Younger & Cohen, 1986). With respect to sensorimotor capacities, infants' developing abilities to differentiate objects by weight and adapt their actions accordingly could also impose limitations at younger ages. Indeed, several aspects of motor planning in service of object control appear to develop gradually over a time course spanning the first several years of life (Forssberg, Kinoshita, Eliasson, Johansson, & Westling, 1992; Mash, 2007).

If 9-month-olds were limited by category learning per se, rather than the sensorimotor demands of the task, then they should perform better in a similar task that does not involve categorization. If, however, 9-month-olds were limited more by sensorimotor weight adaptation, they would likely fail in other similar, experience-dependent tasks irrespective of categorization demands. Experiment 2 was conducted to test these alternatives. An additional sample of 9-month-olds participated in a task in which they were familiarized to only two objects of the same shape but different colors and weights before being tested with a correspondence reversal. This task required the same weight-specific action selection as Experiment 1, but only required discriminating two objects rather than differentiating and generalizing two categories of objects.

This experiment also provides an opportunity to strengthen the interpretation of Experiment 1. Object categorization is typically defined as the treatment of *discriminable* objects as equivalent (e.g., Quinn & Eimas, 1986). Despite our having used contrasting colors and visual textures among exemplars within each category, it is possible that infants may have failed to distinguish objects within categories. If so, the 12-month-olds may merely have discriminated two values of a single dimension (e.g., curved vs. flat surfaces) rather than forming two cohesive and inclusive categories of distinct objects. Evidence for categorization is therefore strengthened by evidence of exemplar discriminability within the same task context. Experiment 2 was designed to provide this information also.

Methods

Participants—Twenty-six infants were examined at 9 months of age ($M=35.96$ weeks, $SD=2.41$; 11 males, 15 females). An additional 7 infants participated, but were not included due to fussiness and/or inattention.

Stimuli and apparatus—The stimuli and apparatus were the same as those used in Experiment 1. For each session, 2 stimuli from the same shape category but different weight levels (standard objects) were used in familiarization and in consistent test trials, and 2 visually identical stimuli bearing the reversed color/weight correspondence (inconsistent test objects) were used for inconsistent test trials.

Procedure—The task was structured much like that in Experiment 1, consisting of 14 10-s trials distributed over two blocks. The first block consisted of 6 familiarization trials in which infants were presented with one of the 2 different familiarization objects on each trial (see Figure 6A). Immediately after the 6th familiarization trial, 2 test trials were presented, one involving a consistent test stimulus and the other involving an inconsistent test stimulus of the same weight level (e.g., light). The second block began immediately after with a 4-trial reinstatement of the familiarization standards (Figure 6B). The familiarization stimuli were reintroduced to reinstate the familiar color/weight correspondence. The 2nd pair of test trials was then presented and was structured like the 1st pair, but differed from the 1st pair in weight level (e.g., if the 1st pair was light, the 2nd pair was heavy). As before, stimuli were taken from the infant and removed from view before a subsequent trial was initiated. Half of the infants were presented with cones, and the other half with bricks.

Results

Familiarization—Because each infant in the present task experienced exemplars from only one category, the baseline category contrasts conducted in Experiment 1 were unnecessary. An ANOVA was conducted to examine performance across the familiarization phase by trial and weight level. There were no differences between weight levels or trials in transport linearity, $F(1,25)=0.11$, ns (see Table 1). In the analysis of transport jerk, there was a main effect of weight level, with greater jerk observed in infants' transport of heavy objects, $F(1,25)=11.74$, $p=.002$, $\eta^2_p=.34$.

Test—Object discrimination was examined by comparing transport measures between test trial conditions (consistent, inconsistent) and weight levels (light, heavy) within subjects and categories (cones, bricks) between subjects. If infants can differentiate objects and their associated affordances for handling, transport outcomes should differ between consistent and inconsistent trials across weight levels and categories. Norm linear residuals were significantly greater on inconsistent ($M=3.45$, $SD=0.85$) than consistent trials ($M=3.02$, $SD=0.90$) across weight levels and categories, $F(1,25)=4.16$, $p=.05$, $\eta^2_p=.15$. Transport jerk was also greater on inconsistent ($M=5.67$, $SD=0.62$) than consistent trials ($M=5.33$, $SD=0.60$) across weight levels and categories, $F(1,25)=4.98$, $p=.04$, $\eta^2_p=.17$.

Discussion

Infants at 9 months detected the object/weight correspondence of the familiarization objects and adaptively selected actions in the test trials. This pattern of results indicates that 9-month-old infants in Experiment 2 were not limited by an inability to differentiate actions by experienced weight differences. Thus, something other than the general sensorimotor demands of the task was limiting 9-month-olds in Experiment 1, and we return to that issue in the General Discussion.

The effect of weight on transport during the familiarization trials of Experiment 2 was intuitively consistent given the substantial weight difference and the novelty of the objects. This result raises the question of why the same effect was not observed in the familiarization trials of Experiment 1. One possibility is that the greater similarity of objects seen in Experiment 2 resulted in a stronger expectation that they would weigh the same amounts. This equivalency would result in greater compromise of transport when a different weight was encountered. Seeing a different object on most trials in Experiment 1 may have induced less uniform expectations.

Finally, the results of Experiment 2 also reveal that infants are capable of distinguishing among exemplars within the same categories used in Experiment 1. This finding confirms the initial conclusion that 12-month-olds in Experiment 1 categorized the stimulus objects while exploring them.

General Discussion

Infants' spontaneous actions on novel, discriminable objects from two contrasting shape/weight categories were measured in fine spatiotemporal detail. Baseline handling of the objects was equivalent between categories. Following a modest amount of experience, 12-month-old infants, but not 9-month-olds, differentiated transport actions for different objects on a weight-specific basis and generalized those actions categorically to previously unseen objects. Between categories, the objects were of very similar size and material, but had different handling demands due to a substantial weight difference. Infants of 12 months appear to have detected this weight variability across individual stimuli, as well as the correspondence between weight and shape, and selectively scaled lift forces for different categories even when the categories' visually specified affordances for action were equivalent. Without online sensory evidence of weight differences from visible size or material differences, the 12-month-olds must have relied on experience with the categories and their hidden affordances for handling to guide their selective action planning. By the end of their first year, infants appear capable of rapidly acquiring and generalizing category experience and knowledge to selectively optimize actions for objects that they have never previously seen or handled.

Participating in the same task, 9-month-olds provided no compelling evidence for categorical generalization of object-directed actions. The same pattern of contrasting results between age groups was observed over separate analyses and over two independent performance measures. When a second sample of 9-month-olds was examined in a simpler object discrimination task, however, they successfully differentiated actions for different

objects following a brief familiarization phase. This finding suggests that the less systematic performance of 9-month-olds in Experiment 1 was not due to sensorimotor limitations in general, but appears to be associated more specifically with category formation and use in the execution of actions.

Task Demands

An alternative explanation of the performance disparity in 9-month-olds may be that Experiment 1 imposed on them a greater processing load than Experiment 2. In Experiment 1, infants were exposed to several different visually distinctive objects of 2 contrasting shapes, whereas those in Experiment 2 had only 2 visually distinctive objects of 1 shape to process. In these ways, Experiment 2 could have been easier with respect to task demands. However, this interpretation must be evaluated in the context of decades of research demonstrating robust perceptual categorization by infants even in the first months of life. Infants as young as 2 months visually categorize objects more complex and dissimilar than those used here (Quinn & Johnson, 2000). Assembling sensory information into categorical memories appears to be a basic part of infants' abilities from near the beginning of life. The role of processing load could be tested directly by examining effects of increasing the familiarization time for 9-month-olds.

Another factor conceivably related to 9-month-olds' failure to demonstrate category formation is shape discrimination. The objects' shapes had to be discriminated in order to be categorized. In light of previous research, however, this factor does not provide a compelling alternative explanation. Infants have consistently used shape differences much like those used here to identify and discriminate objects by or before 9 months (e.g., Kaldy & Leslie, 2003; Ruff, 1982; Spears, 1964; Wilcox, 1999; Wilcox & Chapa, 2004; Woods & Wilcox, 2006). The correlation between shape and the salient weight difference in the present work likely highlighted the shape contrast even more.

With respect to task demands imposed by the selection of actions, the tasks used at 9 months were equivalent in the number of distinctive weight levels involved. Likewise, as noted earlier, infants from 3 months on have demonstrated the ability to map visual categories onto differentiated actions (Hayne et al., 1987). Thus, the results at 9 months do not appear to be best explained by task difficulty alone, but appear instead to be related to the learning and utilization of category structures and functions in the task used here.

Influence of Shape

The stimulus objects we used were very similar in size between categories. Nevertheless, some may wonder whether the differing shapes may have influenced the test-trial effects at 12 months independently of experience with weight. Perhaps objects of one shape required subtly different actions for infants to pick up than those of the other. This explanation is unlikely for two reasons. First, there were no baseline differences between categories in either of the performance measures. Also, the categorization performance of 12-month-olds was revealed by differences in handling within shape categories. If any shape affordance advantage (or disadvantage) had influenced the results in any way, it would have enhanced

(or compromised) performance in one category relative to the other, but no such difference was observed (see Figures 4B and 5B).

Development

As noted earlier, several researchers have documented changes in infants' ability to learn, represent, and remember categories of discriminable stimuli later in the first year. To account for these developments, Oakes and Madole (2003) argued that changes in key information-processing domains, such as background knowledge and context analysis, contribute to the development of category discrimination and generalization. Of particular relevance to the novel objects used presently, they also discuss changes in the detection of relevant features. One aspect of feature processing that appears relevant to the present findings is whether and how object features are combined in category learning. Cohen and Younger (1986) found that infants' processing of correlations between object features developed considerably in the later months of the first year. Using a visual familiarization / novelty preference task, they observed that only infants older than 9 months appeared sensitive to correlations among category-defining attributes in a preferential-looking task. The categories used in the present task were structured by a correlation between shape and weight. Thus, processing of correlated features may be an important part of the age difference observed here.

Also relevant to the age difference reported here, Madole et al. (1993) observed significant differences between 10 and 18 months in infants' detection and use of functional aspects of objects (i.e., sound and movement) in their categorization of those objects. Because an object's weight can determine its potential functions, the stimulus objects used here may be experienced as functionally distinct between categories. The emerging sensitivity to the functions of category exemplars as category-defining features (Madole et al.) may have played a role in the age differences we observed.

Like most prevailing explanations of how categorical knowledge is stored and utilized, the information-processing approach of Oakes and Madole (2003) assumes that categories are represented by systems of amodal units with mappings to referents (e.g., Anderson, 1990; Nosofsky, 1986; Quinn & Eimas, 1986). But how do and when can such units, once acquired, become available to guide goal-directed action in a categorical fashion? A full account of functional cognition requires an explicit link to the online control of action. Other views frame cognition as consisting primarily of the memory and simulation of sensory and motor system activity (e.g., Barsalou, 1999; Hommel, Müsseler, Aschersleben, & Prinz, 2001; Spivey, 2007; Thelen & Smith, 1994), and these interpretations provide a more direct approach to questions about diverse systems interacting. Researchers espousing this sort of embodied view of cognition argue that category representations comprise records of the neural activation that occurred during category learning. Some further contend that object knowledge consists primarily of patterns of potential action (Borghi, 2005; Glenberg, 1997). This approach explicitly predicts an intimate interdependence between knowledge and action, and a number of findings clearly reveal this connection both behaviorally (e.g., Bekkering & Neggers, 2002; Iachini, Borghi, & Senese, 2008) and neurologically (e.g., Chao & Martin, 2000). The present results further illustrate connections between

information processing and action systems, and extend the investigation of their development.

Conclusions

By 12 months, infants possess the ability to categorically differentiate and generalize actions on novel objects following minimal experience with other similar but discriminable objects. Younger infants of 9 months did not demonstrate the same ability, but discriminatively selected appropriate actions when tested with just 2 similar objects of differing weight. Together, the findings of Experiments 1 and 2 suggest that the ability to categorically generalize the selection of action develops between 9 and 12 months. The changes involved appear more associated with detecting and referencing categories than with sensorimotor weight adaptation alone. The acquisition of adaptive generalization is necessary for the effective control of action in a complex environment and enables much more adaptive functioning as infants enter their second year of life.

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A.

B.

Figure 1.
Two exemplars each of the cone category stimuli (A) and the brick category stimuli (B).

A. First block

Phase:		Familiarization						1 st Test Pair	
Trial:		1	2	3	4	5	6	Consistent	Inconsistent
Weight:	light
	heavy
Color:		green	orange	yellow	red	blue	blue	green	orange

B. Second block

Phase:		Reinstatement of Familiarization				2 nd Test Pair	
Trial:		9	10	11	12	Consistent	Inconsistent
Weight:	light
	heavy
Color:		yellow	green	blue	red	yellow	red

Figure 2.

Schematic representation of the categorization task used in Experiment 1. Category/weight correspondence and weight of object presented on first trial were counterbalanced.

Figure 3.

A.) Schematic illustration of the measurement space. The infant is holding an object and transporting it along the plotted trajectory. The black circles represent the wrist's position at the origin of transport, and open circles represent each measured position through the 0.50-s transport. B.) Examples of a 12-month-old's transport trajectories through the measurement space in test trials of each condition and weight level. Transport measures are displayed for each trajectory (l, linearity; j, jerk).

Figure 4. Mean log norm residuals for 9-month-olds (A) and 12-month-olds (B) in Experiment 1 (* $p=.02$).

Figure 5. Mean log movement jerk in infants' transport at 9 months (A) and 12 months (B) in Experiment 1 (* $p=.02$).

A. First block

Phase:		Familiarization					1 st Test Pair		
Trial:		1	2	3	4	5	6	Consistent	Inconsistent
Weight:	light		○	○		○		○	●
	heavy	●			●		●		
Color:		green	yellow	yellow	green	yellow	green	yellow	green

B. Second block

Phase:		Reinstatement of Familiarization				2 nd Test Pair	
Trial:		9	10	11	12	Consistent	Inconsistent
Weight:	light		○	○			
	heavy	●			●	●	○
Color:		green	yellow	yellow	green	green	yellow

Figure 6.

Schematic representation of the discrimination task used in Experiment 2. Object/weight correspondence and weight of object presented on first trial were counterbalanced.

Table 1

Transport performance in familiarization trials

Experiment, and Age	Transport Measure	Light Object Trials			Heavy Object Trials		
		1 st	2 nd	3 rd	1 st	2 nd	3 rd
1, 9 mo.	Linearity	<i>M</i> (<i>SD</i>)	2.26 (1.15)	2.54 (1.32)	2.87 (0.85)	2.52 (1.16)	2.97 (1.10)
	Jerk	<i>M</i> (<i>SD</i>)	3.33 (0.78)	3.43 (0.87)	3.66 (0.59)	3.24 (0.63)	3.64 (0.61)
1, 12 mo.	Linearity	<i>M</i> (<i>SD</i>)	2.64 (1.38)	3.06 (0.97)	3.46 (1.16)	2.85 (1.21)	3.18 (1.34)
	Jerk	<i>M</i> (<i>SD</i>)	3.66 (0.71)	3.93 (0.88)	4.03 (0.99)	3.91 (0.91)	3.82 (1.35)
2, 9 mo.	Linearity	<i>M</i> (<i>SD</i>)	2.49 (1.62)	2.72 (1.42)	2.64 (1.43)	2.96 (1.27)	3.19 (1.09)
	Jerk	<i>M</i> (<i>SD</i>)	4.88 (0.87)	5.12 (0.85)	5.14 (0.80)	5.24 (0.71)	5.52 (0.52)