Manual object exploration and learning about object features in human infants

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Abstract—**Motor activity is central both to cognitive and perceptual development in human infants and to learning in robots. Here we investigated how the quality of 6- to 7-month-old human infants' ($N = 60$) manual activity with objects is related to their learning about objects in general. Infants' object exploration during a toy play context was related to their learning of the features of dynamic audio-visual events. We found that not only was the amount of activity with objects predictive of infants' learning, but the *quality* of their motor actions was related to what infants learned about audio-visual events. These findings extend previous work and begin to uncover how infants interact with objects can reflect their developing abilities to learn about objects in other contexts.**

***Index Terms*—human infants, development, motor activity, learning**

I. Introduction

Learning about objects in the environment presents a significant challenge for both human infants and robots. There is little doubt that human infants and robots learn about objects through active manual exploration [1-3], and both developmental psychologists and scientists interested in learning by robots have been interested in how motor actions contribute to such learning. Typically, the focus of this work is on understanding how motor actions on a set of objects allow the discovery of new features of *those* objects. For example, Gibson [4] argued that through motor activity infants discover the affordances of the objects and surfaces around them. Indeed, studies have shown that the amount and type of manual exploration is related to knowledge about the objects explored both in human infants [5, 6] and robots [1, 2, 7].

This approach raises a fundamental question central to learning both by human infants and by robots: how can experience shape *general* expectations that influence future learning? That is, how do systems "learn to learn" from their activity with and toward objects? Understanding the processes by which systems learn to learn has been of interest in a wide variety of disciplines, from studies of children's acquisition of motor milestones [8] to learning by neural networks [9] to learning by robots [1]. Here we addressed this general question by asking how infants' manual activity with objects induces learning about objects in general, or their learning to learn about objects.

Action and manual activity with objects has long been thought to be important for developing understanding of objects. In human development, classic theories such as those of Gibson [4] and Piaget [10] have argued that infants learn about objects and object properties through the manipulation of those objects. Work in developmental robotics has shown that robots learn about objects through exploratory grasping of those objects [2]. But, it is becoming increasingly clear that human infants' manual activity with objects predicts not only what they learn about *those specific objects from direct exploration*, but also predicts what they learn about *other objects in other contexts*. That is, manual activity seems to be related to human infants' general ability to learn about and perceive objects. For example, infants' level and type of manual exploratory activity with objects in one context is related to their visual attention to properties of objects in other contexts [11, 12], and perceptual abilities such as 3-D object completion abilities in a completely separate visual perception task [13]. The point is that infants' object exploration may provide a context for them to learn how to learn about objects in a variety of situations.

A deeper understanding of the relation between action and object representation will therefore be of interest to researchers interested in how learners—either human or robot—acquire information about the objects around them. Understanding this relation in human infancy may aid the field of developmental robotics, which has as one goal to develop autonomous learners [1]. Understanding how human infants learn how to learn may provide a model for developing robots that can learn from experience.

We propose that changes in human infants' ability to manually manipulate objects induce changes in the salience of specific visual features or properties. This proposal is similar in many ways to the ideas of Bushnell and Boudreau [6] who argued that infants' developing motor abilities allowed them access to new information. For example, the ability to pick up objects gives infants access to information about object weight, and the ability to finger and manipulate objects gives infants access to information about texture. This is also similar to work in developmental robotics in which rich object structures are acquired through different types of exploratory behavior [1] or exploratory grasping behavior [2].

However, our proposal is that not only do infants learn about specific objects and actions through motor actions on

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those objects, but also that infants' experience acting on objects directs their attention when learning about objects and actions in a wide set of contexts—even contexts in which they cannot directly interact with those objects. That is, we propose that actions on objects help infants to *learn how to learn* about the objects they encounter in the world. We further propose that this is a primary mechanism of developmental change in infants' abilities to learn about and represent objects. As infants acquire abilities to manipulate objects, they learn how to control attentional processes and attend to diagnostic dimensions when perceiving and learning about objects, even when they are unable to touch and manipulate those objects. This is similar to the goal of developing robots that develop task-independent learning strategies, which help robots apply past learning to new contexts [14].

This proposal for the role of manual activity on human infants' learning about objects is motivated, in part, by results reported by Perone et al. [12]. In this study, the level of activity with one set of objects in a toy play session was related to what 6- to 7-month-old infants learned about a different set of objects shown in a completely different event perception context. In this event perception context, infants first viewed a single event in which a hand reached for and grasped a colorful, multi-part object, performed an action on the object (e.g., rolling or squeezing), and a sound was produced. It is established that infants have difficulty learning all the information in such events, and research has often revealed that infants selectively attend to and learn the dynamic action or sound features over the relatively static appearance features [15, 16]. Perone et al. asked whether the specific features infants attended to and learned were related to their level of activity with objects during toy play.

Perone et al. [12] found that although 6- to 7-month-old infants learned the highly salient dynamic features (i.e., the particular action that was performed and the sound that was heard), learning of the less salient, more static features, associated with the object's physical appearance (i.e., the object's color and shape) was related to the level of motor activity with objects during toy play. Because Perone et al. measured motor activity very generally, however, these previous results are limited. They reveal that infants who were more active were also more attentive to object appearance in the dynamic audio-visual event, but they only indirectly allow conclusions about whether sensitivity to these features was related to the quality of the interaction.

Different learning will result from different types of exploration [6]. Therefore, it is important to understand how differences in the *quality* of infants' interactions with objects relate to their developing ability to acquire knowledge about objects. Here, we report some results from a replication of Perone et al., evaluating the relationship between the quality of infants' activity with objects and their attention to the appearance of the objects in the dynamic audio-visual events. We have reported other results from this study elsewhere [17], but the main analyses reported here are unique.

Determining whether the quality of infants' interactions with objects—and not just the quantity—is related to how and what they learn about objects in general is a critically important question for understanding the development of infants' ability to learn about objects. Infants not only become more active with development, the kinds of actions they can perform on objects also changes qualitatively [18]. If these qualitative changes in the kinds of actions infants can perform (e.g., touching and stroking an object on the floor versus grasping it, picking it up, and rotating it between the two hands) produce attentional differences in object properties, then it is possible that documented changes in infants' object learning reflect changes in the salience of particular object properties as a result of motor development.

We specifically predicted that infants who spent a higher proportion of their time *holding* objects (as opposed to touching, fingering, or attempting to grasp objects on the ground) would be more sensitive to the appearance features of objects. Holding provides more opportunities to explore aspects of the objects unavailable when those objects remain on the ground (e.g., the weight, the properties on the unseen side). Thus, we expected that the relation observed by Perone et al. [12] was not due to general activity level predicting what infants learned, but rather that the earlier results actually reflected infants who were more sophisticated in their activities—specifically those infants who spent a greater proportion of their contact with objects actually holding the objects—would also be more sophisticated in their learning about the object properties in the event learning context.

We also asked whether the proportion of time infants spent in bimanual versus unimanual manipulation predicted performance in the event perception context. Manipulation using two hands provides infants access to a broader range of object features—for example, they can hold the object while fingering it. But, unimanual manipulation means that one hand is free to explore, even while the other hand is occupied holding or touching an object. Therefore, it is not obvious whether this difference would better predict infants' learning.

We assessed infants' object exploration abilities during a toy play session and their event perception and learning in a habituation task, using the same basic procedures and stimuli as used by Perone et al. [12]. The objects in the two tasks were completely different. In the object manipulation task, infants were allowed to sit and physically manipulate objects. In the habituation task, infants watched events unfold on a computer monitor. The use of these procedures and stimuli would allow us to establish whether the results reported by Perone et al. are replicated in a different sample, and how the *quality* of infants' manipulation is related (if at all) to how they learn about object properties, in general.

II. Method

A. Participants

Participants were 60 6-month-old infants (M = 187.43 days, SD = 11.03 days, range = 162-207 days). There were 27 boys and 33 girls. To control for individual differences in sitting ability [which can influence infants' reaching for and manipulation of objects, 19, 20], we asked parents to report on

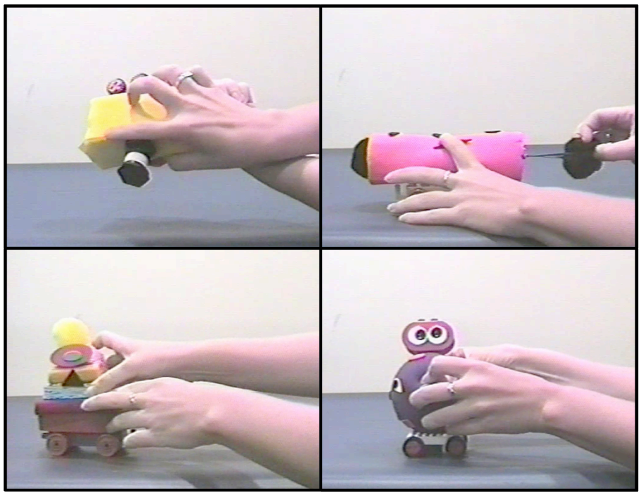

Figure 1. Examples of stimulus events used in the habituation task.

their infants' sitting ability before testing began and out of the hearing of the observer. Infants were classified as either "sitters" (n = 23) or "non-sitters" (n = 37).

B. Apparatus, Stimuli, and Procedure

We tested each infant in two tasks (*Habituation* and *Object Manipulation*), order counterbalanced, with approximately half of the infants (n = 31) completing the habituation task first and the other infants (n = 29) completing the object manipulation task first. Each task was administered in a separate testing room with separate apparatus and stimuli.

1) Habituation task

We measured infants' learning of the features of a dynamic multi-modal event using a standard habituation procedure [21]. The infant was seated on a parent's lap, approximately 100 cm from LCD monitor, and an observer, seated out of sight behind a curtain dividing the room, presented stimuli on the monitor and monitored infant looking time via closed circuit tv. To minimize bias, parents wore felt-lined sunglasses and headphones playing classical music for the duration of the study to prevent them from seeing and hearing the stimulus events during the session.

On each of a series of trials, a single event was presented on the monitor. Trials were initiated when the infant looked at an attention-getting stimulus presented on the monitor (a looming green circle accompanied by a chirping noise), and the event was presented as long as the infant continued to watch, or until 35 s had elapsed (if the infant did not look at all during the first 10 s of the trial, the trial terminated and was repeated). The observer pressed computer keys to present stimuli and record looking durations. Agreement for looking durations on each trial between this observer and a second trained observer recording looking times from video for 23% of the infants was high, average $r > .98$ (mean difference in the look duration on each trial was low, $M < 0.62$ s).

The first phase of this task was the *habituation phase*, during which the same 7 s event was presented repeatedly on each trial to allow the infant to learn about and form a representation of that event. The events consisted of a hand reaching into the frame and acting on an object (approximately 12.75 cm X 11.5 cm, or 7.30° X 6.58° visual angle), producing a sound (see Figure 1). The actions occurred within a region approximately 18 cm X 14.5 cm (10.28° X 8.29°). Each event included one of four objects (purple sphere, pink tube, yellow cube, multicolored pyramid), one of four actions (rolling, squeezing, inverting, pulling), and one of four sounds (clicking, squeaking, mooing, whistling). Each feature (object appearance, action, and sound) was completely crossed with each other feature to create 64 unique stimulus events.

During this phase, the same event was presented on each trial until the infant's looking *habituated* as defined using a predetermined criterion—in this case, when infants' looking on any 3-trial block decreased to 50% of the duration of looking on the first block of 3 trials (12 additional infants were tested but were eliminated from the final analyses because they did not reach this criterion). The number of trials to reach the habituation criterion could range from 4 (i.e., looking on Trials 2-4 was less than 50% of looking on Trials 1-3) to 18.

The *post-habituation test phase*, or *test*, was presented immediately after habituation. Infants were shown five new test events to assess their learning of each of the individual features contained in the habituation event. On the first test trial, infants were presented with the *familiar* event one more time to provide a measure of baseline looking that was not artificially low due to the use of a habituation criterion [21, 22]. Next, infants were shown three change test events: an *appearance change* event in which the familiar action and sound from the habituation event were presented with a novel object appearance, an *action change* event in which the familiar object and sound were presented with a novel action, and a *sound change* event in which the familiar object and action were paired with a novel sound. The order of these three test events was counterbalanced across infants. Individual infants were habituated to different events and tested on different changes in appearance, sound, and action (e.g., following habituation to the purple round object being squeezed, one infant might be tested on an appearance change to the yellow cube object, whereas another infant might be tested on an appearance change to the multicolored pyramid object). Thus, across infants, discrimination was based on comparisons of many different stimulus features. The last test was a *completely novel* test event that consisted of a novel object, action, and sound. This event was always presented last to ensure that infants were still engaged in the task and would dishabituate to a completely novel event.

2) Object manipulation task

We measured infants' manual exploration of objects during a free-play object manipulation task. The infant was seated on a blanket on the floor, and a parent sat behind the infant, providing support as needed to prevent the infant from falling over (See Figure 2). Parents were instructed to provide support, but not to interact with the infant or toys. Thus, all infants were supported and could use their arms to reach for objects, regardless of their ability to sit independently. An experimenter placed four commercially available graspable toys (a multicolored cube with protruding shapes, an orange dog toy covered in bumps, a multicolored beaded loop, and a tubular "worm" toy) within the infant's reach. The infant was allowed to explore the toys for a 2 minute videotaped natural play session. If the infant threw a toy out of reach, the

Figure 2. An infant in the object manipulation task.

experimenter returned it to within the infant's reach.

C. Coding

A trained coder, unaware of parental report of sitting or the infants' responding during the habituation task, used The Observer 5.0 (Noldus, 1991) to code the play sessions off-line from digitized recordings. We focus here on two measures of the quality of infants' interaction that may lead to task-independent learning—these behaviors may induce strategies that infants can use to direct their attention when learning about objects in other contexts [other measures are reported elsewhere, [17]. The first behavior was intentional *touching*, or contact with the object with one or two hands without lifting the object off the ground (i.e., touching a toy while waving one's hand and looking in the opposite direction would not be counted as touching, unless the infant turned to look at the toy while touching it). The second behavior was *holding*, defined as grasping an object with one or both hands, picking it up off the ground, and holding it above the ground for at least 1 s. The coder pressed keys to record the start and end of each target behavior, and whether the action involved one or both hands. A second trained observer coded 28% of the sessions and the agreement between raters was high, $\kappa = .89$, and the percent agreement between the two coders for the behavior coded at any moment was 91.7%. From this coding, we derived three measures for our analysis: 1. the total amount of contact (touching and holding combined), allowing us to test for the relation observed by Perone et al., 2. the proportion of contact that was *holding*; holding is presumably more sophisticated than touching an object without picking it up, and 3. the proportion of contact that involved both hands (i.e., *bimanual* contact).

III. Results

The primary results for this paper were correlations between infants' responding to the change test events and measures of motor activity during the object manipulation task. Infants' responding to the test events is a measure of what they learned during habituation. For example, if infants learned the physical features of the objects in the events (i.e., the appearance), they should dishabituate (i.e., increase their looking time) to a change in appearance. Thus, by examining how infants' motor development is related to each of the types of changes, we can determine how different aspects of infants' motor activity during object manipulation are (or are not) related to their learning about object features.

We have reported in Baumgartner and Oakes [17] that as a group these infants learned the features of these stimuli. There were no effects of task order or whether or not infants could sit independently (according to parental report) on behavior during habituation or test.

Our main measure of learning is whether infants *dishabituated*, or looked significantly longer, to the novel test events than to the familiar test. As a group, infants dishabituated to all of the tests. Although these results were reported in Baumgartner and Oakes [17], to allow for a complete understanding of our data we provide here the results of our one-sample, two-tailed t-tests comparing infants' dishabituation scores to zero. As a group, these infants increased their looking to a change in appearance, $t(59) = 3.64$, $p = .001$, $d = .47$, a change in action, $t(59) = 5.76$, $p < .001$, $d = .74$, and a change in sound, $t(59) = 5.58$, $p < .001$, $d = .72$. Thus, the group of infants as a whole learned all the features of these events.

Our primary question was whether infants' dishabituation to any of the test events was related to the quality of infants' exploration of objects in the toy play (object manipulation) task. Although infants as a group dishabituated to all the tests, there was significant variability in the level of dishabituation and not all the infants dishabituated to the tests. We conducted a series of correlations between infants' manual activity and their dishabituation to each test event. Note that because we tested all infants with all three of the changes, we can conduct these correlations for the whole group of infants. However, because the order of the tests was counterbalanced, such correlations may be misleading if the order of the tests influenced infants' responding. Because approximately 1/3 of the infants received each type of change as the first test, we can also conduct correlations on these groups separately. These correlations are less powerful, however, because the sample is smaller. We report both types of correlations here to provide the most complete picture of our data.

We conducted partial correlations to remove the effects of age, task order, sitting status, and baseline level of interest (the duration of looking during the first habituation block). First, we correlated infants' dishabituation scores for each of the test events with the proportion of their contact with the objects during the toy play session in which they actually held the objects. We created this proportion score by dividing the duration of time infants spent holding the objects (as defined in the *coding* section) by the total amount of intentional contact with the objects (i.e., duration of holding plus the duration of touching). We reasoned that this proportion score would provide deeper insight into the quality of infants' interactions with the objects than would the total amount of contact or the total amount of holding because it reflects controls for different levels of interest in the objects. That is, one infant who was relatively uninterested in the toys and yet spent all of his or her time holding the toy would have a high proportion of contact devoted to holding, while another infant who had precisely the same duration of holding, but spent much more time fingering, patting, and attempting to hold the object, would have a lower proportion of time spent holding. This difference may be significant because the former infant would spend more of his or her time engaged with the object in activities that provide access to multiple views of the object, properties such as weight, and so on, whereas the majority of the latter infant's interaction with the object did not provide access to such information.

The proportion of holding contact was significantly correlated with infants' dishabituation to appearance changes, $r(53) = .31$, $p = .02$, but was not significantly related to their dishabituation to a change in the action performed, $r(53) = .21$, $p = .13$, or a change in the sound heard, $r(53) = .05$, $p = .71$. This pattern was even more pronounced for the correlations only for the first test infants received (see Figure 3). For infants who received the appearance test first, the partial correlation between that test and the proportion of holding contact was $r(15) = .614$, $p = .009$, whereas the same partial correlation was not significant for infants who received the action change first, $r(16) = .02$, $p = .95$, or who received the sound change first, $r(10) = -.31$, $p = .32$. Although the *n*s are small, these correlations confirm the pattern from the group as a whole: Only infants' attention to the appearance of objects was related to the proportion of their manual exploration that was devoted to holding.

Finally, we examined the correlations between infants' dishabituation and the proportion of their manipulation of objects that involved two hands. Bimanual manipulation can provide access to a wider variety of features of objects than can unimanual manipulation [23]. We divided the total amount of time infants were engaged with the objects using two hands (either touching or holding) by the total amount of time they manipulated the objects. This measure was not significantly correlated with infants' dishabituation to a change in appearance, $r(53) = .23$, $p = .09$, change in action, $r(53) = .09$, or change in sound, $r(53) = -.01$; examining these correlations only for infants' first test trial revealed the same pattern. Thus, we did not find that this measure of the quality of infants' interaction with objects was strongly related to their learning about object features.

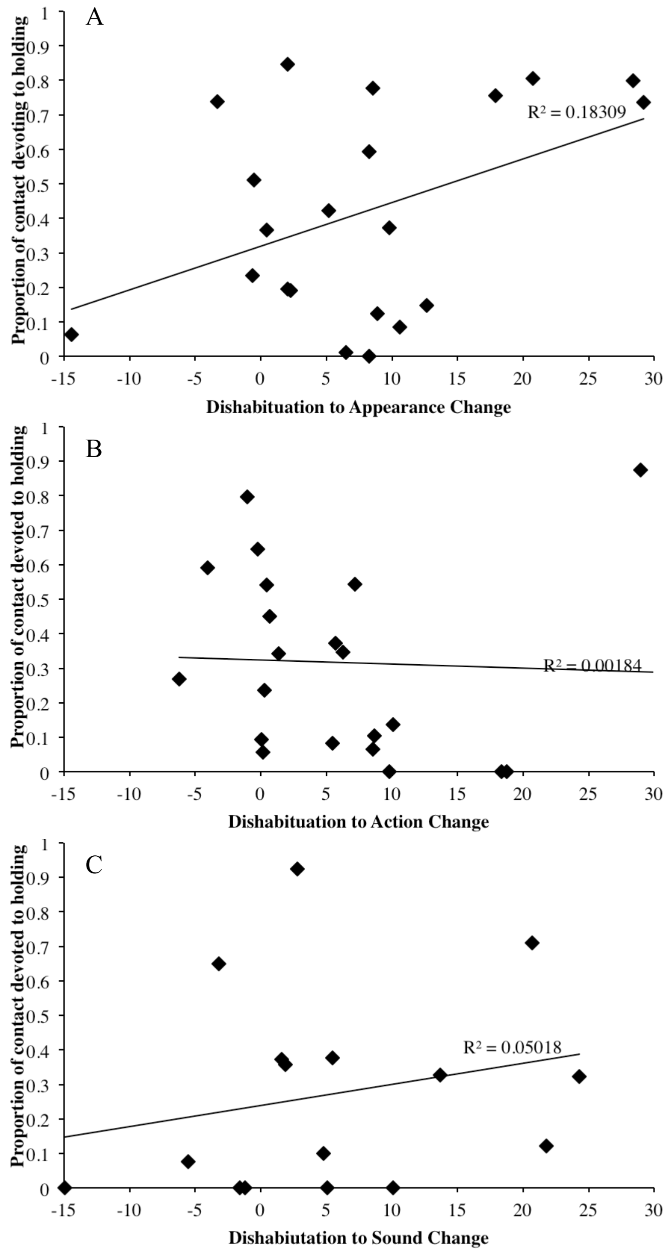

Figure 3. Scatterplots of the zero order correlations between the proportion of contact with toys devoted to holding and dishabituation to the first test item by infants who received a change in appearance first (A), a change in action first (B), and a change in sound first (C).

IV. Discussion

These data extend our understanding of the role of infants' object exploration on their "learning to learn" about object properties. We propose that infants' experience manually acting on objects shapes their attentional processes so that when they encounter new objects—even if they are unable to manipulate them—they focus on diagnostic features. Consider exploring the handle of a cup; once you are a "grasper", the handle (which is a relatively small feature) may be more salient and you may attend more to that physical feature.

Our data go beyond previous results and suggest that the *quality* of infants' interactions with objects is a factor in determining what they learn. Like Soska et al. [13], we found that particular types of manual activity were related to infants' learning. Specifically, the proportion of infants' contact that was actually spent holding objects was related to their sensitivity to the appearance of objects. This finding is particularly informative because *holding* is presumably a more advanced form of manipulation than touching; it requires more advanced motor abilities and it makes available qualitatively different kinds of information than touching alone. Thus, we have found that infants who are more skilled at picking up and manipulating objects are more attentive to object appearance.

This connection between the quality of infants' manipulation and their acquisition of information about objects also makes contact with the literature on how robots learn from exploration. For example, Modayil and Kuipers [1] observed that a robot learned object representations by integrating information acquired by interacting with the object in different ways. Similarly, Kraft et al. [2] described acquisition of rich object representations by a robot through a process of autonomous exploration that involved grasping and visual input about the objects. This work with robots bolsters the conclusion that human infants learn about objects through exploration. Work like that described here provide additional learning strategies that may be of interest to researchers developing such learning systems.

We speculate that the correlation between holding as a proportion of overall contact and infants' attention to appearance features may reflect a causal relation between how these infants manipulate objects and their attention to the features of objects. Specifically, once infants can hold objects they have access to a different set of object features—they can discover object features that were previously unavailable to them [6]. Thus, infants may become more sensitive to object appearance as a result of their experience holding objects. Indeed, work providing younger infants with "artificial" experience picking up and holding objects (i.e., they are given "sticky mittens" that allow them to pick up objects by swiping them) shows a causal relation between such experience and infants' object perception [24]

We believe that developmental changes in infants' abilities to manually explore objects induce changes in infants' perception of object properties. As infants' abilities to pick up and manipulate objects change, properties of objects *in general* change in their salience. Thus, infants learn different properties of objects *even in contexts in which they cannot manipulate those objects* as a result of changes in their perceptual processes induced by the emergence of new motor abilities. This work provides understanding into the processes that contribute to learners' evolving task-independent strategies for learning about objects in a variety of contexts.

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