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Infant Manual Exploration of Objects, Surfaces, and Their Interrelations

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Although a considerable amount is known about the development of object manipulation during the 1st year, less is known about how infants manually explore surfaces and relate objects to surfaces. To address these issues, 60 infants (20 each at 6, 8, and 10 months of age) were presented hard and soft objects on tabletop surfaces, which varied in terms of their material properties. Tabletop surfaces were either liquid, discontinuous, flexible, or rigid. Results indicated that infants explored the objects, surfaces, and their interactions selectively, tailoring their manual actions to the material properties of the objects or surfaces. In some instances, selectivity increased with age. The implications of these findings for understanding the origins of problem solving and tool use are considered.

Over the course of the first year, infants acquire a rich and varied repertoire of actions for manipulating objects. Moreover, infants apply these actions selectively, tailoring a particular kind of movement to an object's unique physical properties. For instance, by the middle of the second half-year, infants finger textured objects more than nontextured ones, shake or bang sounding objects more than nonsounding ones and press pliable objects more than nonpliable ones (Bushnell & Boudreau, 1993; Gibson & Walker, 1984; Lockman & McHale, 1989; Molina & Jouen, 1998; Palmer, 1989; Ruff, 1984).

Collectively, these types of achievements belie accounts of sensorimotor development that suggest that object manipulation is undifferentiated during much of the first year. According to such accounts, lack of specificity in infants' manual behaviors stems from a cognitive gap: Infants are not yet fully able to differentiate

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objects as separate from themselves and thus tend to treat most objects in a like manner (Belsky & Most, 1980; Fenson, Kagan, Kearsley, & Zelazo, 1976; Piaget, 1952). Further, these accounts suggest that with the advent of increased representational or symbolic functioning near the end of the first year, infants begin to attribute meanings to objects independent of themselves. As a consequence, they begin to handle objects more selectively and appropriately, based on objects' true properties and functions.

In contrast, perception–action accounts of sensorimotor development consider objects and the development of object manipulation in a different light. According to such accounts, objects are viewed as rich in information that potentially specifies what they afford for action (Bertenthal & Clifton, 1998; Gibson & Pick, 2000). The developmental challenge for infants, however, is to learn how to register and exploit this information through perception–action routines that are designed for these goals (Gibson & Pick, 2000; Lederman & Klatzky, 1987). Recent evidence on the development of object exploration and manipulation is consistent with this framework. In the first month, infants are already able to use oral–haptic routines to gain information about an object's rigidity or flexibility (Gibson & Walker, 1984). By the middle of the second half-year, infants tailor their manual behaviors to a wide range of material properties of objects (Bushnell & Boudreau, 1993; Lockman & McHale, 1989; Palmer, 1989; Ruff, 1984). Collectively, these findings suggest that perceptual and manual activities are coupled well before the end of the first year: The information that infants register about objects guides their manual actions, but at the same time, these actions help infants to register important information about objects' properties (Bertenthal & Clifton, 1998; Gibson, 1988; Gibson & Pick, 2000).

Although these findings indicate that there is a good deal of specificity in the manual actions that infants direct toward objects, experimenters have mainly considered this issue with respect to actions that occur only between the infant and object. These include behaviors like fingering, rotating, and hand-shaping. This focus on self–object relations, however, overlooks at least two important kinds of manual behaviors that are also critical for adaptive action.

One such class of behaviors involves those infants use to explore extended surfaces. Surprisingly, little is known about the development of this class of manual behaviors, especially the degree to which such exploration is geared to particular surface properties. Research on the onset of another motor system—locomotion—however, suggests that infants adjust their exploratory and motor behaviors with respect to the material properties of surfaces underfoot (Gibson et al., 1987). For instance, depending on the degree of support afforded by a surface, locomotor infants will manually explore and subsequently select a safe mode of locomotion (crawling or walking) to cross that surface. Likewise, similar-aged infants systematically vary their mode of locomotion as a function of the direction and steepness of a pathway's slope (Adolph, Eppler, & Gibson, 1993). In contrast, few studies

have directly addressed corresponding questions about the effects of surface composition on manipulation (e.g., see Eppler, Adolph, & Weiner, 1996; Lockman & Adams, 2001).

As well, investigators have often overlooked manual behaviors that infants use to relate objects to surfaces (Palmer, 1989). Such object–surface behaviors are of interest for at least two important reasons. First many purposeful behaviors involving objects, including problem solving and tool use, require individuals to make objects interact with surfaces in ways that capitalize on the relation between the physical properties of the object and surface (Lockman, 2000; McCarty, Clifton, & Collard, 2001; Smitsman, 1997; Willatts, 1999). For instance, we place the flat edges of objects on flat surfaces so that objects will remain stable, we pound hard objects on rigid surfaces to produce noise, and we push round objects on continuous rather than discontinuous surfaces to permit objects to roll. These examples reveal sensitivity not simply to the physical properties of the object or surface alone, but to the affordances embodied by the relation between the two. Second, relating objects to surfaces selectively suggests that individuals are at some level registering that the properties of their arms or hands have been changed by virtue of the object they are holding. This type of achievement may contribute to the successful performance of many adaptive behaviors, including tool use (Lockman, 2000).

When do infants evidence sensitivity to object–surface relations in their manual behavior? At the level of visual processing, infants in the second half-year already possess a basic understanding of the kinds of physical relations that objects can enter into, including ones involving objects and surfaces (Baillargeon, 2001; Spelke, Breinlinger, Macomber, & Jacobson, 1992). At the level of manual behavior, however, little is known about the ways in which infants direct objects to act on surfaces. In one of the few studies to address this issue explicitly, Palmer (1989) found that 9-month-old infants sometimes displayed sensitivity to object–surface interactions by acting on objects in different ways, depending on whether the objects were presented on tabletop surfaces that were either rigid or flexible.

That infants take into account surface properties when learning to locomote suggests that they might also do so when exploring and manipulating objects on surfaces that immediately surround them. Guided by research demonstrating that infants evidence sensitivity to locomotor affordances associated with a wide range of surface properties (Adolph, 1997, 2002; Adolph et al., 1993; Gibson et al., 1987), we asked similar questions about the development of manual behavior. Specifically, we examined whether infants explore surfaces and object–surface relations as well as objects in a discriminating manner. To address these issues, we presented 6-, 8-, and 10-month-old infants with objects and surfaces that differed systematically in terms of their material properties. On separate trials, we offered infants hard or soft objects on tabletop substrates that were liquid, discontinuous, flexible, or rigid. The properties associated with these substrates represent important functional differences in the composition of our material world, some of

which, as noted, have been investigated previously in the context of research on the perception of surface traversability (Gibson et al., 1987).

Our two primary goals were to determine whether infants manually explore (a) surfaces and (b) object–surface combinations in a discriminating manner. For the first goal, we expected infants to manifest specificity in their exploration of different surface properties. Like previous research on object manipulation (Bushnell & Boudreau, 1993; Lockman & McHale, 1989; Palmer 1989; Ruff, 1984), such a result would suggest another important way in which infants' earliest actions are adapted to the physical world. With respect to the second goal, we were interested in determining whether and when infants begin to relate objects to surfaces in a discriminating manner. If infants selectively perform certain kinds of manual actions more frequently in the presence of particular object–surface combinations and these actions in some way exploit the relation between the physical composition of object and surface, this would suggest that infants are registering something about the relation between the object and surface. Evidence that infants are able to establish appropriate object–surface relations via manual exploration would be significant in suggesting that infants well under a year of age can use objects in more complex ways than typically envisioned, setting the stage for the emergence of even more advanced forms of object use during the second year.

METHOD

Participants

A total of 60 infants participated in the experiment, equally distributed across three age levels. Six- (M = 6.44 months, range = 5.77–7.00, SD = 0.45), 8- (M = 8.49 months, range = 7.9–9.23, SD = 0.39), and 10-month-old infants (M = 10.49 months, range = 9.9–11.371, SD = 0.51) were recruited from lists of recent births in the greater New Orleans metropolitan area. For each age group, half were female. The ethnicity and race of the sample was as follows: 46 were classified as White, 9 as African American, 1 as Hispanic, and 4 as mixed ethnicity or race.

Apparatus

Infants were seated in a Kolcraft Perfect Recliner® high chair that contained a detachable tray surrounding the infant's upper torso. At its longest and widest point, the tray measured 60.96 cm × 27.94 cm. Four trays were used to present infants with different surfaces on which to manipulate the objects. The trays were modified to be either liquid (a tray of water), discontinuous (taut netting), flexible (sponge), or rigid (particle board). The liquid surface consisted of a 45.72 cm × 17.78 cm × 5.08 cm clear Plexiglas container filled with 4 cups of water, which was

secured onto the high chair tray with Velcro tape. The discontinuous surface consisted of crawfish netting with approximately 2.54 cm holes stretched tautly over the tray and secured along the sides. The flexible surface consisted of a sponge, similarly cut to fit into the main surface of the tray. The rigid surface consisted of white Formica-covered particle board cut to fit into the main surface of the tray, creating a continuous hard surface. On separate trials with each surface, each infant was presented a 2.54-cm gray cube made of wood or sponge. A video camera mounted on a tripod and hidden behind a white curtain recorded the trials.

Procedure and Design

The study was organized as a 3 (age) × 2 (gender) × 2 (object: hard or soft cube) × 4 (surface: liquid, discontinuous, flexible, or rigid) design, with repeated measures on the last two factors.

Familiarization phase. During the initial familiarization phase, each infant was held by a parent or remained seated in an infant carrier. The infant was given each cube in random order for 30 sec so that he or she would become acquainted with the objects before the actual testing began.

Test trials. After the familiarization period ended, the parent seated the infant in the high chair. Parents sat in a chair to the infant's right and were told not to prompt the infant to perform in any particular way. The tray was then positioned into the high chair and the cube was placed on the tray, aligned with the infant's midline. Each cube was presented one at a time on each surface for 1 min for a total of eight trials. Trials were blocked for surface type. The infant was presented first with one of the cubes and then with the other on a surface, and then a new surface was presented. Order of object (hard and soft) and surface type was randomized across infants. At the start of a trial, the experimenter quickly tapped the middle of the tray three times with the ball of her fingers (this included tapping lightly at the liquid's surface). The experimenter then set the cube down quickly in front of the infant. (We did not place the object in the infant's hand so as not to bias object over surface exploration.) During a trial, if the cube fell or was thrown off the tray or if the infant could no longer reach the cube, the experimenter placed the cube back on the tray. On a given trial, the cube was available within the infant's reach for approximately 1 min. After the infant completed exploring each object on a given surface, the tray was removed and a new tray was inserted. At the conclusion of the eight trials, parents were thanked for their participation and given a toy for their infant.

Analyses. Trials were videotaped and scored by three independent observers. Trials were coded for three classes of behaviors: object, surface, and ob-

ject–surface exploration. Within each of these classes, the only manual behaviors that were coded were those that were hypothesized to reflect sensitivity to the different material properties of the objects, surfaces, and their potential interrelations.

Object exploration behaviors included the frequency with which infants squeezed or pressed and scratched or picked at the object. Squeezing or pressing the object was coded when the observers detected that the infants were applying pressure to the object with their fingers. Observers coded this behavior when infants' fingers were judged to move into the side of the object or that infants attempted to do so as evidenced by flattening of the finger pad(s).[1] Scratching or picking was coded when observers judged infants to use their fingertips to make an upward and downward motion to dig in and out of the object surface.

Surface exploration behaviors included the frequency with which infants slapped, picked, or pressed the surface and the duration of time infants spent rubbing the surface with their hands. Slapping was coded when the observers detected that infants moved their forearms in an upward then downward motion such that the palm or fingers of their hands struck the surface. Scratching and picking was coded when observers judged infants to use their fingertips to dig in and out of the surface. Squeezing or pressing was coded when observers detected that infants were pushing their hands into the surface. Again, similar to object squeezing, observers coded surface pressing when infants were applying pressure to the surface with their fingers or that the infants attempted to do so as evidenced by flattening of the finger pad(s). Rubbing the surface was coded when observers detected infants moving their hand(s) across the surface in a side-to-side or forward and backward motion.

Lastly, object–surface exploration behaviors included the frequency with which infants pressed the object into the surface and banged the object on the surface and the duration of time infants spent rubbing the object across the surface. Pressing in a relational manner was coded when observers detected that infants held the object in hand and pushed it into the surface. Banging was coded when observers judged the infants to hold the object and move their forearms in an upward then downward motion such that the object came in contact with the surface. Rubbing with the object was coded when observers detected infants holding the object and sliding it across the surface in a side-to-side or forward and backward motion.

Reliability estimates for three independent observers who coded 20% of the entire sample ranged from .71 to 1.00 and averaged .95.

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[1]It is possible that not all instances of squeezing and pressing were either purposeful or, in the absence of a pressure transducer, recorded. Mitigating against the first possibility, the foam for both object and surface was relatively firm, making it more likely that squeezing and pressing were not accidental. Second, observers were able to detect at least some squeezing and pressing of the hard object and rigid surface, given that these behaviors were operationally defined in terms of flattening of the finger pads.

RESULTS

Data for dependent variables (frequencies or duration per participant per object) were initially entered into mixed design multivariate analyses of variance (MANOVAs). Subsequent univariate analyses were then conducted, using Huynh–Feldt correction procedures. All reported MANOVA and univariate results are significant to at least the .05 level. Follow-up post hoc tests were calculated using the estimated marginal means method with the alpha level set at .01 to control for Type I error due to multiple comparisons.

Results are organized according to the type of exploration evidenced by infants. First, we consider how infants acted directly on the objects, when not relating the objects to one of the surfaces. Next we consider how infants acted directly on the surfaces with their hands, without the objects. Then, we consider how infants related the objects to the different surfaces. Finally, we consider developmental differences in the type of exploration infants performed first on each trial.

Object Exploration

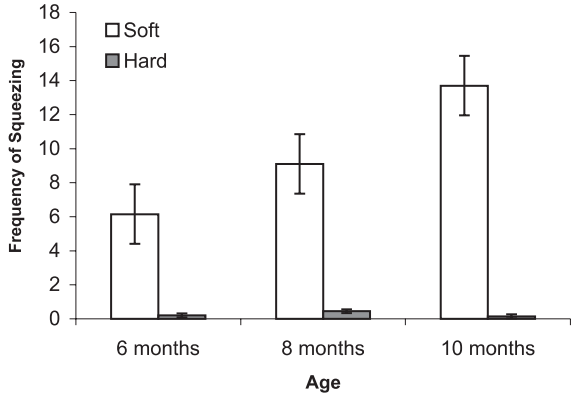
Two kinds of self–object manipulation behaviors were examined: squeezing and scratching. These are behaviors that infants performed directly on the objects without relating the objects to the tabletop surface. Data for squeezing and scratching were entered into a 3 (age) × 2 (gender) × 2 (object) MANOVA with repeated measures on the last factor. A multivariate Age × Object interaction, $F(4, 106) = 2.82$, $p < .05$, qualified main effects of age, $F(4, 106) = 2.77$, $p < .05$, and object, $F(2, 53) = 47.26$, $p < .001$. Subsequent univariate analyses and post hoc testing with alpha set at the .01 level indicated the following.

Squeezing. Analysis of the frequency of object squeezing revealed main effects of age, $F(2, 54) = 4.62$, $p < .05$, $\eta^2 = .15$, and object, $F(1, 54) = 85.93$, $p < .001$, $\eta^2 = .64$, which were qualified by a significant Age × Object interaction, $F(2, 54) = 4.83$, $p < .05$, $\eta^2 = .15$. As indicated in Figure 1a, infants at each level squeezed the soft object significantly more than the hard object. Additionally, this difference became more pronounced with age: Post hoc tests indicated that 10-month-olds squeezed the soft object significantly more than did the 6-month-olds.

Scratching. Analysis of object scratching revealed a significant main effect for object, $F(1, 54) = 6.01$, $p < .05$, $\eta^2 = .10$. As shown in Figure 1b, infants scratched the hard cube ($M = 5.57$) significantly more than the soft cube ($M = 3.50$).

In sum, when infants explored objects without relating them to the surfaces, their manual behaviors were geared to the material properties of the objects, even at 6 months. Infants showed more squeezing of the soft object and more scratching of the hard one. Additionally, squeezing of the soft object increased with age.

a.



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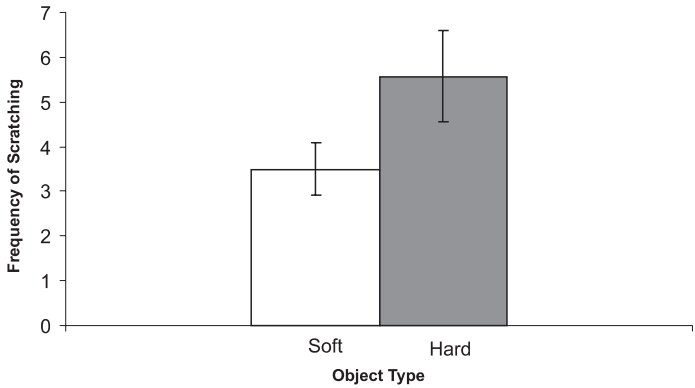


FIGURE 1 Exploration of objects: (a) frequency of squeezing the soft and hard objects as a function of age, and (b) frequency of scratching the soft and hard objects.

Surface Exploration

Four kinds of behaviors involving actions that infants performed directly with their hands on the surfaces were examined: slapping, picking, rubbing, and pressing. These data were initially entered into a 3 (age) × 2 (gender) × 4 (surface) MANOVA with repeated measures on the last factor. There was a multivariate Age × Surface interaction, $F(24, 86) = 2.51$, $p < .01$, with qualified main effects of age,

$F(8, 102) = 2.73$, $p < .01$, and surface, $F(12, 43 = 24.02$, $p < .001$. Subsequent univariate analyses and post hoc testing with alpha set at the .01 level indicated the following.

Slapping. A significant Age × Surface interaction, $F(4.98, 134.36) = 2.83$, $p < .05$, $\eta^2 = .10$, qualified a main effect of surface, $F(2.49, 134.36) = 9.61$, $p < .001$, $\eta^2 = .15$. Subsequent analyses of the interaction indicated that only the 10-month-old infants differentially explored the surfaces by slapping. Ten-month-old infants slapped the liquid surface more than any of the other surfaces (see Figure 2a). Additionally, slapping of the liquid surface increased with age: Post hoc tests indicated that 10-month-old infants slapped the liquid surface significantly more than did the 6-month-old infants.

Pressing. Infants differentially explored the surfaces by pressing (see Figure 2b). A significant main effect of surface, $F(1.64, 88.50) = 15.87$, $p < .001$, $\eta^2 = .23$, indicated infants significantly pressed the flexible surface ($M = 2.02$) more frequently than the liquid, discontinuous, and rigid surfaces (Ms = 0.38, 0.32, and 0.15, respectively).

Rubbing. Infants also differentially explored the surfaces by rubbing them with their hands (see Figure 2c). A significant main effect of surface, $F(1.30, 70.20) = 3.92$, $p < .05$, $\eta^2 = .07$, indicated that infants rubbed their hands for a longer amount of time across the liquid surface ($M = 2.86$ sec) than across the discontinuous, flexible, and rigid surfaces (Ms = 0.33, 0.85, and 0.98 sec, respectively). Post hoc testing using an alpha level of .01 demonstrated statistical trends only in the pairwise comparisons involving the liquid surface ($.023 \leq p$s $< .09$).

Picking. A significant Age × Surface interaction, $F(3.47, 93.64) = 9.06$, $p < .001$, $\eta^2 = .25$, qualified main effects of age, $F(2, 54) = 9.24$, $p < .001$, $\eta^2 = .25$, and surface, $F(1.73, 93.64) = 46.70$, $p < .001$, $\eta^2 = .46$). Analysis of the interaction indicated that each age group demonstrated different patterns of picking behavior across the surfaces (see Figure 2d). Six-month-old infants picked at the discontinuous surface significantly more than any of the other surfaces. Eight-month-old infants picked at the liquid and discontinuous surfaces significantly more than the flexible and rigid surfaces. Finally, 10-month-old infants picked at the discontinuous surface significantly more than the flexible and rigid surfaces. Taken together, the results of the interaction indicate that each age group evidenced either the most picking on the discontinuous or liquid surface and the least amount of picking on the flexible and rigid surfaces.

Additional analyses of the interaction indicated developmental differences in how frequently infants employed picking to explore a given surface. On the liquid surface, 8-month-old infants picked at the surface significantly more than either

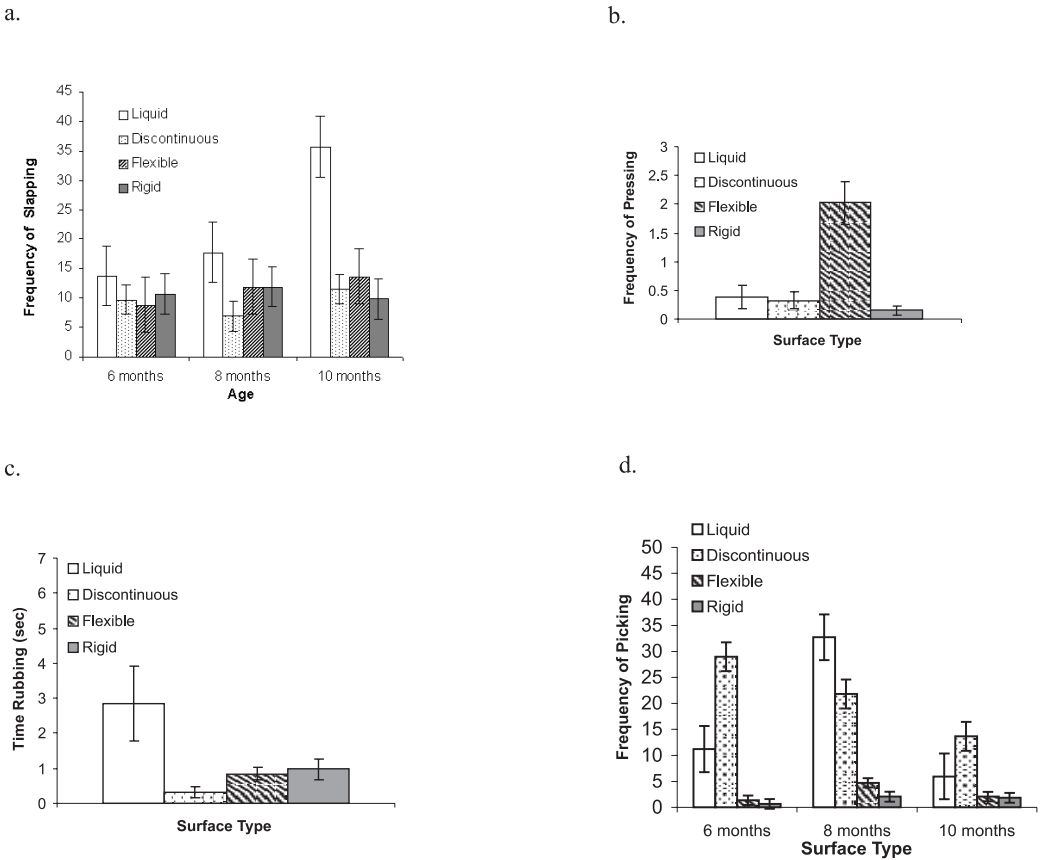


FIGURE 2 Exploration of surfaces: (a) Frequency of slapping the different surfaces as a function of age, (b) frequency of pressing the hand into the different surfaces, (c) frequency of rubbing the hand across the different surfaces, and (d) frequency of picking at the surface as a function of surface and age.

the 6- or 10-month-old infants. On the discontinuous surface, 6-month-old infants picked at the surface significantly more than the 10-month-old infants. On the flexible surface, 8-month-old infants picked at the surface significantly more than did the 6-month-old infants. Finally, on the rigid surface, all age groups performed similarly, picking at the surface very infrequently. Taken together, these results suggest that each age group used picking differentially when exploring the surfaces. However, the pattern differed somewhat by age, primarily due to the way in which the different age groups used this behavior on the liquid and discontinuous surfaces.

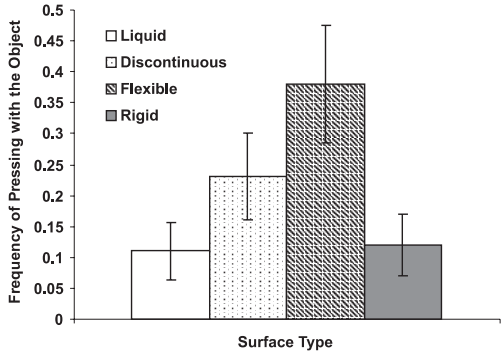
Exploration of Object–Surface Relations

The preceding findings suggest that infants explored both the objects and surfaces in a discriminating manner. We next examined whether infants took into consideration the properties of the object and surface—separately or simultaneously—when engaging in behaviors to explore one with the other. To address this issue, three kinds of relational behaviors were examined: pressing the object into the surface, rubbing the object back and forth across the surface, and banging the object on the surface. The data for these variables were initially entered into a 3 (age) × 2 (gender) × 2 (object) × 4 (surface) MANOVA with repeated measures on the last two factors. Main effects of object, $F(3, 52) = 5.72$, $p < .01$, and surface, $F(9, 46) = 3.07$, $p < .01$, were obtained as well as Age × Gender, $F(6, 104) = 2.79$, $p < .05$, and Object × Surface, $F(9, 46) = 2.12$, $p < .05$, interactions. Follow-up univariate analyses and post hoc testing with alpha set at the .01 level revealed the following.

Pressing. Analysis of pressing when infants were holding the object revealed a significant main effect of surface, $F(2.46, 132.93) = 5.97$, $p < .01$, $\eta^2 = .10$. As shown in Figure 3a, infants pressed the cubes significantly more onto the flexible surface ($M = 0.38$) as compared to the liquid ($M = 0.11$) and rigid surfaces ($M = 0.11$). They pressed the cubes into the discontinuous surface an intermediate amount ($M = 0.23$).

Rubbing. Analysis of the duration of rubbing indicated a significant main effect of object, $F(1, 54 = 9.90$, $p < .01$, $\eta^2 = .15$. Infants rubbed the hard cube (M = .42 sec) across the surfaces significantly more than the soft cube (M = .12 sec). Analyses also revealed a significant effect of surface, $F(2.29, 123.75) = 6.46$, $p < .01$, $\eta^2 = .11$, which was qualified by a significant Age × Surface interaction, $F(4.58, 123.75) = 4.77$, $p = .001$, $\eta^2 = .15$. Analysis of the interaction indicated that only 10-month-old infants differentially rubbed the objects across the surfaces (see Figure 3b). Relative to the other surfaces, 10-month-old infants rubbed the objects across the rigid surface for a significantly longer period of time. In contrast, 6- and

a.



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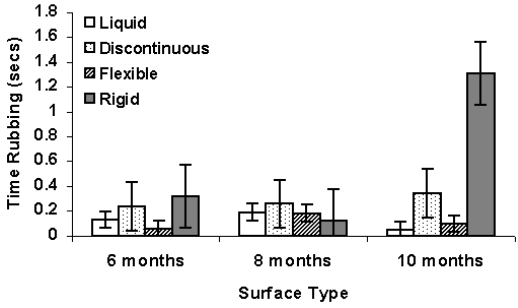

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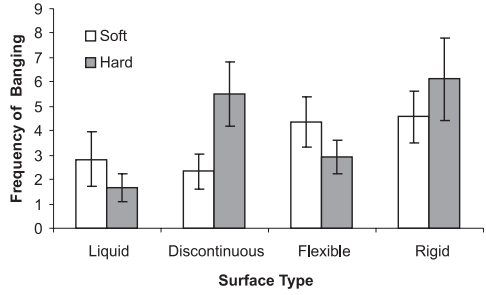

FIGURE 3 Exploration of object–surface relations: (a) frequency of pressing the objects into the different surfaces, (b) duration of time spent rubbing the object on the surface as a function of surface and age, and (c) frequency of bangs as a function of surface and object type.

8-month-old infants did not vary their object rubbing behavior as a function of the surface's material properties.

Banging. Infants used banging differentially when relating the objects to the surfaces. Analysis of the frequency with which infants banged the objects against the surfaces revealed main effects of age, $F(2, 54) = 4.52$, $p < .05$, $\eta^2 = .14$, and surface, $F(2.11, 113.18) = 2.99$, $p = .05$, $\eta^2 = .05$. These effects, however, were subsumed by Age × Object, Age × Gender, and Object × Surface interactions.

Of most importance, the Object × Surface interaction, $F(3, 162) = 4.26$, $p < .01$, $\eta^2 = .07$, indicated that infants used banging selectively, based on the combination of object and surface (see Figure 3c). Tests of simple main effects within each object revealed that infants evidenced different amounts of banging across surfaces with the hard, $F(2.20, 130.05) = 4.86$, $p < .01$, but not the soft object, $F(2.26, 133.11) = 1.74$, $p > .05$. Infants banged the hard object significantly more often on the discontinuous and rigid surfaces than on the flexible and liquid surfaces. Additionally, consideration of the interaction within each surface revealed that infants banged the hard object significantly more than the soft one on the discontinuous surface, $F(1, 59) = 5.92$, $p < .05$. In short, across age groups, infants used banging differentially, exploiting the relation between the material properties of the object and surface.

Apart from the influence of surface composition, the Age × Object interaction, $F(2, 54) = 4.15$, $p < .05$, $\eta^2 = .13$, indicated that the 10-month-old group banged the hard cube ($M = 7.91$) significantly more than the soft cube ($M = 5.56$). By comparison, both 6- and 8-month-old age groups banged the two objects an equivalent amount (for the hard and soft objects, respectively, 6-month-old Ms = 1.45, 2.79; 8-month-old Ms = 2.79, 2.23). Finally, the Age × Gender interaction, $F(2, 54) = 4.22$, $p < .05$, $\eta^2 = .14$, revealed that male infants banged the objects significantly more than female infants, but only at 10 months of age (for boys and girls, respectively, Ms = 10.29 and 3.19). No significant gender differences emerged at 6 or 8 months (for boys and girls, respectively, 6-month-old Ms = 1.75 and 2.49; 8-month-old Ms = 1.48 and 3.54).

In sum, these findings indicate that infants relate objects to surfaces in a manner that is anything but haphazard. Infants demonstrate specificity in their object–surface actions, selecting manual behaviors like pressing, rubbing, and banging that take advantage of the physical composition of the object, surface, or their joint combination.

First Type of Exploration

The analyses presented thus far focus on behaviors within each type of exploration category (object, surface, object–surface), but afford only indirect comparisons across these categories. To examine the latter issue more directly, we considered

whether there were developmental differences in the type of exploration infants performed first. Specifically, for each of the eight object–surface combinations (with respect to the coded target behaviors), we determined whether infants first related object and surface together or instead first explored either the object or surface individually. Chi-square analyses for each of the eight 3 (age) × 2 (type of exploration: object–surface vs. object or surface) contingency tables yielded three significant findings (ps < .05). When the hard object was presented on the discontinuous surface, the flexible surface, and the rigid surface (see Table 1), there were significant differences in the patterning of first exploration type as a function of age. Specifically, in these conditions, older infants appeared more likely than younger infants to explore the objects and surfaces by first relating them to each other. Closer inspection of the data revealed that for the discontinuous surface with the hard object, 10-month-olds either banged (n = 3) or rubbed the object (n = 3) on the surface first. For the flexible surface with the hard object, 10-month-olds either banged (n = 7) or pressed the object (n = 3) on the surface first. For the rigid surface with the hard object, 10-month-olds either banged (n = 6) or rubbed the object (n = 3) on the surface first. In contrast, for the five other object–surface combinations, no developmental differences emerged, with similar proportions as well as most infants at each age level first exploring the object or surface individually.

Taken together, these results suggest that for all of the soft object–surface combinations, similar proportions of infants at each age level first explored either the object or surface individually. In contrast, for most of the hard object–surface com-

TABLE 1
Frequency of First Type of Exploration

Age	*Object or Surface Exploration*	*Object–Surface Relational Exploration*
Discontinuous surface with hard object[a]		
6 months	19	0
8 months	16	3
10 months	14	6
Flexible surface with hard object[b]		
6 months	15	5
8 months	16	1
10 months	8	10
Rigid surface with hard object[c]		
6 months	14	3
8 months	15	1
10 months	7	9

Note. The sample sizes do not total 60 because infants were sometimes exhibiting behaviors (e.g., mouthing) other than those coded in the study.

[a]$\chi^2(2, N = 58) = 6.69, p < .05$. [b]$\chi^2(2, N = 55) = 10.71, p < .01$. [c]$\chi^2(2, N = 49) = 11.32, p < .01$.

binations (with the exception of the liquid surface), greater proportions of older relative to younger infants first explored these combinations relationally.

DISCUSSION

Previous research on perception–action development has indicated that in the second half-year, infants adapt their manual actions to an object's physical properties. This study extends those previous findings by revealing that infants also adapt their manual behaviors to two other basic elements of the physical world: surfaces and object–surface relations. More broadly, these findings, along with earlier work on object manipulation, suggest that later developing and more complex skills that require children to establish precise relations between objects and surfaces might emerge from these earlier adaptive behaviors.

In this connection, the results of this study reveal the targeted ways in which infants adjust their manual behaviors to different features of the material world. Consider first how infants manually explored the objects when not relating them to the surfaces. Confirming the results of previous studies, these findings indicate that even by 6 months of age, infants manipulate objects in a differentiated manner, tailoring their manual actions to an object's properties (see also Bushnell & Boudreau, 1993; Lockman & McHale, 1989; Palmer, 1989; Ruff, 1984). In this study, infants demonstrated specificity in their manual exploration, squeezing soft objects more than hard ones and scratching hard objects more than soft ones. In the case of squeezing, specificity increased with age, becoming even more pronounced by 10 months. However, it should be noted that our measures of squeezing were based on observable flattening of the finger pads against the object and not all instances of squeezing (as might be measured by a pressure transducer) might have been recorded.

Next, note how infants explored the surfaces directly before them. As was the case with objects, infants manipulated the surfaces in a discriminating fashion. Further, in some instances, selectivity increased with age. Across age levels, infants showed more pressing of the flexible surface, more rubbing of the liquid surface, and more picking of the discontinuous and liquid surfaces; older infants also showed more slapping of the liquid surface.

Taken together, these results suggest that infants are exploiting the material properties of surfaces in their immediate world. By pressing the flexible surface, infants are gaining additional information about its pliability. By rubbing and slapping their hands across the liquid surface, infants are gaining information about the surface's wetness and responsiveness to movement. By picking at the netting surface, infants are gaining additional information about its discontinuous quality. Why might it be important to explore surfaces in a discriminating manner? Effective exploration of various surface properties might help infants plan subsequent

actions on these surfaces, whether these actions involve the manual system, the locomotor system, or a combination of both (Adolph, 2002; Adolph et al., 1993; Gibson et al., 1987).

Next, consider how infants related the objects to the surfaces. As noted, the ability to establish object– surface relations selectively suggests sensitivity not just to objects and surfaces alone, but to the affordances entailed by the relation between the two. Further, such behaviors might indicate awareness at some level that the properties of the hand have changed by virtue of the object in it as well as the surface underneath it.

These findings suggest that infants in the second half-year are sensitive to some potential interactions between objects and surfaces. Infants clearly related the objects to the surfaces at all age levels. Developmental differences were also evident. Older infants appeared more likely than younger ones to perform one of the target object–surface relational behaviors first when presented with most of the hard object–surface combinations.

More specifically, what properties of the physical world—surface, object, or a combination of both—governed these relational acts? In some instances, infants selected behaviors based primarily on the properties of the surface, as was the case with pressing. Infants pressed both objects most often into the flexible surface, suggesting that they were exploring the pliability of the surface, even when not directly touching it. Recall that infants also demonstrated the most pressing of the flexible surface when exploring this surface directly with their hands.

In other instances, infants related objects to surfaces based on the property of the object as well as that of the surface, but not their interaction. This was most evident in the case of rubbing. Infants at all age levels rubbed the hard object more than the soft object across the surfaces. However, only the 10-month-old infants treated the surfaces differently as well. They rubbed the objects most frequently across the rigid surface, suggesting that they were exploiting the reduced friction and smoother movement of the objects across this surface. In contrast, neither the 6- nor 8-month-old age group evidenced such selectivity.

At this point, it is instructive to recall how infants used the same action to explore the surfaces with their hands when not holding the object. Across age levels, infants rubbed their hands most often across the liquid surface. Yet, as just noted, with the same action but with an object in hand, infants displayed a different pattern of responding, with only 10-month-old infants exploiting the relation between the object and (rigid) surface. Viewed together, these results suggest that in the second half-year, infants are becoming increasingly sensitive to how the properties of their hands and, consequently, the outcomes of their actions can change by virtue of holding objects.

Recent research indicates that under some circumstances, even very young infants are able to adapt to changes in the properties of their hands. In a clever study, Needham, Barrett, and Peterman (2002) fitted 3-month-old infants with sticky mit-

tens. With the mittens covering their hands, the 3-month-old infants were able to hold and explore objects, behaviors beyond their current developmental level. Taken as a whole, Needham et al. (2002) and the results reported here suggest that exploiting the specific properties of handheld objects might constitute one aspect of a more general perceptuomotor capacity, present to some degree early in life, that enables us to adapt to changes in the properties of our limbs.

Finally, this study also indicates that infants related objects to surfaces by taking into account interactions between the unique properties of particular objects and surfaces. At all age levels, infants varied the frequency with which they banged the hard but not the soft object on the different surfaces. With the hard object, in particular, infants displayed the most banging on the rigid and discontinuous surfaces, presumably to produce noise in the former case and to exploit the bounciness of the surface in the latter. Additionally, within surfaces, infants banged the hard object more than the soft one, but only on the discontinuous surface. Collectively, the findings on banging suggest that infants are already showing some evidence of treating the object–surface combinations in a differential manner, by taking into account how the properties of particular objects and surfaces interact. This result is consistent with Thelen's (1981) observation that prior to the emergence of more skilled actions, infants may exploit rhythmical stereotypies—such as banging—for instrumental ends.

Lastly, it should be noted that at 10 months but not before, male infants displayed more object banging than did female infants. Gender, however, did not interact with either type of object or surface, suggesting that this difference might reflect one of activity level (Campbell & Eaton, 1999) rather than object relational skill.

What underlies the developmental changes in manual specificity that were revealed in this study? As noted, some theorists have suggested that increases in representational capacity and knowledge about self–environment differentiation support infants' efforts to treat their physical surroundings in a more discriminating and appropriate manner (Bates, 1981; Piaget, 1952). In contrast, we favor the idea that this increased specificity is due primarily to the interconnected consequences of perceptual learning (Gibson & Pick, 2000) and advances in motor control (Bushnell & Boudreau, 1993). At the level of the arm, motor development has been described as proceeding in a proximal-distal fashion (Gesell & Thompson, 1934; Kuypers, 1962; Lockman & Ashmead, 1983), with control of the entire arm (e.g., swiping or reaching) emerging before that of the entire hand (e.g., shaping) and control of the hand emerging before that of individual fingers (e.g., pincer movements). These changes in prehensile control, in turn, have important consequences for the kinds of information that are available from the environment and how such information is gathered (Bushnell & Boudreau, 1993). In essence, the gains infants manifest in mastery of these newly emerging perception–action loops are reflected by the increased precision and specificity of infants' manual behaviors in relation to their immediate surroundings.

To conclude, it is interesting to consider the broader developmental implications of these findings. During the second year, children begin to employ objects in increasingly complex and culturally specific ways, solving problems and using tools by placing objects in relation to other objects or surfaces (Belsky & Most, 1980; Damast, Tamis-LeMonda, & Bornstein, 1996; McCarty et al., 2001). Some theorists have attributed advances like these to changes in representational or symbolic ability. By the same token, these theorists have described earlier efforts by infants to relate or juxtapose objects as simple or undiscriminating (e.g., see Belsky & Most, 1980; Fenson et al., 1976; Piaget, 1952). These findings suggest, however, that such object juxtapositions are not that simple. In the second half-year, infants are selective in how they manipulate objects and surfaces and relate the two. Infants choose actions based on the physical composition of the object, surface, or their potential interaction. This early selectivity, however, raises questions about the representational or symbolic foundations of later developing and more complex forms of object use. We suggest that these findings highlight another possibility for understanding the psychological foundations of these more complex skills. Note that many of these more advanced achievements with objects require individuals to relate objects to surfaces in precise ways, capitalizing on the physical properties of each. We propose that the roots of older children's more complex object relational skills may be found in infants' manual efforts to explore and act on the world around them. By doing so, infants learn how to exploit the physical properties of objects, surfaces, and their potential interrelations with different kinds of actions. Additional consideration of how infants use their hands to engage in this discovery process might lead to new insights regarding the origins of problem solving and tool use.

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