Development of role-differentiated bimanual manipulation during the infant's first year

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Abstract:

Role-differentiated bimanual manipulation (RDBM) is a complementary movement of both hands that requires differentiation between actions of the hands. Previous research showed that RDBM can be observed in infants as early as 7 months. However, RDBM could be considered a skill only when its frequency, duration, and use is appropriate for the type of manual task, and there is some evidence of intentionality in use. Twenty-four normally developing infants were studied longitudinally at 7, 9, 11, and 13 months to assess the frequency and duration of five clearly different types of RDBM with three "single-part" and three "two-part" toys as they emerge during development. Also, the sequences of actions that lead to RDBM were examined for evidence of "intentionality." The results show that although the each type of RDBM appears early in infancy, RDBM only begins to exhibit the characters of a skill by 13 months. Moreover, the type of toy influences not only the likelihood of eliciting role differentiation, but also the type of RDBM behavior and the organization of the sequence of actions that lead to RDBM. Some useful criteria for defining an infant sensorimotor skill are provided in discussion. © 2010 Wiley Periodicals, Inc. Dev Psychobiol 52:168–180, 2010

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Article:

Introduction

In the present study, we examined the emergence of an asymmetrical bimanual action that appears late in the first year of infancy; variously called complementary bimanual action (Bruner, 1970; Michel, Ovrut, & Harkins,1985), collaborative hand-use (Bresson, Maury, Pieraut-Le Bonniec, & De Schonen, 1977), asymmetric bimanual cooperation (Fagard & Peze, 1997), or role-differentiated bimanual manipulation s (RDBMs) (Kimmerle, Mick, &Michel, 1995; Ramsay & Weber, 1986). This ''skill'' requires that each hand perform different, but complementary, actions on one or more objects. During RDBM, the different actions of the hands coalesce in the manipulation of an object with one hand serving a supportor stabilizing role as the other manipulates the features of an object. To manifest this new pattern not only must the order of constituent subroutines be changed, but they must be coordinated between hands, which means between hemispheres (Michel, 2002). Thus, the development of this skill has been considered to reflect a major shift in motor organization (Haaland, Elsinger, Mayer, Durgerian, & Rao, 2004), cognitive functioning (Bruner, 1970;Connolly & Dalgleish, 1989; Ramsay & Weber, 1986),and neural functional organization (Michel, 1987, 2002;Serrien, Ivry, & Swinnen, 2006). Our purpose in this study was to chart the developmental progression of this type of manipulation skill during the period from 7 to 13 months, a period of infancy marked by increasing bimanual manipulation (Bruner, 1970; Kimmerle et al., 1995;Ramsay & Weber, 1986).

Previous research has demonstrated that RDBM during toy play is present in most infant s typically by 13 months and infants will show a hand-use preference for the role each hand plays (Bruner, 1970; Fargard & Jacquet, 1989;Fagard & Marks, 2000; Michel et al., 1985; Ramsay, Campos, & Fenson, 1979). However, when provided with a wide range of toys that vary in terms of their physical characteristics (i.e., sounds or movable parts), simple RDBM actions can be observed as early as 7 months in79% of a sample of infants and in all infants by 11 months (Kimmerle et al., 1995). More complex RDBM actions, such as those involving toys that require a cap to be unscrewed using only complementary asymmetrical movements, only appear during 18–24 months (Fargard& Jacquet, 1989). Of course, RDBM skills can continue to emerge throughout the life span and contribute to such skilled tool-use activities as playing most musical instruments, knitting, surgery, etc.

Although RDBM can be identified in infants as early as 7 months, the mere presence of the behavior does not provide any indication of the level of skill involved. An examination of the patterns of expression of RDBM, relative to the toy type used in the assessment, indicated that early expressions of role-differentiation did not appear to involve the independent control of the fingers for toys that afforded this type of fine motor exploration (Kimmerle et al., 1995). That i s, the earliest manifestations of RDBM occurred regardless of the properties of the toy. Toys with no movable parts and no sound production elicited RDBM from infants at7 months as readily as toys that did not provide these effects. This suggests that these early manifestations of the skill may have occurred because the characteristics of particular toys permitted manipulations to be less constrained by such requirements as the type of fine motor precision and velocities of action needed to elicit noise or movement. Thus, it is highly likely that these very young infants may have exhibited RDBM as by products of using both hands to manipulate the object and without purposefulness, intention, or goal directed-ness.

Although RDBM has been proposed to be a distinctive feature of human manual skill (Vauclair, 1993), little is known about the relation of RDBM to: (a) unimanual and nondifferentiated bimanual actions that are common aspects of the infant’s repertoire; (b) the specific sequential organization of the role-differentiated actions;(c) the specific task contexts within which RDBM is best elicited; (d) its neural mechanisms; and (e) the relation between this com plex sensorimotor skill and developing cognitive skills. Although cognitive development and motor development have frequently been regarded as independent and treated as separate domains of ability, the two may be functionally interrelated during the course of development, especially in infancy. For example, learning to solve a bimanual coordination task may have implications for developing a broad range of means-end behaviors such as engaging in tool-use and relating information between objects in space and time (Bojczyk & Corbetta, 2004), all of which have cognitive aspects and consequences.

The present study has three goals. Goal one of the study is to collect evidence concerning when during development the manifestation of RDBM is likely to represent the emergence of a new skill. For the skill to be considered present, it should meet a set of detailed criteria including first whether RDBM represents a reasonable proportion of the infant's manual repertoire and whether the behavior occurs across a wide range of tasks. To meet this goal, the frequency and duration of RDBM actions relative to the infant's existing repertoire of infant manual skills is documented. Since developmental change is alteration in the relative frequency of reliance on different ways of adjusting to conditions, as a skill is acquired, it should exhibit increased use in the infant's repertoire (Siegler & Manukata, 1993). In the present study, the content of the infant's manual repertoire during continuous toy play was examined to identify the proportion of RDBM actions and their du ration relative to other manual skill s. It was hypothesized that RDBM initially would be a minor component of the infant's manual repertoire with objects but that its proportion of the manual repertoire would increase with age.

Infants acquire a hand-use preference during the latter half of their first year with a majority demonstrating a preference for the right hand (Michel et al., 1985). As RDBM becomes a manual skill, it should exhibit a lateral preference consistent with other manual skills. It has been observed that lateral preferences for manual skills that emerge early in development contribute to lateral preferences for manual skills that emerge later in development (Hinojosa, Sheu, & Michel, 2003). There-fore, it is conceivable that infants will have to coordinate a hand-use preference while engaging in RDBM as a skill. Therefore, the study recorded the frequency and duration of right and left hand oriented RDBM actions as a means of assessing the infant's RDBM skill. It was hypothesized that a hand-use preference for RDBM would mark it as a skill.

Initial RDB M actions have been reported to appear at various ages between 7 and 24 months (Bruner, 1970; Fargard & Jacquet, 1989; Fagard & Peze, 1997; Kimmerle et al., 1995; Michel et al., 1985; Ramsay et al., 1979) indicating that different researcher s may not be measuring the same behavior. In the present study, data from manipulation of single- and two-part toys were used to identify five different types of RDBM and to explore their pattern of emergence during the 7- to 13-month period.

Goal two is to determine whether the early presence of RDBM is dependent on the use of a particular set of toys. That is, are certain types of toys more likely to elicit RDBM? The literature on the onset of bimanual coordination has tended to disregard the motor requirements of the task (symmetry vs. asymmetry, simultaneous vs. successive movements) when studying infant performance, although the motor requirements affect rate of success (Fargard & Jacquet, 1989). To address this issue, data from six different toys—three single-part toys that produce some effect (noise, movement) and three two-part toys whose effect (noise, movement) depends upon asymmetric use of the hands (inserting one object into another or removing an object from containment by another)—were used to assess the presence of RDBM from 7 to 13 months. The three two-part or ‘‘double’’ toys afforded clearly differentiated roles between the two hands—a toy feature that has been shown to increase the likelihood of eliciting lateralized hand-use (Fagard &Marks, 2000). It was hypothesized that RDBM with double toys would represent an appropriate deployment of the skill and would appear later in development than RDBM with single toys because RDBM with single toys might emerge incidentally as a consequence of the actions afforded by the single toy.

Finally, Goal three is to examine whether the infant's manifestations of RDBM actions represent ‘‘planned’’ or ‘‘intentional’’ actions. Seemingly purposeful complementary actions of the two hands can emerge during exploratory manipulation of objects; particularly if the objects readily afford such actions (e.g., a hollow sphere with holes into which fingers can slip or be inserted). However, such ‘‘object afforded’’ R DBM actions, while perhaps contributing to the development of RDBM skills, would not be evidence of either the presence of the skill or the intention to perform it (goal directed or purposeful). Although there is no generally accepted operational definition of intentional actions for infants, for the purposes of the present study, an intention to engage in RDBM actions will be identified by evidence of a nonrandom pattern in the sequence of actions preceding the RDBM action. The assumption is that there ought to be a pattern of action that leads to RDBM, if the infant ‘‘intends’’ to engage in RDBM. Moreover, if there is a hand-use preference for the R DBM, the manifestation of RDBM should be preceded more consistently by the nonpreferred hand as oppositional lead-in. That is, the nonpreferred hand should be used to ‘‘set- up’’ the manipulation of the object by the preferred hand by first acquiring or stabilizing the object. To address these issues, we examined the sequential order of events leading to RDBM. It was hypothesized that RDBM would be ‘‘intentional’’ if there were consistent sequences of actions predicting its occurrence. Also, we examined whether the latency to manifest RDBM actions is faster when the infant is presented with toys for which RDBM produces clear effects, as this decreased latency would indicate increased skill. A reduced latency to perform a task ought to indicate the effects of practice.

Thus, longitudinal data were collected four times between 7 and 13 months to provide information about both the relation of RDBM to the infants’ manual repertoire and the sequential organizational structure of actions that lead to RDBM behavior. The skills represented by RDBM reflect both the interface of cognitive and sensorimotor components of emerging skills (Diamond, 2000; Greenfield, 1991; Kimmerle et al.,1995; Siegler & Manukata, 1993) and the neuropsychological character of infant development (Michel, 1987,1991, 2002). Thus, this study continues a programmatic description of the development of RDBM skills during infancy.

Methods

Subjects

Twenty-four infants (12 males) were selected from a larger sample of 65 infants who participated in a study of sensorimotor development. All infants had healthy full-term births (at least 39 weeks gestation and birth weight of at least 6 lbs) after uneventful pregnancies. The infants represented a mix of Middle and Eastern European, Central American, Hispanic and African American ethnic backgrounds. Each infant was observed as 7, 9,11, and 13 months ($\pm$1 week) after their birth date. All had two parents living at home with either blue-collar or white-collar occupations. The selection of these 24 infants provided equivalent demographics and cohort characteristics between the males and females for each age period.

Procedure

At each visit, the infant sat on the caregiver’s lap at a stomach-high table while a reliable and valid handedness assessment (Michel et al., 1985) consisting of a battery of 28 toys was presented. The assessment was part of an investigation of sensorimotor skill. The infants were videotaped simultaneously from two camera angles providing both and overhead and left-side view.

For the current study, six toys—three single-part, effect-producing toys (beeper, cage ball, ball in tube) and three two-part insertable toys (cube and funnel, open cube and screw, open cube and wooden stick)—were presented for systematic coding. Kimmerle et al. (1995)

demonstrated that toys with movable parts or sound production are effective in eliciting RDBM at all four ages. The two-part toys were included to elicit role-differentiated actions that involved the insertion and removable of containable objects. The two sets of toys required different patterns of sensorimotor actions and levels of ‘‘comprehension’’ (e.g., containment). Each toy was presented at midline on the table, with the two-part toys presented both in the inserted (to assess removal actions) and in the separated (to assess insertion actions) conditions. The presentations lasted 15–20 s or until terminated by the infant. These six toys were interspersed, in a variable order, with the other toys in the handedness test protocol. All six toys were small enough (4–6 cm) to be readily grasped by even the youngest infants. In addition, the infants were provided with a cup and block toy that served as a control. The intention of the control toy was to determine whether infants could insert or remove the block irrespective of the means used to accomplish the task (i.e., either a unimanual or bimanual pattern). Such ability would permit identification of infants who did or did not have an ‘‘understanding’’ of the object relations between the cup and block (e.g., concepts of containment and insertion).

Data Coding

Videotapes were played frame-by-frame and coded using the Observer software for on-line data entry (Noldus© Information Technology, Leesburg, VA). Event coding was initiated when an object was released by the experimenter, and terminated when the infant released the object or the experimenter removed the object. This produced sequential data files listing each event with a time code, as well as summary files for each infant at each age of total frequency and duration for each event. The primary observer coded all 96 videotapes (24 • 4), while the second observer independently coded 15% of the tapes for reliability calculations. In addition 10% of the tapes were recoded by the primary observer to provide a measure of intra-coder reliability. Mean percent agreement was 93% with a range from 88% to 99%.

The events coded were 15 mutually exclusive and exhaustive categories of object manipulations, including right and left hand use (see Tab. 1). For certain analyses, these events were collapsed into three categories of unimanual, bimanual undifferentiated, and RDBM actions. Unimanual actions were right or left handed and occurred when only one hand was in contact with one or both of the objects. An important distinction in this study is the difference between types of bimanual activity. The category of bimanual undifferentiated includes all bimanual activity in which the two hands perform similar actions either simultaneously or in alternation, for example, both hands are grasping an object. Role-differentiated actions (RDBM) involve clearly distinct actions performed by each hand. One hand holds, stabilizes, or supports the object on the table or in the air as the other hand is actively manipulating a second object or explores the surface of the held object. Since these actions are lateralized they were coded according to the right or left hand used for manipulation. The object exploration role-differentiated actions of fingering and stroking can be observed both with single- and two-part objects. However, the three object relationship categories of contact, removal, and insertion can only be demonstrated with the two-part container objects.

In a separate coding procedure that involved the two-part control toy (a block and cup), any insertions or removal actions were recorded regardless of whether they were performed as role-differentiated actions, or as bimanual undifferentiated actions, or unimanually. These data were collected to identify whether failure of role-differentiated removals or insertions with the test toys was a consequence of an inability to coordinate the two hands rather than to the lack of an understanding of the relationship between the objects in two-part toys, a more complex sensorimotor (cognitive) skill. Therefore, comparisons were made subsequently between the control (block and cup) data and role-differentiated insertion/removal data from the two-part test toys. Percent agreement of the presence of insertion/removal was 88% between the coders.

Categories	Operational Definition
Unimanual	
Right or left	One hand only manipulates the object
Bimanual undifferentiated	
Both	Two hands are manipulating one object, or two objects in the inserted condition
Bimanual	Objects are separated; one hand possesses or manipulates each object separately
Undifferentiated	Objects are in physical contact but not inserted; both hands perform similar actions
Role-differentiated	
Finger	One or two fingers explore the object
Stroke	The palm and/or whole hand explores the object
Contact	One hand is brought into contact with object as other steadies, orients, or otherwise supports the actions of the first hand (not including fingering or stroking)
Remove	When in inserted condition, one hand holds the object, as other initiates removal of the second object; complete separation is not necessary
Insert	When in the separated condition, one hand holds the object as the other hand inserts second object below rim; object release is not required

Table 1. Categories of Object Manipulation Coded With Operational Definitions for Each Category

Results

Goal one: manipulation repertoire and RDBM

General Manipulation Activity: An ANOVA was con-ducted using the percent of the presentation time that an infant spent manipulating the single and double toys. The variables were infant sex with age (7, 9, 11, 13 months) and toy type (single or double) as repeated measures. The intent of this analysis was to determine whether general manipulation activity differed with the sex, age, or toy type. There were no significant main or interaction effects involving the infant's sex or toy type. There was a significant main effect for age, F(3, 66) ¼ 15.6, p < .001(Fig. 1). Manipulation activity increased with age from7 to 9 months (from 80% to 90% of time) and thereafter remained at about 90% of the presentation time. Thus, although manipulation increases with age, even the youngest infants spent a great deal of task time manipulating the toys. Latency, the time elapsed from object presentation to infant first contact, shows no significant age differences but does show toy effects (Tab. 2). Infants delay almost twice as long before engaging in two-part toy manipulations.

RDBM in the Manipulation Repertoire. RDBMs occurred at least once for 80% of infants tested at 7 months and for all infants by 11 months. Since absolute measures differ for age, all age comparisons for mean frequency and duration were calculated as percentages of total number of actions and total time on task. The relation of frequency and duration of RDBM to unimanual and bimanual manipulation is examined below in relation to toy type.

	Age (Months)				
	7	9	11	13	
Single toys					
Latency (s)	3.4	2.5	3.7	2.3	n.s.
Two-part toys					
Latency (s)	5.7	6.4	4.3	6.6	n.s.

n.s., not significant for age differences.

Table 2. Mean Latency From Presentation to the Onset of Manipulation According to Toy Type and Age

Order of Emergence of RDBM Categories. The order of emergence of the different types of RDBM was examined and defined by the number of infants demonstrating these actions at each age. Figure 2 shows the cumulative percentage of infants who demonstrated each of the RDBM actions by each age. Fingering was seen earlier in more infants than stroking even though stroking appears to involve the simpler combination of a whole hand action while fingering requires the more precisely coordinated isolation of one or two fingers. By 9 months, all infants had demonstrated fingering while less than 61% used stroking. Fingering likely is afforded by the protrusions, slots, and holes in the objects; whereas stroking requires a more ‘‘intentional’’ action.

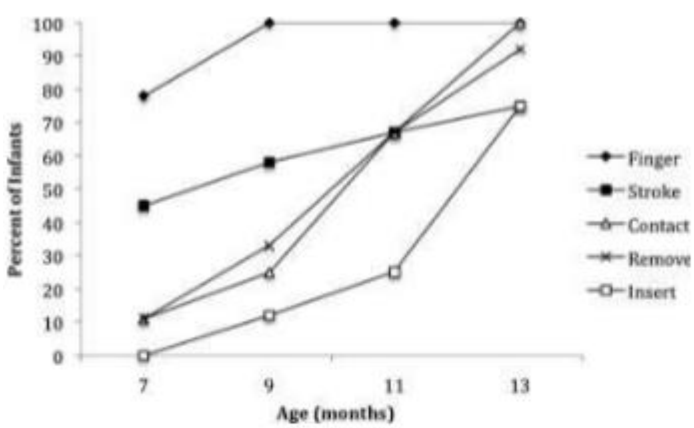

Figure 2 Cumulative percentage of infants demonstrating each RDBM category by each age.

Object removal was observed earlier than object insertion. It first occurred at 7 months but is not frequent at until 11 months. By 11 months, 16 of the 24 infants demonstrate object removal. Insertion is observed as early as 9 months, but does not become a frequent component of the repertoire until 13 months. Eighteen of the 24 infants demonstrated insertion by their 13-month test period.

Table 3 shows the number of infants for whom removal or insertion with the control toy (cup and block) came before, at the same time, or after they exhibited these actions as RDBM skills as part of the assessment task. These data provide a comparison of removal and insertion actions with the block/cup (which could occur with one hand only, or with both hands) to the role-differentiated removal and insertion actions with the three test toys.

	Order of Emergence			
	Control Before	Same	After	Never
Removal ($N = 21$)	17	3	1	0
Insertion ($N = 16$)	4	6	4	2

Table 3. Control Toy Data: Order of Emergence of Removals and Insertions of Block and Cup Compared to the Three Test Toys

Since this was to serve as a control for the ability or cognitive ''understanding'' of object relations, any infant who showed RDBM actions with the cup and block were excluded from the comparison. Significantly more infants demonstrated removal with the cup before demonstrating it with the RDBM assessment tasks (goodness-of-fit, $X^2(31) = 21.7$, $p < .001$). However, there were no order effects with insertion. That is, there was no reliable pattern of when the behavior emerged relative to when the action was exhibited as a RDBM skill.

Lateralized Hand-Use. The frequency (single toys $F(1,19) = 4.77$, $p < .04$; two-part toys $F(1, 19) = 4.6$, $p < .04$)and duration (single toys $F(1, 19) = 6.51$, $p < .02$) of righthand oriented RDBM is significantly greater than left only at 13 months. In contrast, the frequency of right hand unimanual actions are significantly greater than left for single toys at seven months, $F(1, 19) = 5.16$, $p < .03$. For two-part toys, duration of right-hand unimanual action is greater than left for both 7 months, F(1, 19) ¼ 5.87,p < .02, and 9 months, F (1, 19) ¼ 5.91, p < .02. There were no other significant differences for unimanual at other ages. Thus, although RDBM appears early in development, infants do not begin to exhibit a hand-use preference until 13 months of age. Hand-use preferences for unimanual manipulation are present at 7 and 9 months indicating that the infant has a preference and can exhibit such a preference during the execution of manual skills. Infant RDBM, as measured in this study, does not achieve the level of skill needed to exhibit a hand-use preference until 13 months.

The individual hand-use preferences for infants' RDBM were examined at 13 months by comparing the frequency of right and left RDBM actions using the formula: $(R - L)/(R + L)^{1/2}$(Fisher, 1936; Michel et al.,1985). The formula permits identification of infants that use one hand more frequently than the other with a difference that is unlikely to have occurred just by chance. Half of the infants at 13 months had a significant hand-use preference for RDBM (11 right, 1 left), two had no significant preference, and the remainder had an insufficient number of RDBM actions to calculate a statistical preference.

Goal two: toy type and RDBM

Before examining the relation of toy type to RDBM, toy type was examined in relation to the frequency and the duration of all manual actions (the combined categories of unimanual, bimanual, and RDBM) using separate ANOVAs with sex, age, and toy type as variables. There were no significant main or interaction effects for sex on either frequency or duration of manual activity. However, there was a significant interaction effect of age and toy type for both frequency, $F(3, 66) = 21.6$, $p < .001$ (Fig. 3)and duration, $F(3, 66) = 6.7$, $p < .01$ (Fig. 4) of manual activity. There was also a significant linear increase infrequency, $F(1, 22) = 8.1$, $p < .01$, and duration, $F(1,22) = 7.9$, $p < .01$, of manual activity with age for double toys, but not single toys.

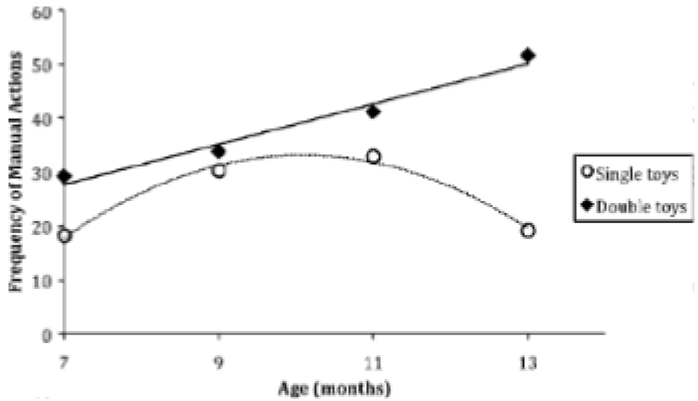

Figure 3 Frequency of manual contacts for single and double toys.

Thus, both the frequency and duration of manual actions with double toys increased with age; whereas, there was no consistent effect of age on the frequency or duration of manual activity with single toys. Indeed, the pattern of frequency and duration of manual activity for single toys appears to be curvilinear; however, the four age points are insufficient to identify reliably a curvilinear pattern.

Relative frequency of manual activity with single toys was examined using an ANOVA with type of manual activity (unimanual, bimanual, and RDBM), sex, and age as factors. Sex had neither a main effect nor interaction effects. However, there was a significant interaction of age and type of manual activity, $F(6, 66) = 4.9$, $p < .005$(Fig. 5). There was a significant linear increase with age for RDBM $F(1, 22) = 9.3$, $p < .005$ whereas both unimanual and bimanual decreased with age. Similarly, for frequency of manual activity with double toys, there was neither a main effect nor interaction effects of sex. Again, there was a significant interaction of age and type of manual activity, $F(6, 66) = 5.3$, $p < .005$ (Fig. 6). There was a significant linear increase with age for RDBM $F(1, 22) = 10.2$,$p < .005$. Although both unimanual and bimanual decreased with age, the change was not significant.

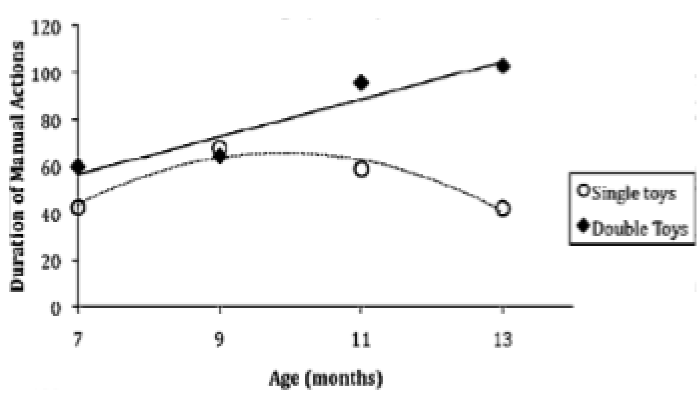

Figure 4 Duration of manual activity with single and double toys.

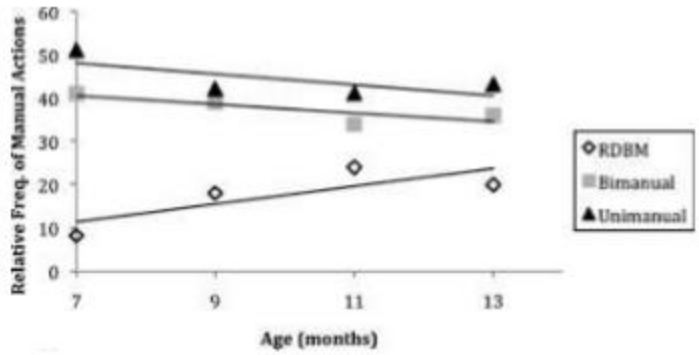

Figure 5 Relative frequency of RDBM, bimanual, and unimanual actions with single toys.

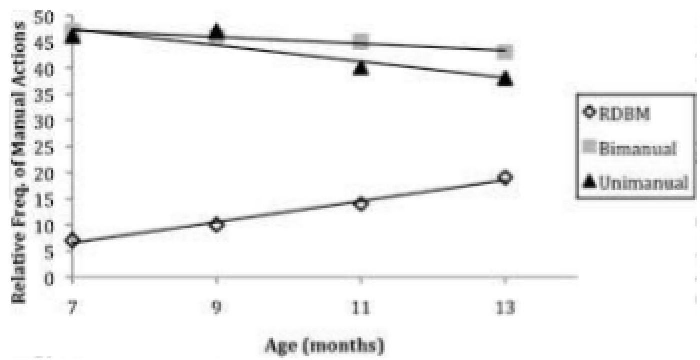

Figure 6 Relative frequency of RDBM, bimanual, and unimanual actions with double toys.

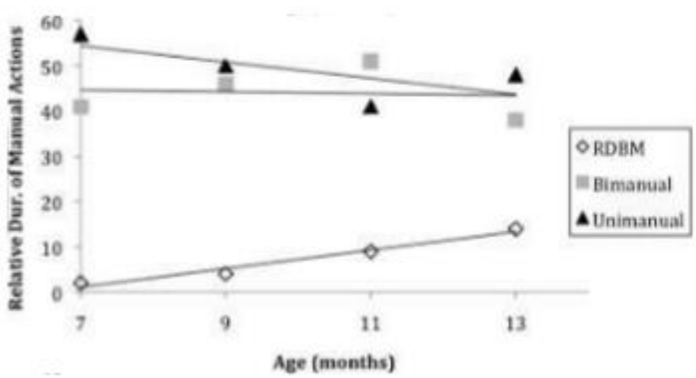

Figure 7 Relative duration of RDBM, bimanual, and unimanual actions with single toys.

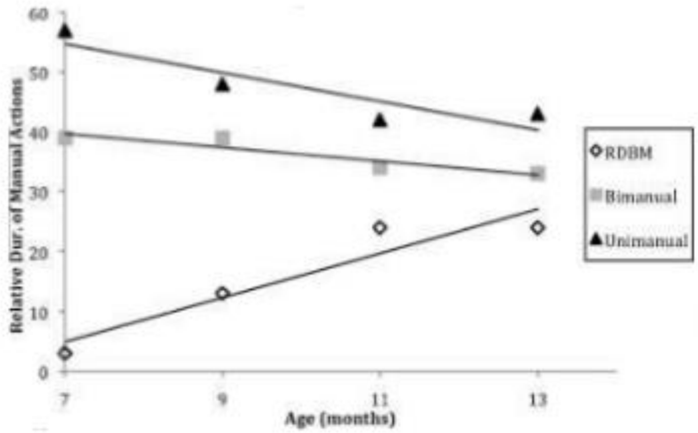

Figure 8 Relative duration of RDBM, bimanual, and unimanual actions with double toys.

Relative duration of manual activity with single toys (unimanual, bimanual, and RDBM) was examined by ANOVA with sex and age as the other variables. Sex had neither a main effect nor interaction effects. However, there was a significant interaction of age and type of manual activity, $F(6, 66) = 4.7$, $p < .005$ (Fig. 7). There was a significant linear increase with age for duration of RDBM, $F(1, 22) = 10.1$, $p < .005$, whereas both unimanual and bimanual decreased with age albeit not significantly. Similarly, for duration of manual activity with double toys, there was neither a main effect nor interaction effects of sex. Again, there was a significant interaction of age and type of manual activity, $F(6, 66) = 5.6$, $p < .005$ (Fig. 8). There was a significant linear increase with age for duration of RDBM, $F(1, 22) = 9.9$, $p < .005$, whereas although both unimanual and bimanual decreased with age, only the duration of unimanual manipulation exhibited a significant linear decrease, $F(1, 22) = 8.1$, $p < .01$.

By the end of the developmental period studied (13 months), infants have extensively increased RDBM frequency and duration during play with both single and double toys. Toy type did not seem to delimit the infant's manifestation of RDBM actions. However, double toys did elicit longer durations of RDBM then did single toys. Also, it should be noted that unimanual and bimanual undifferentiated actions still comprise most of the infants' repertoires.

Analysis of the full range of the RDBM actions was performed with the two-part insertion toys. Table 4 shows the percentage frequency in each category of RDBM at each age with two-part toys. Chi-square analyses revealed significant shifts between 7 and13 months in the types of RDBM manifested, with the distribution of categories differing at each age (between 7 and 9 months, $X^2(4) = 11.2$, $p = < .05$; between 7 and 11 months, $X^2(4) = 47.2$, $p < .001$; between7 and 13 months, $X^2(4) = 116$, $p < .001$; between 9 and 11 months, $X^2 (4) = 31.7$, $p < .001$; between 11 and 13 months, $X^2(4) = 31.3$, $p < .001$). The actions of fingering and stroking accounted for most RDBM actions at 7 months (84%) whereas insert ion, removal, and contact predominate (92%) at 13 months.

These results provide answers to hypotheses of goals one and two of this study. The results confirm a previous report (Kimmerle et al., 1995) of the presence of RDBM during toy play at 7 months. About 80% of the infants in both studies showed RDBM at 7 months and all at11 months. In the previous study, a broad range of toys that varied in their physical characteristics may have contributed to the early elicitation of the behavior. However, in the present study, both the single- and two-part toys elicited RDBM at 7 months.

RDBM actions are not a single, unitary class of skills. Rather, they represent a complex category of behaviors that exhibit developmental progression in their order of appearance. In a previous study (Kimmerle et al., 1995), we examined the simplest RDBM of objects that involved fingering and stroking. In the present study, the object relationship actions of contact, removal, and insertion have been documented with two-part toys. There appears to be a developmental pattern of emergence of these skills with object fingering and stroking appearing in 75% of infants by 7 months, object removal appearing by11 months in 67% of infants and object insertion accomplished by 75% of the infants by 13 months.

Goal three: sequence of hand actions leading to RDBM

The order of events preceding each occurrence of RDBM was analyzed from the sequence files. The files were entered into a computer program written using the FoxPro Database software (Kotwica, 1994). The sequential contingency program generated separate 1st-, 2nd-, and3rd-order lag sequential distributions of behavioral acts (Markov chains) for single- and two-part toys at each age. The model can be used to analyze events that exhibit temporal dependence such that it can be determined whether the probability of occurrence of future events is dependent on past events. Thus, behaviors that occur closely together in time may have the same underlying causal factors (Fagen & Young, 1978).

The software used to analyze the sequences identifies all significant contingent relationships between coded acts. The program uses Chi-square analysis to determine whether a distribution matrix of acts is significantly nonrandom. Within a distribution, significance was determined using the formula: $A = n_{ij} - e_{ij}/e_{ij}^{1/2}$, where n_{ij} is the observed frequency and e_{ij} is the expected frequency. Any post hoc values greater than 3 were considered significant (Fagen & Mankovich, 1980). Only contingent sequences ending with RDBM actions were examined. The resulting frequency distribution of these contingent sequences were converted into percentages and grouped into mutually exclusive categories to allow longitudinal comparisons of sequences used by the infants. Sequences were grouped based on the type of behavior immediately preceding RDBM (Tab. 1 for descriptions) using the following categories:

(1) RDBM was preceded by another RDBM action, for example, stroking preceding fingering;
(2) A ‘‘both’’ preceded RDBM;
(3) The same unimanual action preceded a lateralized RDBM, for example, a right unimanual fingering preceded a role-differentiated fingering;
(4) A unimanual action of the same type, but with a different hand preceded a lateralized RDBM, for example, a left unimanual fingering preceded a right role-differentiated action;
(5) Another object exploration RDBM preceded contact, removal or insertion, for example, contact preceded insertion;
(6) A bimanual action preceded contact or insertion.

The order of actions and the combination of action sequences were examined in four ways: (1) the action initially used for contact with the object(s), (2) the number of actions that make up the RDBM sequences, (3) the action immediately preceding RDBM, and (4) the sequence of two or three actions preceding RDBM.

Initial contact is most frequently made by unimanual manipulation of objects at all ages, regardless of whether there in one object or two (a range of 62–82% with single toys, 61–83% with two-part toys). With single toys, there is a shift at 11 months to a greater proportion of initial contacts occurring with the left hand (60% left). Thus, with single toys, at age 11 months we have the first potential evidence of an intention to engage in RDBM because the left hand is being used to obtain the toy (nearly all of our infants had manifested a right hand preference for acquiring objects).

The number of actions comprising a sequence that ended with a RDBM was analyzed as actions occurring from initial contact to release of the object. Several of these sequences of manipulation might occur during the20 s time period during which the object was available. The mean sequence length was slightly longer with single toys (7, 10, 11, and 8 actions at 7, 9, 11, and 13 months, respectively) than for two-part toys (6, 8, 8, 6 actions) a teach age. When RDBM was present, the majority (63%) of RDBM events occurred after at least four actions for both single- and two-part toys with a range of 50–74%. Less than 3% occurred immediately on presentation. Younger infants did not have a shorter sequence of actions than older infants. This can be taken as supporting evidence for the notion that RDBM emerges from the manipulation activity and need not be an intentional action.

All occurrences of RDB M, regardless of where they occurred in the sequence of action were analyzed in order to identify any significant patterns of actions leading up to RDBM. Since the frequency of event sequences is affected by the total frequency of occurrence of particular events in the repertoire, many of the sequences that occur are trivially nonrandom. That is, the more sequences that are identified the more likely it is that some of them are significantly contingent just by chance. To control for such chance contingencies, the Chi-square statistic was used to identify which sequences in the matrix occurred in greater frequency than chance.

Since the types of RDBM behaviors vary between single- and two-part toys, the contingency of sequence sending in RDBM was examined separately for the two toy types. Contingent (nonrandom) sequences were identified by the FoxPro program. Table 5 shows the total number of random and contingent two-, three-, and four-event sequences that ended with a RDBM when playing with single- and two-part toys. For single toys at 7 months, there were only 4 contingent two- and three-event sequences and 6 four-event sequences. The number of contingent sequences was significantly less than that of the random sequences for all event sequences, $X^2(1) = 4.0$, $p < .05$. At 9 months, both the absolute and relative frequency of contingent sequences increases for all event sequences, although random sequences are still more frequent than contingent sequences, $X^2(1) = 4.9$, $p < .05$. Only at 11 months and only for two-event sequences is the number of contingent sequences significantly greater than that of random sequences $X^2(1) = 4.6$, $p < .05$. Thus, only at 11 months and with simple two event sequences is there evidence supporting the notion that RDBM may be intentional.

	Age (Months)			
	7	9	11	13
Single-part toys RDBM sequences				
No. two-event RDBM sequences	41	142	227	102
No. three-event RDBM sequences	36	118	193	81
No. four-event RDBM sequences	30	105	159	66
RDBM contingent sequences				
No. two-event cont. RDBM sequences	4	54	137	28
No. three-event cont. RDBM sequences	4	30	23	17
No. four-event cont. RDBM sequences	6	24	43	5
Two-part toys RDBM sequences				
No. two-event RDBM sequences	34	98	137	206
No. three-event RDBM sequences	29	91	129	183
No. four-event RDBM sequences	21	79	106	144
RDBM contingent sequences				
No. two-event cont. RDBM sequences	0	48	63	144
No. three-event cont. RDBM sequences	2	30	44	127
No. four-event cont. RDBM sequences	2	29	24	69

Table 5. Lag Sequential Data: Number of RDBM Sequences and Number of Contingent RDBM Sequences for Single- and Two-Part Toys at Each Age

Table 6 shows the percent distribution of the types of contingent sequences for the three-event sequences for single-part toys. Although contingent sequences of RDBM are not a significant aspect of the infant's manual repertoire when playing with single toys, the table reveals some potentially interesting patterns. At 7 months, contingent patterns either involve a lead-in from ''both'' or are repetitions of RDBM with one RDBM preceding another, much like a circular reaction. By 9 months, infants begin to use a single hand to precede a RDBM thereby permitting that hand's actions to support the use of the other active hand during RDBM (i.e., unimanual to opposite). This may signal the beginning of a distinction between the hands in the coordination of RDBM acts. A similar pattern was seen in both the two- and four-event sequences.

	Age (Months)			
	7	9	11	13
Percent in each category				
Repetition	50	0	0	0
Both to RDBM: same	50	70	24	35
Both to RDBM: opposite	0	0	0	0
Unimanual to same	0	17	27	0
Unimanual to opposite	0	13	49	65

Table 6. Three Event Sequence Single Toys: Percentage in Each Category of Contingent RDBM Sequences

For two-part toys, there were no contingent two-event sequences at 7 months and only two each for three- and four-event sequences (Tab. 5). The absolute and relative frequency of contingent sequences increase with age for all event sequences, $X^2(3) > 24$, $p < .001$. However, only at 13 months were the number of contingent sequences significantly greater than those of the random sequences for two- and three-event sequences ending in RDBM actions. The number of four-event sequences was equivalent to that of rando m sequences. Only at 13 months does the distribution of contingent sequences differ from chance (two-event $X^2(2) = 6.5$, $p < .05$; three-event $X^2(4) = 53$, $p < .001$; four-event $X^2(4) = 34.3$, $p < .001$). Thus, it appears that by 13 months infants are organizing their manual actions to engage in RDBM.

Table 7 shows the percent distribution of the types of contingent sequences that constitute three-event sequences with the two-part toys. At 7 months all of the contingent sequences involve only object exploration categories (fingering or stroking) with object relationship sequences (contact, insertion, or removal) appearing at later ages. The dramatic increase in the frequency of ‘‘bimanual’’ actions (i.e., the ability to hold one object in each hand) is reflected in the increase in contingent bimanual sequences at 9 months. Only at 13 months do sequences occur which end with RDBM insertion actions. Moreover, when the object relationship action sequences (contact, remove, insert) occur, they are highly lateralized, favoring right-handed RDBM (range of 67–100%).

	Age (Months)			
	7	9	11	13
Category of RDBM sequence				
Finger and stroke	100	7	25	4
Start together nonrole-diff.	0	7	27	28
Start doing RDBM	0	0	5	10
Bimanual to contact	0	86	43	40
Bimanual to contact to insert	0	0	0	17

Table 7. Three-Event Sequence Two-Part Toys: Percentage in Each Category of Contingent RDBM Sequences

Discussion

This study had three goals: To determine when during development RDBM is likely to emerge as a new skill; to determine whether RDBM during early infancy is dependent on particular types of toys; to determine when RDBM likely represents a planned action by the infant. The data in this study confirm the early presence of RDBM at 7 months. However, at this age, it is a brief and infrequent behavior in the infant’s manual repertoire while engaging in toy play. The type of toy does not affect RDBM expression until13 months of age. Also, by 13 months, RDBM is a robust skill consisting of a range of different behaviors that are used more frequently and for longer periods of time and are related appropriately to the characteristics of the toy. Moreover, the manifestation of RDBM at 13 months is organized in predictable sequences that are coordinated to match the infant’s hand-use preference.

Although a variety of RDBM behaviors are present before 1 year of age, RDBM has yet to become a fully functional and integrated behavior. Even by 13 months, RDBM represents less than 20% of the infant’s toy play repertoire when presented with objects that are well suited for eliciting RDBM actions. Previous research reported that 25% of hand actions by 19-month-old infants and 50% of hand actions by 3-year-old children were RDBM actions (Kimmerle, 1991). Therefore it appears that the 7- to 13-month period represents the emergence of RDBM as a new skill in the manual repertoire. During the next 2 years it builds to predominate in the repertoire of object manipulation.

Although RDBM actions are bimanual motor skills, they reflect cognitive abilities that enable the infant to recognize that the particular pattern of relation between objects permits and encourages actions of removing one from containment by the other and/or inserting one into another. Such sensorimotor and cognitive skills may not be independent. For example, although stroking is motorically simpler than fingering, it was not seen in greater frequency at the youngest ages. Perhaps, the infant at 7 months recognizes that fingering is a more effective method for producing movement or sound from the object.

Several other lines of evidence point to a reciprocal relationship between motor and cognitive skill in RDBM behavior. Latency to start exploring double toys took almost twice as long as with single toys. Perhaps the two-part (double) toys are sufficiently unfamiliar or complex so as to delay elicitation of the actions that matched their functional characteristics (i.e., the action the two-part toys afford may not have been as apparent and therefore the infants were slower to initiate manipulations). This argument is supported by the notion that perceptual development is determined by the action capabilities of the child and what objects and events afford in the context of those actions (Gibson & Pick, 2000).

As infants aged, they increased RDBM activity with double toys by engaging in the object relationship actions of contact, removal, and insertion. However, increased RDBM of the two-part toys is accompanied by a decrease in overall activity and RDBM with single toys. The infant's skills may have advanced sufficiently to make the effects produced by single toys less appealing (i.e., the number of novel and interesting actions afforded by the toy is constrained by its limited number of parts).

The RDBM action of removal of objects from containment is demonstrated earlier than insertion with both the control and test toys. This earlier appearance of removal may be because the skills involved in comprehending removal are not as tightly linked with the motoric ability to perform removal in a role-differentiated manner. That is, the protruding object may have been viewed simply as a graspable handle which, when grasped with sufficient force, caused the ‘‘unified’’ object to simply come apart. Although insertion only requires lowering the block below the rim of a large cup (very little accuracy is involved, and itis not necessary to release the block), the role-differentiated action of holding on to the receptacle object, while transporting the other object to the receptacle may be a prerequisite for comprehending the object relationship of inserting. Bushnell and Boudreau (1993) make a similar point in relating the ability to comprehend distinctions in object shapes to the presence of surface and edge exploratory hand action. Interestingly, these notions are not unlike Piaget's argument for sensorimotor intelligence providing important prerequisites for the development of conceptual skills (Piaget, 1952).

The data revealed evidence of some contribution of hand-use preferences to the organization of RDBM, but only at 13 months of age. This is also the age at which a majority of infants exhibit a right hand-use preference in their organization of RDBM actions. The lag sequential analysis of two, three, and four events showed that at11 months there is an oppositional hand lead-in to RDBM which continues at 13 months. This suggests that the activity of each hand at 13 months may have been coordinated to achieve a RDBM action that reflects the infant's hand-use preference.

The sequential analysis failed to provide strong evidence of ‘‘planned’’ RDBM. Although there were some contingent two-, three-, and four-event sequences ending with RDBM for single toys, they were not significant aspects of the infant’s manual behavior. The two-part toys, in contrast, did manage to elicit strong evidence of contingent RDBM sequences, but only at13 months of age. It is possible that early expressions of RDBM emerge during the infant’s exploration of the objects. Only at 13 months of age does the infant appear to manipulate the object in order to engage in RDBM and, at that age, as many as three acts can be organized to precede a RDBM. Furthermore, the infants’ hand-use preference plays a role in the organization of those acts.

Thus, although RDBM expression is possible before13 months, the occurrence of the behavior may only begin to become goal directed at 13 months. This creates a dilemma for those who consider intentionality to be an aspect of the abilities of very young infants. Perhaps, organizing the sequences of action to result in RDBM is not a sufficiently sensitive way to identify intentionality. The data demonstrate that although RDBM does occur early, it is a very minor aspect of the infant’s manipulatory repertoire. This is consistent with the notion that RDBM behavior emerges from the manipulation of objects rather than that it is deliberately employed to produce that manipulation. Of course, it could be argued that the infant may intentionally employ only well-established skills. Unfortunately, there is no evidence of such a prescription for intentionality. It is possible also that intentionality is expressed in these manual skills differently than in other skills or abilities. Perhaps, intentionality is not a unitary characteristic, especially during infancy, requiring separate analyses for different systems and circumstances. It is likely that the coordination of RDBM skills represents an important feature of the infant’s development of certain conceptual schemes involving object properties. Whether this behavioral organization and the emergence of new concepts represent ‘‘intentionality,’’ however, remains an open question.

Our results also raise the issue of distinguishing an emerging behavior from a well-established skill (Haith,1998). At what point has the infant acquired the skill of RDBM? Clearly, infants between 7 and 11 months demonstrate a variety of emerging RDBM actions, but these are not yet examples of ‘‘skilled’’ behavior. However, by 13 months, the infant provides some evidence of RDBM skill. As mentioned earlier, the definition of what constitutes a ‘‘skill’’ is debatable but there are several common characteristics among definitions. Whereas evaluating whether a ‘‘skill’’ is goal-directed, purposeful, intentional action that consists of organized sequences and a certain level of proficiency is feasible in older children, such characteristics are more difficult to evaluate in infants. For example, what level of proficiency is appropriate; how does one determine an infant’s intention? Kinematic analyses have provided some answers to questions of organization of motion, such as the pattern of the reaching trajectory and the size of the hand opening in the grasp (Newell & Vaillancourt, 2001; Thelen et al.,1993). Together with kinetic analyses, these tools can identify decreased variability in the mechanics of the action, force modulation, the coupling on one joint action to that of another and the approximation to an adult motion pattern. However, they are not useful tools for looking more broadly at the organization of the infant’s repertoire of actions in response to a variety of task contexts.

For the RDBM behavior we have studied, ‘‘skill’’ would be demonstrated when presentation of a toy elicited an immediate reach for the toy with the nonpreferred hand, followed by its manipulation with the preferred hand to produce an effect on the first attempt. Thus, when presented with insertable toys, the infant would grasp one toy in each hand, the inserting toy in the preferred hand, and then insert the toy without extraneous exploratory movements. Both of these behavior sequences would be repeated with a large variety of similar toys.

Therefore, we offer a set of criteria that may be useful for evaluating emerging bimanual role-differentiated skills in infancy, and may apply more broadly to other infant skills. These include measures of:

(1) Frequency: RDBM should make up a greater proportion of the infant's toy manipulation repertoire. They should replace less efficient actions, such as undifferentiated bimanual actions. In a study of 3- to5-year-old children, Kimmerle (1991) found a manual repertoire in toy play consisting of 50% RDBM with the remaining half being unimanual. By this age, undifferentiated bimanual had disappeared.
(2) Motor control: RDBM should be more efficiently coordinated between the actions of the two hands to allow more complicated hand actions.
(3) Success criteria: The mere presence of the behavior does not necessarily demonstrate skill. Competency and proficiency in performing the functional aspect of the task need to be included.
(4) Lateral preference: RDBM should exhibit a hand-use preference consistent with those preferences exhibited for previously achieved skills.
(5) Latency: Shorter latency to the functional use of RDBM would suggest that the infant has comprehended the match between particular ‘‘skills’’ in his/her manual repertoire and the demands of the task.
(6) Fewer noncontingent sequences: Organized, planned behavior should result in more predictable orders of actions preceding the skill in questions.
(7) Fewer types of noncontingent sequences: In the initial stages, the infant is still experimenting with a number of ways to accomplish the task. As he becomes more skilled, he will settle on a few more efficient series of actions.
(8) Transfer: The skill would need to be demonstrated with a number of similar tasks, and not be elicited with a specific task.

Thus, we have provided operational definitions of five different categories of RDBM that clearly show a developmental progression. The importance of analyzing the total repertoire of the infant's manual skills and not just a specific skill and the value of investigating the organization of manual actions has also been demonstrated. It is evident, moreover, that evaluating the infant's comprehension of toy concepts and intention to engage in goal-directed behavior is not readily separated from the manual skills in his/her repertoire. Equally, evaluating motor skills status cannot be done in isolation from the child's comprehensions of object properties, functions, and relationships.

Notes

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