Development of role-differentiated bimanual manipulation in infancy: Part 1. The emergence of the skill

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Abstract:

This is the first paper in a series of three discussing different aspects of the development of role-differentiated bimanual manipulation (RDBM—two hands performing different but complementary actions on an object). Emergence of RDBM is an important shift in the development of infant manual skills. Trajectories of monthly changes in the number of RDBMs and RDBM hand preference were explored in a sample of 90 (57 males) normally developing infants (30 with a right preference for acquiring objects, 30 with a left preference, 30 with no preference) during the 9–14 month period. Multilevel analysis revealed that infants performed more RDBMs with age, with similar patterns of change in all hand preference groups. A hand-use preference for RDBM became more prominent with age with most right-preferring infants and those without a preference for object acquisition developing right-hand preference for RDBM. Left-preferring infants exhibited more heterogeneity in their hand-use for RDBM. © 2015 Wiley Periodicals, Inc. Dev Psychobiol 58: 243–256, 2016.

Keywords: bimanual manipulation | hand preference | development | infancy

Article:

Introduction

This paper initiates a series of three papers discussing different aspects of the development of role-differentiated bimanual manipulation (RDBM) and its relation to other manual skills developing during infancy. This paper one provides a detailed account of the development of RDBM skill and hand-use preference for RDBM. Paper two further relates developmental patterns of hand-use preference for RDBM to those of hand preference for object acquisition, allowing an opportunity to test the cascade theory of hand preference development (1983, 1988, 1998, 2002). Finally, paper three relates the development of RDBM skill to the development of bimanual object acquisition (BOA)and non-differentiated bimanual manipulation (NDBM)and explores whether BOA or NDBM manual skills facilitate the development of RDBM skill.

The cascade theory of hand preference development (Michel, 1983, 1988, 1998, 2002), similar to Wadding-ton's (1957) idea of epigenetic landscape, proposed that hand preference in earlier developing skills would concatenate into hand preference of the later developing skills. Thus, establishing a hand preference for simple reaching and acquisition of objects would make more probable the establishment of a hand preference for unimanual manipulation (Hinojosa, Sheu, & Michel,2003), which, in its turn, would influence the development of hand preference for later-emerging more complex role-differentiated bimanual manipulation (Michel, 1998; Michel, Ovrut, & Harkins, 1985; Ramsay, 1980). The cascade theory also proposed that clear hand preferences would likely not be observed in the initially emerging skill. For instance, earlier developing role-differentiated bimanual manipulation may not require highly developed skills such as precision, strength of grip and speed and, thus, may occur in the absence of efficient callosal transfer, and may emerge more from the properties of the objects than from planning (Kimmerle, Ferre, Kotwica, & Michel, 2010). However, as the RDBM actions become more sophisticated and less constrained by object properties, a hand-use preference would be expressed.

Many researchers have suggested that a major shift in the infant's manual skills occurs with the transition from unimanual actions with objects (e.g., grasping, banging, shaking) to their bimanual manipulation in a role-differentiated manner (e.g., Bruner, 1970; Connolly & Dalgleish, 1989). Role-differentiated bimanual manipulation refers to manual actions in which two hands perform different but complementary movements on one or more objects. Unlike unimanual manipulation, RDBM requires coordinated sensorimotor control between the two hands as they perform complementary sequences of actions. Such coordination likely requires collaboration between the two cerebral hemispheres (Michel, 1987, 2002; Ramsay, Campos, & Fenson,1979; Serrien, Ivry, & Swinnen, 2006). If so, then the development of RDBM reflects an important shift in the organization of motor control (Haaland, Elsinger,Mayer, Durgerian, & Rao, 2004) that may have consequences for cognitive functioning (Bruner, 1970;Connolly & Dalgleish, 1989; Ramsay & Weber, 1986).

Rudimentary complementary bimanual manipulations were reported for infants as young as 4–5 months (Rochat, 1989). However, distinct role-differentiated bimanual manipulation has been reported to occur as early as 7 months of age (Kimmerle, Mick, & Michel,1995, 2010) or at 9–10 months of age (Bruner, 1971;Fagard & Pezé, 1997; Ramsay et al., 1979). Differences in the reported timeline of RDBM development not only reflect differences in methodology, but also are likely because RDBM is not a homogenous skill, but rather represents a set of skills that exhibit a heterogeneous pattern of emergence during development (Kimmerle et al., 2010). For example, fingering (one or two fingers manipulating an object) seems to emerge first followed by stroking (the palm and/or whole hand exploring an object); 75% of infants demonstrate these skills by7 months. Object removal, first observed at 7 months and becoming more frequent (67% of infants) by11 months, precedes object insertion, observed first at9 months and manifested by 75% of the infants by13 months. Kimmerle et al. (2010) noted that even by the age of 13 months, RDBM actions represent only20% of the infant's manual repertoire during a play with toys that readily afford RDBM. Also, previous research showed that RDBM represents approximately 25% of manual repertoire of the infant at the age of 19 months, and 50% at the age of 3 years (Kimmerle, 1991).

Kimmerle et al. (1995) demonstrated that RDBM actions occurring as early as 7 months are restricted to those characteristics of objects (such as holes, slots, and protrusions), that strongly afford the "accidental" manifestation of RDBM. Thus, Kimmerle et al. (2010)

concluded that early RDBMs are likely to represent "accidental" actions derived from the affordances of particular toys rather than an understanding of object properties and the coordination of sequential actions for RDBM on the part of the infant. They proposed that RDBM emerges initially from accidental irregular manual manipulation of objects and only later becomes controlled in the organization of its manifestation. This controlled action only begins to become apparent at about 12–13 months and seems to be associated with the emergence of hand-use preference for RDBM. Thus, the later ("controlled"), but not the earlier ("accidental"), RDBM actions better reflect the infant's manual lateralization. This notion stems from the cascade theory of hand-use preference development (Michel, 1983, 1988,1998, 2002), and requires direct investigation.

Previous research showed that the hand preference for RDBM does not appear until after the first year for a majority of infants (Bruner, 1970; Fagard, 1994; Fagard & Jacquet, 1989; Fagard & Lockman, 2005; Ramsay et al., 1979; Ramsay & Weber, 1986). For example, in a longitudinal study, Ramsay et al. (1979) tested 24 infants at monthly intervals from 10 to 18 months of age. They found the onset of the hand preference for RDBM to beat the age of 12.8 months in 18 right-hand preferring infants (75% of the sample) and at 14.9 months in five "left-handers" (21% of the sample). In a cross-sectional study conducted on a larger sample of 100 infants, Ramsay et al. (1979) showed that 85 infants (71 "right" and 14 "left-handers," with hand preference defined by the consistent vs. inconsistent hand-use for acquiring nine toys presented two to four times each) manifested hand preference for bimanual manipulation (defined by the active hand attempting or performing RDBM) during the 14–16-month period. Additional nine infants (six "right-handers" and three "left-handers") exhibited a hand preference for RDBM later during 18–21-month period. Thus, with the procedure used by Ramsay et al. (1979), only by the age of 18 months, did 94% of infants exhibit a hand preference for RDBM. In contrast, using the procedure of Kimmerle et al. (2010), half of the 24tested infants (11 right and 1 left) were lateralized for RDBM at 13 months, whereas two infants had no significant preference, and the remaining 10 infants did not perform enough RDBM actions to enable any reliable conclusions about their hand preference.

Interestingly, in bot h studies by Ramsay et al. (1979), "left-handers" on average were found to be delayed in their development of hand preference for RDBM compared to "right-handers." The study by Kimmerle et al. (2010) also appears to support this observation. Although more research in this area is needed in order to make confident conclusions, Michel (1987, 2002) proposed that hand preference for other manual actions (e.g., acquiring objects, manipulating them unimanually) may be an important contributor to the development of RDBM hand preference.

Early acquisition of hand-use preferences has been proposed to facilitate cognitive, motor, and emotional development in infancy (e.g., Cohen, 1966; Hildreth,1949). Also, a stable hand preference was shown to be associated with more effective object management skills involving the "storage" of objects ("retaining control of an object by transferring it to another hand or placing, without haphazardly dropping, an object within reach"; Kotwica, Ferre, & Michel, 2008, p. 519). Object storage skills have been interpreted as the first evidence of representational abilities and are considered to have implications for the development of other perceptual and cognitive skills, such as knowledge of object properties, understanding the relations among object properties and "planning" of actions (Bruner, 1973). Although a hand preference was associated with the development of more effective bimanual control of the movement of the hands in space (Goldfield & Michel, 1986; Michel, 2002), Fagard and Corroyer

(2003) reported better bimanual coordination (the essential skill for RDBM), as manifested in the crank-rotation task, among non- "right-handed" than "right-handed" individuals. However, this was observed for an older sample of 3–8-year-old children.

Unfortunately, in most of the research, the over-whelming majority of infants with a stable hand preference for acquiring objects are right-handed infants. If hand preference per se is the explanation for the reported differences in performance, then the reported advanced development should be predicted for both right- and left-hand preferring infants compared to infants without a stable hand-use preference. Thus, it is essential to include left-hand preference participants in any study examining the consequences of handedness.

According to the cascade theory (Michel, 1983,1988, 1998, 2002), the hand preference for role-differentiated bimanual manipulation in the current study is predicted to become more distinctive with age as the skill of RDBM is being mastered. Those infants with a right-hand preference for object acquisition are predicted to develop a right-hand preference for RDBM, whereas those with a left-hand preference for acquisition are predicted to develop a left-hand preference for RDBM. It also is predicted that a hand preference for earlier developing "simple" RDBMs (e.g., poking and stroking) will appear sooner than a hand preference for later developing "difficult" RDBMs (e.g., insertion and removal) because the manifestation of "simple" RDBMs is more likely to be accidently afforded by the object, and, thus, is less likely to reflect the infant's earlier manual lateralization for acquiring and unimanually manipulating objects (Kimmerle et al.,1995, 2010). A significant increase in the proportion of infants lateralized for RDBM (right- and left-hand preference) is expected to occur around the age of13 months. Also, infants with an established hand preference for object acquisition (both right- and left-preference) are expected to perform more RDBM actions (especially "difficult" RDBMs) at an earlier age when compared to infants without a stable hand preference for object acquisition.

Methods

Participants

Hand-use preference for object acquisition was assessed monthly from 6 to 14 months of age for a large sample of38 0 infants. From this sample, 47 infants were identified as manifesting a consistent left-hand preference for acquiring objects. From these 47 infants, thirty infants (19 males) were randomly selected and matched for sex and patterns of postural skill s development (age of onset for sitting, crawling, and walking—assessed by the Touwen's (1976) Neurological Assessment Scale) with 3 0 infants (19 males) having a consistent right-hand preference and 30 infants (19 males) without a consistent hand preference (drawn from the sample of 380 infants). All infants came from full-term pregnancies (a minimum of 37 weeks gestation) and uncomplicated single births. The sample of 90 infants (57 males) used for this study was ethnically diverse (54% of Caucasian, 28% of African American, 3% of Hispanic or Latino, 3% of Asian and 12% of mixed ethnicity) and representative of the local North Carolina population. All participants were tested monthly, within ±7 days from infants' monthly birthdays, from 6 to 14 months (total nine visits) for hand-use during object acquisition, and from 9 to 14 months (total six visits) for role-differentiated bimanual manipulation. Infants' mean age at the beginning of the study was 6.13 months (roughly 6 months and 4 days, SD = .15 or 4.5 days) and at the end of the study the mean age was 14.25 months (roughly 14 months and 7 days, SD = .16 or 4.8 days).

Procedure

Recruitment of participants, informed consent, data collection and presentation were done in accordance with the regulations set by the UNCG Institutional Review Board for the protection of human subjects. Parents received a $10 gift card per visit. For each monthly visit, infants' hand preference for acquiring objects and role-differentiated bimanual manipulation was assessed in the Infant Development Center at the University of North Carolina at Greensboro.

Assessment of a Hand-Use Preference for Object Acquisition. In the current study, object acquisition was defined as an action of lifting a toy from the surface of the table or moving an object on the table. Hand preference for object acquisition was assessed longitudinally from 6 to 14 months during the infant's play with 34 single-part infant toys (see Babik, Campbell, & Michel, 2014 for details). Infants' manual activity was digitally recorded using two synchronized cameras that provided a split-screen with an overhead and a side view. The coding for acquisition hand preference was done in the Observer1XT (Noldus Information Technology, Wageningen, Netherlands) which permitted frame-by-frame coding of infants' manual actions. Coders viewed all recordings in slow motion in order to identify precisely the hand used for an object acquisition. Twenty percent of all coded videos were re-coded by a second coder for inter-rater reliability, which resulted in the observed mean percentage of agreement .91 (Mdn = .91, range = .82–.99). Another 20% of the videos were re-coded for intra-rater reliability which resulted in the observed mean percentage of agreement .94(Mdn = .94, range = .88–.99).

Assessment of a Hand-Use Preference for Role-Differentiated Bimanual Manipulation. Role-differentiated bimanual manipulation is an action in which one hand has an active manipulating role while the other has a role of supporting the active hand's maneuvers by holding the object. RDBM and a hand preference for RDBM were assessed longitudinally during play with an additional set of 20 multiple-part infant toys administered separately from the administration of the acquisition hand-use assessment task (see Fig. 1). Each toy was presented at midline on the table in random order. All multiple-part toys were presented with one part inserted in the other part. During the play with "complex" multiple-part toys, infants may perform different RDBM actions. "Poke" was coded when one or two fingers of one hand touch any part of the surface of a toy as the other hand steadied the toy (all 20 toys afforded poking); "stroke"—when more than two fingers or the whole hand is moving along the outside or inside surface of a toy (all 20 toys afforded stroking);"push"—when more than two fingers or the whole hand is repeatedly touching the surface of a toy (toys #3, 8, 13, 16, 19,20 afforded pushing); "spin"—when one hand spins a movable part of a toy (toys #1, 2, 3, 4, 12, 17 afforded spinning); "pull"—when one hand pulls a part of a toy, similar to "removal" in Kimmerle et al. (1995) (all toys except #3, 7, 14, 15 afforded pulling); "insert"—when one hand inserts a smaller part of a toy into a larger part (toys #6, 9, 11, 13, 19, 20 afforded inserting).

RDBM actions were coded in the Observer1XT in real time. The hand used for active manipulation (poke, stroke, push, spin, pull, insert) was identified for coding hand-use preference. Bouts of the same behaviors (e.g., repetitive spins of the same part of the toy by the same finger) were coded as single RDBM instance, unless interrupted by a pause or another behavior. For the current paper, only right- and left-handed manipulative actions were considered since only they highlight hand-preference for this manual skill. Bimanual manipulations are considered in another paper.

Twenty percent of all coded videos were re-coded by a second coder for inter-rater reliability resulted in the observed mean percentage of agreement .85 (Mdn = .85, range = .80–.93). Another 20% of the videos were re-coded for intra-rater reliability which resulted in the observed mean percentage of agreement .89 (Mdn = .88, range = .88–.93). All coding was done blind to the infant's hand-preference for acquiring objects.

Measures

To depict and statistically analyze developmental trajectories of hand preference for object acquisition and RDBM in infancy, the infant's monthly hand-use preferences for object acquisition and RDBM were defined using a Hand-preference Index [$HI = (R-L)/(R+L)^{1/2}$], where R and L represent the total number of performed right-hand preferring and left-hand preferring actions for each infant during each monthly visit. Then, hand preference of each participant was determined using a group-based trajectory modeling procedure (GBTM, Nagin, 2005) that was conducted on 380 infants' monthly (from 6 to 14 months) hand preference scores (Michel, Babik, Sheu, & Campbell, 2014), using SAS TRAJ procedure (Jones, Nagin, & Roeder, 2001). Group-based trajectory modeling is a statistical method that allows identification of distinctive patterns in the distribution of a sample's trajectories and enabled us to use the infant's developmental trajectory to define the infant's hand preference as consistent right, left, or no consistent preference.

The GBTM for acquiring objects revealed three different types of developmental trajectories: Those with a right-hand preference, those with a left-hand preference, and those without a distinct preference (see Michel et al., 2014 for details). From the 380 infants tested in the Infant Development Center at UNCG, 30 infants (of 47) with a developmental trajectory exhibiting a consistent left-hand preferences for acquiring objects were selected and matched with 30 infants in each of the other two developmental trajectory groups (those with a consistent right-hand preference and those without a hand preference) according to their sex and motor development (age of onset of sitting, crawling, and walking, Touwen, 1976).Then, frequency of RDBM actions and the hand preferences for RDBM were calculated for these 90 infants from a separate set of data collected monthly from 9 to 14 months of age. Hand preferences for RDBM also were examined with the group-based trajectory model (Nagin, 2005) and using SASTRAJ procedure (Jones et al., 2001) to identify the number of latent classes in the trajectories of RDBM hand preference.

Then, frequency of RDBM actions and the hand preferences for RDBM were calculated for these 90 infants from a separate set of data collected monthly from 9 to 14 months of age. Hand preferences for RDBM also were examined with the group-based trajectory model (Nagin, 2005) and using SASTRAJ procedure (Jones et al., 2001) to identify the number of latent classes in the trajectories of RDBM hand preference.

In the current set of three papers, all multi level analyses were conducted using the Hierarchical Linear Modeling (HLM; Raudenbush, Bryk, Cheong, Congdon, & du Toit, 2004) to account for non-independence of multiple observations of the same subject. In all statistical models, linear, quadratic, and cubic trends of change with age were tested. If a final model included only linear and quadratic trends of change, the cubic trend was not statistically significant. Also, to assess developmental parameters in infants with different hand-use preferences, we tested all models including the dummy-coded hand preference status variable HS (HS1 would compare right-h and preferring to left-hand preferring infants; HS2 would compare right-hand preferring infants to those without a distinct hand preference; right-hand preferring infants were chosen as a reference group).

Figure 1. Pictures of toys presented to infants for bimanual manipulation.

Results

Development of Role-Differentiated Bimanual Manipulation

One of the hypotheses in the current study was that hand preference for “difficult” RDBM skills (e.g., insertion and removal), in contrast to hand preference for “simple” RDBMs (e.g., poking and stroking), would become more pronounced with age and would differentiate according to the infants’ hand-use preferences for acquiring objects. To test this hypothesis, separate multilevel analyses were conducted for the trajectories of the number of RDBM actions recorded for each of the six observed RDBM skills (poke, stroke, pull, spin, insert, push). “Simple” RDBM skills are predicted to appear much earlier in development than the “difficult” RDBM skills. It should be noted that many of these skills may not occur for some infants at some ages which means that there often will be many zero instances contributing to the trajectories.

The multilevel analysis showed a significant quadratic trend of change in the number of pokes and spins with age (POKES: Intercept: β = -20.623, $t(89)$= -2.951, p=.004; AGE; β = 4.405, $t(89)$ = 3.552, p<.001; $(AGE)^2$: β=-.167, $t(359)$ = -3.097, p=.002; SPINS: Intercept: β = -6.077, $t(89)$ = -2.316, p = .023; AGE: β = 1.249, $t(448)$ = 2.671, p = .008; $(AGE)^2$: β = -.050, $t(448)$ = -2.48 6, p = .013). There was a significant linear trend of change in the number of pulls, inserts and pushes with age (PULLS: Intercept: β = -11.967, $t(89)$ = -15.748, p < .001; AGE: β = 1.465, $t(89)$ = 19.744, p < .001; INSERTS: Intercept: β = -6.673, $t(89)$ = -14.965, p < .001; AGE: β = .776, $t(449)$ = 16.937, p < .001; PUSHES: Intercept: β = -.155, $t(89)$ = =.423, p = .673 ; AGE: β = .060, $t(89)$ = 2.012, p = .047). In contrast, the number of strokes did not change significantly with age (Intercept: β = 5.819, $t(89)$ = 6.128, p < .001 ; AGE: $t(449)$ = -.007, p = .929). The observed mean trajectories of different role-differentiated bimanual manipulation skills are presented in Figure 2A, whereas the estimated trajectories are illustrated in Figure 2B.

Inspection of Figure 2 suggested that relatively high numbers of pokes and strokes were observed at the early age (9 months), whereas the number of other types of role-differentiated bimanual manipulation such as pulls, inserts, spins, and pushes was negligible at the age of 9 months, but on average tended to increase with age. These results supported the prediction that pokes and strokes represent “simple” and early dev eloping RDBMs, whereas pulls, inserts, spins, and pushes represent more “difficult” later developing RDBMs, confirming previous reports (Kimmerle et al., 1995, 2010).

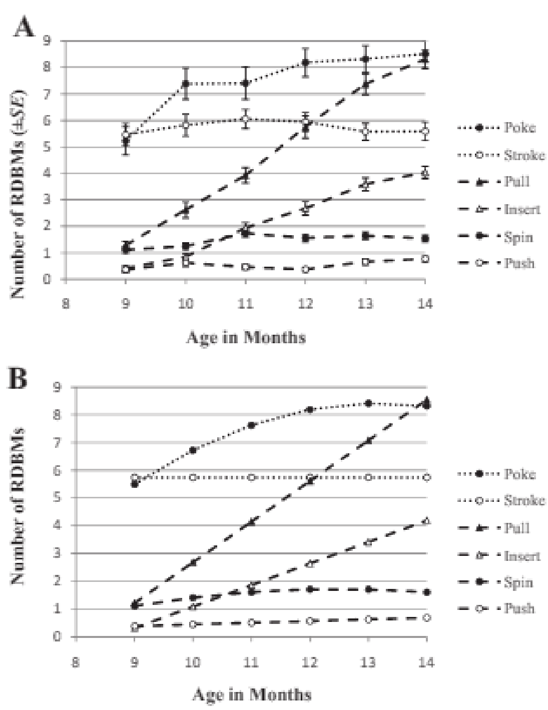

Figure 2 Observed (A) and estimated (B) trajectories of change in the mean number of different types of RDBM actions.

It was hypothesized also that infants with an established consistent hand-use preference for object acquisition (both right- and left-preferring) would perform more RDBM actions (especially "difficult" RDBMs) at an earlier age as compared to infants without a consistent hand preference for object acquisition. For testing this prediction, the total number of pokes and strokes were combined to provide an estimate of the frequency of "simple" RDBMs, and the total number of pulls, inserts, spins and pushes were combined to provide an estimate of the frequency of "difficult" RDBMs. Then, changes in frequency trajectories for all, "simple," and "difficult" RDBMs with age were explored for infants with different hand preference for acquisition of objects.

The estimated parameters for the final multilevel model exploring the number of all role-differentiated bimanual manipulations are provided in Table 1(Model 1). In this model, the residual ε_{ij} corresponds to the portion of infant i's total number of all RDBMs unpredicted at time j. The random effects for the intercept and the age variable, δ_{0i} and δ_{1i}, respectively, permit accounting for heterogeneity of infants in their intercepts and linear components of change. A non-significant random effect for the quadratic trend of change was dropped from the model. The model revealed no significant differences in the trajectories of the number of all RDBMs among infants with different hand preference for object acquisition (HS1: $t(87) = -.980$, $p = .330$; HS2: $t(87) = -1.025$, $p = .308$).

The estimated parameters for the final multilevel model exploring the number of "simple" RDBMs are provided in Table 1 (Model 2). The model revealed no significant difference in the trajectories of the number of "simple" RDBMs among infants with different hand preferences for object acquisition (HS1: $t(87) = -.406$, $p = .686$; HS2: $t(87) = -1.038$, $p = .302$).

The estimated parameters for the final multilevel model estimating the number of "difficult" RDBMs are provided in Table 1 (Model 3). Similar to the Models 1and 2, Model 3 revealed no significant difference in the trajectories of the number of "difficult" RDBMs among infants with different hand preferences (HS1: $t(87) = -.774$, $p = .441$; HS2: $t(87) = -.959$, $p = .340$). Estimated trajectories of the number of all, "simple" and "difficult" RDBMs in relation to the infants' hand preference are represented in Figure 3.

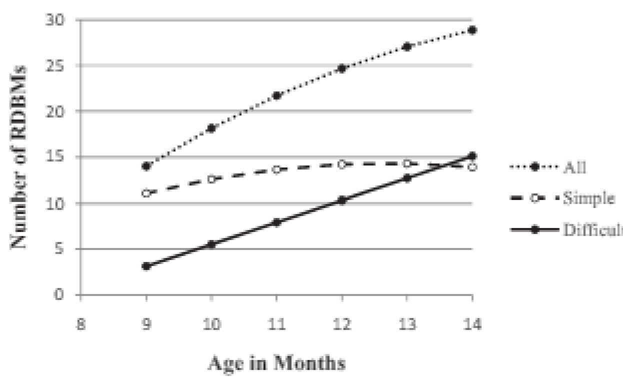

Figure 3. Estimated trajectories of change in the mean number of all, "simple," and "difficult" RDBM actions with age.

Development of Hand-Use Preference for RDBM

The exploration of trajectories of change in the different types of role-differentiated bimanual manipulation allowed us to group the six RDBM actions into "simple" and "difficult" RDBMs.

Consequently, the hypothesis that hand preference for role-differentiated bimanual manipulation becomes more distinctive with age can be tested. Also, the hypothesis that later developing “difficult,” rather than earlier developing “simple,” RDBM skills would mark differences between the hand preference groups (as defined according to the infant’s hand preference for object acquisition). Thus, trajectories of the variation in the hand preference for all, “simple” and “difficult” role-differentiated bimanual manipulations were examined next.

The estimated parameters for the final multilevel model exploring the development of a hand preference for all RDBMs are displayed in Table 2 (Model 1).The multilevel analysis revealed a significant linear, but not quadratic, trend of change in hand preference for all role-differentiated bimanual manipulations(Tab. 2, Model 1 and Fig. 4A). However, no statistically significant differences among infants with different hand preferences for acquiring objects were found (HS1: $t(87) = -1.851$, $p = .068$; HS2: $t(87) = -.355$, $p = .723$). Thus, all infants tended to increase use of their right hand for all of their role-differentiated bimanual manipulations during 9–14 month period.

The estimated parameters for the final multilevel model assessing change in the hand preference for “simple” RDBMs are provided in Table 2 (Model 2). This model revealed a linear trend of change in the development of “simple” RDBMs with no significant difference in the trajectories among infants with different hand preferences for acquiring objects (HS1: $t(87) = -.832$, $p = .408$; HS2: $t(87) = .122$, $p = .903$) (see Fig. 4B).

The estimated parameters for the final multilevel model assessing change in the hand preference for “difficult” RDBMs are provided in Table 2 (Model 3).This model revealed no significant difference in the trajectories of hand for “difficult” RDBMs among those infants with a right-hand preference and those without a preference for object acquisition (HS2: $t(427) = -.692$, $p = .489$), but a significant difference between these two groups and those infants with a left-hand preference for acquiring objects (Tab. 2, Model 3 and Fig. 4C).

Table 2. Estimated Fixed and Random Effects for the Hand Preference for All (Model 1), “Simple (Model 2), and “Difficult” (Model 3) RDBMs

Level 1 Effects	Level 2 Effects	Parameters	Model 1	Model 2	Model 3
Fixed effects					
Initial status, π_{0i}	Intercept	β_{00}	−2.183***	−.603	−5.340
	HS1	β_{01}	—	—	15.149**
AGE, π_{1i}	Intercept	β_{10}	.296***	.112**	.780
	HS1	β_{11}	—	—	−2.632**
AGE^2, π_{2i}	Intercept	β_{20}	—	—	−.017
	HS1	β_{21}	—	—	.104**
Random effects					
Level 1:	Within-person, ε_{ij}	σ_{ε}^2	1.880	1.689	1.438
Level 2:	Intercept, δ_{0i}	σ_0^2	8.686***	3.588*	—
	AGE, δ_{1i}	σ_1^2	.115***	.045**	.009***

Note: $^*p < .05$. $^{**}p < .01$. $^{***}p \leq .001$.

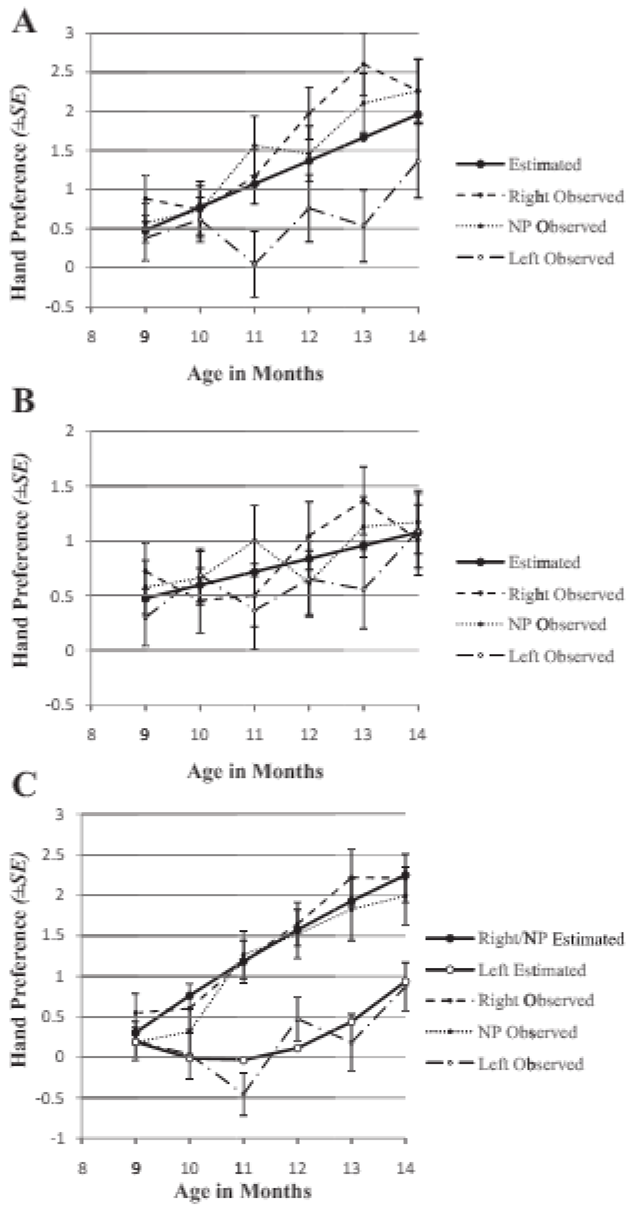

Figure 4 Observed and estimated trajectories of hand preference for all (A), "simple" (B), and "difficult" (C) RDBMs; NP = no preference infants; Right/NP = right-preferring and no preference infants.

A hand preference for "simple" RDBMs was predicted to appear at an earlier age than that for "difficult" RDBMs. A significant increase in the proportion of infants lateralized for RDBM (right- and left-preferring) was expected around the age of 13 months. To test this hypothesis, monthly HI-scores were coded into categorical hand preferences (right, left, and no preference) using HI = $\pm$1.65 as a decision criterion (cf., Hinojosa et al.,2003; Siegel, 1956, p. 40). The distribution of infantsacross the three hand preference categories for both "simple" and "difficult" RDBMs changes significantly across 6 monthly visits ("Simple":X^2 (10, N = 540) = 28.156, p = .002; "Difficult": X^2(10, N = 522) = 78.313, p < .0001) (Tab. 3). Multiple comparisons were performed separately for "simple" and "difficult" RDBMs in order to explore the significance of change in thenumber of left-, right-, and no preference infants frommonth to month; five comparisons for each type ofRDBM resulted in the Bonferroni corrected α-level being set at α = .01.

For “simple” RDBMs, a significant increase of lateralized infants occurred only between 10 and11 months (X^2(2, N = 180) = 9.216, p = .010). For “difficult” RDBMs, a significant increase of lateralized infants occurred only between 12 and 13 months (X^2(2, N = 177) = 8.986, p = .011). Thus, chi square analysis revealed that a statistically significant increase in number of lateralized infants for “simple” RDBMs occurs on average two months sooner than the significant increase of lateralized infants for “difficult” RDBMs (10–11 months vs. 12–13 months).

Table 3. Distribution of Infants Among the Three Hand Preference Groups for “Simple” and “Difficult” RDBMs With Age (in Months)

	“Simple” RDBMs			“Difficult” RDBMs		
Age	Right	NP	Left	Right	NP	Left
9	18	65	7	6	70	4
10	22	65	3	18	62	6
11	28	49	13	27	51	11
12	32	50	8	38	48	3
13	40	42	8	46	31	11
14	37	46	7	49	36	5

Note: NP = no preference.

Latent Classes in RDBM Hand Preference

Figure 4C seems to show that all infants in the current sample increased their right-hand preference for role-differentiated bimanual manipulation with age. If so, how does a left-hand preference for RDBM develop? To explore this question in more detail, we tested for possible latent classes among the developmental trajectories of infant hand preferences for RDBM. However, we analyzed not only the entire 9 to 14 month period, but also (and more importantly) the period when the skill of RDBM becomes more distinctive, later in the development, while still including enough monthly assessments to capture any potential developmental change in RDBM hand preference.

We demonstrated above that infants become significantly more lateralized for “simple” RDBMs at the age of 11 months, and for “difficult” RDBMs— at the age of13 months. Thus, we decided to explore how the trajectory of hand preference for RDB M would change if we considered the sequence of 11–14 months (Tab . 4, Model 1) and 12–14 months (Tab . 4, Model 2). Two data points (13–14 months) would be meaningless for a trajectory analysis (Roisman & Fraley, 2013).

All the following analyses were done for the “difficult” RDBMs which was shown to provide a more reliable measure of manual lateralization for RDBM. The results of the multilevel analyses showed the linear trend of change in the 3 and 4 month sequences (Fig. 5).

Table 4. Estimated Fixed and Random Effects for RDBM Hand Preference for the Sequences of Four (Model 1) and Three (Model 2) Months

Level 1 Effects	Level 2 Effects	Parameters	Model 1	Model 2
Fixed effects				
Initial status, π_{0i}	Intercept	β_{00}	-2.387^{**}	-1.205
	HS1	β_{01}	-1.456^{***}	-1.393^{***}
AGE, π_{1i}	Intercept	β_{10}	$.329^{***}$	$.239^{**}$
Random effects				
Level 1:	Within-person, ε_{ij}	σ_{ε}^{2}	1.481	1.574
Level 2:	Intercept, δ_{0i}	σ_{0}^{2}	1.590^{***}	1.743^{***}

Note: $^{**}p < .01$. $^{***}p \leq .001$.

Figure 5 suggested that the pattern of change resulted from the 3 month model was not apparently different from the pattern of change shown by the 4 month model. Thus, we decided that the 3 month sequence (12–14months) would adequately represent the change in RDBM hand preference during the period when RDBM likely is becoming a more developed skill. As a result, the subsequent latent class analyses, aiming at identifying classes in the developmental trajectories for RDBM hand preferences, were performed separately for the9–14 month sequence that includes the period before the RDBM becomes a prominent skill, as well as for 12–14month period when RDBM is a more prominent skill in the infant's repertoire.

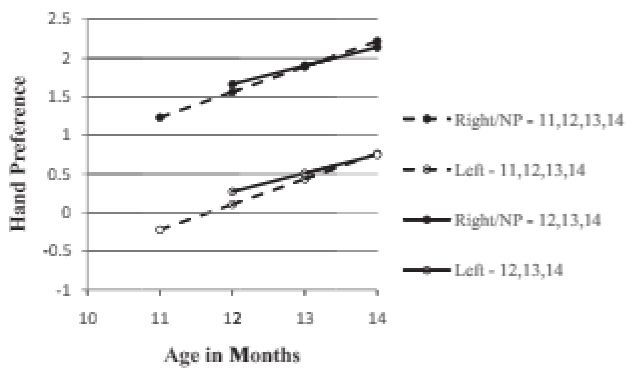

Figure 5 Estimated trajectories of RDBM hand preference for the sequences of 4 and 3 months; NP = no preference.

The group-based trajectory modeling (Nagin, 2005) with SAS TRAJ procedure (Jones et al., 2001) was used to identify the number of latent classes in the trajectories of RDBM hand preference for the periods of 9–14 and 12–14 months (cf., Michel et al., 2014). Since hand preference for RDBM was found to exhibit a significant quadratic, but not cubic, trend of change with age (see Tab. 2 and Fig. 4), the mixture model trajectories were assumed to follow a second-order polynomial function. The group-based trajectory modeling suggested that the best fitting model has three latent classes underlying RDBM hand preference for the entire 9–14 month age period (Tab. 5, Model 1, Fig. 6A), and only two latent classes in RDBM hand preference for 12–14 month period (Tab. 5, Model 2, Fig. 6B). It is likely that six data points (9–14 months) permitted greater variability in infants' developmental trajectories to be captured in comparison to three data points (12–14 months).

Since our model is a mixture of censured normals, after defining the latent classes for Models 1 and 2, we ensured that HI-scores for each of the obtained latent classes did not show any considerable departure from normality. Monthly q–q plots and Kolmogorov–Smirnov test of normality for each of the months by each of the three and two latent classes showed that data are normally distributed.

According to Figure 6A, the three latent classes estimated from RDBM hand preference for the 9–14 month period represent infants with a right-hand preference for RDBM (22.2% of infants, SE = 5.53), infants with a left-hand preference (21.1% of infants, SE = 5.17) and infants without an identifiable hand preference trending toward greater right-hand use (56.7% of infants, SE = 6.38). The latent class analysis revealed significant quadratic trends of change for all three hand preference groups (Tab. 6, Model 1) with "right-preference" and "no preference" infants increasing their right-hand use and "left-preference" infants increasing their left-hand use during the 9–14 month age period (Fig. 6A).

Table 5. Tabulated BIC and 2 Delta BIC for the Models1 and 2 From the Latent Class Analysis

	Model 1		Model 2	
Number of Classes	BIC	2ΔBIC	BIC	2ΔBIC
1	−1,033.26	—	−564.72	—
2	−968.23	130.06	−532.89	**63.66**
3	−945.77	**44.92**	−534.84	−3.90
4	−955.29	−19.04	−539.71	−9.74
5	−963.99	−17.40	−546.26	−13.10

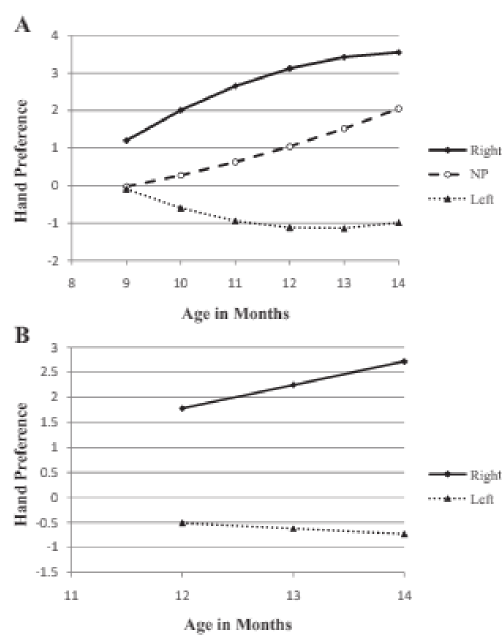

Figure 6 Estimated trajectories of RDBM hand preference for the three classes defined by the latent class analysis for 9–14 month period (A), as well as for the two class solution for 12–14 month period (B); NP = no preference.

Furthermore, from Figure 6B, we inferred that the two latent classes estimated from RDBM hand-use scores for the 12–14 month period represent “right-preference” infants (71.1% of infants, SE = 5.96) and “left-preference” infants (28.9% of infants, SE ¼ 5.96). The latent class analysis revealed significant linear, but not quadratic trends of change for both latent groups (Tab . 6, Model 2) with “right-preference” infants increasing their right-hand use and “left-preference” infants increasing their left-hand use during the 12 to 14 month age period (Fig. 6A).

Next, we explored the distribution of infants among the three latent classes for RDBM hand preferences (estimated from 9 to 14 month age period) according to their hand preference estimated from the three latent classes identified for acquiring objects (Tab. 7). The association between these two estimates of the infant’s hand preference is significant ($X^2(4, N = 90) = 17.096$, $p = .002$, $\Phi = 0.44$). Infants from the latent class of “right-preference” for object acquisition tended to be in “right-preference” (36.7% of the 30 infants) or “no preference” by latent class analysis for RDBM hand preference. In contrast, infants from the latent class of “left-preference” for object acquisition tended to be “left-preference” (43.3% of 30 infants) or “no preference” for RDBM. Infants from the latent class of “no preference” for object acquisition tended to remain in the latent class of “no preference” for RDBM hand preference (63.3% of 30 infants).

Table 7. Distribution of Infants (in %) Among the Three RDBM Latent Classes According to Their Latent Class for Acquisition Hand-Use Preferences; NP = No Preference

	Latent Class for RDBM		
Latent Class for Acquisition	Right	NP	Left
Right	36.7	56.7	6.6
NP	23.3	63.3	13.4
Left	6.7	50.0	43.3

The distribution of infants among the two latent classes for RDBM hand preference, estimated from 12 to 14 month age period, according to their hand preference for object acquisition had a somewhat different pattern. Whereas the latent class of “right-preference” and “no preference” infants for object acquisition tended to be in the latent class of “right-preference” for RDBM (86.7%and 73.3%, respectively) during 12–14 month period, the latent class of “left-preference” for object acquisition was approximately equally divided between the latent class of “left-preference” (46.7%) and “right-preference” (53.3%)for RDBM (Tab. 8). Thus, nearly half (46.7%) of infants with a left-hand preference for object acquisition developed a left-hand preference for RDBM during 12–14month period; whereas only 13.3% of infants with a right-hand use preference for acquisition and 26.7% of infants with no preference for object acquisition seemed to exhibit a left-hand preference for RDBM.

Table 8. Distribution of Infants (in %) Among the Two RDBM Latent Classes According to Their Latent Class for Acquisition Hand-Use Preferences; NP = No Preference

	Latent Class for RDBM	
Latent Class for Acquisition	Right	Left
Right	86.7	13.3
NP	73.3	26.7
Left	53.3	46.7

Discussion

The goal of the current study was to examine the development of role-differentiated bimanual manipulation (RDBM) in relation to the hand-use preference for acquiring objects during infancy. Group-based trajectory modeling allowed identification of the three groups of infants (left-, right-, and no hand preference) based on the trajectories of the development of their hand preference for acquiring object assessed monthly from6 to 14 months. The development of role-differentiated bimanual manipulation was examined in these three hand preference groups (n = 30 in each) during the period from 9 to 14 months.

We found, as did Kimmerle et al. (1995), that pokes and strokes appeared much sooner in the infant's repertoire, and thus might represent "simple," more "accidental" RDBMs, whereas pushes, pulls, inserts, and spins appeared only much later, and thus might represent "difficult," more "planned" RDBMs. The total number of all, "simple" and "difficult" RDBMs was found to increase during 9–14 month age period. Moreover, the multilevel analysis showed no differences in the trajectories of change in the number of all, "simple," or "difficult" RDBMs with age among infants with different hand preference for object acquisition. Thus, early establishment of hand preference for acquisition did not seem to facilitate the development of role-differentiated bimanual manipulation. These results do not support the hypothesis that lateralized infants are more efficient in RDBM as derived from results with certain other "complex" manual skills (e.g., Goldfield & Michel,1986; Kotwica et al., 2008; Michel, 2002), nor does it support the idea that children with a weak hand preference are better in tasks requiring bimanual coordination (e.g., Fagard & Corroyer, 2003). Our results, also, failed to support the notion that infants with a left-hand preference for acquiring objects would be delayed in their RDBM development when compared to those with a right-hand preference (cf., Kimmerle et al., 2010; Ramsay et al., 1979).

Previous research (Kimmerle et al., 1995) led us to hypothesize that differences in the hand preference for acquisition would relate to differences in the trajectories of hand preference for RDBM for "difficult," but not for "simple," RDBMs. In support, we found that the infant's hand preference for acquisition did relate to distinct developmental trajectories of a hand preference for "difficult" RDBMs, but not for "simple" RDBMs. Consequently, when researchers do not differentiate between "simple" and "difficult" RDBMs, but rather explore the general category of all RDBM actions, they are unlikely to find differences in RDBM hand preference trajectories among infants with different hand preferences for object acquisition. In future research, itis important that "simple" and "difficult" RDBMs be distinguished because they provide different information about patterns of RDBM development in infancy. Perhaps, they represent a difference between more "accidental" RDBMs, elicited by the structure of the object, as compared to more coordinated and "planned" RDBMs, expressed by the infant (Kimmerle et al.,1995, 2010).

Examination of RDBM hand-use trajectories for “difficult” RDBMs during 9–14 month period for infants with different hand preferences for acquiring objects revealed that infants with a right-hand preference for acquiring objects did not differ from infants without a hand preference, whereas these two groups differed from infants with a left-hand preference for object acquisition. Right-hand preference infants and those without a hand preference for acquiring objects significantly increased in their frequency of right-hand use for “difficult” RDBMs. These results support previous research showing that infants with a right-hand preference and the majority of infants without a hand preference for object acquisition during the first year of life become right-hand preferring for RDBM by the end of the second year (Nelson, Campbell, &Michel, 2013). These results also support the cascade theory of hand preference development (Michel, 1983,1988, 1998, 2002) predicting that hand preference for earlier developing manual skills like object acquisition would concatenate into hand preference for later developing manual skills like RDBM.

We also found that those infants with a left-hand preference for acquiring objects increased the use of their left hand for RDBM from 9 to 11 months, but showed an increased use of their right hand from 11 to14 months. Although, as predicted, infants from each of the three hand preference groups for acquisition showed an increase in their hand preference for role-differentiated bimanual manipulation, we did not observe left-hand preferring infants increasing their preference to use their left hand for “difficult” RDBMs with age. Instead, all infants increased their right-hand use for “difficult” RDBMs with age. When the data for all 6 monthly visits (9–14 months) were analyzed for latent classes among the developmental trajectories of infant hand-use for “difficult” RDBMs, three latent classes were identified. Within these classes, those infants with a right-hand preference for RDBM and those without a RDBM hand preference tended to increase the use of their right hand for RDBM, whereas those with a left-hand preference for RDBM increased the use of their left hand for RDBM with age.

When latent developmental trajectories were identified for the period when the skill of RDBM becomes more distinctive (12–14 months), only two latent classes were revealed in developmental trajectories (likely because of the small sample size (90 infants) and the small number of assessments (3)). These included a majority of right-preference infants who increase the use of their right hand with age and a minority of left-preference infants who increased the use of their left hand with age. Further analysis showed that the majority of infants with a right-hand preference for object acquisition and those without such a stable hand preference showed a right-hand preference in their trajectory for RDBM. In contrast, the group of infants with a left-hand preference for object acquisition was more heterogeneous in the trajectory of their hand preference for RDBM with approximately half of the infants manifesting a preference to use their right hand and the other half manifesting a preference to use their left hand for RDBM. However, these latent classes for RDBM were identified using data from only three age periods and for only 90 infants (the recommended minimum sample size for GBTM analyses is 100). While such results do not support any strong conclusions about the relation between hand preference for acquisition and RDBM, they do reveal the need for monthly investigation of RDBM development during the age period from 12 to 18 months when hand preference for this skill is likely to stabilize. Previous research (Nelson et al., 2013) indicated that RDBM hand preferences seem to be well established by 18months and may not develop any further thereafter.

If the evidence for the 12–14 month latent classes is considered to be reliable, then the heterogeneity of hand-use for RDBM among the group of infants with a left-hand preference for object acquisition fits with previous research showing that, as a group, “left-handers” are usually more heterogeneous in their hand preference scores as compared to a group of “right-handers” (e.g., Gonzalez & Goodale, 2009; Gur, Gur, & Harris, 1975). One explanation for the heterogeneity of left-preferring infants derives from the influence of parents on the development of the hand preference of their offspring. Maintaining a strong left-hand use preference may be more difficult, especially during infancy because the majority of left-hand preferring infants are likely to have right-handed parents (Harkins& Michel, 1988; Michel, 1992). Michel (1992) reported that infants with an apparent left-hand preference for acquiring objects who had right-hand preferring mothers significantly reduced their left-hand preference by11 months; whereas infants with an apparent right-hand preference and right-hand preferring mothers increased their right-hand preference by 11 months. Moreover, Michel (1998) observed that right-hand preferring mothers unintentionally, but significantly, biased their infants’ use of the right hand during interactive play with objects.

Previous research indicated that hand preference for RDBM does not appear until about 13 months when the skill appears to be better coordinated (Kimmerle et al.,2010). In the current study, a significant increase in the proportion of infants lateralized for “simple” RDBMs occurred at the age of 11 months, whereas a similar significant change in manual lateralization for “difficult” RDBMs occurred, as it was hypothesized, at the age of13 months. Thus, a hand preference for “simple” RDBMs seems to appear about two months before a hand preference for “difficult” RDBMs. We conclude that the difficulty of the skill defines the timing of lateralization of the skill, which fits with the cascade theory of hand preference development (cf., Michel, 2002; Michel, Babik, Nelson, Campbell, & Marcinowski, 2013).

In summary, this is the first study with a large sample of infants, divided into equal groups of infants with a known hand-use preference (right, left, and no preference)for acquiring objects, whose RDBM skills (including the establishment of a hand preference) were assessed longitudinally, with a large number of RDBM eliciting items (20), across six age periods. The frequency of RDBM actions increased during the 9–14 month period with no significant differences in trajectories among infants with different hand preference for object acquisition. The hand preference for role-differentiated bimanual manipulation became more distinctive with age. A hand preference for “simple” RDBMs appeared about 2 months sooner than a hand preference for “difficult” RDBMs. Differences in the developmental trajectories of hand preferences for RDBM were observed in later developing “difficult” RDBMs, but not in earlier developing “simple” RDBMs, for infants with different hand p references for object acquisition. Therefore, we propose that hand preferences for acquiring objects influence the development of hand-use preferences for “difficult” RDBMs. Hence, future research should examine separately the developmental trajectories of “simple” and “difficult” RDBMs. Moreover, future research must examine the development of hand preferences beyond 14 months of age and in relation to maternal hand preference in order to clarify the relation of left-hand preferences for acquisition to the hand preferences for RDBM.

Notes

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