Development of role-differentiated bimanual manipulation in infancy: Part 3. Its relation to the development of bimanual object acquisition and bimanual non-differentiated manipulation

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Abstract:

This third paper in a series of three related developmental trajectories of bimanual object acquisition and non-differentiated bimanual manipulation (NDBM) to patterns of role-differentiated bimanual manipulation(RDBM) development to help identify the sequence of events that might predict (and potentially facilitate) the development of RDBM skill. Ninety infants were tested monthly from 6 to 14 months of age for object acquisition, and from 9to14 months for NDBM and RDBM. The results did not support the hypothesis proposing that the onset of RDBM would require decoupling of the hands in unimanual acquisition, but supported the prediction that coupling of the hands in bimanual acquisition would predict increasing expertise in the RDBM skill. The relation between the bimanual object acquisition and RDBM was found to be mediated by NDBM, which prompts the hypothesis that bimanual acquisition of objects facilitates the development of NDBM, which, in its turn, facilitates the development of the RDBM skill. ß 2015 Wiley Periodicals, Inc. Dev Psychobiol58:268–277, 2016.

Keywords: bimanual manipulation | reaching | development | infancy

Article:

Introduction

Role-differentiated bimanual manipulation (RDBM)requires complementary and intermanually coordinated movements of both hands which become more efficient with interhemispheric communication through the corpus callosum (Jeeves, Silver, & Milne, 1988; Sacco, Moutard, & Fagard, 2006; Trevarthen,1978). Thus, patterns of development of RDBM skills may serve as a possible marker of more efficient callosal functioning (Fagard, Hardy, Kervella, &Marks, 2001; Kim merle, Mick, & Michel, 1995;Wolff, Mi chel, & Ovrut, 1990) which, in turn, contributes to the hemispheric specialization that is common in neurobehavioral functioning.

RDBM is a bimanual skill that develops gradually during the first two years of the child's life, from non-differentiated bimanual movements through partially differentiated movements to complex patterns of hand-use differentiation (e.g., de Schonen, 1977; Fagard, 1998; Fagard & Jacquet, 1989; Fagard & Marks, 2000; Fagard & Pezé, 1997). Differentiation here means a distinct division of roles between the two hands: completely differentiated with one hand playing a supporting role, and the other preforming an active manipulation; non-differentiated with both hands playing active manipulating roles; and partially differentiated with the alternation between the roles of the two hands, such that they are neither completely differentiated nor are they undifferentiated. Before 11 months, the infant's manipulation of objects often produces "in-phase" or mirror movements, whereas "anti-phase", or parallel, movements are minor occurrences in the infant's repertoire because, supposedly, they demand higher levels of intermanual coordination (Kelso, Putnam, & Goodman, 1983) and, thus, depend on more extensive interhemispheric communication. Beginning at 11 months, however, infants engage in more parallel (non-mirror) actions that necessitate complementary actions performed by both hands (Goldfield & Michel, 1986). Thus, the appearance of incomplete differentiation of manual control of the hands may precede the onset of role differentiation in the manual repertoire of infants.

The onset of symmetrical bimanual manipulation before the onset of asymmetrical manipulation was observed by Fagard and Jacquet (1989) who concluded that whereas symmetrical bimanual actions in the infant's repertoire typically can be observed as early as the age of 9-10 months, more complex RDBM actions requiring complete differentiation between the two hands (e.g., unscrewing a cap from a container) are manifested by infants only at 18-24 months. Fagard and Lockman (2005) reported that only 64% of infants performed RDBM actions at the age of 12 months, whereas 100% of infants manifested fully differentiated hand-use for RDBM at the age of 18 months. Similarly, Ramsay and Weber (1986) proposed the "progressive differentiation" of bimanual coordination, based on results showing that only 50% of the bimanual actions performed by 12-13-month-old infants are completely differentiated, whereas at the age of 17-19 months 78% of the infant bimanual actions become completely differentiated. Kimmerle, Ferre, Kotwica, and Michel (2010) reported that RDBMs comprise less than 10% of the infant's manual repertoire with toys at 7 months of age (unimanual actions dominate at more than 50% and non-differentiated bimanual manipulations (NDBM) represent about 40% of the infant's manual engagement with toys). By 13 months, RDBM represents about 20% of the repertoire with declines in both unimanual and NDBM actions, but with unimanual actions declining the most.

Previous research suggested that asymmetrical coordination between the two hands in bimanual manipulation becomes possible with a decrease in intermanual coupling. Thus, Fagard and Pezé (1997) observed a significant decrease in infants' bimanual reaches just before the onset of successful role-differentiated bimanual manipulation at the age of 7 months. They concluded that the increased independence between hands (demonstrated in reaching) facilitates the onset of complementary movements of the two hands necessary for successful RDBM. A similar conclusion had been proposed previously by others (Diamond, 1991; Goldfield & Michel, 1986).

Previous research also reported that the frequency of bimanual reaches increases by the end of the infant's first year (Babik, Campbell, & Michel, 2014; Corbetta & Bojczyk, 2002; Corbetta & Thelen, 1996; Fagard & Pezé, 1997), and associated this increase with the development of role-differentiated bimanual manipulation (Babik et al., 2014; Fagard & Pezé, 1997; Goldfield & Michel, 1986). It was suggested that as infants become more proficient in asymmetrical bimanual manipulation of objects, they might begin acquiring objects bimanually in order to immediately start the “anticipated” object manipulation – the non-preferred hand being positioned for support, and the preferred hand being ready for active manipulation of the object (Babik et al., 2014; Fagard & Pezé, 1997; Ferre, Babik, & Michel, 2010; Goldfield & Michel, 1986). Although the latter hypothesis is persuasive, it has never been examined systematically in previous research.

Thus, the development of RDBM may derive from two alternative hypotheses: One proposing that the onset of RDBM requires decoupling of the hands to produce unimanual acquisition, and the other proposing coupling of the hands for bimanual acquisition as a sign of increasing expertise in the RDBM skill. In the current study, we investigated developmental trajectories of bimanual acquisition and tested whether patterns of bimanual acquisition development would relate to the development of both non-differentiated bimanual manipulation and role-differentiated bimanual manipulation. These analyses would provide evidence about whether the onset of RDBM and emergence of the RDBM skill (estimated by both the number of performed RDBM actions, as well as by the level of manual lateralization manifested in this skill) are associated with the increase or decrease in bimanual acquisition. Furthermore, in an attempt to extend our understanding of the factors relating to the development of RDBM skill, we explored developmental trajectories of NDBM and examined whether patterns of NDBM development relate to patterns of RDBM development, and whether NDBM might mediate the relation between bimanual acquisition and RDBM.

Methods

Participants

As discussed in paper 2 (Babik & Michel, this issue), we implemented two different procedures: the unimanual procedure that used toys not readily affording RDBM and the bimanual procedure that used toys affording RDBM. For each observation visit, we recorded each infant's: 1) hand choice for object acquisition (right, left, or both) in the unimanual procedure; 2) hand choice for object acquisition (right, left, or both) in the bimanual procedure; 3) number of performed NDBMs; 4) number of performed RDBMs; 5) the choice of manipulating hand (right or left) for RDBM. It should be noted that the unimanual procedure was tested during the age range from 6 to 14 months of age, whereas the bimanual procedure was tested during the age range from 9 to 14 months. For additional details on this paper's procedure and measures, see methods in Babik & Michel (Part I, this issue).

Measures

The proportion of bimanual object acquisitions [$BIM\_ACQ = B/(R + L + B)$] was estimated as a ratio of the number of bimanual object acquisitions (B in formula) over the total number of acquisitions across all toy presentations calculated for each infant at each monthly visit. Multilevel analyses (HLM; Raudenbush, Bryk, Cheong, Congdon, & du Toit, 2004) were used to relate developmental trajectories of bimanual acquisition to those of NDBM and RDBM, and to relate developmental trajectories of NDBM to those of RDBM. Finally, using the Sobel test (MacKinnon & Dwyer, 1993; MacKinnon, Warsi, & Dwyer, 1995; Sobel, 1982) and the Aroian version of the Sobel test (Aroian, 1944; Baron & Kenny, 1986), we examined the hypothesis that NDBM mediates the relation between bimanual acquisition and RDBM.

Results

First, we explored developmental trajectories of bimanual object acquisition during 6- to 14-month period. The final estimated model (Table 1, Fig. 1) suggested that the proportion of bimanual object acquisitions among all acquisitions had a quadratic trend of change, decreasing from the age of 6 months to approximately 9–10 months, and increasing thereafter. Lateralized (right- and left-hand preferring) infants tended to perform fewer bimanual object acquisitions in their repertoire as compared to those without a distinct hand-use preference during the entire 9- to 14-month period. Also, lateralized infants started increasing their bimanual object acquisition later than infants without a stable hand-use preference. Thus, the lowest point in the estimated trajectory of change in the proportion of bimanual object acquisitions appears to occur at the age of 10 months in right- and left-handers (67% of infants), and at the age of 9 months in no preference infants (33% of infants).

Level 1 Effects	Level 2 Effects	Parameters	Model Estimates
Fixed Effects			
Initial status, π_{0i}	Intercept	β_{00}	0.790***
	HS2	β_{01}	−0.083
AGE, π_{1i}	Intercept	β_{10}	−0.103***
	HS2	β_{11}	0.015**
$(AGE)^2$, π_{2i}	Intercept	β_{20}	0.005***
Random Effects			
Level 1:	Within-person, ε_{ij}	σ_{ε}^2	0.016
Level 2:	Intercept, δ_{0i}	σ_0^2	0.039***
	AGE, δ_{1i}	σ_1^2	0.0002***

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

Table 1. Estimated Fixed and Random Effects for the Proportion of Bimanual Object Acquisitions

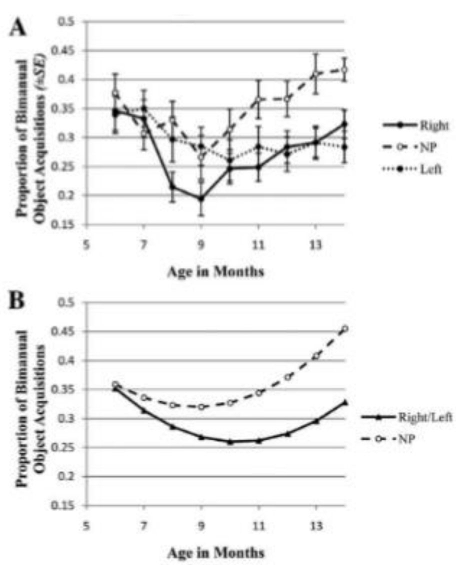

Figure 1. Observed (A) and estimated (B) trajectories of change in the proportion of bimanual object acquisitions in infants with different hand-use preference; NP ¼ no preference; Right/Left ¼ right- and left-hand preferring infants.

Next, we investigated developmental trajectories of non-differentiated bimanual manipulation during 9- to 14-month period. The final estimated model (Table 2, Fig. 2) suggested a significant quadratic trend of change in NDBM in all hand-use preference groups. In lateralized infants, the average number of NDBMs increased from 9 to 14 months, whereas in infants without a stable hand-use preference it increased from 9 to 12 months, and decreased thereafter. The average number of NDBMs varied from 1.5–2 per infant at 9 months to 3–4 per infant at 14 months. Thus, infants generally performed rather few NDBM actions.

Level 1 Effects	Level 2 Effects	Parameters	Model Estimates
Fixed Effects			
Initial status, π_{0i}	Intercept	β_{00}	2.414
	HS2	β_{01}	−30.168**
AGE, π_{1i}	Intercept	β_{10}	−0.279
	HS2	β_{11}	5.515**
$(AGE)^2$, π_{2i}	Intercept	β_{20}	0.025
	HS2	β_{21}	−0.243**
Random Effects			
Level 1:	Within-person, ε_{ij}	σ_{ε}^2	5.036
Level 2:	Intercept, δ_{0i}	σ_0^2	38.581***
	AGE, δ_{1i}	σ_1^2	0.361***

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

Table 2. Estimated Fixed and Random Effects for the Number of NDBMs

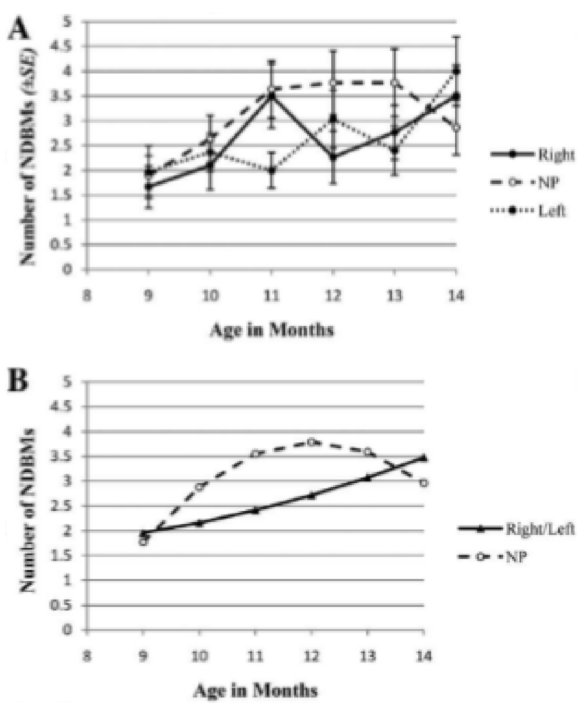

Figure 2 Observed (A) and estimated (B) trajectories of change in the number of NDBMs in infants with different hand preference; NP ¼ no preference; Right/Left ¼ right- and left-hand preferring infants.

We tested whether patterns of bimanual object acquisition development relate to those of NDBM development. According to the final model (Table 3, Fig. 3), no differences in the trajectory of change in the number of NDBMs were identified among infants with different hand-use preference for acquiring objects (HS1: $t(87) = -0.135$, $p = .893$; HS2: $t(87) = 0.209$, $p = .835$). Also, the proportion of bimanual object acquisitions was positively related to the number of NDBMs during 9- to 14-month period (Table 3); that is a higher proportion of bimanual object acquisitions in the repertoire of the infant was associated with a higher number of performed NDBMs, irrespective of age and hand preference (Pearson correlation: $r(538) = .233$, $p < .0001$). This association, however, could be affected by the high number of zeros for the NDBM, although we still observed positive correlation even when all zero values for NDBM were removed from the analysis (Pearson correlation: $r(415) = .104$, $p = .033$).

Level 1 Effects	Level 2 Effects	Parameters	Model Estimates
Fixed Effects			
Initial status, π_{0i}	Intercept	β_{00}	1.624***
BIM_ACQ, π_{1i}	Intercept	β_{10}	3.869***
Random Effects			
Level 1:	Within-person, ε_{ij}	σ_{ε}^2	6.418
Level 2:	Intercept, δ_{0i}	σ_0^2	2.237***

Note. ***$p < .001$

Table 3. Estimated Fixed and Random Effects for the Number of NDBMs According to the Proportion of Bimanual Object Acquisitions

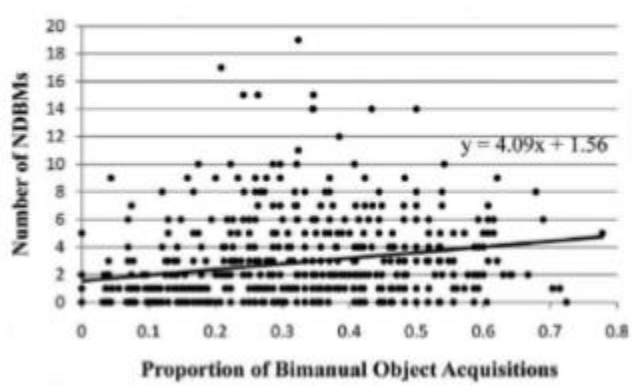

Figure 3 Observed (scatterplot) and estimated (trend-line) number of NDBMs according to the proportion of bimanual object acquisitions.

When patterns of bimanual object acquisition development were examined in relation to patterns of RDBM development, the multilevel analysis showed that the proportion of bimanual object acquisitions positively related to the number of performed RDBMs (Table 4, Fig. 4); that is, a larger proportion of bimanual object acquisitions performed by the infant was associated with a higher frequency of role-differentiated bimanual manipulations in the repertoire of the infant (Pearson correlation: r(538) = .214, p < .0001).

Level 1 Effects	Level 2 Effects	Parameters	Model Estimates
Fixed Effects			
Initial status, π_{0i}	Intercept	β_{00}	18.585***
BIM_ACQ, π_{1i}	Intercept	β_{10}	12.652***
Random Effects			
Level 1:	Within-person, ε_{ij}	σ_{ε}^2	69.432
Level 2:	Intercept, δ_{0i}	σ_0^2	29.432***

Note. ***$p < .001$

Table 4. Estimated Fixed and Random Effects for the Number of RDBMs According to the Proportion of Bimanual Object Acquisitions

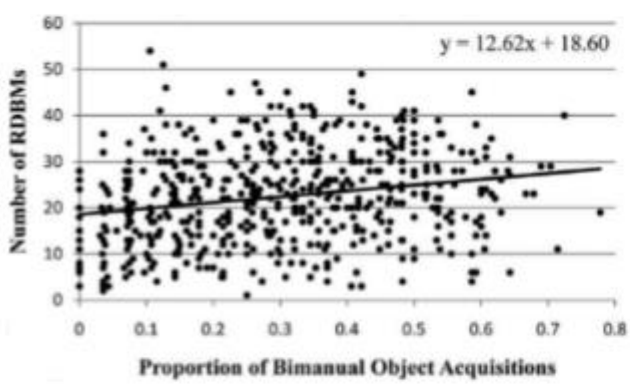

Figure 4 Observed (scatterplot) and estimated (trend-line) number of RDBMs according to the proportion of bimanual object acquisitions.

We explored whether patterns of NDBM development relate to patterns of RDBM development. The multilevel analysis showed that the number of performed role-differentiated bimanual manipulations positively related to the number of performed non-differentiated bimanual manipulations (Table 5, Fig. 5). Thus, infants who performed more NDBMs also performed more RDBMs (Pearson correlation: r(538) = .204, p < .0001). Again, the rather small number of instances of NDBM may be influencing this association, although we still observed positive correlation even when all zero values for NDBM were removed from the analysis (Pearson correlation: r(415) = .118, p = .016).

Level 1 Effects	Level 2 Effects	Parameters	Model Estimates
Fixed Effects			
Initial status, π_{0i}	Intercept	β_{00}	20.614***
NDBM, π_{1i}	Intercept	β_{10}	0.635***
Random Effects			
Level 1:	Within-person, ε_{ij}	σ_{ε}^2	69.715
Level 2:	Intercept, δ_{0i}	σ_0^2	29.531***

Note. $^{***}p < .001$

Table 5. Estimated Fixed and Random Effects for the Number of RDBMs According to the Number of NDBMs

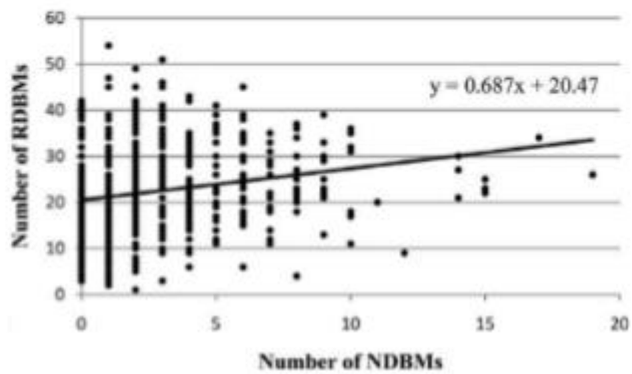

Figure 5 Observed (scatterplot) and estimated (trend-line) number of RDBMs according to the number of NDBMs.

In order to more directly examine whether the observed change in the number of RDBMs is associated with the frequency of performed bimanual object acquisitions and/or NDBMs, we compared developmental trajectories of the number of RDBMs in groups of infants performing fewer vs. more bimanual object acquisitions and fewer vs. more NDBMs. First, we estimated the average proportion of bimanual object acquisitions for 6- to 11-month period for each participant (M = 0.298 (meaning that approximately 29.8% of all object acquisitions during this period are bimanual), Mdn = 0.296, SD = 0.126, range = 0.042–0.615). Second, we ranked all participants according to their average proportion of bimanual object acquisitions, and then compared developmental trajectories of the number of RDBMs between the top and bottom thirds of the sample. The same procedure was repeated for the average number of NDBMs performed by each participant during 9- to 11-month period (M = 2.419, Mdn = 2, SD = 0.1.933, range = 0–9.333). Although RDBM as a skill was reported to emerge only after the age of 11 months (Kimmerle et al., 2010), in order to obtain a more complete account of RDBM development, we explored the trajectories of the number of performed RDBMs in the entire 9- to 14-month period.

Using multilevel modeling, we compared trajectories of change in the number of RDBMs in infants with a low frequency of bimanual object acquisitions (n = 30; M = 0.162; Mdn = 0.176, SD = 0.062, range = 0.042–0.245) and in infants with a high frequency of bimanual object acquisitions (n = 30; M = 0.434; Mdn = 0.415, SD = 0.075, range = 0.340–0.615). In the multilevel model, we included the categorical dummy-coded variable BIM_ACQ_C reflecting the frequency of performed bimanual object acquisitions (0–low, 1–high). The final estimated model (Table 6, Fig. 6A) showed that infants, who, compared to their peers, performed more bimanual object acquisitions during 6- to 11-month period, also performed more RDBMs during the 9- to 14-month period.

Level 1 Effects	Level 2 Effects	Parameters	Model Estimates
Fixed Effects			
Initial status, π_{0i}	Intercept	β_{00}	−7.124*
	BIM_ACQ_C	β_{01}	−8.611
AGE, π_{1i}	Intercept	β_{10}	2.420***
	BIM_ACQ_C	β_{11}	0.931*
Random Effects			
Level 1:	Within-person, ε_{ij}	σ_{ε}^2	33.321
Level 2:	Intercept, δ_{0i}	σ_0^2	158.890**
	AGE, δ_{1i}	σ_1^2	1.231**

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

Table 6. Estimated Fixed and Random Effects for the Number of RDBMs According to the Level (Low vs. High) of Bimanual Object Acquisitions Performed During 6- to11-Month Period

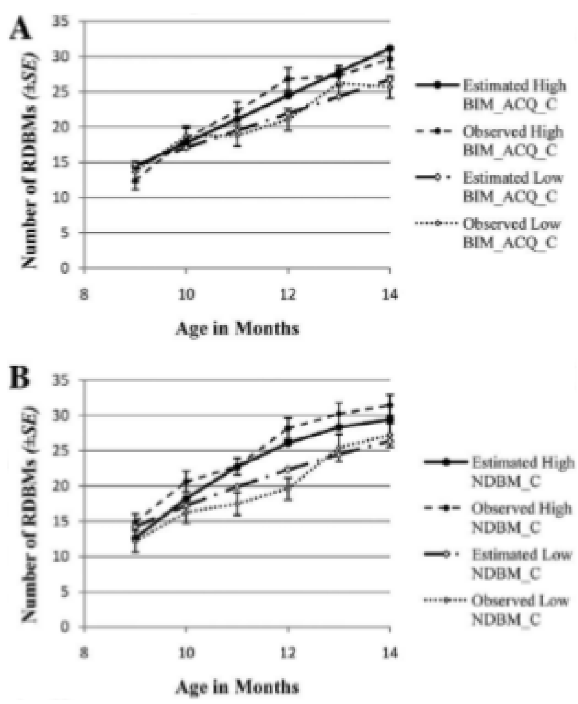

Figure 6 Observed and estimated number of RDBMs according to the level (low vs. high) of bimanual object acquisitions (A) and NDBM (B); High BIM_ACQ_C = group of infants performing more bimanual object acquisitions; Low BIM_ACQ_C = group of infants performing fewer bimanuall object acquisitions; High NDBM_C = group of infants per-forming more NDBMs; Low NDBM_C ¼ group of infants performing fewer NDBMs.

Then, we compared trajectories of change in the number of RDBMs for infants with a low frequency of NDBMs (n = 30; M = 0.567; Mdn = 0.667, SD = 0.352, range = 0–1) with the trajectories of RDBM for infants with a high frequency of NDBMs (n = 30; M = 4.578; Mdn = 4, SD = 1.630, range = 3–9.333). In the multilevel model, we included the categorical dummy-coded variable NDBM_C reflecting the frequency of performed NDBM (0–low, 1–high). The final estimated model (Table 7, Fig. 6B) showed that infants, who, compared to their peers, performed more NDBMs during 9- to 11-month period, also performed more RDBMs during the 9- to 14-month period.

Level 1 Effects	Level 2 Effects	Parameters	Model Estimates
Fixed Effects			
Initial status, π_{0i}	Intercept	β_{00}	−24.754
	NDBM_C	β_{01}	−64.271*
AGE, π_{1i}	Intercept	β_{10}	5.555†
	NDBM_C	β_{11}	10.830*
AGE^2, π_{2i}	Intercept	β_{20}	−0.136
	NDBM_C	β_{21}	-0.430*
Random Effects			
Level 1:	Within-person, ε_{ij}	σ_ε^2	31.998
Level 2:	Intercept, δ_{0i}	σ_0^2	169.412***
	AGE, δ_{1i}	σ_1^2	1.308***

Note.† $p < .10$; * $p < .05$; *** $p < .001$

Table 7. Estimated Fixed and Random Effects for the Number of RDBMs According to the Level (Low vs. High) of NDBM Performed During 9- to 11-Month Period

Finally, we examined whether NDBM mediates the relation between the bimanual object acquisition and RDBM. Since previous research suggested that 12 months is the age of emergence of the RDBM skill (e.g., Kimmerle et al., 2010), we included in the analysis the development of the bimanual acquisition and NDBM (as predictors) before 12 months, and the development of RDBM starting at 12 months. Thus, for the mediation analysis we used each participant's mean proportion of bimanual acquisitions across 6 months during 6- to 11-month period, the mean of the total number of NDBMs across 3 months during 9- to 11-month period, and the mean of the total number of RDBMs across 3 months during 12- to 14-month period (M = 26.804; Mdn = 27.833, SD = 7.448, range = 6.333–41).

To judge whether or not mediation occurs, MacKinnon and Dwyer (1993), as well as MacKinnon et al. (1995) suggested checking the following criteria: (1) the independent variable (BIM_ACQ) significantly affects the potential mediator (NDBM) (and it does – βa = 4.545, SE = 1.564, t = 2.905, p = .005); (2) the independent variable (BIM_ACQ) significantly affects the dependent variable (RDBM) in the absence of the mediator (NDBM) (and it does – math formula = 16.244, SE = 6.068, t = 2.677, p = .009), (3) the potential mediator has a significant unique effect on the dependent variable (and it does – math formula = 1.398, SE = 0.383, t = 3.652, p < .0001); and (4) the effect of the independent variable (BIM_ACQ) on the dependent variable (RDBM) shrinks upon the addition of the mediator (NDBM) to the model (and it does – math formula = 10.840, SE = 6.081, t = 1.783, p = .078). In addition, we tested the effect of the potential mediator (NDBM) on the dependent variable (RDBM) while controlling for the independent variable (BIM_ACQ) – math formula = 1.189, SE = 0.396, t = 3.004, p = .003. As we see, all of the above mentioned criteria for potential mediation were satisfied, which allowed us to evaluate our mediation model using the Sobel test (MacKinnon & Dwyer, 1993; MacKinnon et al., 1995; Sobel, 1982).

Sobel test statistic equaled 2.088 (p = .037), whereas the Aroian version of the Sobel test, that does not make the unnecessary assumption that the product of SEa and SEb2 is negligibly small (Aroian, 1944; Baron & Kenny, 1986), produced the test statistic 2.031 (p = 0.042). Thus, we concluded that the relation between the bimanual object acquisition and RDBM is mediated by NDBM (Figure 7).

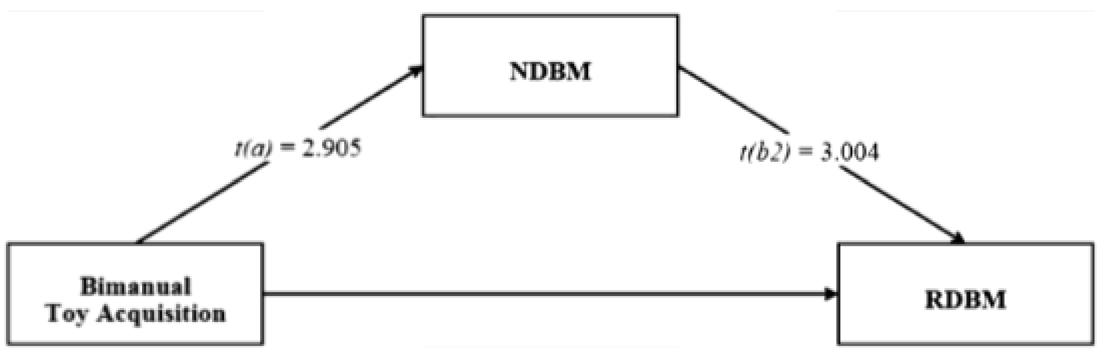

Figure 7 T-test statistics for the relation between bimanual object acquisition and RDBM as mediated by NDBM.

Discussion

The goal of the current study was to examine the potential influence of bimanual acquisition development and non-differentiated bimanual manipulation development on the developmental trajectories of role-differentiated bimanual manipulation. Does bimanual acquisition and NDBM facilitate later development of RDBM? Does NDBM mediate the relation between bimanual acquisition and RDBM? These questions, among others, were examined in the current paper.

First, we explored developmental trajectories of bimanual object acquisition during 6- to 14-month period. The proportion of bimanual object acquisitions out of the total number of object acquisitions decreases with age from 6 to approximately 9–10 months, and increases thereafter until the age of 14 months in all infants. It should be noted that Fagard and Pezé (1997) reported the lowest point of the bimanual acquisition trajectory at the age of 7 months, and an increase in bimanual acquisition from 7 to 11 months. Based on their finding, Fagard and Pezé (1997) concluded that first RDBM actions observed at the age of approximately 7 months (in other words, the onset of RDBM) correspond to the decoupling of hands in reaching. In contrast, our results suggest that the frequency of bimanual acquisition at the age of 7 months (presumably the onset of RDBM) is quite high and roughly equals that at the end of the first year (the average proportion of bimanual acquisitions at 7 months is 0.330 (meaning that on average 33% of all acquisitions are bimanual), and at 12 months is 0.307). Thus, our results did not support the hypothesis that the onset of RDBM would require decoupling of the hands.

Second, we investigated developmental trajectories of non-differentiated bimanual manipulation during 9- to 14-month period. These trajectories vary depending on the hand preference of the infant – the average number of performed NDBMs increases during the entire 9- to 14-month period in lateralized (right- and left-hand preferring) infants, whereas in infants without a stable hand preference it increases from 9 to 12 months, and decreases thereafter.

Furthermore, the proportion of bimanual object acquisitions was found to be positively related to the average number of performed NDBMs and RDBMs during 9- to 14-month period; that is, a higher proportion of bimanual object acquisitions performed by the infant predicts a higher number of both NDBMs and RDBMs by the infant. Since toys have to be acquired before manipulation can occur, we have chosen to describe the relation between bimanual acquisitions and NDBMs and RDBMs as predictive. A similar positive relation was observed between the number of performed NDBMs and RDBMs; that is infants performing more NDBMs also had more RDBMs in their repertoire. However, we must note that the frequency of NDBMs was quite low generally and, therefore, this result requires confirmation by additional research.

The relation between bimanual acquisition and RDBM, as well as between NDBM and RDBM was explored by comparing the developmental trajectories of the frequency of manifestation of RDBMs between infants with low vs. high frequencies of both bimanual acquisitions and NDBMs. We found that infants performing more bimanual object acquisitions during 6- to 11-month period performed more RDBMs during the 9- to 14-month period. The same association was true for NDBM; that is infants performing more NDBMs during 9- to 11-month period performed more RDBMs during the 9- to 14-month period. Thus, we suggest that the development of both bimanual acquisition and non-differentiated bimanual manipulation might be important precursors for the development of role-differentiated bimanual manipulation.

We observed that infants without a stable hand-use preference on average perform more bimanual object acquisitions and more non-differentiated bimanual manipulations when compared to infants with a hand preference. If both the proportion of bimanual object acquisitions and the average number of performed NDBMs positively relate to the average number of performed RDBMs, infants without a stable hand preference should be expected to develop the skill of RDBM faster, performing more RDBM actions, and doing this sooner than infants with a hand preference. However, developmental trajectories of the total number of performed RDBM actions do not differ between infants according to their hand-use preference (Babik & Michel, Part 1, this issue). Since frequency of NDBMs was quite low, future research should address this inconsistency by using tasks that increase the frequency of NDBMs.

Both the Sobel and the Aroian tests showed that the relation between the proportion of bimanual object acquisitions and the number of performed RDBMs is mediated by the number of NDBMs. Thus, bimanual acquisition of objects likely facilitates the development of non-differentiated bimanual manipulation, which, in its turn, likely facilitates the development of the RDBM skill.

We also tested the hypothesis proposing coupling of the hands for bimanual acquisition as a sign of increasing expertise in the RDBM skill (Babik et al., 2014; Corbetta & Bojczyk, 2002; Corbetta & Thelen, 1996; Fagard & Pezé, 1997). Previous research suggested that the onset of a manual skill (e.g., skill or expertise in RDBM), can be determined either by the peak of performance (estimated by the number of performed actions) or by the peak of the hand preference for this skill (Michel, Babik, Nelson, Campbell, & Marcinowski, 2013a; Michel, Nelson, Babik, Campbell, & Marcinowski, 2013b). Using the peak of performance, we observed that the total number of RDBM actions gradually increases with age during 9- to 14-month period (Babik & Michel, Part 1, this issue). Thus, the onset of RDBM skill (or expertise) occurs at the age of 13-14 months (this is consistent with Kimmerle et al., 2010) and this corresponds with the presumably highest level of coupling between the hands, as manifested by the highest proportion of bimanual acquisitions in the repertoire of infants. When the peak of the hand preference is used for the onset of RDBM skill, we observed that the hand preference for RDBM first appeared at 10–11 months in "simple" RDBM actions (pokes, strokes), which might not require understanding of object affordances, and then at approximately 13 months the hand preference appeared in more sophisticated "difficult" RDBM actions (pull, insert, spin, push), which might require understanding the relations among objects and the "planning" of actions (Babik & Michel, Part 1, this issue). Thus, for either measure, we suggest that the onset of RDBM skill corresponds with the increasing coupling of the hands manifested by the increase in the proportion of bimanual object acquisitions.

Thus, both mediation analysis and the examination of RDBM development according to the frequencies of bimanual acquisition and NDBM, support the hypothesis that the development of RDBM is not only associated with the bimanual acquisition and non-differentiated bimanual manipulation, but also that RDBM development may require previous experience with bimanual acquisition and non-differentiated bimanual manipulation.

A Comprehensive View of the RBDM Development: The Three Papers

The current series of three papers discussed the development of RDBM skill and hand preference for RDBM. Results suggested that it is important to differentiate between "simple" and "difficult" RDBMs, since the latter are more likely to represent more sophisticated "planned" actions, and better reflect infants' lateralization for role-differentiated bimanual manipulation. A hand-use preference for RDBM was found to become more prominent with age. Thus, right-hand preference infants and those without a hand preference for acquiring objects significantly increased in their right-hand use for "difficult" RDBMs with age. In contrast, the group of infants with a left-hand preference for object acquisition was more heterogeneous in their trajectories of RDBM hand preference 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, the frequency of RDBM actions is still quite low during these ages, typically representing only 20% of the infant's manual repertoire when engaging with objects (Kimmerle et al., 1995). Therefore, hand preferences for RDBM may be less effectively measured even at 13–14 months of age. Assessments of hand preferences for RDBM during the age period from 18 to 24 months, when such actions are much more frequent, revealed rather stable preferences (Nelson, Campbell, & Michel, 2013).

Moreover, a significant increase in RDBM lateralization occurred at the age of 10–11 months for "simple" RDBMs, and at 12–13 months for "difficult" RDBMs. Thus, the timeline of lateralization for a skill (in this case hand preference for RDBM) seems to be defined by the difficulty of that skill, which fits with the cascade theory of hand preference development.

Since the infant's hand preference for acquiring objects was related to the hand preference for "difficult" RDBMs, but not for "simple" RDBMs, these two types of RDBM might provide different information about how RDBM develops. As predicted by the cascade theory of hand preference development (Michel et al., 2013b), a hand preference for earlier developing manual skills (e.g., object acquisition) would concatenate into a hand preference for later developing manual skills (e.g., RDBM). Moreover, infants with a hand preference for acquiring objects decreased the use of their preferred hand for object acquisition after the age of 12 months, which coincided with the development of a hand preference for sophisticated RDBM actions. Thus, we conclude that at the age of 12 months infants might begin to discern RDBM affordances of objects and consequently they begin to adjust their manual activity toward acquiring objects with their non-preferred hand so as to more efficiently use their preferred hand for active manipulation for the more sophisticated RDBM actions.

Finally, our results support the interpretation that bimanual acquisition of objects facilitates the development of non-differentiated bimanual manipulation, which, in turn, facilitates the development of the RDBM skill. That increase in RDBM skill results in the manifestation of a hand preference, and that hand preference is likely derived from the earlier developing hand preference for acquiring objects. Future research must examine the development of hand preferences for RDBM during the age period from 12 to 20 months in order to strengthen the link between hand preferences for RDBM that begin to manifest by 13–14 months and those that are robust for the age period from 18 to 24 months (Nelson et al., 2013).

Notes

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References

Aroian, L. A. (1944). The probability function of the product of two normally distributed variables. Annals of Mathematical Statistics, 18, 265–271. DOI: 10.1214/aoms/1177730442

Babik, I., Campbell, J. M., & Michel, G. F. (2014). Postural influences on the development of infant lateralized and symmetrical hand-use. Child Development, 85, 294–304.DOI: 10.1111/cdev.12121

Baron, R. M., & Kenny, D. A. (1986). The moderator-mediator variable distinction in social psychological research: Conceptual, strategic, and statistical considerations. Journal of Personality and Social Psychology, 51,1173–1182. DOI: 10.1037/0022-3514.51.6.1173

Corbetta, D., & Bojczyk, K. E. (2002). Infants return to two-handed reaching when they are learning to walk. Journal of Motor Behavior, 34, 83–95. DOI: 10.1080/00222890209601933

Corbetta, D., & Thelen, E. (1996). The developmental origins of bimanual coordination: A dynamic perspective. Journal of Experimental Psychology: Human Perception and Performance, 22, 502–522. DOI: 10.1037/0096-1523.22.2.502

de Schonen, S. (1977). Functional asymmetries in the development of bimanual coordination in human infants. Journal of Human Movement Studies, 3, 144–156.

Diamond A., (1991). Neuropsychological insights into the meaning of object concept development. In S. Carey, & R. Gelman, (Eds.), The epigenetics of mind: Essays on biology and cognition (pp. 67–110). Hillsdale, NJ: Erlbaum.

Fagard J., (1998). Changes in grasping skills and the emergence of bimanual coordination during the first year of life. In K. J. Connoly, (Ed.), Psychobiology of the hand (pp. 123–143). London: Mac Keith Press.

Fagard, J., Hardy, I., Kervella, C., & Marks, A. (2001).Changes in interhemispheric transfer and the development of bimanual coordination. Journal of Experimental Child Psychology, 80, 1–22. DOI: 10.1006/jecp.2000.2623

Fagard, J., & Jacquet, A. Y. (1989). Onset of bimanual coordination and symmetry versus asymmetry of movement. Infant Behavior and Development, 12, 229–235.DOI: 10.1016/0163-6383(89)90009-X

Fagard, J., & Lockman, J. J. (2005). The effect of task constraints on infants' (bi) manual strategy for grasping and exploring objects. Infant Behavior and Development,28, 305–315. DOI: 10.1016/j.infbeh.2005.05.005

Fagard, J., & Marks, A. (2000). Unimanual and bimanual tasks and the assessment of handedness in toddlers. Developmental Science, 3, 137–147. DOI: 10.1111/1467-7687.00107

Fagard, J., & Pezé, A. (1997). Age changes in interlimb coupling and the development of bimanual coordination. Journal of Motor Behavior, 29, 199–208. DOI: 10.1080/00222899709600835

Ferre, C. L., Babik, I., & Michel, G. F. (2010). Development of infant prehension handedness: A longitudinal analysis during the 6- to 14-month age period. Infant Behavior and Development, 33, 492–502. DOI: 10.1016/j.infbeh.2010.06.002

Goldfield, E. C., & Michel, G. F. (1986). Spatiotemporal linkage in infant interlimb coordination. Developmental Psychobiology, 19, 259–264. DOI: 10.1002/dev.420190311

Jeeves, M. A., Silver, P. H., & Milne, A. B. (1988). Role of the corpus callosum in the development of a bimanual motor skill. Developmental Neuropsychology, 4, 305–323.DOI: 10.1080/87565648809540415

Kelso, J. A. S., Putnam, C. A., & Goodman, D. (1983). On the space-time structure of human inter-limb coordination. Quarterly Journal of Experimental Psychology, 35(A),347–375. DOI: 10.1080/14640748308402139

Kimmerle, M., Ferre, C. L., Kotwica, K. A., & Michel, G. F.(2010). Development of role-differentiated bimanual manipulation during the infant's first year. Developmental Psychobiology, 52, 168–180. DOI: 10.1002/dev.20428

Kimmerle, M., Mick, L. A., & Michel, G. F. (1995). Bimanual role-differentiated toy play during infancy. Infant Behavior and Development, 18, 299–307. DOI:10.1016/0163-6383(95)90018-7

MacKinnon, D. P., & Dwyer, J. H. (1993). Estimating mediated effects in prevention studies. Evaluation Review,17, 144–158. DOI: 10.1177/0193841x9301700202

MacKinnon, D. P., Warsi, G., & Dwyer, J. H. (1995). A simulation study of mediated effect measures. Multivariate Behavioral Research, 30, 41–62. DOI: 10.1207/s15327906mbr3001_3

Michel, G. F., Babik, I., Nelson, E. L., Campbell, J. M., & Marcinowski, E. C. (2013a). How the development of handedness could contribute to the development of language. Developmental Psychobiology, 55, 608–620. DOI:10.1002/dev.21121.

Michel G. F., Nelson E. L., Babik I., Campbell J. M., & Marcinowski E. C. (2013b). Multiple trajectories in the developmental psychobiology of human handedness. In R. M. Lerner, & J. B. Benson, (Eds.), Embodiment and epigenesis: Theoretical and methodological issues in understanding the role of biology within the relational developmental system (Part B: Ontogenetic Dimensions. pp. 227–260). New York: Elsevier Inc.: Academic Press.

Nelson, E. L., Campbell, J. M., & Michel, G. F. (2013). Unimanual to bimanual: T racking the development of handedness from 6to 24 months. Infant Behavior and Development, 36, 181–188.DOI: 10.1016 /j.infbeh.2013.01.009

Ramsay, D. S., & Weber, S. L. (1986). Infants' hand preference in a task involving complementary roles for the two hands. Child Development, 57, 300–307.

Raudenbush S., Bryk A., Cheong Y. F., Congdon R., & du Toit M (2004). HLM 6: Hierarchical linear and nonlinear modeling. Lincolnwood, IL: Scientific Software International, Inc.

Sacco, S., Moutard, M. L., & Fagard, J. (2006). A genesis of the corpus callosum and the establishment of handed-ness. Developmental Psychobiology, 48, 472–481. DOI:10.1002/dev.20162

Sobel M. E., (1982). Asymptotic intervals for indirect effects in structural equations models. In S. Leinhart, (Ed.), Sociological methodology 1982 (pp. 290–312). San Francisco: Jossey-Bass.

Trevarthen C., (1978). Manipulative strategies of baboons and origins of cerebral asymmetry. In M. Kinsbourne, (Ed.), Asymmetrical function of the brain (pp. 101–139). NewYork: Cambridge University Press.

Wolff, P. H., Michel, G. F., & Ovrut, M. R. (1990). Rate and timing precision of motor coordination in developmental dyslexia. Developmental Psychology, 26, 82–89. DOI:10.1037/0012-1649.26.3.349